



# Comprehensive assessment of heavy metal pollution of agricultural soils impacted by the Kalsaka abandoned gold mine and artisanal gold mining in northern Burkina Faso

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**Abstract** In this study, the environmental quality of agricultural soils around the Kalsaka abandoned gold mine was evaluated. A total of 117 samples including industrial mine wastes, topsoil, and control soil were collected in and around the mine, and their heavy metal concentrations were determined using ICP-MS after aqua regia digestion. Except for Zn, the average concentrations of the metals were higher in mine wastes and the agricultural soils than their average upper continental crust (UCC) counterpart, whereas those of Ag, As, and Hg exceeded the UCC in the control soils. The control soils had the lowest contaminations and the lowest pollution levels for all metals except for Hg. Based on the average concentrations and coefficients of variation, it can be concluded that Cr, Ni, and Zn abundance in the agricultural soils was controlled by natural factors, whereas that of Ag, As, Hg, Co, Cu, and Mn was mainly associated with mining. The absence of Hg in industrial mine wastes and its high contents in agricultural and control soils reflected the artisanal gold mining

source of this metal. Thus, single and integrated pollution indices showed that ecological risk and toxicity are much higher when Hg is included in the index calculation, suggesting cumulative effects of industrial and artisanal gold mining on the agricultural soil quality. The results also showed that Hg and As are the pollutants of major concern in the Kalsaka abandoned gold mine. Because of its proximity to human settlements, the Kalsaka abandoned gold mine necessitates an immediate rehabilitation.

**Keywords** Artisanal gold mining · Ecological risks · Heavy metals · Industrial gold mine · Pollution indices

## Introduction

The abundance of potentially toxic heavy metals in the terrestrial ecosystems is directly related to both natural and anthropogenic sources (Owsianiak et al., 2015; Tembo et al., 2006). Natural sources include volcanic eruption, fugitive dusts, forest fires, weathering of the parent material, and erosion, whereas anthropogenic sources include landfill, agriculture, human settlement, transportation, and extractive industries (Gu et al., 2016; Jin et al., 2019; Wang et al., 2015; Wei & Yang, 2010). It has been reported that the contribution of extractive industries to heavy metal background levels in soils is far more important than that of natural sources (Armah et al., 2014;

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Chen et al., 2008, 2009; Luo et al., 2007; Qishlaqi et al., 2009; Shi et al., 2008). In that sense, during the extraction, separation, and beneficiation of critical raw materials, such as copper, zinc, platinum, and gold, colossal quantities of solid and liquid wastes, collectively known as “mine wastes,” are produced (Lottermoser, 2010; Yilmaz, 2011). These wastes consist of topsoil, waste rocks, overburden material, mill tailings, and processing chemicals laden with a series of heavy metals (Falagán et al., 2016; Matinde et al., 2018).

The volume of the wastes is a function of the mine size, the local geology, contrast between orebody and its host rocks, and mining techniques, which can be open-pit or underground operations (Abiahu et al., 2019; Abzalov, 2016). Although open-pit mining is less complex and more economic, the technique is characterized by high stripping ratios (i.e., amounts of wastes produced for given ore quantities) and thus generates larger quantities of overburden and waste rocks compared to underground mining (Ben-Awuah et al., 2016; Opoku & Musingwini, 2013). Management of fugitive dusts from drilling, blasting, waste rock dumps, and haul roads is also a major environmental challenge on open-pit mines (Mkpuma et al., 2015; Noble et al., 2017). These wastes, that are stored in piles or in tailings impoundments around or near the mining sites, are often close to human settlements and farmlands (Johnson et al., 2016; Pascaud et al., 2015). Through runoff, wind, and seepage from impoundments, the fine silicate minerals, fugitive dusts, and leachates can be spread over large areas and contaminate the nearby agricultural soils and surface and groundwater resources (Candeias et al., 2015; López et al., 2008; Mpanza et al., 2020).

In the absence of waste characterization and remediation schemes, the highly enriched mine wastes may continue to be mobilized into the surrounding environment several decades or centuries after the mining has ceased (Bacchetta et al., 2015; Kossoff et al., 2016; Laurence, 2011). That is, thousands of abandoned mines have been contaminating soils, water, and air with heavy metals worldwide (Bell & Donnelly, 2006; Chang et al., 2005). Although South Africa, with a long history of mining activities in Africa, is the country with hundreds of abandoned gold mines (Venkateswarlu, 2016), other countries including Burkina Faso also began to have abandoned gold mines on the continent (Pathé et al.,

2021; Salom & Kivinen, 2020). It has been reported that a progressive remediation program of mine sites is the most holistic approach of reducing mining-related pollution (Lamb et al., 2015; Purtil et al., 2022; Unger et al., 2015). However, for many technical and administrative constraints, countries often fail to adopt this remediation approach (Mabaso, 2023; Mills, 2022). Consequently, various abiotically and biologically mediated oxidation reactions of sulfide minerals within the mine waste heaps may lead to a generation of acid or alkaline mine drainage rich in dissolved heavy metals (Nordstrom et al., 2015; Vriens et al., 2020). Not only do the generated leachates represent direct environmental hazards, but they may also enhance the desorption and mobility of previously immobilized heavy metals in the receiving soils (Beane et al., 2016; Ma et al., 2016). It can also be noted that the abandoned mines are the hotspots for illegal artisanal miners who use rudimentary tools to dig old workings, hence exacerbating environmental degradation and further exposing the local populations to physical and health hazards (Mhlongo & Akintola, 2021; Mhlongo & Amponsah-Dacosta, 2015).

The rise of gold prices in the global marketplace and the adoption of flexible mining codes have prompted multinational companies to invest in gold exploration and exploitation in Burkina Faso. As a result, 12 foreign-owned industrial gold mines and hundreds of artisanal gold mining sites are currently operating in the country. Although gold mining has significantly contributed to the economic growth and social development of rural communities across Burkina Faso, active and derelict gold mines represent serious environmental hazards and health threats. In recent years, two industrial gold mines, namely the Poura gold mine and Kalsaka gold mine, were closed in Burkina Faso without any rehabilitation. The Kalsaka gold mine, which is the focus of the present study, not only produced tons of mine wastes, but also left behind access adits, shafts, tailing storage facilities, and workings. This has resulted in widespread environmental degradation and loss of livelihood for the local population (Asensio et al., 2013; Kim et al., 2016).

In order to set up reclamation strategies for the Kalsaka abandoned gold mine, an effective assessment of the environmental quality of the agricultural soils around the mine is urgently required. Several

mono-elemental (e.g., index of geoaccumulation and contamination factor) and integrated pollution indices (e.g., pollution load index) and risk (e.g., ecological risk index) have been successfully used to assess heavy metal pollution of soils (Yang et al., 2013; Hu et al., 2014; Kowalska et al., 2016; Mazurek et al., 2017). These indices can be subsequently used to map soil contamination at local and regional scales through spatial interpolation techniques. Hence, spatial interpolation quantifies spatial patterns of individual heavy metals at unsampled areas, allowing identification of priority areas. Conversely, the spatial interpolation could be used to differentiate between anthropogenic and natural sources of heavy metals in soils. To the best of our knowledge, there are no available peer-reviewed studies on the environmental impacts of mining-derived heavy metal contamination of agricultural soils around the Kalsaka abandoned gold mine.

The objectives of the research described in the present article were therefore to (1) use contamination factor (Cf), index of geoaccumulation ( $I_{geo}$ ), and pollution load index (PLI) to comprehensively assess the degree of agricultural soil pollution by nine heavy metals (As, Ag, Co, Cr, Cu, Hg, Mn, Ni, and Zn) with respect to the average composition of the upper continental crust (UCC); (2) to evaluate the potential ecological and environmental risks of the metals using the ecological risk index (RI), mean effect range median quotient (MERMQ), and mean probable effect level quotient (MPELQ); and (3) to assess the impact of the abandoned gold mine versus artisanal gold mining using a spatial interpolation approach. In the semi-arid environments such as northern Burkina Faso, with scarce vegetation cover and low rainfall, the spread of mining-derived heavy metals in soils will be primarily controlled by wind and topography. The findings of the present study would have wide applicability to other mining sites in Burkina Faso and elsewhere in the world and assist local decision makers and epidemiologists in setting up a sound strategy for land-use suitability.

## Materials and methods

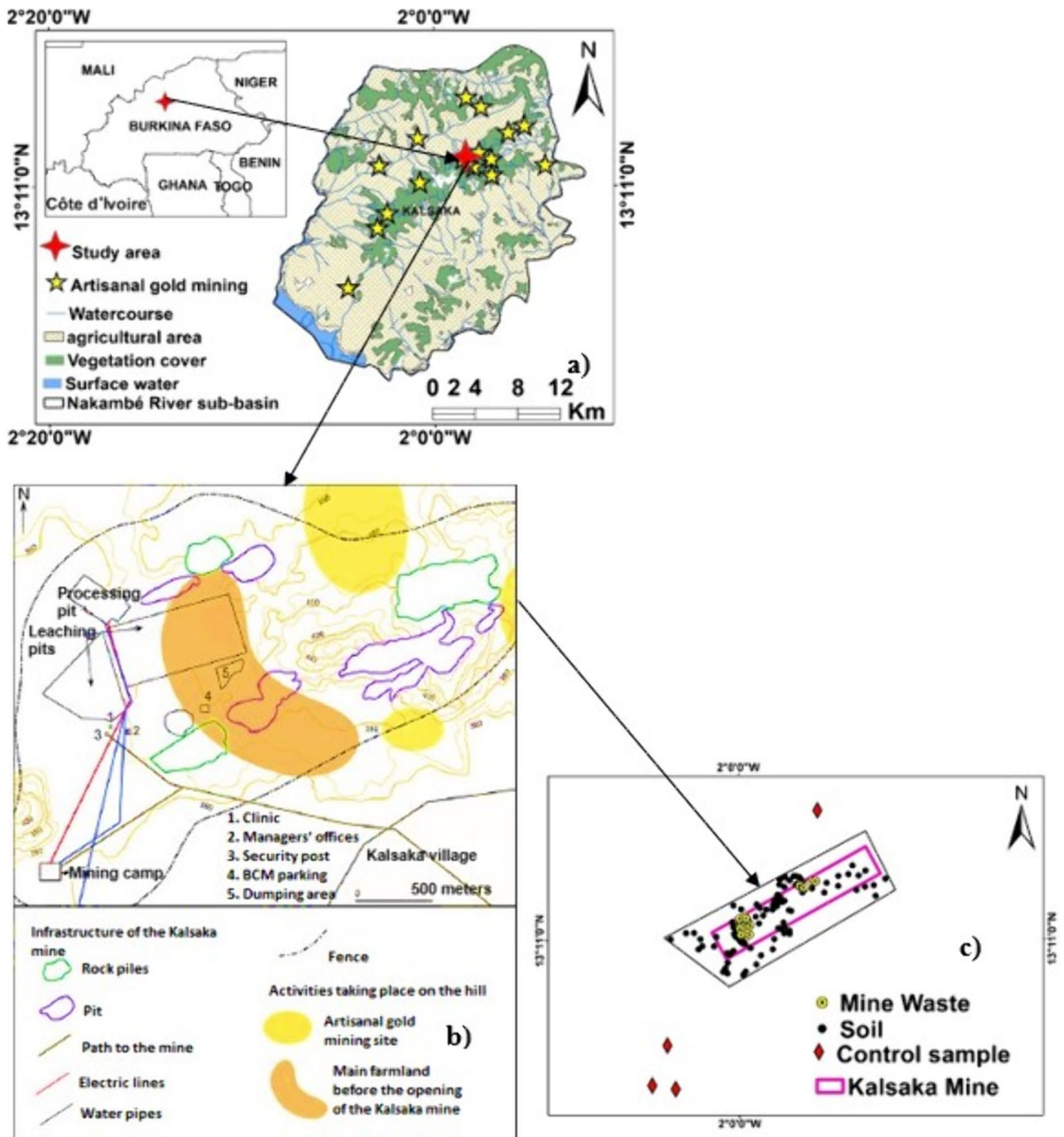
### Environmental setting and land use

The Kalsaka abandoned gold mine is located in the village of Kalsaka in northern Burkina Faso (Fig. 1a). The area belongs to the Sudano-Sahelian semi-arid climatic zone with low and irregular annual rainfalls, which vary from 500 to 800 mm (Kwaw et al., 2018; Kabore et al., 2022). In northern Burkina Faso, the wind blows from the south to southwest direction during the rainy season and from north to northeast in the dry season with an average annual speed of 2.6 m/h (Ouoba, 2023). The study area is part of the ephemeral Nakambé River watershed that follows into the neighboring Ghana (Fig. 1a). The local vegetation cover is characterized by savannah shrubs and sparse trees with a gradual increase in vegetation density along the Nakambé River bank. Like the entire country, the study area is flat (280–480 m asl) with a few hills formed by outcrops and lateritic cuirasses (Bretzler et al., 2017).

The local soil is poorly developed and made of leached ferruginous tropical soils with low organic matter content and low pH values (Da Costa et al., 2015; Kagambega et al., 2023). Because of the persistent droughts, high population density, and widespread of artisanal gold mining, the local soil is also characterized by high erodibility and poor structural stability and hence low heavy metal immobilization capacity (Huang et al., 2020; Zhang et al., 2020). Before the construction of the Kalsaka gold mine, the majority of the people living in the village of Kalsaka and its surrounding were involved in seasonal artisanal gold mining (Misafir, 2021). In contrast, during the rainy season, farmers practice subsistence farming based on millet and sorghum (Pokorny et al., 2019).

### Geology and gold mineralization

Burkina Faso belongs to the Baoulé-Mossi domain within the West Africa Craton (Castaing et al., 2003). About 80% of the country's surface area is made of crystalline basement rocks composed of the early Proterozoic Birimian greenstone belts of plutonic and metamorphic rocks such as amphibolite, diorites, granites, metagabbro, metasediments, and green schists (Tshibubudze et al., 2013). The Loumana, Banfora, Houndé, and Boromo belts are the four



**Fig. 1** Location maps showing the Kalsaka abandoned gold mine (a) and its facilities (b; modified from Thune, 2011) within the Nakambé River watershed in northern Burkina Faso and sampling points (c)

major Birimian greenstone belts that cross the country (Baratoux et al., 2011). These belts host enormous gold deposits within their core or at their borders (Béziat et al., 2008).

The Kalsaka gold mine project lies within the Boromo greenstone belt, and its gold deposits are

associated with metavolcanic-sedimentary sequences and syntectonic quartz veins of north-northeast trending (Milési et al., 1990, 2006). The auriferous veins occupy openings within the shears and adjacent altered rocks (Béziat et al., 2008). However, the structures controlling the gold mineralization are often

second-order shears that differ from the first-order structures. The gold mineralization in these geological formations is often associated with sulfide minerals rich in a series of chalcophile elements such as Cu, As, Ag, Pb, Ni, Fe, Mo, Sb, and Zn. Ultimately, mining of these deposits will produce tailings with distinctive heavy metal pollution trends (El Rasafi et al., 2021; Kahangwa, 2022; Fodoué et al., 2022; Yoon et al., 2023). In Burkina Faso, both industrial gold mines and artisanal gold mine sites compete for overlapping areas in the greenstone belts (Fig. 1b).

### Gold mining at Kalsaka

Opened in October 2008, the Kalsaka gold mine was closed after 5 years of activities. With ore deposits in the Kalsaka gold field extending from near surface to several hundred meters in depth (0–400 m), open-pit appeared to be the most adequate mining technique for the Kalsaka gold mine. Although the mine and its infrastructures were entirely fenced off (Fig. 1b), nowadays, the fence is completely damaged leaving free access to artisanal gold miners.

Traditionally, several beneficiation techniques such as Hg-gold amalgamation, biological extraction, and cyanidation have been used to extract gold from crude ores, and each technique affects differently heavy metal pollution of the surrounding environment (Chakraborty et al., 2022; Fashola et al., 2016). Thus, Hg-gold amalgamation and biological extraction seem to aggravate mercury and arsenic pollution, respectively (Huang et al., 2019; Xiao et al., 2017). In contrast, there is little understanding of the influence of cyanidation on heavy metal pollution (Zhang et al., 2021). About 2 tons of cyanide were used in the Kalsaka gold mine on a daily basis to concentrate gold, and the resulting liquid waste (up to 200 m<sup>3</sup>) was diverted toward a storage basin for treatment and later poured onto the nearby agricultural fields. Although Burkina Faso banned mercury in 2015 (UNEP, 2019), artisanal gold miners practice Hg-gold amalgamation and subsequently recover gold through heating without or rarely using retorts to condense Hg, thereby releasing high quantities of Hg into the atmosphere (Black et al., 2017). This practice gives rise to airborne mercury pollution of soil and surface water resources. As a result, artisanal gold mining could be the largest anthropogenic source of local atmospheric Hg emission.

Under Burkina Faso's mining law, all mining companies are required to contribute to a fund during the period of exploitation, which should enable the rehabilitation of the Kalsaka gold mine. The dilemma is that the mine has been bought out by another mining company without any indication of the intended use of the fund. Nevertheless, it was stipulated in the rehabilitation plan of the mine that the sterile heaps would be decontaminated of cyanide and compensatory woodlands would be created. Unfortunately, the rehabilitation process has been hampered by leadership disputes over the fund management. To date, piles of non-decontaminated mine wastes are washed away by runoff without any environmental monitoring and control measures. A situation has been exacerbating environmental hazards such as degradation of vegetation cover and biodiversity, loss of agricultural lands and soil and water pollution, mercury emissions, siltation, and erosion. As a result, the local population's access to farmlands becomes a forlorn hope in this semi-arid environment.

### Soil sampling and analysis

A total of 117 surface soils (0–15 cm), four control soils, and 30 industrial mine waste samples were randomly collected in and around the Kalsaka abandoned gold mine in 2022 (Fig. 1c). The four control soil samples were collected at remote areas far from the Kalsaka gold mine (~5 km) in the opposite direction of the surface flow. All samples were sealed in clean plastic bags. Back in the soil laboratory, the samples were air-dried at room temperature and subsequently sieved (2-mm mesh). The subsets of 2 mm fraction of individual samples were sent to the Bureau Veritas Laboratories Ltd (Vancouver, Canada) for heavy metal analysis.

The samples were finely powdered and digested according to a modified aqua regia method (Bureau Veritas AQ 250 method). That is, about 0.5 g of each sample was digested in 2:2:2 of HCl: HNO<sub>3</sub>: H<sub>2</sub>O ratio at 95 °C for 1 h in a heating block. The analytes were made up to a final volume of 300 mL with 5% HCl, and the “pseudo-total concentrations” of As, Ag, Co, Cr, Cu, Hg, Mn, Ni, and Zn were determined using an inductively coupled mass spectrometer (ICP-MS, Perkin Elmer Elan 9000, US). Sample dilution was applied in order to lower the concentration of analytes in the samples to the appropriate range of

detection limit. All reagents including standard stock solutions of known concentrations were of American Chemical Society analytical grade (ACS) and were purchased from Inorganic Ventures (Virginia, US).

To assess the accuracy of the digestion and the precision of analytical, duplicates of two in-house certified reference materials (STDDS11, OREAS262) and two blind duplicates provided by the authors were used. The reproducibility of the digestion method was better than 99% for all metals. The blank concentrations were used to determine the instrumental detection limits of the individual heavy metals, which were 0.1, 0.002, 0.1, 0.5, 0.01, 0.005, 1, and 0.1 mg/kg for As, Ag, Co, Cr, Cu, Hg, Mn, Ni, and Zn, respectively. The percentage coefficients of relative standard deviation were below 10%.

### Descriptive statistics

Descriptive statistics such as mean, median, minimum, and maximum concentrations were used to investigate the central tendency of heavy metals in the three datasets, whereas standard deviation and skewness were used to evaluate heterogeneity and normality of the heavy metal distribution. Likewise, coefficients of variation (CV) were used to describe the heavy metal variability within the samples. A heavy metal with a CV value of less than 10% is considered to have weak variability,  $10\% \leq CV < 100\%$  indicates moderate variability, and  $CV \geq 100\%$  implies strong variability (You, 2014). Boxplots were used to compare the index of geoaccumulation between the three datasets. These statistics may help identify sources and transport of heavy metals around the mining site and beyond. Statistical analyses were carried out using PAST (Version 4.0) and Origin 2023.

### Spatial interpolation of heavy metals

Estimation of heavy metal concentrations at unsampled areas using concentrations of sampled areas is known as spatial interpolation. In environmental studies, geostatistical and deterministic methods are the two interpolation methods commonly used by researchers to investigate soil pollution status and potential ecological risks (Li et al., 2021; Saha et al., 2022). Because geostatistical methods are sensible to sampling design and data skewness, an inherent characteristic of geoscience data, they take into account

exploratory data analysis and prediction errors (Zakeri & Mariethoz, 2021). In contrast, deterministic methods do not require normal distribution of data, and they are simple and easy to interpret.

Among these methods, distance inverse weighting (IDW) is the most widely used deterministic method. The method assumes that the attribute concentrations of unsampled points are the weighted average of known concentrations within the neighborhood, and the weights are inversely related to the distances between the prediction location and the sampled locations (Lu & Wong, 2008). In the present study, the IDW method was used to produce the spatial distribution maps of different environmental pollution and risk indices. The produced maps will assist environmental practitioners in site-specific monitoring of mine-affected agricultural soils. The IDW maps were produced using Geostatistical Analyst within the Geostatistical wizard of ArcMap (version 10.8).

### Evaluation of soil contamination with heavy metals

Environmental quality indices are powerful tools used to summarize large and complex environmental data into a few interpretable indicators (Dung et al., 2013; Karimi et al., 2017). The indices can also be used to distinguish between natural and anthropogenic sources of pollutants in soils (Esmaeili et al., 2014; Pejman et al., 2015; Soltani-Gerdefaramarzi et al., 2021). However, the application of most environmental quality indices requires unimpacted local sample concentrations (Kowalska et al., 2016). In the absence of such samples in this highly anthropogenically impacted area, the UCC (Rudnick & Gao, 2004), that provides a more stable and universal characteristic, was used as reference geochemical background values to calculate the different pollution indices (Kowalska et al., 2018).

Single pollution indices such as index of geoaccumulation ( $I_{geo}$ ), contamination factor (Cf), and potential ecological risk index ( $E_r$ ) were employed to determine the extents of contamination and potential ecological risk of individual heavy metals at a given sampling site, whereas PLI, RI, MERMQ, and MPELQ were used as integrated pollution indices to assess soil ecological quality of the agricultural soils at different sampling sites.

Contamination factor

Assessment of heavy metal contamination status of soils can be carried out using contamination factor ( $C_f^i$ ). The index is based on the concentration of a given heavy metal in soil samples and its corresponding background concentration. The contamination factor, proposed by Håkanson (1980), was calculated by the following relation (Eq. 1):

$$C_f^i = \frac{C_s^i}{C_{BG}^i} \tag{1}$$

where  $C_s^i$  is the mean concentration of individual heavy metals in the sample,  $C_{BG}^i$  is the background concentration (UCC; Rudnick & Gao, 2004). Four categories are used to interpret  $C_f^i$  (Håkanson, 1980);  $C_f^i < 1$  indicates low contamination;  $1 < C_f^i < 3$  is moderate contamination;  $3 < C_f^i < 6$  is considerable contamination; and  $C_f^i > 6$  is very high contamination.

Index of geoaccumulation

To estimate the degree of soil pollution, the index of geoaccumulation ( $I_{geo}$ ) was calculated (Müller, 1969). Not only the index considers the influence of human activities and soil natural geochemical background concentrations, but also includes the variability of the local lithology. The  $I_{geo}$  is calculated as follows (Eq. 2):

$$I_{geo} = \log_2 \left( \frac{C_i}{1.5BG_i} \right) \tag{2}$$

where  $C_i$  is the measured concentration of a heavy metal  $i$  in a soil sample, and  $BG$  is the geochemical background concentration of a heavy metal  $i$  in the upper continental crust (Rudnick & Gao, 2004). The factor 1.5 is a variation conversion factor that eliminates possible variations in background concentrations due to lithogenic effects. The  $I_{geo}$  is grouped into seven classes: class 0 (uncontaminated soil),  $I_{geo} < 0$ ; class 1 (uncontaminated to moderately contaminated),  $0 < I_{geo} < 1$ ; class 2 (moderately contaminated),  $1 < I_{geo} < 2$ ; class 3 (moderately to heavily contaminated),  $2 < I_{geo} < 3$ ; class 4 (heavily contaminated),  $3 < I_{geo} < 4$ ; class 5 (heavily to extremely

contaminated),  $4 < I_{geo} < 5$ ; class 6 (extremely contaminated),  $I_{geo} > 5$ .

Pollution load index

The pollution load index is a multielement index that assesses the global pollution level of individual soil samples. The index provides an easy way to highlight a possible deterioration of a soil sample as a result of anthropogenic loadings of heavy metals (Ennaji et al., 2020). Pollution load index was calculated using Eq. 3 (Peng et al., 2016; Wu et al., 2018):

$$PLI = (Cf_1 \times Cf_2 \times Cf_3 \dots \dots Cf_n)^{\frac{1}{n}} \tag{3}$$

where  $n$  is the number of analyzed heavy metals, and  $Cf$  is the calculated values for the contamination factor of each heavy metal in soils. When  $PLI < 1$ , it suggests no pollution;  $1 < PLI < 2$  denotes moderate pollution;  $2 < PLI < 3$  represents heavy pollution; and  $PLI > 3$  denotes extreme pollution (Banerjee & Gupta, 2012; Tomlinson et al., 1980).

Ecological risk index

The potential adverse effects of potentially toxic heavy metals on soils were assessed using the potential ecological risk index (RI) proposed by Håkanson (1980), which takes into account the sensitivity of the soil biological community to these toxic heavy metals was used (Liu et al., 2015). The ecological risk estimation is usually based on Hg, Cd, As, Ni, Pb, Cr, and Zn (Canli & Atli, 2003). In the present study, the ecological risk index was calculated based on As, Cu, Cr, Co, Hg, Mn, Ni, and Zn concentrations as follows (Eqs.4).

$$RI = \sum_{i=1}^n E_r^i = \sum_{i=1}^n T_r^i \times C_f^i \tag{4}$$

where  $E_r^i$  is the potential risk of individual metals;  $C_f^i$  is the pollution factor of a metal  $i$ ; and  $T_r^i$  is the biological toxic-response factor for a given heavy metal. The biological toxic-response factors for As, Cu, Cr, Co, Mn, Ni, Hg, and Zn are 10, 5, 2, 1, 5, 40, and 1, respectively (Håkanson, 1980; Soliman et al., 2015; Swarnalatha et al., 2013).

Håkanson (1980) defined four categories for  $E_r$ : low ( $E_r^i < 40$ ), moderate ( $40 \leq E_r^i < 80$ ), considerable

( $80 \leq E_r^i < 380$ ), and very high ( $E_r^i \geq 320$ ). RI were classified as follows: low ( $RI < 95$ ), moderate ( $95 \leq RI < 190$ ), considerable ( $190 \leq RI < 380$ ), and very high ( $RI \geq 380$ ).

### Probability of toxicity indices

The mean effect range median quotient (MERMQ) and the mean probable effect level quotient (MPLEQ) are relatively new indices used as a tool to recognize the extents of possible biological effects of potentially toxic substances on the soil environment based on freshwater sediment quality guidelines (SQGs). These indices can be applied in case of the existence of multiple contaminants in the soil where the adverse effects caused by each contaminant are additive and not antagonistic (Violintzis et al., 2009). As a result, the indices can provide spatially representative patterns of soil contamination and be used as a key recognition of exposure to pollution (Pejman et al., 2015). To gain more realistic insight into both industrial and artisanal gold mining effects on the agricultural soils around the Kalsaka abandoned mine, both MERMQ and MPELQ were calculated according to the following equations (Eqs. 5 and 6; Long & MacDonald, 1998):

$$\text{MERMQ} = \frac{\sum_{i=1}^n C_i / \text{ERM}_i}{n} \quad (5)$$

$$\text{MPLEQ} = \frac{\sum_{i=1}^n C_i / \text{PEL}_i}{n} \quad (6)$$

where MERMQ and MPELQ are the average ratios between the individual heavy metal concentrations ( $C_i$ ) in the soil sample and the related effect range median ( $\text{ERM}_i$ ) and probable effect level ( $\text{PEL}_i$ ) values, which have been determined through several toxicity tests in laboratory and field (Gao & Chen, 2012), and reported by Long and MacDonald (1998), whereas  $n$  is the number of the concerned heavy metals. According to Long and MacDonald (1998) and MacCready et al. (2006), soils can be classified based on the MERMQ and MPELQ values as follows:  $\text{MERMQ} < 0.1$ ,  $0.11 < \text{MERMQ} < 0.5$ ,  $0.51 < \text{MERMQ} < 1.5$ , and  $\text{MERMQ} > 1.5$  correspond to 12, 30, 46, and 75% of toxicity, respectively. Likewise,  $\text{MPELQ} < 0.1$ ,  $0.11 < \text{MPELQ} < 1.5$ ,

$1.51 < \text{MPELQ} < 2.3$ , and  $\text{MPELQ} > 2.5$  coincide with 10, 25, 50, and 76% of toxicity, respectively.

## Results and discussion

### Heavy metal concentrations in mine wastes and soils

The extensive gold mining activities in Kalsaka have dramatically increased heavy metal concentrations in the surrounding agricultural soils. To assess the environmental risk caused by heavy metal distribution, the concerned metal concentrations in soil samples must be determined and compared to reference values. It is worth noting that the average concentrations of certain metals in this study appeared to be a function of the distance from the mining areas and their physico-chemical properties (Table 1). Among the nine heavy metals studied, the average concentrations of As, Ag, Cu, Ni, and Zn were higher in the mine wastes compared to the agricultural and control soils, respectively. Except for control soil, the average concentrations of As, Ag, Cu, Ni, and Zn also exceeded those of UCC (Rudnick & Gao, 2004), reflecting the gradual dispersion of heavy metals from the Kalsaka gold mine to the surrounding areas. Interestingly, heterogeneous distribution characterized by high standard deviation and high mean concentrations relative to median concentrations and high variability (i.e., high CV) further suggested that these heavy metals were mainly derived from mining activities (Sako et al., 2018; Umlaufová et al., 2018). Mine wastes and agricultural soils showed high CV values with all metals having CV greater than 50%, whereas only As (85%), Ag (86%), Co (74%), Cu (71%), and Mn (62%) had high CV values in the control soils. Heavy metals with a relatively high degree of variability are considered dominated by anthropogenic sources, whereas those with low variability are affected by natural sources (Guo et al., 2012; Niu et al., 2019).

In contrast, Hg was only detected in agricultural and control soils with concentrations ranging from 5 to 68 mg/kg. The high Hg concentrations in the agricultural soil ( $16.77 \pm 12.73$  mg/kg) compared to the control soil ( $10 \pm 2.94$  mg/kg) can be attributed to the influence of artisanal gold mining activities taking place in the abandoned mine. Yet, Hg concentrations in both soils were higher than UCC value, indicating more widespread contamination of Hg relative



**Table 1** Statistical summary of heavy metal concentrations (mg/kg) of samples collected in and around the abandoned Kalsaka gold mine in northern Burkina Faso

Heavy metal	Mine waste (n = 30)									
	Min	Max	Mean	SD	Median	Skewness	CV (%)	UCC <sup>1</sup>	ERM <sup>2</sup>	PEL <sup>3</sup>
As	32.3	2681.4	560.4	558.4	441.85	2.6	100	4.8	70	17
Ag	0.01	0.35	0.07	0.08	0.04	1.88	103	0.053	3.7	-
Co	0.5	73	30.14	24.83	-	-	82	17.3	-	-
Cr	3.8	513.1	97.5	123.4	27.5	0.1	127	92	270	160
Cu	2.54	192.06	66.23	66.15	52.5	2.4	100	28	370	108
Hg	-	-	-	-	-	-	-	0.05	0.71	0.7
Mn	9	2460	817	701	811	0.36	86	438.6	-	-
Ni	3.6	293.9	65.5	70.0	42.3	1.8	107	47	51,6	43
Zn	8.3	149.5	65.7	38.3	64.7	0.4	58	67	410	271
Agricultural soil (n = 117)										
As	1.4	1205.4	90.9	166.9	37.8	4.1	184	4.8	70	17
Ag	0.01	1.06	0.06	0.12	0.03	7.04	209	0.053	3,7	-
Co	2.9	124.8	33	30.4	14	1.72	92	17.3	-	-
Cr	27	1690	177	197	22.6	1.3	111	92	270	160
Cu	3.66	227.47	59.22	49.72	124	4.6	84	28	370	108
Hg	5	68	16.77	12.73	42.98	1.2	76	0.05	0,71	0,7
Mn	122	6553	1347	1372	753	1.72	102	438.6	-	-
Ni	5.6	570.6	54.4	71.3	31.4	4.2	131	47	51,6	43
Zn	6.1	161.2	39.8	31.3	30.6	1.5	79	67	410	271
Control soil (n = 4)										
As	1	5.9	2.63	2.24	1.8	1.72	85	4.8	70	17
Ag	0.01	0.04	0.01	0.01	0.01	2	86	0.053	3,7	-
Co	3	19.5	9.78	7.27	10	0	74	17.3	-	-
Cr	34.8	52.5	46,3	8,3	8.3	0.94	18	92	270	160
Cu	5.23	25.51	12.81	9.12	48.85	-1.25	71	28	370	108
Hg	7	13	10	2.94	10.26	1.27	29	0.05	0,71	0,7
Mn	179	769	418	259	362	1.02	62	438.6	-	-
Ni	3.9	15.5	9.8	4.9	9.8	-0.08	50	47	51,6	43
Zn	5.8	18.2	12.5	6.1	13.1	-0.22	48	67	410	271

<sup>1</sup> UCC is the average upper continental crust composition (Rudnick and Gao, 2004)  
<sup>2</sup> and <sup>3</sup> ERM and PEL and the effect range median and probable effect level, respectively (Long and MacDonald, 1998)

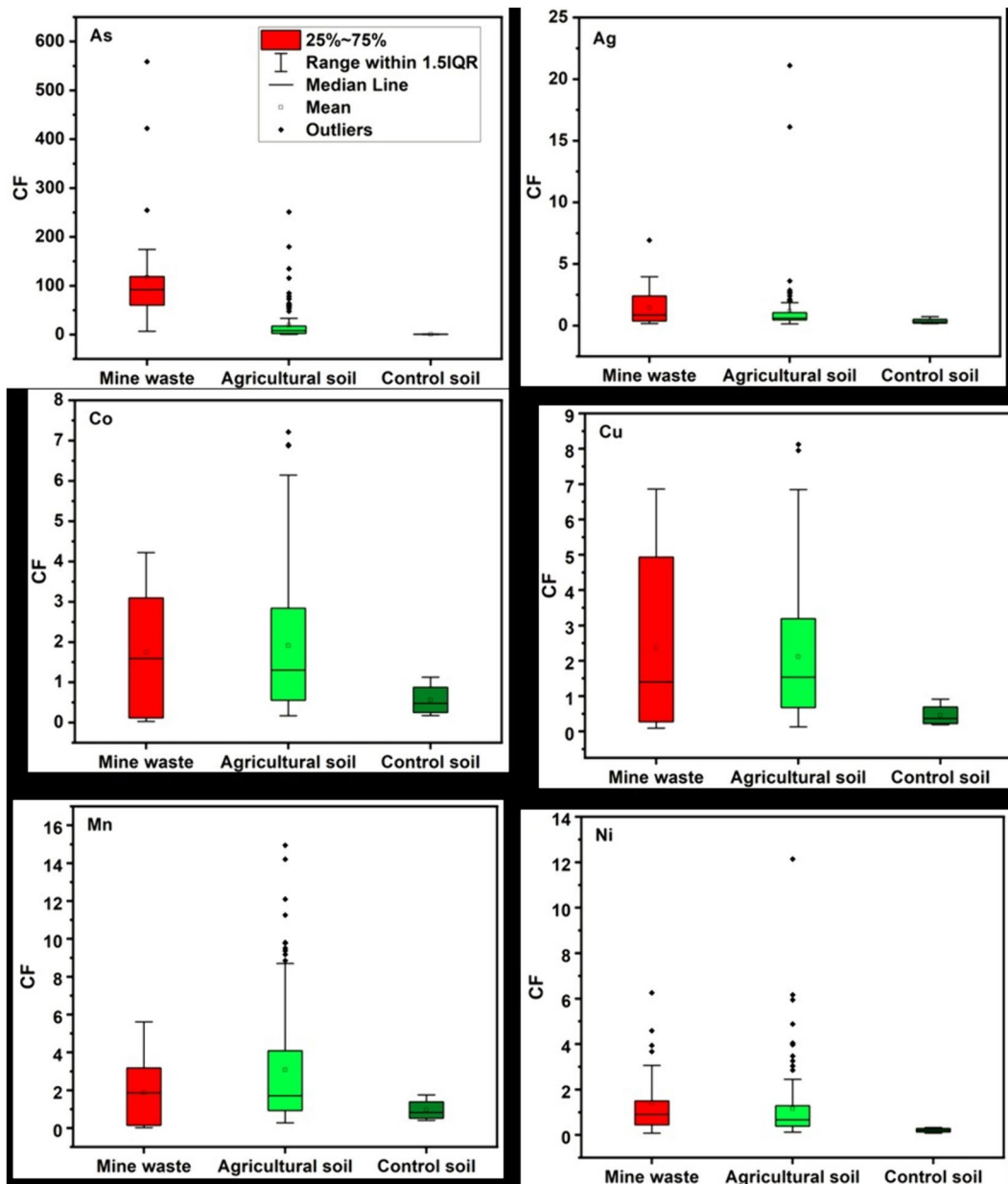
to other heavy metals. Indeed, Hg can be emitted to the environment in different forms such as gaseous, particulate, and dissolved forms (O'Connor et al., 2019). As a result, this metal's dispersion is easily channeled by both runoff and wind over considerable distances. Thus, the low variability of Hg (CV = 29%) in the control soils is rather attributable to homogeneous mode of this metal dispersion than to its sources. The average concentrations of Co, Cr, and Mn in the samples were in the following decreasing order: agricultural soils > mine wastes > control soil (Table 1). The agricultural soil showed the highest average concentrations of Co, Cr, and Mn followed by the mine wastes and control soils. Concentrations of these metals in the agricultural soils were also higher than their

corresponding UCC concentrations. Cobalt, Cr, and Mn might have derived from weathering of mafic and ultramafic rocks encountered in the study area (Alexakis & Gamvroula 2014; Ayoubi et al., 2014). However, the high average concentrations relative to the UCC and high CV values of Co (74%), Cu (71%), and Mn (62%) in the control soils suggest that the local geochemical background concentrations of these metals have been increased by mining activities. With low average concentrations (i.e., below the geochemical background concentrations) coupled with low CV values, it can be concluded that Cr, Ni, and Zn distribution in the control soils was mainly controlled by natural processes such as weathering and pedogenic processes.

## Heavy metal pollution status of agricultural soils

The contamination factor was used to evaluate the extents of agricultural soil contamination. The highest Cf values of As ( $Cf > 5$ ) and moderate values ( $1 < Cf < 3$ ) of Ag, Co, Cr, Cu, Mn, Ni, and Zn ( $1 < Cf < 3$ ) were found in the mine wastes (Fig. 2). In

contrast, the agricultural soils had high Cf values for Hg and As and moderate values for Co, Cu, Ni, Cr, and Zn. Except for Hg, the control soils had the lowest Cf values for all the heavy metals. Thus, the Cf values indicated that the agricultural soils around the Kalsaka abandoned gold mine are contaminated with As, Hg, Mn, and to a lesser degree, Co, Cr, Cu, and



**Fig. 2** Boxplots of contamination factors (Cf) of selected heavy metals in different samples collected in and around the Kalsaka abandoned gold mine in northern Burkina Faso

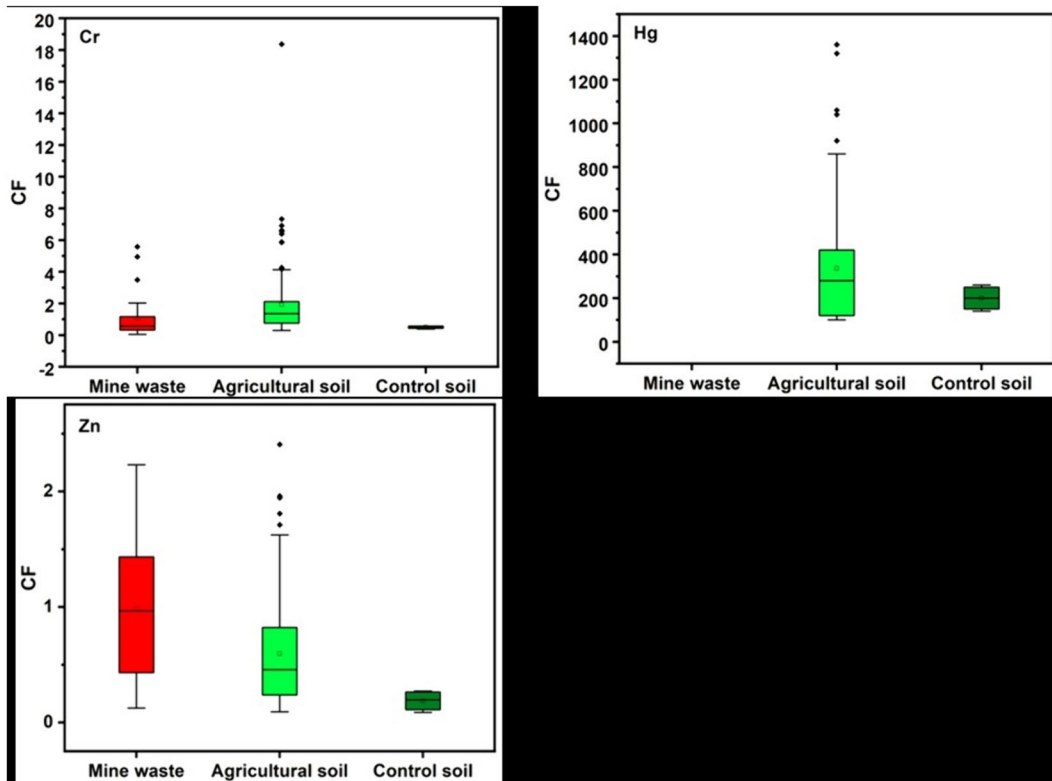


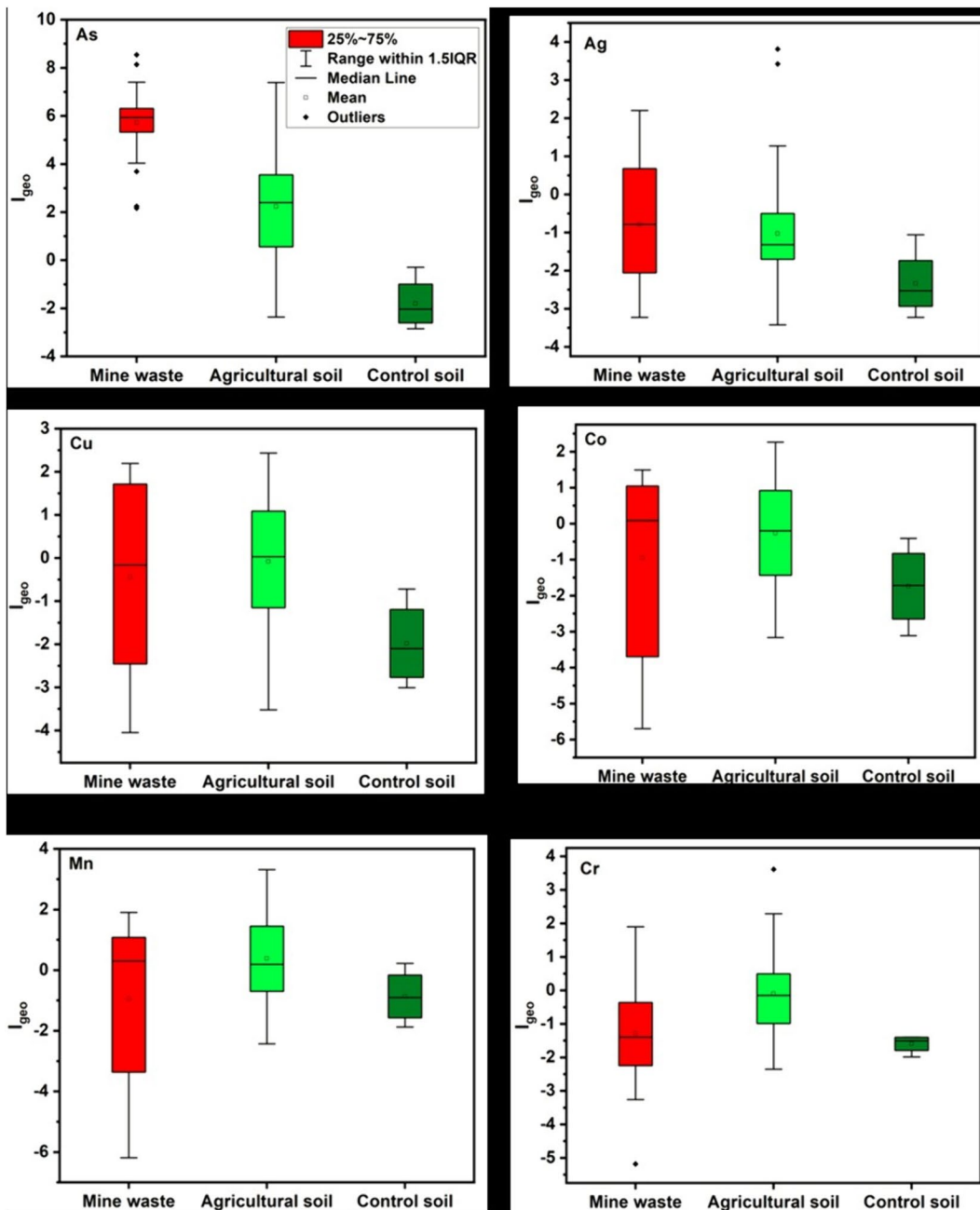
Fig. 2 (continued)

Ni. Excessive concentrations of these heavy metals in soils may have detrimental effects on living organisms including humans (Kabata-Pendias & Mukherjee, 2007).

The index of geoaccumulation is another well-known pollution index, which is traditionally used to assess heavy metal contamination of soils (Adimalla & Wang, 2018; Keshavarzi & Kumar, 2020; Ma et al., 2017; Song et al., 2018; Stevanović et al., 2018). Considering the high  $I_{geo}$  values of As ( $5.21 \pm 1.96$ ), the mine wastes were strongly contaminated (Fig. 3). Contrary to mine wastes, agricultural soils were strongly contaminated with Hg ( $I_{geo} = 6.95 \pm 1.07$ ) and moderately to strongly contaminated with As ( $I_{geo} = 1.72 \pm 4.39$ ), whereas the control soils were only strongly contaminated with Hg ( $I_{geo} > 5$ ). This is an indication of the impacts of both the abandoned Kalsaka gold mine and artisanal gold mining on the surrounding agricultural soil quality.

The high Hg concentrations and  $I_{geo}$  values in agricultural soil samples collected in and in the immediate vicinity of the Kalsaka abandoned mine compared

to control soils, and its absence in the industrial mine wastes, suggest that Hg was derived from the artisanal gold mining. However, the relative Hg pollution of the control soil samples could be attributed to the influence of the physico-chemical properties of Hg and to the environmental factors such as wind strength and direction, temperature, and runoff on Hg mobility in the environment (Pataranawat et al., 2007, Telmer et al., 2008; Rumayor et al., 2013, Reis et al., 2015). That is, during the washing of Hg-gold amalgamation, liquid Hg(0) can be released into the adjacent soils and rivers, whereas gaseous Hg(0) is emitted into the atmosphere during the amalgamation burning. According to Farid et al. (1991), when retorts are used to reduce Hg emission, about 70% of Hg goes into the atmosphere, 20% remains in tailing, and 10% volatilizes during gold purification. In semi-arid environments, under wind action, such as the current study area, atmospheric Hg emission from the mining site is likely to be deposited into terrestrial and aquatic ecosystems far from the mining site (Obrist et al., 2018). Although it is not clear how far



**Fig. 3** Boxplots of index of geoaccumulation ( $I_{geo}$ ) of selected heavy metals in mine wastes and agricultural soils with respect to the control soils

airborne Hg can spread in the environment, previous studies showed high Hg concentrations in soils and crops up to 20 km away from artisanal gold mining sites, which was attributed to artisanal gold mining

activities (Adjorlolo-Gasokpoh et al., 2012; Golow & Adzei, 2002).

The extents of the agricultural soil pollution by mining were evaluated using PLI. The spatial distribution of PLI values without taking into consideration

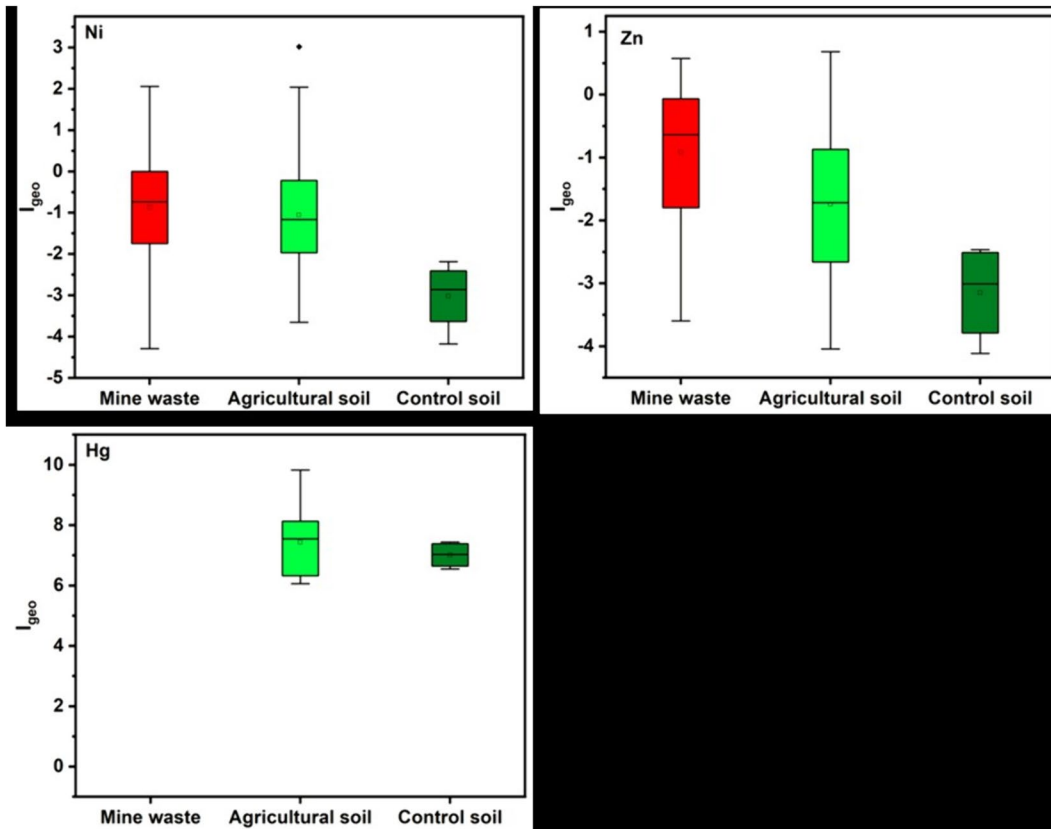


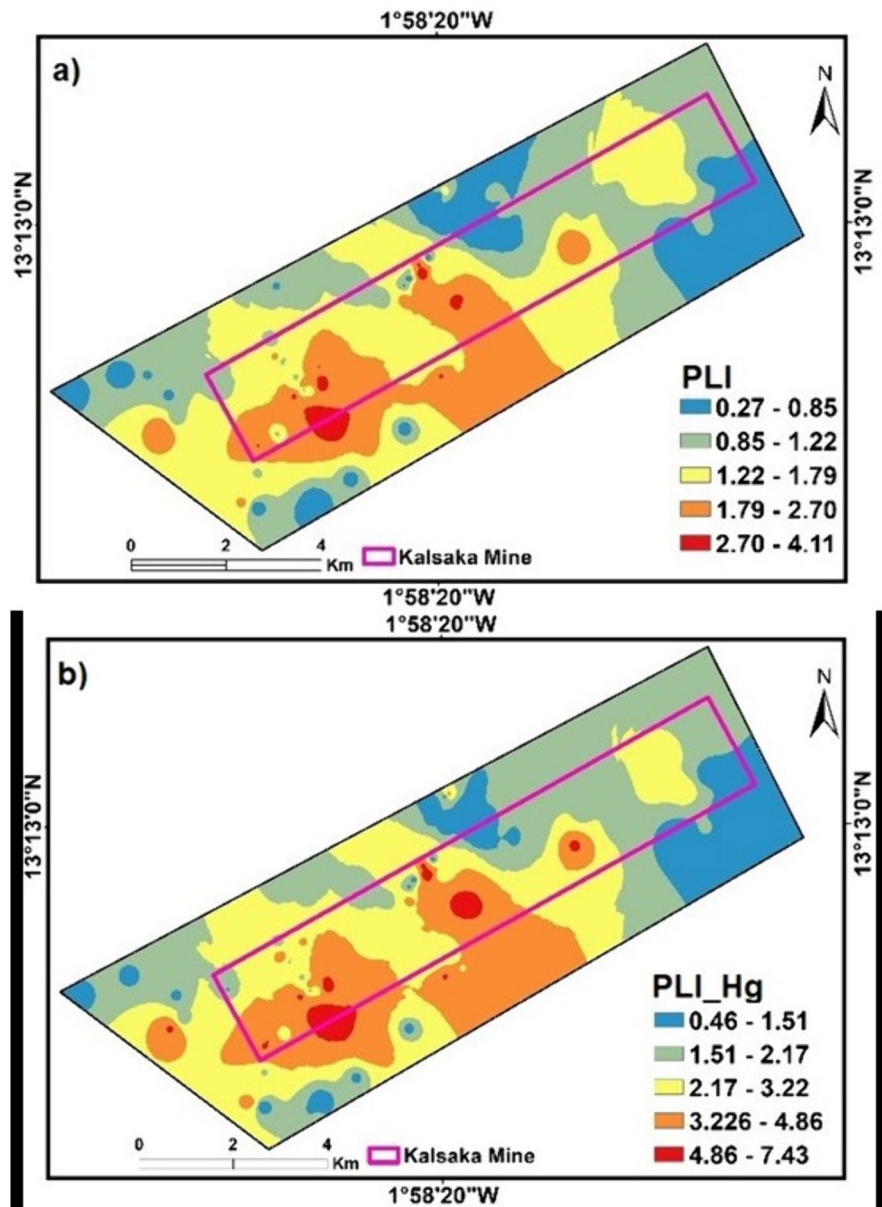
Fig. 3 (continued)

Hg concentrations, which is solely derived from artisanal gold mining, ranged from 0.25 to 4.11 (Fig. 4a) with 35.6, 18.6, and 7.6% of the samples considered moderately, heavily, and extremely polluted, respectively. When Hg concentrations are included in PLI calculation, the PLI values range from 1.51 to 7.43 (Fig. 4b) with 34.7, 23.7, and 33.9% of the samples being moderately, heavily, and extremely polluted. This suggests that artisanal gold mining activities have exacerbated the overall agricultural soil pollution around the Kalsaka abandoned gold mine. To avoid possible toxicological effects of high heavy metal loadings on soil ecosystems and human health, the extents of the heavy metal pollution and associated ecological risks must be thoroughly assessed (Gall et al., 2015; Khan et al., 2015; Kumar et al., 2019).

### Environmental risk assessment of heavy metals

Heavy metals are naturally occurring in the soil environment, and some, at trace concentrations, are bio-essential, whereas others may be toxic even at low concentration (Gomes & Silva, 2021; Jan et al., 2015; Suhr et al., 2021). Assessment of ecological risk of heavy metals is required in order to shed light on potential hazards that elevated concentrations of these metals may have on the soil environment. Several indices such as RI, MERMQ, and MPELQ have been used to investigate the impacts of harmful heavy metals on the soil environment (Liao et al., 2022; Manzoor et al., 2017). That is, RI, MERMQ, and MPELQ values provide powerful tools for controlling pollution sources. The interpretation of RI is fundamental for decision-making and management and protection of the natural resources (Kowalska et al., 2018). Contrary to RI, MERMQ and MPELQ gauge the potential biological effects of the composite heavy metals (i.e.,

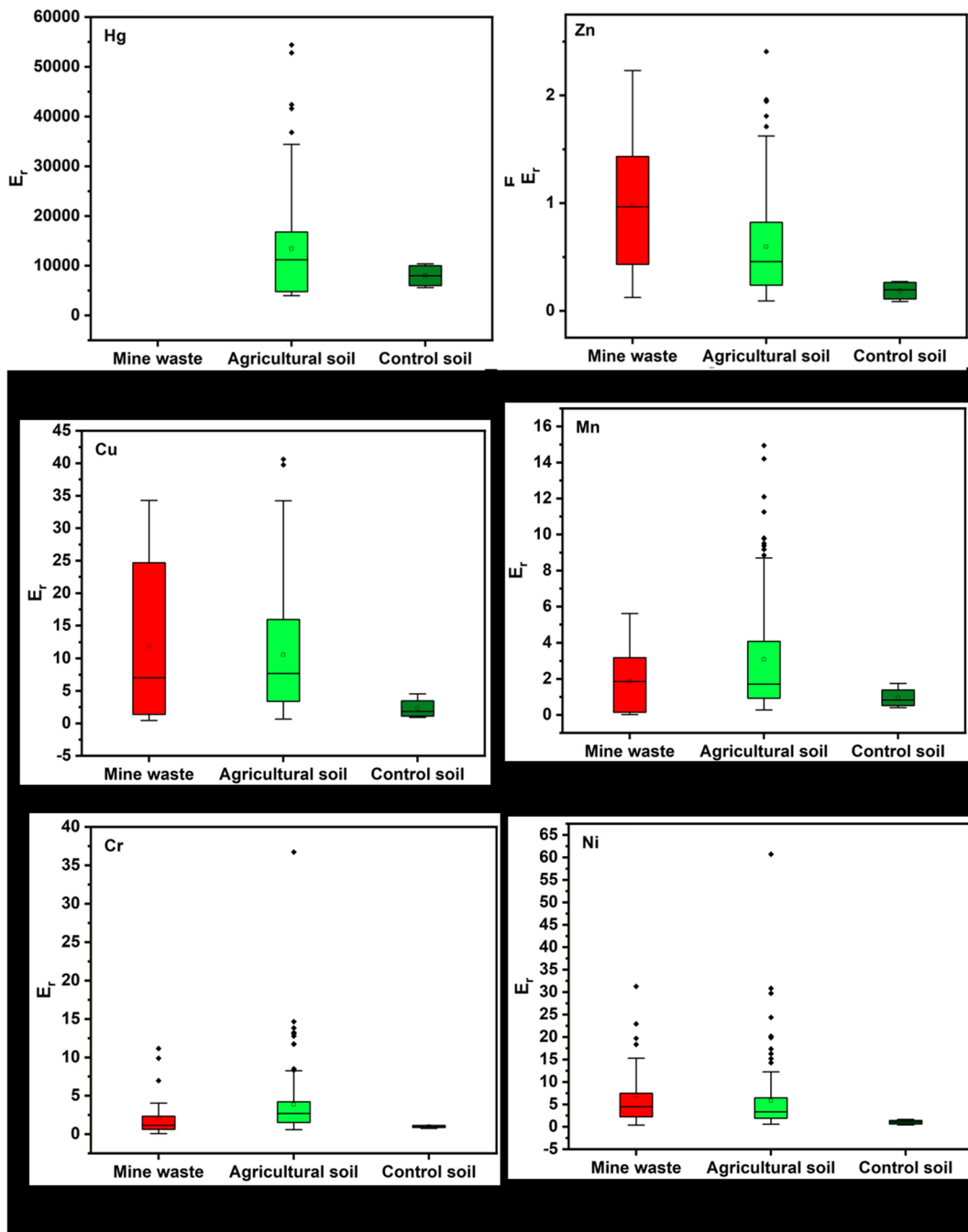
**Fig. 4** **a** Spatial distribution map of pollution load index (PLI) of eight heavy metals (As, Ag, Cu, Zn, Cr, Ni, Mn, and Co) in agricultural soils around the Kalsaka abandoned gold mine without Hg and **b** spatial distribution map of the nine heavy metals including Hg



Ag, As, Cu, Cr, Ni, and Zn) using threshold values (Long and MacDonald, 1998). These relatively new indices can be used to assess human exposure to pollution (Kowalska et al., 2018).

In the present study, the average  $E_r$  values were in the following decreasing order in the agricultural soils: Hg > As > Cu > Co > Ni > Cr > Mn > Zn. With the highest  $E_r$  values, Hg ( $13,415 \pm 10,182$ ) had the highest potential ecological risk, whereas As had a moderate potential risk ( $189 \pm 377$ ). For other heavy metals (Cu, Co, Ni, Cr, Mn, and Zn), the potential

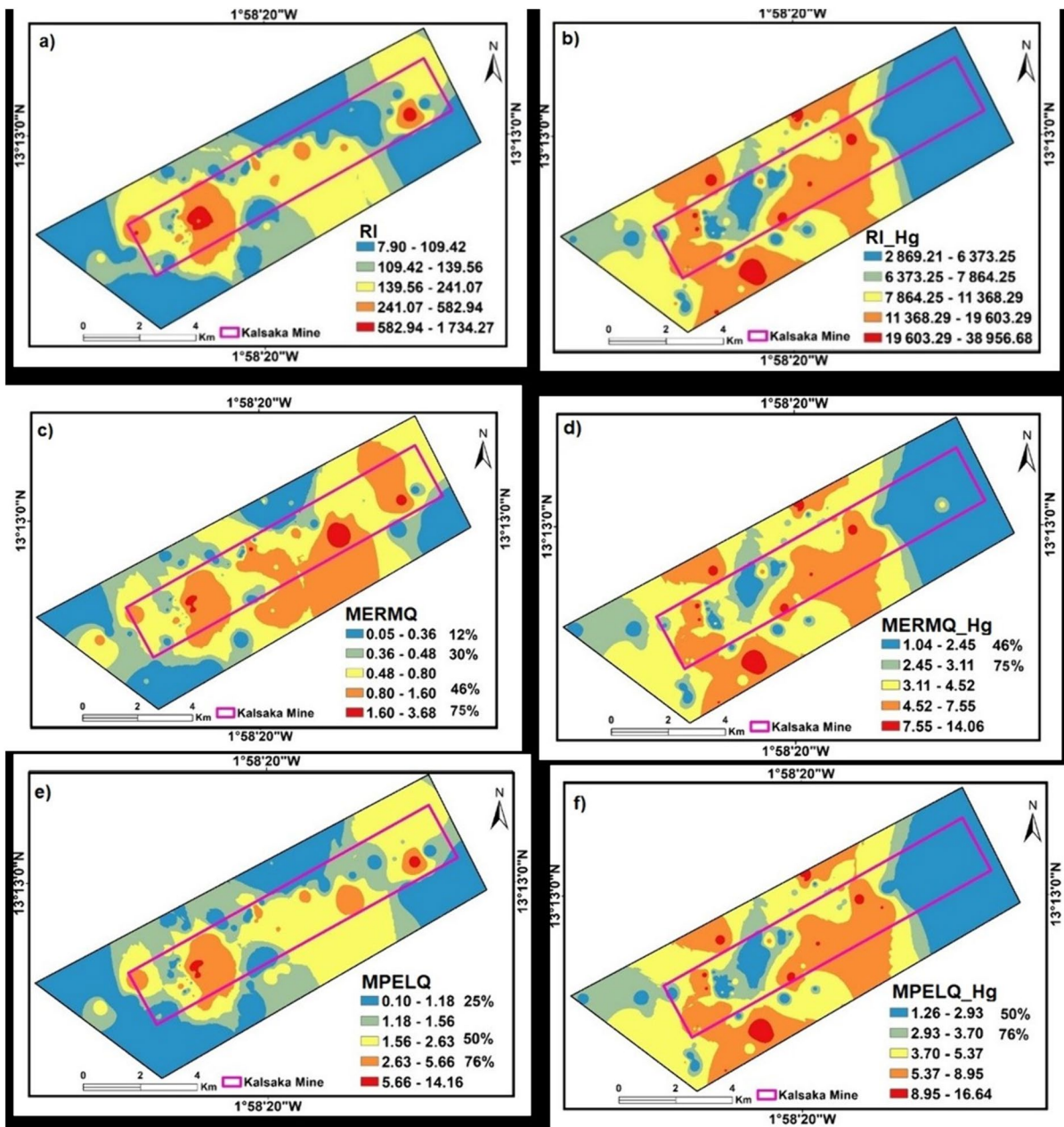
ecological risk is low ( $E_r < 40$ ; Fig. 5). The overall ecological risk (RI) of the agricultural soils (without Hg) varied from 7.42 to 2555 with an average value of  $223 \pm 345$  (Fig. 6a), whereas RI values based on eight heavy metals including Hg ranged from 4007 to 54,591 with an average value of  $13,638 \pm 10,113$  (Fig. 6b). Without taking into account Hg concentrations, 16% of agricultural soils showed very high ecological risk, whereas 46, 25.4, and 70.3% showed low, moderate, and considerable ecological risks, respectively. However, when Hg concentrations are taken



**Fig. 5** Boxplots of potential ecological risk index ( $E_r$ ) of individual heavy metals in different samples collected in and around the Kalsaka abandoned gold mine in northern Burkina Faso

into account all agricultural soil samples showed very high ecological risk index values. In all of this, artisanal gold mining following decommissioning of the Kalsaka gold mine has considerably increased

ecological risk of the surrounding agricultural soils. As a result, the site requires immediate decontamination and rehabilitation.



**Fig. 6** Left panel: **a** Spatial distribution maps of ecological risk index (RI), **c** mean effect range-median quotient (MERMQ), and **e** mean probable effect level quotient

(MPELQ) of seven heavy metals (As, Cu, Zn, Cr, Ni, and Mn) without Hg. Right panel: **b** Spatial distribution maps of RI, MERMQ, and MPELQ of heavy metals including Hg

The MERMQ values for the seven metals without Hg ranged from 0.1 to 3.8 (average value =  $0.6 \pm 0.6$ ) with 63, 31, and 5.5% of the samples having 30, 46, and 75% probability of being toxic indicating 76%, 49%, 21%, and, to a lesser, 9% probability of being toxic (Fig. 6c). However, when Hg is included, the

MERMQ values vary from 1 to 14 (Fig. 6d) with an average value of  $3.8 \pm 6.6$ , and the percentage of the samples that has 46 and 75% probability to be toxic are 23 and 77%, respectively. The same toxicity pattern was observed for MPELQ with 67.5, 15.6, and 16.8% of the samples being toxic when Hg is not



included in the calculation (Fig. 6e). The extent of the toxicity became much larger when Hg is used in MPELQ calculation (Fig. 6f). Hence, 6.8, 22.2, and 70.9% of the samples had 25, 50, and 70.9% of being toxic. The MERMQ and MPELQ results are consistent with PLI and RI, suggesting that these new indices solely based on ERM and PEL limits can be used as independent and comprehensive indicators of investigating the integrated toxicity of mining-affected agricultural soils.

### Recommendations and future research

In the light of the present study, it should be noted that further environmental geochemical studies are required so that behavior and fate of heavy metals in the receiving environment can be fully understood. The present study investigated pollution status and potential environmental risks of selected heavy metals in industrial mine wastes and agricultural soil samples collected in and around the Kalsaka gold mine. It should be borne in mind that not only the abandoned mine is located in the vicinity of human settlements, but also adults and children are actively involved in artisanal mining on the site. Therefore, it would be desirable to evaluate the dominant exposure pathways of contaminated soils to both adults and children. Non-carcinogenic and carcinogenic hazards of the contaminated soils to the exposed population should also be assessed.

The mobility and bioavailability of heavy metals in soils are a function of several soil physico-chemical properties such as pH, electrical conductivity, grain-size distribution, organic matter content, and cation exchange capacity. To gain more insight into the factors that control heavy metal dispersion and bioavailability around the Kalsaka abandoned gold mining site, relationships between heavy metals and soil physico-chemical properties should be studied. Finally, given the volatility of Hg in the environment, it should be interesting to use Pb isotopes in association with Hg and other heavy metals in agricultural soils, control soils, and those of some reference materials (e.g., petrol, fertilizers, and crop protection chemicals) to thoroughly study the extent of atmospheric Hg deposition patterns in soils around the artisanal gold mining sites and beyond.

### Conclusion

A comprehensive study of the agricultural soil quality around the abandoned Kalsaka gold mining site was conducted using a series of pollution indices. The “pseudo-total” concentrations of all heavy metals, except for Zn, exceeded the corresponding upper continental crust concentrations. The widespread of artisanal gold mining brings to the area a potential increase in pollution from the mining itself and indirect consequences of population growth. The Hg emission patterns into the environment suggest that artisanal gold mining has dramatically increased pollution, ecological risk of the agricultural soils, and the probability of human exposure to the heavy metals. The semi-arid climate of the study area appeared to be conducive to the spread of atmospheric pollution of heavy metals, particularly Hg. The consistency between the classic pollution indices such as Cf,  $I_{geo}$ , and PLI and more recent toxicity indices (i.e., MERMQ and MPELQ) suggests that the later indices can be applied independently to assess soil pollution. Due to overlapping between industrial gold mine and artisanal gold mining sites, closing industrial gold mines without any decontamination will ultimately exacerbate environmental pollution and degradation of natural resources.

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**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Competing interests** The authors declare no competing interests.

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