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Asamoah et al.
Hazard / Risk Assessment
Receptor modeling, ecological risks, and human health impacts of mercury in some Ghanaian
topsoils due to mining and commercial activities
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Abstract: Globally, elevated environmental mercury levels have been linked to artisanal and
small-scale gold mining; however, investigations into mining communities often overlook other
potential sources and their contributions to soil mercury accumulation. This study explored the
positive matrix factorization receptor model to identify other possible sources of mercury
contamination in two major mining communities (Kenyasi and Obuasi) and a commercial city
(Sunyani) in Ghana. The mercury concentrations across the three study areas showed no
significant differences ($p = 0.257$ at the 95% confidence level). The positive matrix factorization
model identified mining as the major contributor to mercury accumulation in Obuasi and
Kenyasi, with other activities, such as farming, also contributing substantially. The generation
and burning of hazardous waste in the Sunyani municipality due to increased commercial

activities have contributed significantly to mercury contamination. Although the hazard quotient indicated no adverse health effects in the study areas ($HQ < 1$), the pollution and ecological risk indices showed that Obuasi was significantly enriched with mercury, with considerable levels found in Kenyasi and Sunyani. The results from this study will serve as a good database for environmental studies on mercury particularly in Kenyasi and Sunyani, where there has not been any extensive research on mercury contamination.

Keywords: Factorization model; pollution factor; enrichment factor; hazard quotient.

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Introduction

Mercury is a potent environmental pollutant and poses risks due to its toxicity, tendency to accumulate in the environment and magnify in food chains. According to the United Nations Environment Programme (UNEP) Global Mercury Assessment, natural sources account for roughly 10% of global mercury emissions, with the remaining 90% originating from human activities (UNEP, 2012). The 2013 UN Minamata Convention, which regulates mercury usage worldwide, places particular emphasis on its application in artisanal gold mining and mandates that member countries, including Ghana, monitor all sources of mercury (Ansah et al., 2022; UNEP 2012). Reports indicate that both large-scale and artisanal small-scale gold mining (ASGM) contribute to the release of harmful metals, such as mercury, into the environment (Darko Asamoah et al., 2024). Mining activities in Ghana date back to the late 19th century, primarily focusing on gold extraction. Ghana is Africa's largest gold producer, contributing about 6% to the country's gross domestic product and 30% to export revenues (Yankson & Gough, 2019). In 1983, the Ghanaian government implemented the Economic Recovery Programme (ERP) with guidance from the World Health Organization (WHO). Subsequently, the mining

sector experienced substantial expansion, marked by a 700% increase in gold production (Gyamfi et al., 2020). In Ghana, approximately 1.1 million workers are employed in the gold mining sector, while an additional 4.4 million people depend on income generated from these activities, all within a population of 30 million (Ros-Tonen et al., 2021). Recent reports indicate an increase in ASGM activity (Adranyi et al., 2023), but the long-term impact of government regulations remains unclear.

Mercury is commonly used in gold extraction due to its perceived convenience and individual applicability (Saldarriaga-Isaza et al., 2015). During the gold extraction process, mercury is combined with gold ore to form an amalgam, which consists of approximately equal portions of mercury and gold. This amalgam is subsequently heated to evaporate the mercury, resulting in pure gold remaining (Hilson, 2006). While some mercury is recovered, a portion escapes into the surrounding environment, with the majority evaporating. The primary environmental challenges linked to gold mining in Ghana consist of mercury contamination from gold processing (particularly from amalgam burning), the destruction of ecosystems, and the degradation of the environment (Yevugah et al., 2021). Unfortunately, practical alternatives to mercury in mining have not yet been widely adopted, leading to continued mercury use in most mining activities. In Ghana, most ASGM operations, popularly known as “galamsey” hide behind large-scale mining companies and are mostly seen in towns where large-scale mining operations are located (Akoto et al., 2018; Asamoah et al., 2023).

Most studies on mercury contamination in Ghana have focused on mining-impacted areas, emphasizing communities known to be engaged in artisanal small-scale gold mining activities. Indeed, all these studies have reported relatively high levels of mercury ranging up to 6.0 mg/kg in surface soils (Armah et al., 2013; Boamponsem et al., 2010; Miguel, 2016).

Furthermore, extremely high concentrations can be found in vicinities with extensive mining operations. For instance, a previous study conducted in an ASGM community within the Talensi District (Gyamfi et al., 2021) reported an average soil mercury concentration of 71 mg/kg at active mining sites, compared to 2.7 mg/kg across transects throughout the community.

While human activities are anticipated to have raised global soil concentrations of mercury, levels in unpolluted areas are still likely to be predominantly from natural sources, such as mineral weathering or volcanic eruptions (Angon et al., 2024). Globally, the highest natural concentrations of mercury are anticipated in areas that have elevated mercury levels linked to tectonic plate boundaries and in organic soils (Kumari et al., 2020). Identifying the possible sources of mercury contamination is a step toward mitigating environmental pollution. Some traditional source apportionment methods such as principal component analysis (Podlasek et al., 2024) and chemical mass balance (Rejivas et al., 2024), have been used to apportion sources of contamination. The positive matrix factorization (PMF) receptor model, however, gives more accurate and realistic factors and contribution rates to the sources of the metal pollutants. The PMF is particularly useful for analyzing environmental data because it accounts for the varying uncertainties often present in environmental sample measurements (Reff et al., 2007). It also ensures that all values in the solution profiles and contributions are non-negative, making it more realistic compared to older methods like principal component analysis (Gu et al., 2020). Therefore, the PMF was employed in this study as a tool for identifying the possible sources of mercury contamination (Keeler et al., 2006) within the study areas.

While mercury contamination in Ghana has been extensively documented in areas impacted by artisanal small-scale gold mining activities, the potential contributions from non-mining commercial activities remain underexplored. Given the high socioeconomic dependence

on gold mining, mercury pollution poses significant environmental and public health risks. By employing the PMF model, this study seeks to quantify mercury levels across mining and commercial areas, identify spatial distribution patterns, distinguish key sources of mercury, and assess potential human health risks. These findings will fill a critical research gap by providing comparative data on mercury contamination and offering baseline information crucial for policy development and effective environmental management in Ghana.

Methodology

Study Areas

Figure 1 illustrates the three study areas along with the sampling points within each location. Obuasi, the capital of the Obuasi Municipality in the Ashanti Region of Ghana, and Kenyasi, the capital of the Asutifi North District in the Ahafo Region, were selected as the mining communities. The commercial hub for this study was Sunyani, the capital of the Bono Region of Ghana.

Obuasi (latitude 6.2073° and longitude 1.6636°) is a historically significant mining town that spans about 162.5 km² and has an estimated population of 288,000 (Ghana Statistical Service, 2014). The town is characterized by rolling hills and has a semi-equatorial climate. It experiences a bimodal rainfall pattern, with monthly rainfall ranging from 3.5 cm in January to a considerable 283 cm in July. The average annual temperature is around 25.5 °C, and relative humidity during the wet season varies between 75% and 80%. Obuasi is well-known for its mining activities, which include both large-scale and small-scale operations, many of which are illegal, popularly known as "galamsey". The galamsey primarily involves surface mining methods, carried out through artisanal small-scale mining, which, according to research (Donkor et al., 2024), has impacted livelihoods in cocoa farming communities in the country. The

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3 municipality is the hub for the AngloGold Ashanti mine, one of Sub-Saharan Africa's largest
4 gold mines. It is prominent in Ghana's gold production and plays a vital role in the country's
5 economic landscape. In addition to mining, a smaller number of residents participate in petty
6 trading, usually from their farm produce.
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12 Kenyasi (latitude 6.98° and longitude -2.39°), on the other hand, is a comparatively new
13 mining area which houses the Newmont Ghana Ahafo Mines and other artisanal small-scale
14 mining activities (Asamoah et al., 2023). The vegetation in Kenyasi falls within the high forest
15 zone and is characterized by a double-peak rainfall pattern. The average annual rainfall is 180
16 mm, with a primary rainy season from February to July, a secondary season from August to
17 October, and a dry season from December to February. The region is underlain by Birimian and
18 Tarkwaian rocks, which are composed of metavolcanic and metasedimentary units, respectively
19 (Perrouy et al., 2012). The residents of Kenyasi primarily participate in agricultural activities.
20 Residents mainly cultivate plantain and cassava for personal consumption, while cocoa serves as
21 the primary cash crop.
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35 In contrast, Sunyani (latitude 7.34°; longitude -2.33°) does not have any mining activities,
36 with agriculture being the primary occupation of its residents (Asamoah et al., 2021). The
37 Municipality, located in Ghana's Wet Semi-Equatorial Climate Zone, experiences temperatures
38 ranging from 24 °C to 34 °C. The coolest temperatures are typically recorded in July, while the
39 warmest month is in April. The average annual rainfall is approximately 89.01 cm (Ghana
40 Statistical Service, 2014). Sunyani follows a double maxima rainfall pattern, with the main rainy
41 season from February to July and a shorter secondary rainy season between September and
42 December. During the wet season, relative humidity averages between 75% and 80%, creating
43 favorable conditions for lush vegetative growth. Conversely, the dry season sees relative
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3 humidity levels below 70%. Geologically, the municipality rests on Precambrian formations,
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5 believed to be to be abundant in mineral resources (Ghana Statistical Service, 2014).
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8 *Soil Sampling*
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10 Based on the relative sizes of the study locations, Obuasi was mapped on a 2x2 km² grid
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12 net, whereas Kenyasi and Sunyani were mapped on a 0.5 x 0.5 km² grid net using the GPS
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14 Essentials software (Malaga, Spain). Topsoil samples were collected at points of coordinate
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16 intersection as shown in Figure 1. Using a clean, dry shovel, 49 soil samples were collected at
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18 Kenyasi, 48 at Obuasi, and 90 at Sunyani based on the GPS coordinates generated. Five samples
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20 were collected from the pristine surface soil of the University of Energy and Natural Resources
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22 botanical gardens as a control site. Three replicates were collected at each sample point by
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24 moving 3 m to the front, back, and side from the original point (Dodd et al., 2023). The digging
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26 implement was used to fetch about 400 g of surface soil at the 0 – 10 cm depth, assumed to be
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28 the layer for human exposure during daily activities, and thus provides a more succinct
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30 assessment of human health risk (Darko et al., 2017). To prevent cross-contamination, the
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32 sampling tools were cleaned with laboratory detergents and water between sample collections.
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34 All the samples were taken to the laboratory, air-dried at room temperature, and processed by
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36 removing stones, pebbles, and debris. The dried soil clumps were gently disaggregated using a
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38 clean mortar and pestle. Subsequently, the samples were ground and sieved to a particle size of
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40 less than 250 µm, which is the size that typically sticks to children's hands (Dodd et al., 2017),
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42 and placed in Ziploc bags for storage.
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49 *Soil physicochemical parameters*
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51 The pH and electrical conductivity of each soil sample were measured using an Oakton
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53 PCSTestr35 multiparameter probe, with measurements based on a supernatant liquid prepared by
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3 mixing soil and water at a 1:5 ratio. The total organic carbon (TOC) content was quantified using
4 the loss on ignition method (Panico et al., 2023), with each measurement performed in triplicate
5 to ensure accuracy. Briefly, an aliquot of 1.5 g portion of the soil was weighed into a crucible,
6 heated to 105 °C for 2.5 h, allowed to cool to room temperature in a desiccator, and then
7 transferred to a preheated oven at 550 °C for 3 h. After oven treatment, the samples were cooled
8 to room temperature in a desiccator and re-weighed. The TOC was determined by calculating the
9 difference between the initial and final weights.
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19 *Mercury concentration determination*

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21 Mercury concentration for all the soil samples was assessed using direct pyrolysis
22 (Abdkram et al., 2014) on the Lumex PYRO-915+ pyrometer for atomization, followed by
23 measurement with atomic absorption spectrometry on the RA-915 M Zeeman mercury analyzer
24 (Lumex, St. Petersburg, Russia). The mercury level was calculated based on the integrated
25 analytical signal and calibration coefficient derived from the activated charcoal-certified
26 reference material (Catalog No. 500292; Lumex, Russia). The soil samples (approximately 1.0 g
27 each) were placed in the injection spoon of the PYRO-915+ attachment. The Lumex was
28 operated at an airflow rate of 1 L/min.
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40 *Quality assurance and quality control*

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42 The validity of the results was verified by analyzing a standard reference material
43 (Mercury AA Standard, LabChem, Inc., SKU: LC167501, lot C071-20). The accuracy of the
44 measurements, determined by comparing the measured values to the certified values of the
45 reference material, showed relative errors of less than 5%. The certified values are 2.0, 5.0, and
46 10.0 ng/kg. Additionally, the precision, represented by the percentage of the coefficient of
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variation from five separate measurements, was below 10%. The method's limit of detection, determined as thrice the signal-to-noise ratio, was established at 0.0005 mg/kg.

Spatial distribution map

The coordinates collected at each sampling location along with their corresponding mercury concentration measurements were systematically stored and processed using ArcMap. For consistency, all spatial data were collected in a geographic coordinate system (longitude and latitude). Data from field surveys underwent extensive cleaning, including the removal of duplicates, correction of errors, and treatment of missing values to ensure data integrity. To model these concentrations, the Inverse Distance Weighting (IDW) interpolation method was employed. IDW was chosen for its ability to generate smooth, continuous surfaces that effectively captured local variations in the data, creating an ideal method for predicting values in unsampled areas.

Statistical analysis

Statistical analyses were performed using Minitab version 16.2.1 (Minitab Inc., USA). The data were evaluated against international environmental soil quality guidelines, in the absence of soil quality standards for Ghana. For this evaluation, the Canadian Environmental Soil Quality Guidelines (Canadian Council of Ministers of the Environment [CCME], 2007) and the Dutch Target and Intervention values (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu [VROM], 2000), were utilized. These guidelines have been previously applied in research carried out in Ghana (Amponsah et al., 2022; Konwuruk et al., 2021) to provide a robust assessment in the absence of national standards.

Pollution factor (PF) and Geo-accumulation index (Igeo)

The PF for mercury in a sample was calculated by comparing the mercury concentration in the sample to the background mercury concentration, as shown in Equation 1.

$$PF = \frac{Hg_s}{Hg_b} \quad (1)$$

Equation 2 was used to calculate the geoaccumulation index, which is a measure of the extent of mercury contamination (Asare et al., 2019).

$$I_{geo} = \log_2 \left[\frac{Hg_s}{1.5 * Hg_b} \right] \quad (2)$$

Hg_s and Hg_b are the concentrations of mercury in the sample and the background, respectively.

Enrichment factor (EF) and ecological risk coefficient (ERC).

An enrichment factor was used to differentiate between mercury contamination arising from natural and anthropogenic sources, as shown in Equation 3 (Qing et al., 2015), whereas Equation 4 was applied to calculate the ERC to evaluate the potential environmental risk posed by mercury (J. Huang et al., 2021).

$$EF = \left[\frac{Hg_s \times Fe_b}{Hg_b \times Fe_s} \right] \quad (3)$$

$$ERC = PF \times TRF \quad (4)$$

Hg_s and Fe_s are the mercury and iron concentrations in the sample respectively, while Hg_b and Fe_b are the background concentrations, PF is the pollution factor, and TRF is the toxic response factor for mercury, which is 30 (Gyamfi et al., 2021). The ERC is classified as: low ($ERC \leq 50$), average ($ERC = 50-100$), considerable ($ERC = 100-300$), and high ($ERC \geq 300$) (Asamoah et al., 2021).

Human health risk

Human health risks were assessed in both the mining communities and the commercial city. Humans living within these communities can come into contact with the mercury

contaminant through dust inhalation, skin contact, and incidental ingestion. However, the oral ingestion pathway is typically the most critical of the three when contaminant concentrations in soil are higher than those of other sources (Amponsah et al., 2022). Therefore, the risk associated with the oral ingestion route was specifically calculated for the potential human health risks in both children and adults. This was estimated using the hazard quotient (HQ) method, as shown in Equation 5 (USEPA, 2011).

$$HQ = \frac{\text{Chemical Daily Intake (CDI)}}{\text{Tolerable Daily Intake (TDI)}} \tag{5}$$

The CDI (in mg/kg/day) results from the inadvertent intake of mercury and incorporates the modelled soil ingestion rate (20 mg/day), assuming a child and adult body weight of 30 kg and 70 kg, respectively, and exposure term of 1 assuming 7 days/week and 365 days/year (Canada, 2004). The 95%tile value of the concentrations was used in the calculations of the CDI.

$$CDI = \frac{\text{concentration.} \times \text{Ing.rate} \times \text{Exp. term}}{\text{Body weight} \times \text{life expectancy}} \tag{6}$$

Positive matrix factorization

The PMF model was used to analyze the sources of mercury contamination within the study areas. The primary methods used are detailed in Equations 7, 8, and 9 (Zheng et al., 2023).

$$X_{ij} = \sum_{k=1}^P (G_{ik} \times F_{kj}) + E_{ij} \tag{7}$$

X_{ij} represents the level of the j^{th} metal in the i^{th} sample, while G_{ik} denotes the contribution rate of the i^{th} sample to the contribution of the k^{th} pollution source. F_{kj} reflects the characteristic value of the k^{th} contamination source associated with the i^{th} metal concentration. E_{ij} corresponds to the residuals, and P indicates the number of factors. In this context, i , j , and k can take values of 1, 2,

3, etc. The receptor model breaks down the original matrix X into optimized matrices F and G, thereby minimizing the objective function Q, as defined in Equation 8.

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left(\frac{E_{ij}}{U_{ij}} \right)^2 \quad (8)$$

U_{ij} is the magnitude of the uncertainty of the j^{th} metal in the i^{th} sample and is given in Equation 9 as:

$$U_{ij} = \sqrt{(\delta \times c)^2 + (0.5 \times MDL)^2} \quad (9)$$

where δ represents the error fraction, c denotes the metal concentration, and MDL stands for the method detection limit. This study utilized the U.S. Environmental Protection Agency (USEPA) PM 5.0 software (USEPA, 2014) and set the number of factors and operation runs to 3 and 20, respectively, to execute the PMF model. The Q values obtained from the model are 0.01, 0.05, and 0.00 for Kenyasi, Obuasi, and Sunyani, respectively, indicating that the PMF model provides a better fit to the data.

Results and discussion

Soil physicochemical parameters

Figure 2 shows box plots of the soil pH, EC, and total organic carbon observed in the three study areas. The soil samples collected from Kenyasi exhibited an average pH value of 7.02, with approximately 53% of the samples having pH values below 7. This connotes the acidity of the Kenyasi samples with the remaining 47% ranging from slightly basic to strongly basic of the soil. At Obuasi, approximately 58% of the surface soils recorded pH values below 7, indicating the acidity of the soil. However, the mean value was 7.05. The mean pH values in these two areas were consistent with those of mined topsoils (Gyamfi et al., 2021; Y. Huang et al., 2019). In contrast, the commercial hub had a relatively basic topsoil, with approximately

70% of the samples exhibiting pH values above 7 and a mean pH value of 7.39. The lower pH in the mining-impacted surface soils may increase the mobility of mercury in the soils (Sintorini et al., 2021).

The mean electrical conductivities at all the study locations were significantly lower than the 2000 $\mu\text{S}/\text{cm}$ Canadian soil quality guideline (CCME, 2007). In the mining areas, Kenyasi and Obuasi recorded mean EC values of $159.45 \pm 44.87 \mu\text{S}/\text{cm}$ and $209.08 \pm 16.17 \mu\text{S}/\text{cm}$, respectively. The commercial hub recorded a relatively higher mean EC value of $238.78 \pm 91.45 \mu\text{S}/\text{cm}$, which may reduce the mobility of mercury in the soil due to the relatively high levels of hydrogen and other ions present (Opoku et al., 2020). The mining areas exhibited total organic carbon levels of 3.31% and 3.28% in Kenyasi and Obuasi, respectively, with the commercial city recording 5.91%. The relatively higher TOC levels in the commercial city might be due to various land use practices, vegetation types, or organic inputs from nearby areas (Gao et al., 2021).

Mercury levels across the study areas

The descriptive statistical analysis for the mercury levels across the three study areas is shown in Table 1. The results were compared to the pristine surface soil of the University of Energy and Natural Resources botanical gardens (control site), the Dutch target and intervention value for soil remediation, Dutch IV (VROM, 2000), and the Canadian soil quality guidelines (CCME, 2007). The comparison with these international standards is because Ghana currently lacks soil quality guidelines. The mean mercury levels recorded were 148 times higher in Obuasi, 32 times higher in Sunyani, and 14 times higher in Kenyasi than in the control site, decreasing in the following order: Obuasi (0.446 mg/kg) > Sunyani (0.096 mg/kg) > Kenyasi (0.043 mg/kg). This suggests that anthropogenic activities within the study areas are increasing

the mercury levels in the soils although the concentrations were lower than the international soil quality guidelines.

Sunyani, the commercial hub, recorded a mean mercury value that is twice as high as that observed in Kenyasi, the mining community, although the difference was not statistically significant ($p > 0.05$). This can be attributed to the increased improper disposal of waste, industrial discharge, and the burning of waste within the Sunyani municipality (Agbeshie et al., 2020; Asamoah et al., 2024). Also, the result of such a commercial city is consistent with similar research conducted in Kumasi, Ghana, another city popular for its commercial activities, which recorded mean levels of mercury ranging from 0.02 mg/kg in Bantama to 0.15 mg/kg in Kejetia (Akoto et al., 2017). Furthermore, the majority of the soil samples in Kenyasi were collected from farmland and residential soils, which may not necessarily be linked to high levels of mercury in soils.

At Obuasi, the mercury concentrations displayed significant variability, with standard deviation exceeding the interquartile ranges. This variability was due to the high values (outliers) included in the datasets because they indicated areas of high concentration (hotspots). For instance, the maximum mercury content of 15.67 mg/kg was collected at an area where some illegal miners were spotted on site. Illegal mining (galamsey) is known to increase the mercury burden in soils globally (Ondayo et al., 2023; Rajaei et al., 2015; Steckling et al., 2017). The average mercury level of 0.446 mg/kg at Obuasi is about 4 times higher than that in Sunyani and 10 times higher than that in Kenyasi. The relatively higher concentration in Obuasi may be attributed to the increased mining activities in the municipality over the past century (Bempah & Ewusi, 2016). A previous study conducted at the Obuasi municipality recorded significantly lower mercury levels of 0.05 ± 0.01 mg/kg, which is about 8 times lower than observed in this

study (Akoto et al., 2018). Accumulation of mercury in the surface soil of Obuasi due to constant mining practices may have increased the mercury content in the lithosphere (Meloni et al., 2023).

Spatial distribution pattern

Figure 3 illustrates the distribution pattern of mercury at the three study locations. At Kenyasi, mercury was largely concentrated in the northwestern corridor of the town. This zone is near a suburb called Akyerensua, which is known for illegal mining activities, although miners were not present on-site at the time of sampling. Therefore, mercury accumulation in this area may be attributed to the activities of the "galamseyers." Additionally, the burning of waste may have contributed to the observed mercury concentrations in the area (Natasha et al., 2020), as dump sites were observed in this part of the town. The mercury levels in Obuasi are widely distributed around the southern and middle belts of the municipality. The activities observed within this vicinity include a "galamsey" washing site in a residential area. It can, therefore, be concluded that illegal mining activities within the municipality are elevating the mercury levels in the soil.

Conversely, the mercury concentrations in Sunyani were widely dispersed across the middle belt and partly in the eastern corridor of the municipality. Commercial activities within the Sunyani municipality have increased in recent times, generating hazardous waste in the city. The central incinerator of the Sunyani municipality is located between the middle and eastern zones. Some samples were collected around these areas which may account for the distribution pattern observed since the burning of hazardous materials has been linked to the discharge of mercury into soils (Chalkidis et al., 2020).

Extent of mercury contamination

Table 2 shows the various pollution and ecological indices used to determine the level of mercury contamination at the three study sites. The pollution factor showed extremely high contamination of mercury in the surface soils at Obuasi which is characteristic of mining-impacted surface soil. The pollution factor (PF) also showed appreciable mercury contamination at Kenyasi and high contamination in Sunyani. This indicates that both mining and non-mining areas are prone to mercury pollution. In addition, I-geo values showed high pollution of the surface soils of Kenyasi and Sunyani but extreme pollution at Obuasi.

The enrichment factor confirmed the extreme mercury contamination at Obuasi and the high enrichment at both Kenyasi and Sunyani. Furthermore, the ecological risk coefficients showed a considerable risk of mercury contamination at Kenyasi and Sunyani but a high risk at Obuasi. These results confirm the overall mercury contamination due to anthropogenic activities in the study areas. This means that, beyond lithogenic contributions, human activities within these areas pose risks to indigenes. An ecological risk coefficient value of 1337 at Obuasi indicates a highly extreme risk of mercury in the vicinity.

PMF analysis

The positive matrix factorization model was configured with three factors in the base model to determine the potential sources and contributions to mercury contamination in the study locations, as shown in Figure 4. However, the model identified only two possible contributing factors for mercury contamination in the commercial city of Sunyani; Factor 1 (61.3%) and Factor 2 (39.7%). In Kenyasi, the receptor model revealed Factor 1 as the major contributor (37.8%) to mercury contamination, which was attributed to mining and related activities. Factor 3, which contributed 34.1% of the overall mercury contamination, was attributed to farming activities within the town. Historically, the use of mercury-contaminated pesticides and

fertilizers has been associated with the introduction of mercury into the soil (Li et al., 2019). Factors such as the residential use of wood and charcoal for heating and cooking (Costa et al., 2022) and lithogenic contributions were assigned to Factor 2. This is consistent with the distribution pattern of mercury within the Kenyasi township.

At Obuasi, the PMF model identified Factor 2 as the major contributor to the mercury accumulation in the topsoil, contributing approximately 79.6%. This was attributed to mining activities carried out by illegal miners in the town. Factor 1 contributed 11.4% of the variance and may be identified as farming activities within the municipality. Previous studies have reported considerable levels of mercury in water bodies in Obuasi (Armah et al., 2013), and they may have been transferred into the topsoils through irrigation practices (Abedi et al., 2023). The remaining 9% was attributed to geogenic contributions and residential activities carried out by the inhabitants.

In the commercial city, the PMF receptor model identified two possible factors with Factor 1 being the major contributor (61.3%). Previous studies within the Sunyani municipality have shown that dumpsites in the municipality pollute the surface soil (Agbeshie et al., 2020), which conforms to the distribution pattern observed in this current study. Therefore, Factor 1 was assigned to the burning of waste and hazardous materials. The remaining 38.7% could be due to other activities such as farming, residential, and geogenic contributions.

Human Health Risks

The hazard quotient (HQ) of mercury at the three study locations is presented in Figure 5. The HQ was used to ascertain the potential risks associated with mercury ingestion and its detrimental effects on human health and the environment. The findings showed a notable difference in HQ values between children and adults, with children having values about 1.5 times

higher than those for adults. This discrepancy underscores a concerning reality: children are at a notably greater risk of non-cancer health issues due to mercury exposure compared to their adults. The HQ values of 0.0002, 0.0007, and 0.0016 among children in Kenyasi, Sunyani, and Obuasi, respectively, indicated low risks associated with mercury exposure at the study locations. However, for highly toxic elements such as mercury, there is always a need to monitor their presence in the environment.

Conclusion

This study successfully investigated mercury contamination across two mining communities and one commercial city in Ghana. Although the average mercury concentrations at all the study locations were lower than international standards, they were greater than those at the control site. The results showed that Obuasi is the most polluted location owing to mining and its related activities. Sunyani, the commercial city in this study, recorded a mean mercury level that is two times higher than that in Kenyasi, a renowned mining community in Ghana. This is, therefore, an indication that mercury contamination in surface soils is not only linked to mining. The pollution and ecological risk indices also confirmed that Obuasi was extremely enriched with mercury, whereas there was considerable mercury enrichment in Sunyani and Kenyasi. The spatial distribution pattern showed high concentrations of mercury in the middle and southern zones of the Obuasi municipality, where some people were spotted engaging in illegal mining activities. The northwestern corridor of Kenyasi is closer to an illegal mining area and recorded a higher concentration of mercury, whereas the middle and eastern corridors of the Sunyani municipality recorded relatively higher levels of mercury due to the waste burning. The positive matrix factorization identified and confirmed mining and its related activities as the major sources and contributing factors to mercury accumulation in Obuasi and Kenyasi. The receptor

model attributed the burning of hazardous waste, farming, and other geogenic factors to mercury release and deposition in the Sunyani surface soils. Although the health risk assessment showed no adverse health effects ($HQ < 1$), long-term or high-level exposure, particularly among children, may be detrimental. Identifying and assessing sources of mercury contamination, and implementing effective management strategies, are essential to protect vulnerable populations, especially children, from the far-reaching consequences of mercury exposure on health and the environment.

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Authors Contributions

Benjamin Darko Asamoah: Conceptualization; Investigation; Data Curation; Formal Analysis; Writing – original draft; **Lily Lisa Yevugah:** Conceptualization; Investigation; Data Curation; Formal Analysis; Writing. **Lawrence Sheringham Borquaye:** Conceptualization; Formal Analysis; Writing. **Matt Dodd:** Conceptualization; Data Curation; Formal Analysis; Writing; Resources; Supervision. **Godfred Darko:** Supervision; Resources; Conceptualization; Data Curation; Formal Analysis; Writing.

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Declarations

The authors declare that none of their known affiliations, financial conflicts, interpersonal connections, or management relationships might have had an impact on the work presented in this paper.

Data Availability

Data is included as Supplemental Material.

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Figure 1: A map showing the sampling points and land use, including forests, farmlands, mining and stone quarries in the study areas

Figure 2: Physicochemical parameters in the study areas

Figure 3: Spatial distribution map of mercury in the study areas. [Kenyasi A; Obuasi B; Sunyani C].

Figure 4: Sources and contribution rates of mercury by the PMF receptor model

Figure 5: Hazard quotient for mercury in adults and children across the study areas.

Receptor modeling, ecological risks, and human health impacts of mercury in some Ghanaian topsoils due to mining and commercial activities

Table 1

Table 1: Descriptive statistics for mercury concentrations (mg/kg) across the study areas

	Mean	Std Dev	Median	25 quartiles	75 quartiles	95% tile	Min	Max
Kenyasi (n = 49)	0.043	0.005	0.032	0.022	0.049	0.10	0.009	0.278
Obuasi (n = 48)	0.446	2.225	0.074	0.044	0.149	0.705	0.013	15.670
Sunyani (n = 90)	0.096	0.012	0.056	0.032	0.092	0.319	0.012	0.765
Control Site (n = 5)	0.003	0.001	0.003				0.002	0.004
CCME (CCME, 6.6 2007)								
Dutch IV 10 (VROM, 2000)								

CCME – Canadian Council of Ministers of the Environment

VROM - Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu

Table 2: Contamination and risk indices of mercury at the three study locations

Study Area	Contamination and risk indices			
	Pollution factor	Geoaccumulation index	Enrichment factor	Ecological risk coefficient
Kenyasi	4.27	1.51	4.92	128
Obuasi	44.6	4.89	42.3	1337
Sunyani	9.62	2.68	8.58	288









