



Spatial distribution, bioaccessibility, and human health implications of potentially toxic elements in mining-impacted topsoils in Obuasi Municipality of Ghana

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Abstract Potential toxic elements emanating from extracted ores during gold processing present occupational and unintentional health hazards in communities, the general populace, and the environment. This study investigated the concentrations and potential health effects of metal content in the topsoils of Obuasi municipality, which has been mined for gold over the past century. Surface topsoil samples, sieved to 250 µm, were initially scanned for metals using x-ray fluorescence techniques, followed by confirmation via ICP-MS. In vitro bioaccessibility assays were conducted using standard methods. The geoaccumulation indices (I_{geo}) indicate high enrichment of As (I_{geo}=6.28) and Cd (I_{geo}=3.80) in the soils, especially in the eastern part of the municipality where illegal artisanal mining is prevalent. Additionally, the

southern corridor, situated near a gold mine, exhibited significant levels of As and Mn. Results obtained for the total metal concentrations and contamination indices confirmed the elevation of the studied potential toxic elements in the Obuasi community. A hazard index value of 4.42 and 3.30 among children and adults, respectively, indicates that indigens, especially children, are susceptible to non-cancer health effects.

Keywords Soil contamination · Environmental pollution · In-vitro bioaccessibility assay · Mining activities · Ecological risks

Introduction

Gold mining, particularly artisanal and small-scale mining, has increased rapidly due to a lack of alternative employment opportunities, the potential for high earnings, community development, and a lack of proper regulations (Painter, 2023). Roughly, 2 million people are actively engaged in artisanal and small-scale gold mining (ASGM) worldwide, supporting the livelihoods of over 20 million people and indirectly benefiting up to 100 million people (World Gold Council, 2022). The swift growth of gold mining has given rise to growing global public health concerns due to the toxic pollution it generates. Artisanal and small-scale gold mining operations are typically characterized by their limited financial resources, being motivated by poverty, reliance on

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rudimentary technology, and frequently taking place in remote villages (Siegel & Veiga, 2010). Substantial quantities of potentially toxic elements, such as polluted dust, gases, and both solid and liquid waste materials originating from mining activities, are commonly discharged into neighbouring environments, presenting significant health hazards to mine workers and the adjacent communities (O. Gyamfi et al., 2020).

Gold mining accounts for about 20% of gross domestic product (GDP) in countries where gold is predominant (World Gold Council, 2022). In Ghana, for example, 90% of mineral exports are attributed to gold mining, making gold the focal point of the mining and mineral industry, sustaining the livelihoods of more than 200,000 gold workers, and supporting around one million family members who depend on them (Karn et al., 2021). While mining provides economic benefits to individuals and communities, it poses numerous challenges, including environmental degradation, health and safety risks, conflicts over land and resources, and releasing hazardous elements into the environment (Ding et al., 2019). In Ghana, the government and various organizations are working to formalize and regulate this sector to promote safer and more sustainable practices while ensuring miners benefit from their activities.

Toxic elements, such as As, Cd, Hg, and Pb, contaminate surface soils in communities where mining activities are prevalent (Dintsi, et al., 2023; Henry & Djallalluddin, 2023). These potentially toxic elements can enter humans through inhalation, skin contact, and/or ingestion and become available for adsorption into the bloodstream (Konadu et al., 2023). Gold extraction in Obuasi and surrounding areas dates back to the nineteenth century, with underground mining being the most common method used. The Anglo-Gold Ashanti mine, situated in Obuasi, is one of the largest gold mines in the region, single-handedly contributing over 50% of the nation's annual gold production (Aryee, 2001). Gold, constituting approximately 45% of the total export revenue, is pivotal in the economic landscape (Ros-Tonen et al. 2021). Despite its economic significance, the mining and processing of gold ore have taken a toll on the environment in the region. Significant environmental degradation and pollution have resulted from the dispersal of fine sands and silts from the wastes into the surrounding

areas, facilitated by surface runoff and particles suspended in the wind.

Detrimental effects associated with potentially toxic element pollution in soils and other environmental media around the Obuasi mine have been previously studied (Bempah & Ewusi, 2016; Perrouy et al., 2012). However, data on these metals' distribution and in-vitro bioaccessibility in the Obuasi Municipality is unavailable. Hence, the primary focus of this research was to assess the environmental and potential human health impacts associated with mining within the Obuasi municipality of Ghana. This study had three main goals: determining the concentrations of potentially toxic elements in the top soils of the Obuasi municipality, analyzing the spatial distribution of potentially toxic metals within the study area, and assessing potential human health risks from ingesting soil-borne contaminants. The study will also contribute to the geochemical baseline values of heavy metals within Ghanaian mining areas, informing environmental management and public health and potentially advancing broader knowledge in mining-heavy regions.

Methodology

Study area

Figure 1 shows the study area and sampling points for this study. Obuasi is an ancient town located in the Ashanti region of Ghana, West Africa. It is approximately 64 km south of the Ashanti regional capital, Kumasi, and about 260 km northwest of Ghana's capital city, Accra. The town's geographic coordinates are approximately 6.160° and 6.246°N latitude, 1.588°W and 1.711°W longitude, covering an area of about 162.5 km² and an approximate population of 288, 000 (Ghana Statistical Service, 2014). The landscape features rolling hills, and the climate is semi-equatorial, characterized by a dual rainfall pattern. Monthly precipitation varies from 3.5 cm in January to 283 cm in July. The yearly average temperature stands at 25.5 °C, accompanied by a relative humidity ranging from 75–80% during the wet season. Obuasi is popularly known for its large and small-scale mining activities, some of which are illegal (galamsey). While few people engage in petty trading in Obuasi,

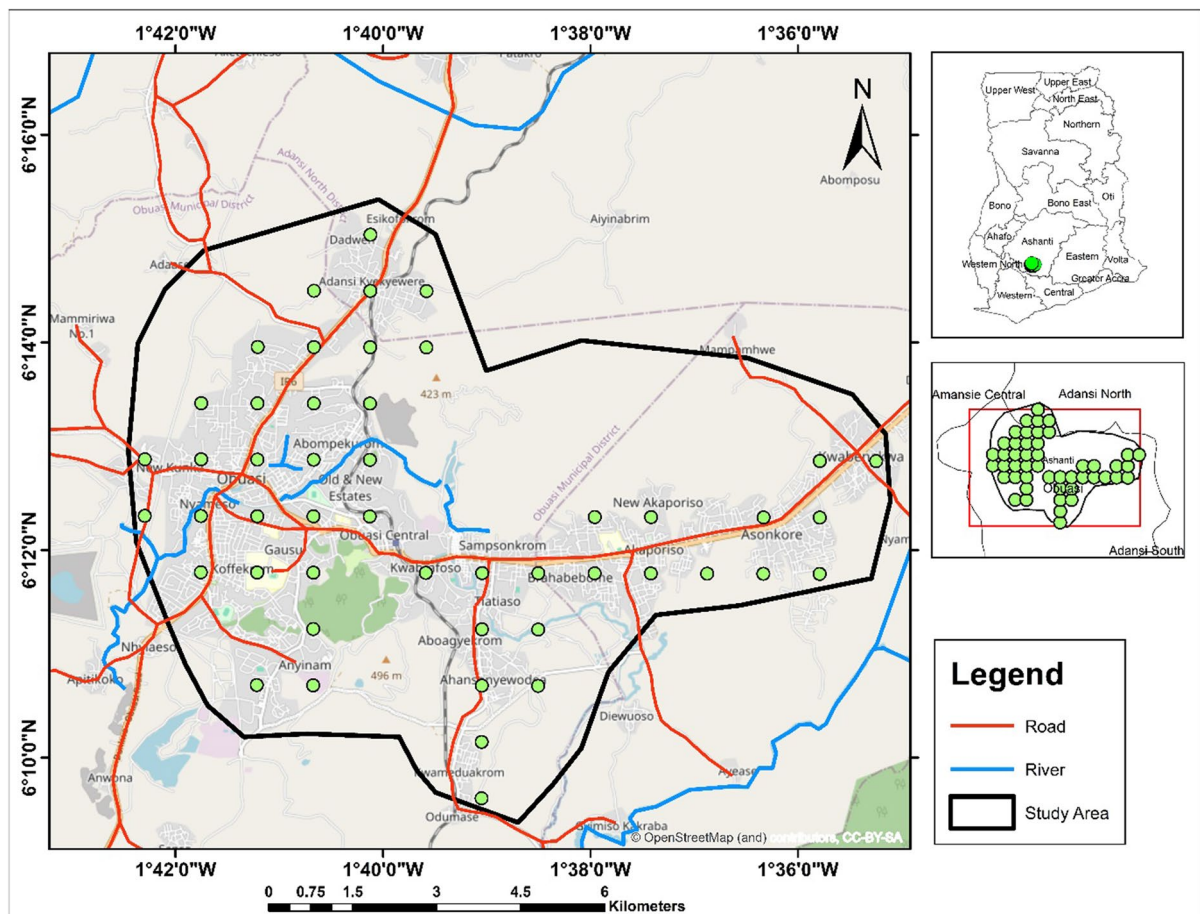


Fig. 1 Map of Obuasi showing the sampling points

farming is the primary occupation of the indigenes, and it is typically done outside of the city.

Soil sampling and sample preparation

Obuasi municipality was mapped on a $2 \times 2 \text{ km}^2$ grid net before sampling by use of GPS Essentials application (Malaga, Spain). Surface soil samples were collected from 49 locations by following the points on the map. At each sample point, two replicates were fetched by moving 5 m to the left and the right from the original position (Akanchise et al., 2020). At each sample point, a clean dry shovel was used to collect about 400 g of topsoil (0–10 cm), assumed to be the layer most likely encountered by humans during daily activities, thereby enhancing human risk assessment (Rweyemamu et al., 2020). All soil samples were transported to the laboratory, air-dried, cleared

of debris, stones, and pebbles, then pulverized and sieved to a particle size of $250 \mu\text{m}$. This size represents the fraction of soil particles that can adhere to the skin, especially on the hands. Five samples were obtained from pristine, undisturbed surface soils at the Botanical Gardens of the University of Energy and Natural Resources, Ghana. Concentrations of these samples were used as the baseline levels for the metals.

Soil physicochemical parameters

The pH and electrical conductivity of each soil specimen were assessed using an Oakton PCSTestr35 multiparameter probe, employing a supernatant liquid formed by a 1:5 ratio of soil to water (Panico et al., 2023). The total organic carbon (TOC) of each sample was determined using the loss on ignition

technique (Mavakala et al., 2022), and was conducted in triplicates for precision. In summary, a 1.5 g portion of soil was measured and placed directly into a crucible, subjected to a 2-h heating at 105 °C, allowed to cool to room temperature in a desiccator, and subsequently introduced into a pre-heated oven set at 550 °C for 4 h. Once taken out of the oven, the samples were cooled to room temperature overnight in a desiccator and re-measured. The determination of TOC was accomplished by computing the difference between the initial and final weights.

Elemental concentrations

Concentrations of the metals in the sample were determined using a Niton XL3t GOLDD+ X-ray fluorescence (XRF) analyzer following the protocols of the US EPA (US EPA, 2007). ICP-MS was used to validate the XRF data, and this yielded a good correlation for the metals (Asamoah et al., 2023). The quality assurance and quality control processes involved the XRF calibration verification using of NIST 2709a standard reference materials. The results indicated acceptable standard recoveries for different elements: arsenic ($86 \pm 8\%$), cadmium ($59 \pm 6\%$), chromium ($80 \pm 7\%$), copper ($101 \pm 13\%$), lead ($88 \pm 9\%$), manganese ($109 \pm 15\%$), nickel ($92 \pm 9\%$), and zinc ($106 \pm 12\%$).

ICP-MS analysis

Prior to the ICP-MS analysis, 1.0 g of the sample was placed into a 50 mL digestion tube. Subsequently, the tube was filled with 5 mL of deionized water, 2.5 mL of concentrated HCl, and 2.5 mL of concentrated HNO₃. The mixture underwent heating at 95 °C for 2 h in a heating block. After digestion, the mixture was diluted to 40 mL with deionized water, followed by centrifugation at 5000 g for 10 min. The resulting solution was stored at 4 °C and later subjected to analysis using an Agilent 7800 ICP-MS, following the US-EPA method 6020B as outlined elsewhere (Dodd et al., 2023). The limit of detection for the analyses were (As: <0.4, Cd: <0.2, Cr: <1.5, Cu: <0.7, Ni: <0.8, Mn: <0.8, Pb: <0.5, Zn: <0.7) mg/kg. The data quality control measures involved the evaluation of a procedure blank, a standard reference material, and a replicated sample. The concentrations found in the procedure blank samples were less than 0.1 mg/

kg, suggesting negligible contamination from the chemicals and apparatus used (Konadu et al., 2023).

In vitro bioaccessibility

The in vitro bioaccessibility assay followed the US-EPA protocols (US EPA, 2007). In vitro bioaccessibility testing simulates the sequential digestion process in the human gastrointestinal tract and was performed to evaluate the bioaccessible fraction of each of the eight elements. To outline the procedure briefly, a 1 g portion of the sieved sample underwent extraction through end-to-end rotation in 100 mL of glycine buffered to a pH of 1.5 for 1 h. The resulting extract was filtered using a 0.45 µm cellulose acetate syringe filter, and the filtrate underwent metal analysis using ICP-MS. The elemental bioaccessibility of each sample was quantified as a percentage, representing the ratio of the extract concentration to the total metal concentration. Bioaccessibility values were not computed for metals with extract concentrations falling below the detection limits. The limit of detection was (As: <0.9, Cd: <0.2, Cr: <3.0, Cu: <3.0, Ni: <2.0, Mn: <4.0, Pb: <2.0, Zn: <3.0) µg/L.

Statistical analysis and soil quality evaluation

Statistical analyses were conducted using both Excel and Minitab version 16.2.1

(Minitab Inc., USA). The data underwent assessment using international environmental soil quality guidelines due to the absence of specific Ghanaian soil quality standards. Notably, the Canadian environmental soil quality guidelines (CCME, 2007), and the Clarke values (Burchfiel, 1983) were chosen for this evaluation. These guidelines have been previously employed in other research conducted in Ghana (Amponsah et al., 2022; Asamoah et al., 2021; Konwuruk et al., 2021). The aim was to ensure a good assessment despite the lack of local standards.

Contamination estimation

Contamination factor (CF), contamination load index (CLI), index of geoaccumulation (I-geo), enrichment factor (EF), and potential ecological risk index (PERI), were employed to estimate the extent of pollution by the potentially toxic elements.

Contamination factor and contamination load index

The contamination factor for each metal in a sample was determined as a ratio of the metal concentration in the sample to the baseline concentration using Eq. 1.

$$CF = \frac{M_s}{M_b} \quad (1)$$

The CF values were categorized into non-contamination ($CF < 1$), minimal ($CF = 1-3$), appreciable ($CF = 3-6$), or high contamination ($CF > 6$), (Amoakwah et al., 2020).

CLI estimates the overall contamination burden at a particular site and can be represented mathematically as shown in Eq. 2.

$$CLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \dots CF_n} \quad (2)$$

where n = number of studied metals (eight in this study). $CLI < 1$ = perfect site quality, $CLI \approx 1$ = baseline levels of metals, $CLI > 1$ = deterioration of site quality (Mostafa et al., 2023).

Index of geoaccumulation and enrichment factor

Equation 3 was used to calculate the index of geoaccumulation, which estimates contamination from anthropogenic sources, and Eq. 4 (Enrichment factor) was employed to distinguish contamination from anthropogenic and natural sources (Qing et al., 2015).

$$I_{geo} = \log_2 \left[\frac{M_s}{1.5 \times B_n} \right] \quad (3)$$

$$EF = \frac{M_s}{M_b} \div \frac{Fe_b}{Fe_s} \quad (4)$$

where M_s and M_b are elemental concentrations in the sample and geochemical background respectively, whereas Fe_s and Fe_b are iron concentrations in the sample and geochemical background respectively. Fe was employed for normalization due to its comparatively elevated level in the natural surroundings. $EF < 1$ connotes low metal enrichment whereas $EF > 1$ suggests enriched metal from an anthropogenic source.

Potential ecological risk

Equation 5 was used to determine the ecological risk coefficient (ERC) to assess the potential ecological risk, the individual metal poses.

$$ERC = TRF \times CF \quad (5)$$

TRF explains the toxicity factor for each metal. TRF of As=10, Cd=30, Cr=2, Ni=6, Cu=Mn=Pb=5, and Zn=1 (Asamoah et al., 2021).

The categorization of ERC was classified as low ($0 < ERC < 50$), moderate ($50 < ERC < 100$), significant ($100 < ERC < 300$), and high ($ERC \geq 300$). Potential ecological risk index (PERI), the overall sum of each metal risk index was used to ascertain the extent of metal contamination (Eq. 6).

$$PERI = \sum_i^n (ERC) \quad (6)$$

The literature-based classification of PERI is as follows: low ($0 < PERI < 80$), moderate ($80 < PERI < 100$), considerable ($100 < PERI < 200$), high ($PERI \geq 200$) (Nna Orji et al., 2018).

Human health risks

The calculation of the chemical daily intake (CDI in mg/kg/day) resulting from the inadvertent ingestion of metals was determined using Eq. 7. This equation incorporated the modeled soil ingestion rate ($1.6 \text{ mg}^{-1} \text{ kg}^{-1} \text{ day}^{-1}$), assuming an adult body weight of 70 kg, life expectancy of 64 years, and lifelong exposure (Myers et al., 2023).

$$CDI = \frac{\text{Bioaccconc.} \times \text{Ing.rate} \times \text{Exp.term}}{\text{Bodyweight} \times \text{lifexpectancy}} \quad (7)$$

The hazard quotient (HQ) for non-cancer risk was then computed by dividing the product of the CDI and adjusting for relative bioavailability (RBA) by the respective tolerable daily intake (TDI in mg/kg/day), as presented in Eq. 8.

$$HQ = \frac{CDI \times RBA}{TDI} \quad (8)$$

The RBA of As and Pb were determined using validated bioaccessibility-to-bioavailability conversions as outlined in Eqs. 9 and 10, respectively (Dodd et al., 2023).

$$\text{As RBA(\%)} = 0.79 \times \text{IVBA(\%)} + 3 \quad (9)$$

$$\text{Pb RBA(\%)} = 0.878 \times \text{IVBA(\%)} - 2.8 \quad (10)$$

Because there are currently no available *in vivo* or *in vitro* equations for the remaining metals, their bioaccessibility values were directly employed as a substitute for the relative bioavailability (RBA). The TDI values used were (As: 0.0003, Cd: 0.0005, Cr: 0.003, Cu: 0.01, Ni: 0.02, Mn: 0.011, Pb: 0.0036, Zn: 0.3) mg/kg/day (Dodd et al., 2023). Hazard index (HI) was computed as a sum of each metal's hazard quotient, using Eq. 11. Where HI greater than one connotes a high possibility of non-carcinogenic effects occurring, and the possibility increases as the HI value also increases.

$$\text{HI} = \text{HQ1} + \text{HQ2} + \text{HQ3} \dots + \text{HQn} \quad (11)$$

Results and discussion

Physicochemical parameters (pH, EC, and TOC)

The values obtained for soil pH, electrical conductivity, and total organic carbon, are presented in Table 1. Soil pH ranged between 4.80 and 8.59 with about 58% of the soil samples recording pH values < 7, indicating the slightly acidic nature of the topsoils. This is very characteristic of most mining area top soils

in Ghana (Opoku et al., 2020), but in contrast with the control site which had a mean pH of 8.13, denoting the basic nature of the undisturbed soil. Low pH has been reported to increase the mobility of metals in surface soils (Agbeshie et al., 2020; Sintorini et al., 2021). Electrical conductivity which measures the concentration of available ions in the soil, ranged from 58.70 μScm^{-1} to 926.00 μScm^{-1} with a mean of $(209.08 \pm 16.17) \mu\text{Scm}^{-1}$. Total organic carbon showed a range of 2.25 to 8.95% and a mean of $3.31 \pm 1.42\%$ which was approximately 50% lower than that recorded for the control site. Lower total organic carbon is usually associated with mining activities due to surface soil interference, vegetation disruption, and pollution (Mostafa et al., 2023). This reduction in TOC content reduces the capacity of organic matter to coordinate with metals and may adversely affect nutrient cycling, and soil structure, and impede plant growth due to a rise in metal mobility (Cetin et al., 2023).

Elemental levels across Obuasi municipality

The descriptive statistics for each metal are presented in Table 1. Levels of As within Obuasi municipality ranged from 11.16 to 1360.58 mgkg^{-1} with a mean of $175.48 \pm 30.19 \text{ mgkg}^{-1}$. The observed mean value was about 5000 times higher than the control sample of 0.03 mgkg^{-1} , 14 times greater than the CCME guideline of 12 mgkg^{-1} (CCME, 2007), and approximately 110 times greater than the Clarke values of 1.5

Table 1 Descriptive statistics of potentially toxic elements' concentrations (mgkg^{-1}) and physicochemical parameters in the Obuasi Municipality

Elements/physicochemical parameters	Min	Max	Mean $\pm$ SD	Control sample's mean	References	
					(CCME, 2007)	Clarke values
As	11.16	1360.58	175.14 ± 30.19	0.03	12	1.5
Cd	4.57	11.43	6.30 ± 1.32	0.02	10	0.3
Cr	10.15	249.18	75.45 ± 4.72	5.62	64	-
Cu	8.77	361.01	36.22 ± 5.10	1.03	63	28
Mn	36.92	958.97	228.19 ± 20.93	34.05	-	600
Ni	15.28	112.48	33.05 ± 1.99	1.87	45	47
Pb	2.92	739.48	24.22 ± 10.69	1.61	70	17
Zn	13.84	2814.75	124.06 ± 40.03	1.78	200	71
pH	4.80	8.59	7.05 ± 1.09	8.13	6 to 8	
EC (μScm^{-1})	58.70	926.00	209.08 ± 16.17	142.10	2000	
TOC (%)	2.25	8.95	3.31 ± 1.42	3.14		

mgkg⁻¹ (Burchfiel, 1983). This indicates that mining activities contribute significantly to the elevated levels of As within the Obuasi municipality. A previous study (Bempah & Ewusi, 2016) reported As levels of 6.83 ± 2.42 mgkg⁻¹ which was about 25 times lower than that observed in this study. Another study in a mining area in Ghana (E. Gyamfi et al., 2019) also found that the average As level was 55.20 ± 12.42 mgkg⁻¹, which was thrice lower than the As content in this study.

The mean concentration of Cd was 6.30 ± 1.32 mgkg⁻¹. Although the average Cd content was slightly lower than the CCME guideline value of 10 mgkg⁻¹ (CCME, 2007) it was about 300 times greater than the control sample of 0.02 mgkg⁻¹ and 20 times higher than the Clarke values of 0.3 mgkg⁻¹ (Burchfiel, 1983). Cadmium possesses high toxicity and can bioaccumulate in the body, posing a hazard with prolonged, low-level exposure (Ejaz et al., 2023). The Cd level in this study far exceeded the value recorded (0.27 ± 0.04 mgkg⁻¹) for a similar study conducted in and around the forest zone of Bontesso, an area dominated by artisanal mining in Ghana (Opoku et al., 2020). Lead levels in this study ranged from 2.92 to 739.48 mgkg⁻¹ with a mean value of 24.22 ± 10.69 mgkg⁻¹. Lead contamination and exposure result in permanent detrimental effects on brain development, impacting the kidneys, blood-nervous system, and skeletal system, particularly in children (Muhammad et al., 2022). Additionally, alterations in gene expression, increasing the risk of disease and mortality in life among children, have been attributed to Pb exposure (Yang et al., 2018). High Cd and Pb levels in Ghanaian surface soils have been linked to gold mining activities for several years now (Boamponsem et al., 2010).

The concentration of Cr in the top soils within the Obuasi municipality ranged from 10.15 to 249.18 mgkg⁻¹ with a mean of 75.45 ± 4.72 mgkg⁻¹ whereas Ni concentrations ranged between 15.28 and 112.48 averaging 33.05 ± 1.99 mgkg⁻¹. The average Cr content observed in this study exceeded the control sample (5.62 mgkg⁻¹) by 15 times, and was slightly greater than the CCME guideline value of 63 mgkg⁻¹. Also, the Ni content exceeded the control sample by 30 times but was slightly lower than both the CCME guideline and Clarke value of 45 mgkg⁻¹ and 47 mgkg⁻¹, respectively. A previous study in selected mining communities in the southwestern zone of

Ghana (Kazapoe et al., 2022), recorded a Cr content of 86.25 ± 38.97 mgkg⁻¹, slightly greater than in this study, and Ni content of 11.24 ± 9.65 mgkg⁻¹, which was thrice lower than observed in this study. Chromium and its compounds can cause a variety of health issues, including lung cancer, kidneys and liver damage, genetic alterations, skin irritations, gastrointestinal discomfort, ulcers, respiratory issues, compromised immune function, nasal irritation, nasal ulcers, and hypersensitive reactions, and in extreme instances, fatality (Mavakala et al., 2022; Ondayo et al., 2023). Exposure to Ni has been documented to result in various health issues, including nasal cancer, gastrointestinal symptoms, respiratory problems, lung cancer and fibrosis, contact dermatitis, headaches, cardiovascular diseases, and epigenetic effects (Huang et al., 2019; Kirk et al., 2014).

Both Cu and Zn levels were generally higher than the control sample but lower than CCME guideline values. Copper and Zn mean levels of 36.22 ± 5.10 mgkg⁻¹ and 124.06 ± 40.03 mgkg⁻¹ respectively, corroborate similar research conducted around the Obuasi community which recorded Cu and Zn values of 36.0 ± 10.1 mgkg⁻¹ and 95.8 ± 16.4 mgkg⁻¹ respectively (E. Gyamfi et al., 2019). This indicates that mining and its related activities elevate copper and zinc levels in the lithosphere. It has been reported elsewhere that excess Cu in the body causes detrimental health effects to the kidney and liver (Huang et al., 2019). High levels of Zn in the body may also cause a reduction in lymphocyte stimulation and alteration in cholesterol metabolism (Asamoah et al., 2021).

Figure 2 is a spatial distribution based on the empirical Bayesian kriging for each of the potentially toxic elements (Yevugah et al., 2023) within Obuasi municipality. It was observed that five out of the eight potentially toxic elements; Cu, Mn, Ni, Pb, and Zn were more concentrated in the eastern zone of the municipality where Obuasi East district is situated. Around such areas are ongoing illegal artisanal mining (galamsey) activities. Also, these areas are very close to roads, where vehicular emissions may be a contributing factor to high levels of metals (Aradhi et al., 2023). Although Cr levels were evenly distributed across the municipality, a higher concentration was observed in the eastern zone. At the northern corridor of the municipality, several construction works have been carried out and may account for the

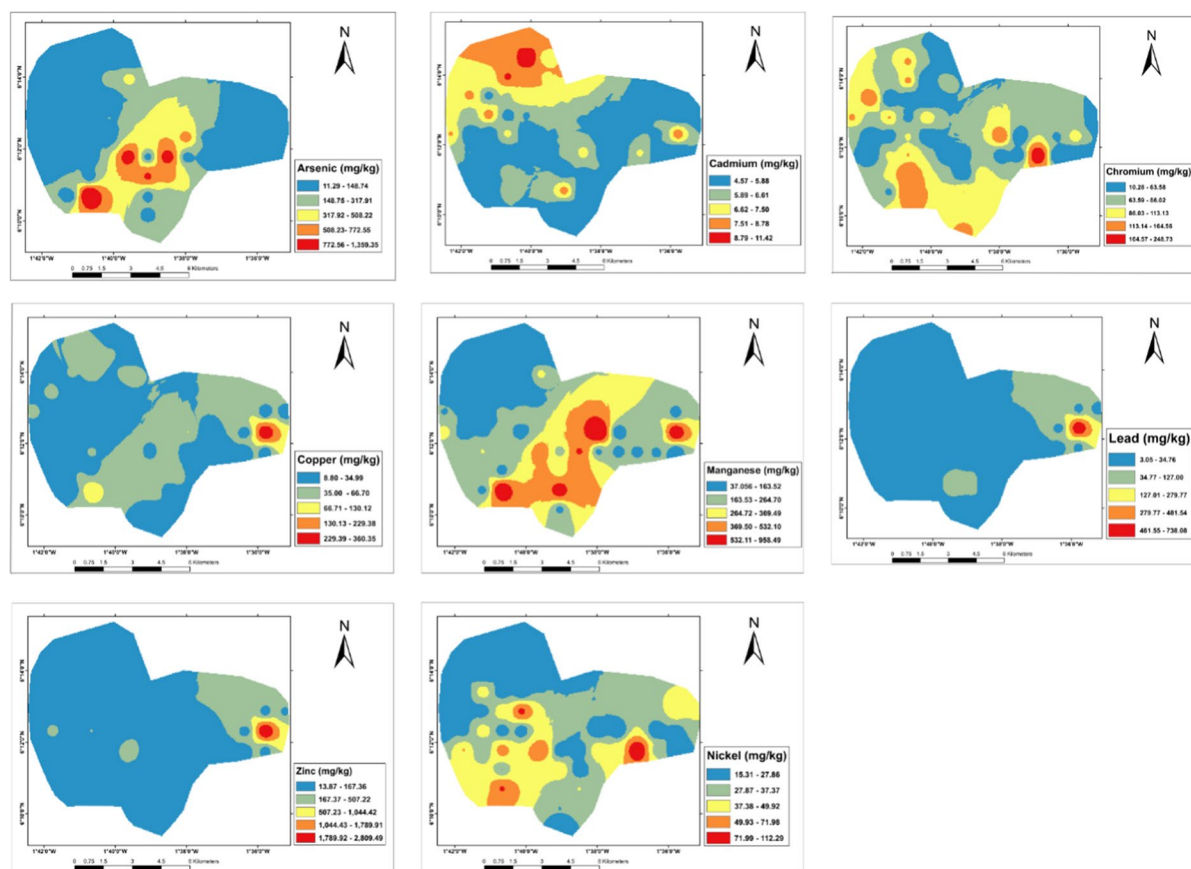


Fig. 2 Spatial distribution of the potentially toxic elements

relatively high levels of Cd and significant amounts of Cr. The southern zone recorded significant levels of Mn and elevated concentrations of As probably due to its closeness to a gold mine. The city center also recorded high levels of Mn and moderate concentrations of As and Cd. Increased human activities such as uncontrolled waste disposal and automobile emissions may account for such levels of the elements (Rweyemamu et al., 2020).

Extent of elemental contamination

In this investigation, the contamination factor (CF), index of geoaccumulation (I-geo), and enrichment factor (EF) as summarized in Table 2, were utilized to determine if the origins of potentially toxic metal contamination were of human influence (Keshavarzi & Kumar, 2020). CF values revealed practically minimal contamination for all the metals except for Cd and As which showed very high contamination. The I-geo values affirmed the extreme pollution of As and

Table 2 Contamination and risk indices of potentially toxic elements

Element	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Contamination factor	14.59	20.98	1.18	1.30	0.38	0.73	1.42	1.75
Enrichment factor	216.70	38.94	2.19	2.40	0.71	1.30	2.64	3.24
Index of geoaccumulation	6.28	3.80	-0.35	-0.21	-1.98	-1.09	-0.07	0.22
Risk index	145.95	629.50	2.36	6.47	1.91	4.41	7.12	1.75

Cd, moderate pollution of Zn, and unpolluted of the remaining five metals. Furthermore, except for As and Cd which were highly enriched in the top soils, EF values showed minimal enrichment with all the other metals. The observed contamination status of the metals conforms with previous findings within Obuasi vicinities (Akoto et al., 2018). Contamination load index value of 2.06 ($CLI > 1$), is an indication of a general decline in the quality of the top soils within the municipality. The potential ecological risk indices were also employed in this study to characterize the overall contamination status of the study area. Again, except for Cd and As all other potentially toxic elements showed low risk. The risk index of 632.55 and 145.40 for Cd and As respectively, connotes extremely high risks of the metals. This is very alarming and needs the attention of all stakeholders within the municipality.

Notes: Contamination factors (CF) were classified as non-contamination ($CF < 1$), minimal ($CF = 1-3$), appreciable ($CF = 3-6$), or high contamination ($CF > 6$). Ecological risk coefficient (ERC) categories were determined as low ($0 < ERC < 50$), moderate ($50 < ERC < 100$), significant ($100 < ERC < 300$), and high ($ERC \geq 300$). An enrichment factor (EF) below one indicates low metal enrichment, while values above one suggests metal enrichment from anthropogenic sources.

Pearson's correlation analysis

Pearson's correlation analysis was performed to study relationships between the physicochemical properties and the potentially toxic element concentrations. A strong but negative correlation was observed between pH and EC though statistically insignificant ($p > 0.05$). Furthermore, there existed a strong negative correlation for pH/Ni and EC/Mn, a moderate negative correlation for pH/Pb, and a weak positive correlation between pH and As, Cu Mn, Zn, with pH/Pb and pH/Cd showing a positive moderate correlation. Conversely, a strong positive inter-elemental correlation was identified between Mn/Cd, and As/Zn but a weak positive correlation for Ni/Mn, Cu/Cd, Cr/As, and Ni/As. Correlation analysis among parameters suggests similar origins for these potentially toxic elements and the primary factors governing their availability and variability.

In vitro bioaccessibility assay (IVBA) and hazard indices

Table 4 presents the results obtained from in vitro bioaccessibility assay and hazard indices for adults and children. The average bioaccessible portion of the elements followed the order: $Cu > Zn > Pb > Cd > Mn > As > Ni > Cr$. This order is similar to a previous study conducted at a mining site in Kenyasi, Ghana (Asamoah et al., 2023) except for Pb and As which recorded relatively higher mean bioaccessibility in this study. Also, these mean bioaccessibility results were lower than another study conducted in the Gbani mining community in Ghana (Darko et al., 2019). Elemental speciation and physiochemical parameters have been linked to discrepancies in elemental bioaccessibilities (Dodd et al., 2017). The bioaccessibility values for As and Pb were modified for the relative bioavailability by applying their corresponding in vivo/in vitro regression equations (Eqs. 9 and 10). These adjusted values were then utilized in the computation of hazard quotients.

The hazard quotient (HQ) values for children and adults, as outlined in Table 4, represent the cumulative non-cancer risk for soil ingestion within a specific context. The ingestion of soil is a prevalent route through which individuals, particularly children, come into contact with metals (Petrucelli et al., 2020). When HQ and HI values are below 1, it suggests no apparent risk to the population. However, if these values exceed 1, there is a potential concern for non-cancer health effects (Ondayo et al., 2023). For both children and adult populations, all the potentially toxic elements, except As recorded HQ values less than 1, indicating a general low risk of non-cancer health effects for the Obuasi populace. An extremely high HQ value of As in both adults (2.52) and children (3.37) poses a great threat to the populace, especially children. Excess levels of As in children have negative impacts on the brain and increased mortality rates (Dintsi, et al., 2023). Furthermore, the collective hazard posed by all the metals (HI) surpassed the threshold by threefold and fourfold, correspondingly, at the adult population and children population. It is crucial to monitor and manage these metals effectively to mitigate their adverse effects on human health and the environment particularly among children.

Table 3 Pearson's correlation analysis of physicochemical parameters and potentially toxic elements

	pH	EC	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
pH	1									
E.C	-.001	1								
	.994									
As	.314*	-.082	1							
	.028	.575								
Cd	.099	-.089	-.068	1						
	.498	.543	.642							
Cr	-.136	-.073	.165	.234	1					
	.350	.616	.258	.106						
Cu	.205	.010	.202	.300*	.232	1				
	.159	.946	.163	.036	.108					
Mn	.312*	-.001	.624**	.013	.345*	.597**	1			
	.029	.993	.000	.931	.015	.000				
Ni	-.055	.039	.223	-.240	.341*	-.022	.135	1		
	.709	.788	.123	.096	.017	.881	.353			
Pb	.112	.038	-.001	.222	.097	.953**	.479**	-.063	1	
	.445	.796	.995	.125	.506	.000	.001	.669		
Zn	.125	.089	.012	.181	.069	.950**	.444**	-.059	.985**	1
	.391	.544	.932	.213	.638	.000	.001	.686	.000	

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

Conclusion

This study assessed the contamination status of surface soils within the Obuasi municipality by comparing the current results to previous study findings. Mean levels of all the potentially toxic elements far exceeded those recorded at the control site, indicating contamination of the topsoil in the study location. All the potentially toxic elements except Mn and Ni had average concentrations greater than a

previous study conducted in 2016. This suggests that the concentrations of the metals in the municipality are increasing, probably due to the mining activities that take place in the municipality. Higher concentrations of the elements were observed in the eastern corridor of the municipality where some illegal miners were spotted on site. Results from this study reveal a detrimental impact of mining and related activities in the Obuasi municipality. Risk indices and human health risk assessment results also suggest a high overall risk among children and adults within the municipality. It is recommended that future work should explore and establish a relationship between the bioaccessibility of metals in air and water within the Obuasi municipality. To inform the public about the dangers presented by potentially toxic elements, regulatory agencies should implore the findings from this study and other studies of a similar nature. Pragmatic steps should be taken to ensure monitoring to mitigate, if not eliminate the lithospheric contamination stemming from mining activities.

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Table 4 In-vitro bioaccessibility assay and hazard indices for the potentially toxic elements

Metal	Mean IVBA $\pm$ SD (%)	Hazard Quotient (HQ)	
		Adult	Children
As	10.2 $\pm$ 4.6	2.52	3.37
Cd	42.5 $\pm$ 19.7	0.21	0.28
Cr	6.3 $\pm$ 3.9	0.06	0.08
Cu	63.6 $\pm$ 22.8	0.09	0.12
Mn	39.5 $\pm$ 15.7	0.32	0.42
Ni	9.8 $\pm$ 5.8	0.01	0.01
Pb	42.9 $\pm$ 16.3	0.07	0.12
Zn	57.4 $\pm$ 11.9	0.01	0.01
		HI = 3.30	HI = 4.42

Authors' contribution GD, MD, LSB, and BDA conceptualized the research idea, while LLY and BDA carried out the fieldwork and map work. GD, BDA, and MD performed the laboratory and statistical analyses, respectively, while BDA, GD, MD, and LSB wrote the manuscript. All authors completed the final proofreading process.

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Data availability Data are available upon request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Competing interest The authors affirm that they do not have any known financial or personal associations with individuals or organizations that could unduly impact their work. They have thoroughly reviewed and comprehended the guidelines regarding the "Ethical responsibilities of Authors" and have acted accordingly.

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