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RESEARCH

Assessment of heavy metals concentration in soils in the central parts of Tanzania using pollution indices and multivariate statistical approach: implication on the source and health

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Abstract

The presence of potentially toxic elements (PTEs) in soils has been known to have harmful effects on humans, plants, and the overall ecological system. Consequently, ongoing research is needed to investigate the concentration, sources, and spatial distribution of PTEs. In central Tanzania, where there are significant mineral deposits, anthropogenic activities, such as mining and commercial agriculture have contributed to soil pollution. This study aimed to assess the concentrations, sources, and spatial distribution of PTEs in the Singida region, which is part of central Tanzania. The order of the studied PTEs concentrations is Mn > Zn > Cr > Cu > Pb > As > Cd, and generally falls within acceptable limits according to the Tanzania Ministry of State (TMS) standards except for As and Cr, which pollute 50% and 5.3% of the stations exceeding 1 mg kg^{-1} and 100 mg kg^{-1}, respectively. The pollution indices indicate that all PTEs reach moderate to highly polluted levels in the region. The mafic–ultramafic rocks of this region significantly contribute to the PTEs contents in soils. The robust compositional contamination index (RCCI) indicates moderate (22.7%), high (57.3%), and very high (13.3%) levels caused by anthropogenic activities and the geology of the region. Mining and fertilizer run-offs from agricultural lands may affect Cd concentrations in the soil. The PTEs reach hotspots with high concentrations in the southern, eastern, northern, and southeastern parts of the study area. The region is at risk of cancer, mortality, reproduction challenges, and other non-carcinogenic issues in the future. In this paper, the terms heavy metals, PTEs, and trace elements are used interchangeably implying similar elements or metals.

Keywords Potential toxic elements · Concentration · Pollution · Statistical methods · Health effects · Tanzania

1 Introduction

Trace elements in soils, especially heavy metals, have been identified as a major source of soil pollution (Chen et al., 2009; Rezaei et al., 2019). The discussion around this issue is crucial because of the unacceptable concentration levels of some heavy metals such as As, Cd, Cr, Cu, Pb, Zn, Se, Co, Ni, and Mo (Abu et al., 2021; Mclaren, 2003; Shi et al., 2010) in soils, which have been linked to life-threatening health conditions like lungs, kidney and hearth diseases (ABS, 1999; Abu et al., 2021; Lottermorser, 2007; Tchounwou et al., 2012). Toxic elements can enter human systems through the soil–plant–human or soil–plant–animal–human pathways (Nieder, 2018; Wuana et al., 2007). Trace elements have also significantly modified land use, inhibiting organic matter biodegradation and affecting environmental biodiversity and activity (Nieder, 2018; Rezaei et al., 2019). Trace elements have both natural and anthropogenic sources, including volcanic activities, mining, commercial agriculture, and industrialization (Abu et al., 2021; Kazapoe et al., 2021; Khan et al., 2008; Nieder, 2018; Sargaonkar & Deshpande, 2003). Thus, two main sources of heavy metals and PTEs are: (1) natural processes of weathering and volcanic

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activities and (2) anthropogenic activities of industrialization and extraction of geo-resources. Extensive research has been conducted on the sources and concentrations of PTEs in soils. It is essential to understand these aspects because soils play a crucial role as the primary reservoir for trace elements, heavy metals, and PTEs in the environment, as highlighted by Senesi et al. (1999) and Nieder (2018).

Indices such as contamination factor (CF), enrichment factor (EF), pollution index (PLI), robust compositional contamination index (RCCI) and potential risk index (PRI) have been utilized to assess the environmental health over the years (Abu et al., 2021; Arhin et al., 2016; Kazapoe et al., 2021; Lermi & Sunkari, 2020; Reyes et al., 2020; Rezaei et al., 2019; Rinklebe et al., 2019; Somma et al., 2021). Multivariate statistical approaches like cluster analysis (CA) and factor analysis (FA) and/or principal component analysis (PCA) have proven suitable for bringing patterns and elemental associations that elucidate the sources and processes that control trace element and PTE occurrence (Abu et al., 2021; Kazapoe et al., 2021; Lermi & Sunkari, 2020).

The central parts of Tanzania belonging to the Tanzanian Craton (TC) are well known for their mineral endowment (Mvile et al., 2021), including gold mines and artisanal mining activities (Kabete et al., 2012). Heavy metals and PTEs pollution, largely attributed to mining activities, have been reported worldwide, with artisanal mining activity regions being the most affected (Lemi & Mseli, 2017). Developing countries like African countries suffer the most from heavy PTEs pollution (Abu et al., 2021; Heman & Kihampa, 2015; Li et al., 2014; Yusuf et al., 2015; Salomons, 1995). High concentrations of some heavy metals, including mercury (Hg), have been found in soils from some parts of the central Singida area, such as Sambaru and Londoni (Heman & Kihampa, 2015; Lema & Mseli, 2017), with mining activities and its associated ancillary activities being the source of PTEs. With the ubiquitous distribution of anthropogenic activities especially mining in this part of the country, with their accompanying probable environmental issues (Lema & Mseli, 2017), the information on the concentration levels of the PTEs in soils within the Singida region is scanty for effective management practices implementation purposes (Lema & Mseli, 2017; Sikakwe et al., 2020). The available literature on heavy metals sources and concentrations does not commensurate with the pace of industrialization and other anthropogenic activities in this part of Tanzania. The availability of this data, literature, and its continuous revision is key to sustainable development in every country and most especially, Tanzania where artisanal mining activities are strongly supported by the Government (Tanzania Ministry of Minerals and Energy, 2015).

To contribute to the ongoing global discussion on trace, heavy, and PTEs in soils, this study aims to use soil geochemistry, focusing on As, Cd, Cr, Cu, Pb, Zn, Co, Ni, Mn, V, Al, Na, K, and Fe (Table 1) coupled with multivariate statistics and semi variograms through ArcGIS. This approach aims to determine the concentration level of these elements in soils, identify their sources, explore their health implications and map their spatial distribution in the central parts of Tanzania. This research will enhance

Table 1 The statistical summaries (mg kg^{-1}) of PTEs together with the TMS (2007) regulatory standards of heavy metals in agricultural soil (mg kg^{-1})

	Minimum	Maximum	Mean	Std. deviation	TMS, 2007	Mean values of this study	Number of samples above standard
Cu	3.3	67.7	26.1	15.0	200	26.4	
Pb	5.5	41.0	19.1	5.9	200	19.2	
Zn	6.0	112.0	59.7	23.6	150	59.9	
Ni	2.8	66.2	24.1	14.6	100	24.4	
Co	1.0	29.6	12.2	5.5			
Mn	90.0	1821.0	713.5	264.7			
As	0.0	8.0	1.7	1.8	1	1.8	39 (52%)
Cd	0.0	0.9	0.1	0.2	1	0.1	
V	0.0	188.0	67.2	38.9			
Cr	18.0	130.0	51.9	23.1	100	52.5	4 (5.3%)
Al	1.4	11.5	6.8	1.9			
Na	0.2	4.1	1.3	0.7			
K	0.5	4.0	1.9	0.6			
Fe	0.3	7.6	3.3	1.4			

the environment, and contribute to monitoring and management practices in the central parts of the country.

2 Geological setting

The Singida region, situated in the central part of Tanzania, covers a total area of approximately 48,345 km^2 and is entirely located within the Tanzania Craton (TC) (Fig. 1). The region is characterized by gold mineralization, which is distributed throughout the area (Heman & Kihampa, 2015). The region's geology is typical of a greenstone belt, with the main lithology being basalts, granitoid, volcaniclastics, gneisses, and their metamorphic progenies (Abu et al., 2021; Kabete et al., 2012). Auriferous gold is found in the form of alluvial deposits, lateritic materials, stream sediments, placer, and disseminated sulfide deposits (Spiegel, 2009). Artisanal mining activities are mainly focused on the alluvial and placer deposits, which are less labor intensive and relatively inexpensive to exploit (Mpangile et al., 2020).

3 Methods

3.1 Sampling and analysis

Soil samples were randomly collected from the top 20–30 cm layer from the surface in the Singida region using an auger. This depth of sampling, thus the B horizon ($\sim$5–30 cm), is the sink of heavy elements and has largely been sampled for soil pollution assessment purposes (Abu et al., 2021; Henderson et al., 1998; Lermi & Sunkari, 2019; Razaei et al., 2019; Schulin et al., 2007). A total of 97 samples were collected of which 22 samples were collected as duplicates for analytical quality assurance. The samples were kept in improvised canvas bags sewn out of cotton material and handled according to the guidelines and protocols described in Kazapoe et al. (2021). To remove debris, the samples were sieved in the field to <2 µm and then transported to the sample preparation laboratory of the Geological Survey of Tanzania (GST) situated in Dodoma, where the samples were further sieved to <75 µm. The results of the duplicate samples were used to check the reproducibility

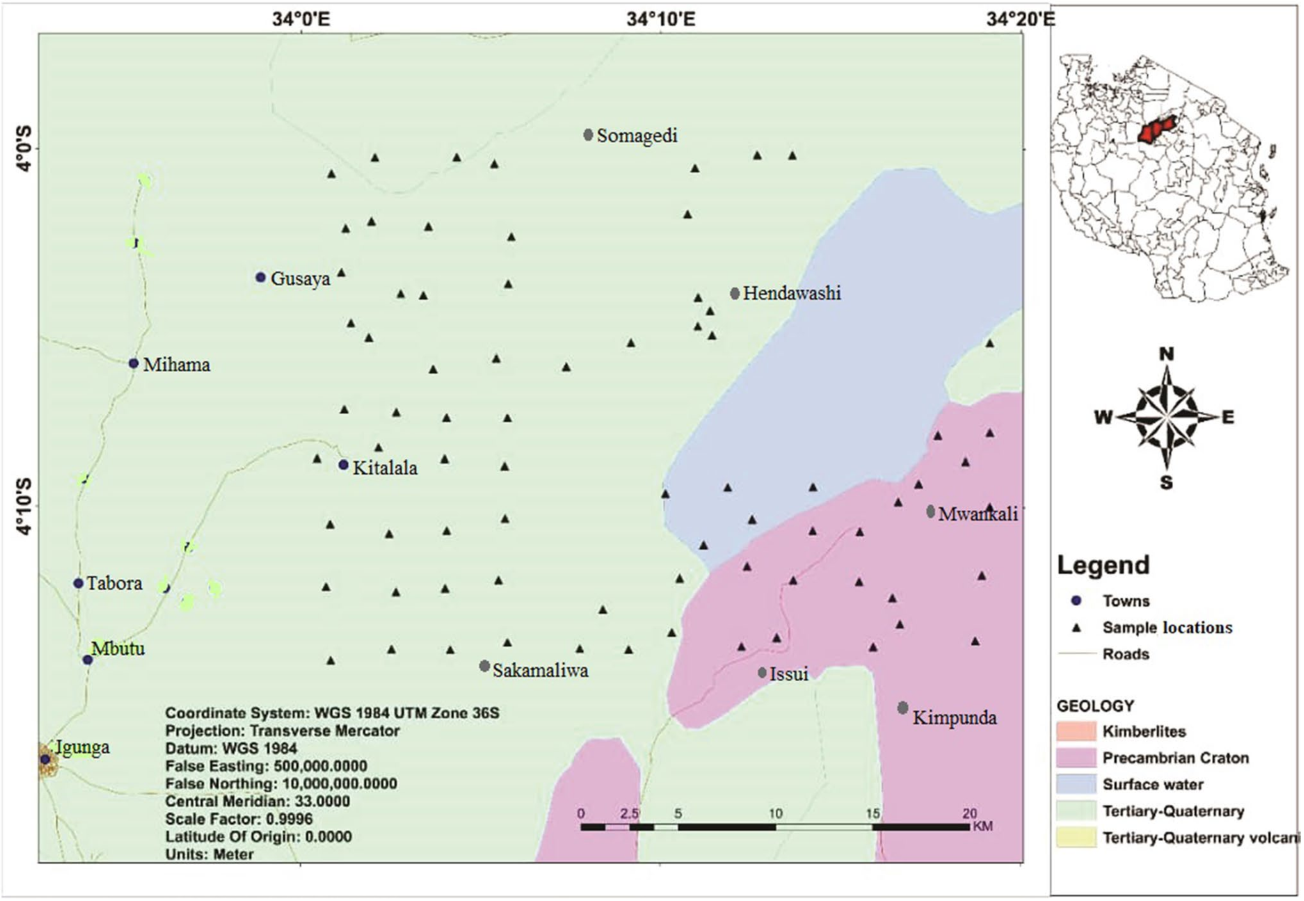

Fig. 1 Geological map and sampling locations of the study area

of the analytical procedure. The results of the duplicates and the actual samples elemental recovery varies between 89.5 and 110%, which is satisfactory for the study according to Guevara et al. (2018). The 22 duplicate samples, results, and their locations are not used in the discussions presented in the paper. Copper (Cu), zinc (Zn), nickel (Ni), manganese (Mn), arsenic (As), cadmium (Cd), vanadium (V), and chromium (Cr) were analyzed using Inductive Coupled Plasma Atomic Emission Spectroscopy (ICP-AES); while, lead (Pb) and the copper oxides, zinc oxides, nickel oxides, manganese oxides, arsenic oxides, cadmium oxide, vanadium oxide and chromium oxide were analyzed using Inductive Coupled Plasma Mass Spectrometer (ICP-MS) following the analytical details of Reyes et al. (2020). The samples were analyzed at Acme Analytical Laboratory Ltd. in Vancouver, Canada.

3.2 Pollution indices

Soil pollution evaluation methods have adopted pollution indices that effectively reveal soil pollution (Abu et al., 2021; Andrews & Sutherland, 2004; Kazapoe & Arhin, 2019; Kazapoe et al., 2021; Kumar et al., 2021; Lermi & Sunkari, 2020; Muller, 1969; Reyes et al., 2019). The study utilized three indices: the enrichment factor (EF—Eq. 1), contamination factor (CF—Eq. 2), and geo-accumulation index (Igeo—Eq. 3). The calculations and standards used in the process are consistent with Abu et al. (2021). For the robust compositional contamination index (RCCI), the procedures followed those of Reyes et al. (2019) and Kazapoe et al. (2021) and the details of that estimations can be seen in the supplementary data (SD) provided. The classification and implications of the RCCI values is shown in Table 1.

$$\mathrm{EF} = (\mathrm{C}e/\mathrm{C}Al)\mathrm{S}/(\mathrm{C}e/\mathrm{C}Al)b, \tag{1}$$

where C*e* is the concentration of the heavy metal in the sample and Al in the sample $(\mathrm{C}e/\mathrm{C}Al)S$, while $(\mathrm{C}e/\mathrm{C}Al)b$ represents their respective background values ratio. Mostly, the background values of average shale; Cd = 2.6, Cu = 100, Ni = 68, Pb = 20, Zn = 95; (Turekian & Wedepohl, 1961) are often used in the pollution assessment of sediment (Abu et al., 2021; Kazapoe et al., 2021; Lermi and Sunkari, 2020). Pollution in soils has been grouped into five classes based on EF by Andrews and Sutherland (2004)

$$\mathrm{Contamination factor(CF)} = \mathrm{C}e/\mathrm{C}b \tag{2}$$

These are the concentrations of the heavy metals in the sample Ce and their respective background values. According to Hakanson (1980), four soil pollution groups and implications can be inferred from the CF values. The standard values used in the calculations are; As = 10; Cd = 30, Cu, Co, Ni, Pb = 5, Zn = 1, Cr = 2.

Geo-accumulation index (Igeo) estimation values were obtained using Müller's (1969) equation (Eq. 3); this method has seven categories of pollution implications.

$$\mathrm{Igeo} = \log_2(\mathrm{C}m/1.5\mathrm{B}m), \tag{3}$$

where Cm and B*m* are the metal concentrations in the samples collected and their background values, respectively, and the 1.5 accounts for possible variations in the background value due to any lithological contribution.

3.3 Statistics and geostatistics

A correlation matrix is a statistical method used to indicate the relationships and elemental associations of compositional data, such as geochemical data. It has been widely used to decipher the controls of hydrochemical and geochemical data (Abu et al., 2021; Mvile et al., 2021; Sunkari et al., 2019, 2021, Zango et al., 2019). In this study, Spearman's correlation matrix with $r \geq 0.5$ values are considered to be significant, together with other multivariate statistical approaches, was used to elucidate the elemental associations and infer the source of PTEs deduced from these associations.

The Factor analysis (FA) with principal component analysis (PCA) as the extraction method was the multivariate statistical technique applied. The method followed the same procedures described by Mvile et al. (2021) and Abu et al., 2021). IBM SPSS version 20 was used for all statistical and multivariate statistical analytical approaches in this study. The geostatistical method applied in the generation of the spatial distribution maps was interpolation using the Kriging method. The maps were generated using Surfer version 11.

4 Results and discussion

4.1 Characteristics of PTEs

The concentrations of the selected oxides (wt%) and the PTEs (mg kg^{-1}) are presented as supplementary data (SD). The average concentrations of oxides range from 1.3 to 6.8 wt% (Table 1) and are in the order of Al > Fe > K > Na. The concentration of PTEs, on the other hand, ranges as follows: Cu (3.3–67.7 mg kg^{-1}, with a mean value of 26.1 mg kg^{-1}), Pb (5.5–41.0 mg kg^{-1} with a mean value of 19.7 mg kg^{-1}), Zn (6.0–112.0 mg kg^{-1}, with a mean value of 59.7 mg kg^{-1}), Ni (2.8–66.2 mg kg^{-1} with a mean value of 24.1 mg kg^{-1}), Co (1.0–29.6 mg kg^{-1} with a mean value of 12.2 mg kg^{-1}), Mn (90.0–1821.0 mg kg^{-1} with a mean value of 713.5 mg kg^{-1}), Cr (18.0–130.0 mg kg^{-1} with a mean value of 51.9 mg kg^{-1}), and V (0.0–188.0 mg kg^{-1} with a mean value of 67.2 mg kg^{-1}) (Table 1). Arsenic (As) and Cd have mean values of 1.7 mg kg^{-1} and 0.1 mg kg^{-1}, respectively (Table 1). The concentrations of PTEs of interest in the study area are in the order of Mn > Zn > Cr > Cu > Pb > As > Cd.

According to Allaway (1969) and Feng et al. (2009), all PTEs in uncontaminated soil are within the acceptable ranges. However, in comparison to the Tanzania Minister of States' (TMS) (2007) standards for Zn, Pb, Ni, Cu, Cr, Cd, and As in agricultural lands (Table 1), As and Cr exceed the standard in some of the sampled areas.

Arsenic (As) has 39 samples above the TMS standard, representing 50% of the total area under consideration. Although the mean value of Chromium (Cr) is less than the TMS recommended standard, four samples, representing 5.3% of the total samples, have values higher than 100 (SD and Table 1). Long-term exposure to high levels of Cr (above acceptable levels) through the intake of food crops from these areas can cause nasal septum reactions, systematic liver effects, acute irritative dermatoses, allergic eczematous, mutagenic effects, kidneys problems, and skin relative issues (World Health Organization, 2000). Arsenic is a high-impact toxicant that can cause health-related problems, such as cardiovascular disorders, endocrine issues, renal problems, immune system disorders, and reproduction complications (Abdul et al., 2015; Drake et al., 2001; Kazapoe et al., 2021).

Crops grown on arable lands in the study area are likely to be contaminated with arsenic (As) through adsorption. The PTEs of concern in the area, from their concentration values relative to the TMS (2007) standards, are As and Cr.

Copper occurs naturally (geogenic) and through human activities (European Institute of Copper, 2018). Also, copper is associated with gold (Au) mineralization in Precambrian terrains, including that in Tanzania (Masindi & Muedi, 2018; Mvile et al., 2021). It is also associated with fertilizer application and industrial activities. According to the New Hampshire Department of Environmental Services (2013), Kazapoe and Arhin (2019), and Kazapoe et al. (2021), high concentration of copper above acceptable limits can cause serious issues including hypotension, kidney damage, headache, mouth irritation, cognitive retardation, and jaundice. Copper can enter the human body through the soil–plant–animal–human pathway (Nirel & Pasquini, 2010). The concentration of Cu in the study area is below the TMS (2007) limit, thus not a concern.

Nickel concentration in soils is considered to be within acceptable limits if its concentrations do not exceed 8.67 mg kg^{-1} (Kazapoe & Arhin, 2019). Although Ni is within TMS (2007), the recommendation for Ni concentration in other mining-dominated greenstone belts (Kazapoe & Arhin, 2019) suggests that Ni concentration from the study area exceeds 8.76 mg kg^{-1} with a mean value of 24.1 mg kg^{-1} (Table 1).

According to Rangel (2000), plants can be affected by soils with high Mn contents as it is one of the heavy metals that is abundant in soils. The permissible levels of Mn in soils have been pegged at 500 mg kg^{-1} (Mclaughlin et al., 2000). In the studied area, 63 sites had Mn concentration > 500 mg kg^{-1} (SD and Table 1). This represents 84% of Mn contaminated soils in the study area. Long periods of consuming farm produce from the affected area by the populates standing the chance of suffering from respiratory tract disorders, skin, brain birth defects, and nervous system disorders (Williams et al., 2012).

4.2 Pollution indices

Tables 2 and 3 presents the values of the selected indices (mg kg^{-1}) of relevance to pollution, their classification and health implications in the area. The enrichment factors (EF) of the PTEs are as follows; Cu, Zn, Mn, Ni, Co,

Table 2 The statistical summaries of the PTEs (mg kg^{-1}) and their indices after Müller (1969); Hakanson (1980), Andrews and Sutherland (2004)

PTEs and indices	Min	Max	Mean
Cu	3.30	67.70	26.35
EF	0.80	6.30	1.55
CF	0.10	1.50	0.59
Igeo	3.50	7.80	6.16
Pb	5.50	41.00	19.21
EF	0.80	6.30	1.55
CF	0.30	2.10	0.97
Igeo	4.20	7.10	5.90
Zn	6.00	112.00	59.71
EF	0.80	6.30	1.55
CF	0.10	1.20	0.66
Igeo	2.00	6.20	5.12
As	0.00	8.00	1.81
EF	0.00	6.30	0.99
CF	0.00	0.60	0.15
Igeo	0.00	5.70	2.59
Cd	0.00	0.90	0.15
EF	0.00	2.70	0.82
CF	0.00	3.00	0.49
Igeo	0.00	4.20	1.19
Cr	18.00	130.00	52.49
EF	0.80	6.30	1.55
CF	0.20	1.40	0.58
Igeo	4.60	7.40	5.99
RCCI	8.90	91.60	50.69

Geochemical background values used in the calculation of the RCCI are; Cu = 55, Pb = 12.5, Zn = 70, Ni = 75, Co = 25, Mn = 950, As = 1.8, Cd = 0.2, V = 135, Fe = 5.63 (mg kg^{-1}) from Allaway (1969) and Feng et al. (2009)

Table 3 Classes of indices and their health implications

Contamination factor (CF) ranges and implications		
CF	Implication	
< 1	No/low pollution	
1–3	Moderately polluted	
3–6	Considerably polluted	
> 6	Very highly polluted	
Enrichment factor (EF) ranges and their implications		
EF	Implication	
< 2	Minimal pollution	
2–5	Moderately polluted	
5–20	Sign. polluted	
20–40	Highly polluted	
> 40	Extreme pollution	
Geo-accumulation indices and implication		
Igeo	Implication	
Class 0 (= 0)	Unpolluted	
Class 1 (0–1)	Polluted–moderately polluted	
Class 2 (1–2)	Moderately polluted	
Class 3 (2–3)	Moderately–heavily polluted	
Class 4 (3–4)	Heavily polluted	
Class 5 (4–5)	Heavily–extremely polluted	
Class 6 (> 5)	Extremely polluted	
RCCI range	Interpretation	Number of samples
≤ 15%	Low values	3 (4%)
> 15–25%	Medium	2 (2.7%)
> 25–40%	Moderate	17 (22.7%
> 40–75%	High	43 (57.3%)
> 75–100%	Very high	10 (13.3%)

and Cr have EF values ranging from 0.8 to 6.3 with a mean value of 1.5, while Cd has a range of 0.0–2.7 with a mean value of 0.8 (Table 4). The average EF values of all the PTEs suggest that the area is minimally polluted with an average EF < 2 (Table 2). However, Cu is moderately polluted in 7 sampled areas with an EF range of 2–5, representing 9.33% of the total area sampled, with one sample showing significant pollution within the range of 5–20 (Table 3). The area shows moderate to significant pollution by As, with 36 and 3 samples having EF values within the ranges of 2–5 and 5–20, respectively (see SD), representing 40% of moderately polluted stations and 4% of stations with significant pollution. Cadmium, Cr and Pb are also moderately polluted in 2, 7 and 7 sampled areas, respectively, while a single sample area shows significant pollution by Cr (see SD) which represents 9.3% of the sampled area (Andrews & Sutherland, 2004; Grygar et al., 2014).

The ranges of the contamination factors (CF) of the PTEs; Cu, Mn, and Zn are 0.1–1.5, 0.1–2.1, and 0.1–1.2, respectively (Table 4), with respective average values of 0.6, 0.8, and 0.7. Cadmium, Ni, and Cr have CF values ranging from 0.0 to 3.0, 0.0 to 1.0, and 0.2 to 1.4, respectively, with average values of 0.5, 0.4, and 0.6, respectively (Tables 2, 3) (Müller, 1969). The average CF values of the PTEs (Table 2) suggest that the soils in the area are minimally or not polluted. However, Cu has 14 stations representing 18.7% of the analyzed sites, indicating moderate contamination based on the CF values (Muller, 1969; Hakanson, 1980). Cadmium, Cr, and Pb are moderately polluted in 4, 6, and 29 sampling areas (SD), respectively, representing 5.3%, 8%, and 38.7%, respectively, of Cd, Cr, and Pb pollution in the area.

The mean geo-accumulation index (Igeo) of the PTEs (Table 2) are as follows; Cu, Pb, Cr, and Co have mean

Table 4 Spearman's correlation matrix

	Cu	Pb	Zn	Ni	Co	Mn	As	Cd	V	Cr	Al	Na	K	Fe
Cu	1.0													
Pb	0.2	1.0												
Zn	0.7	0.6	1.0											
Ni	0.9	0.1	0.6	1.0										
Co	0.9	0.2	0.6	0.9	1.0									
Mn	0.5	0.5	0.6	0.3	0.5	1.0								
As	0.6	0.0	0.2	0.6	0.7	0.3	1.0							
Cd	0.1	0.4	0.3	**−0.1**	0.0	0.3	0.0	1.0						
V	0.7	0.2	0.5	0.6	0.7	0.6	0.6	0.0	1.0					
Cr	0.9	0.1	0.5	0.9	0.9	0.3	0.6	**−0.1**	0.6	1.0				
Al	0.6	0.5	0.7	0.6	0.7	0.4	0.4	0.3	0.7	0.5	1.0			
Na	**−0.4**	0.1	**−0.2**	**−0.5**	**−0.3**	0.1	**−0.2**	0.4	0.0	**−0.5**	0.2	1.0		
K	**−0.4**	0.5	0.0	**−0.5**	**−0.5**	0.0	**−0.4**	0.4	**−0.2**	**−0.6**	0.1	0.7	1.0	
Fe	0.8	0.4	0.8	0.8	0.8	0.6	0.5	0.2	0.8	0.7	0.8	**−0.2**	**−0.3**	1.0

values of 6.2, 5.9, 5.1, and 5.2, respectively, while As, Cd, and Ni have mean values of 2.6, 1.2, and 6.0, respectively. The area is moderate to extremely polluted based on the Igeo. Twenty-eight stations (37.3%) have Cd Igeo values ranging of 2–4 (Table 3), indicating moderate to heavy pollution (Table 4). Arsenic has 50 samples with concentration > 2 (SD) suggesting moderate to heavy As pollution (Table 3). Chromium has all 75 soil samples with Igeo values ranging from 3 to > 5 (SD), indicating heavy to extreme pollution in the area (Table 1; Andrews & Sutherland, 2004; Hakanson, 1980; Müller, 1969). Zinc, Pb, and Cu also show high levels of pollution with Igeo values ranging from 2 to > 5 (see SD). The concentrations of Cr, Pb, Mn, and Cu in soils are attributed to the weathering of mafic rocks (Sakyi et al., 2019). Thus, the concentrations of As, Pb, Cr, Mn and Cu (Table 1) in the area have a strong link to the underlying geology and may have been facilitated by activities that involve interaction with the underlying geology of the area. Therefore, the Igeo values suggest that the area is moderate to extremely polluted by Cd, As, Pb, Cu, Cr, and Zn at various sites and with varying percentages.

The robust compositional contamination index (RCCI) is a suitable proxy in elucidating the effect of chemical weathering of the underlying geology and anthropogenic effect on the concentrations of the PTEs (Reyes et al., 2020; Kazapoe et al., 2021). Table 2 shows the statistical summaries of RCCI values calculated for Ni, Co, Mn, Cd, As, Cu, Pb, Zn, and Fe using background geochemical parameters from Allaway (1969) and Feng et al. (2007). According to Reyes et al. (2020), RCCI values ≤ 15%, > 15–25%, > 25–40%, > 40–75% and > 75–100% indicate low, medium, moderate, high and very high values, respectively. The calculated RCCI values (Tables 2, 3), indicate that 3, 2, and 17 samples have RCCI values within ≤ 15%, > 15–25% and > 25–40%, respectively. This means that 4% of the samples are low, 2.7% indicate medium and 22.7% show moderate RCCI values (Tables 2, 3). Also, 43 and 10 samples representing 57.3% and 13.3% of the samples, respectively, have RCCI values within the range of 40–75% and 75–100% implying high to very high RCCI values (Table 3). These percentages of the RCCI values are also indicative of geogenic sources facilitated by anthropogenic activities in these areas. The RCCI values suggest that 70.6% (53 of the samples) of the contaminated area is controlled by anthropogenic activities related to the geology. This means that the main anthropogenic-geology-related activities such as small-scale mining are the main drivers of contamination in the area, as these are one of the major activities or processes through which soils are contaminated with PTEs (Abu et al., 2021; Kazapoe et al., 2021; Nieder, 2018; Reyes et al., 2020).

4.3 Sources of PTEs

The correlation matrix (Table 4) shows that correlation coefficients of ≥ 0.5 are considered significant and relevant in the source characterization of the PTEs. Copper shows significant positive correlations (≥ 0.5) with Zn, Ni, Co, Mn, As, V, Cr, Al, and Fe (Table 5), while Pb correlates significantly with Zn, Mn, and Al. Zinc has significant positive correlations with Ni, Co, Mn, V, Cr, Al, and Fe. Manganese shows positive and significant correlations with Cu, Pb, Zn, Co, and Fe (Table 4). Arsenic correlates significantly and positively with Cu, Ni, Co, V, Cr, and Fe. Cadmium has positive but not significant correlations ($r = 0.4$) with Na and K. Chromium, on the other hand, correlates significantly and positively with Cu, Zn, Ni, Co, As, Al, and Fe (Table 4). According to Taylor and Mclennan (1985), Anani et al. (2017), Abu & Sunkari (2019) and Abu et al. (2021), Ni, Cu, Co, V, Cr, Fe, and Mn are associated with mafic–ultramafic rocks. The concentration of these elements in soils can be

Table 5 Percentage of variance of the eigenvalues of the components and principal components

Component	Initial Eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	7.223	51.594	51.594	7.223	51.594	51.594	5.936	42.399	42.399
2	2.932	20.941	72.535	2.932	20.941	72.535	2.824	20.17	62.569
3	1.046	7.468	80.004	1.046	7.468	80.004	2.441	17.435	80.004

	Principal components		
	1	2	3
Cu	**0.946**	−0.081	−0.061
Pb	0.320	**0.728**	−0.438
Zn	**0.732**	0.382	−0.442
Ni	**0.910**	−0.274	−0.021
Co	**0.946**	−0.127	0.100
Mn	**0.600**	0.442	−0.077
As	**0.674**	−0.194	0.363
Cd	0.083	**0.683**	0.072
V	**0.812**	0.124	0.348
Cr	**0.874**	−0.347	−0.007
Al	**0.744**	0.455	0.200
Na	−0.340	0.673	**0.583**
K	−0.414	**0.796**	0.016
Fe	**0.939**	0.175	0.022

Bold values are those values with significant correlation values, i.e. 0.5 and > 0.5

linked to the chemical weathering of mafic–ultramafic rocks within the area under consideration. Additionally, Ni, Co, V, and Fe in soils are reported to be the weathering products of mafic–ultramafic rocks (Abu et al., 2023; McLennan et al., 1993; Sakyi et al., 2019). Therefore, the association of PTEs, such as, Cu, Zn, Mn, Cr, and As with Ni, Co, V, and Fe (Table 5), can be attributed to the chemical weathering of mafic–ultramafic rocks in the area. The Al content in soils suggests the weathering of clay minerals. These PTEs also show a correlation with Al, suggesting their contribution or association with clay minerals or clay-dominated soils in the area. Lead is largely sourced from clay minerals and clay-dominated soils in the area (Table 5). The source of cadmium, unlike the other PTEs, is not likely from the mafic–ultramafic rock suite in the area. Muntau & Baudo (1992) reported that some fertilizers contain cadmium up to 40 mg kg^{-1}, making anthropogenic activities related to farming, waste from mining activities, discharge of wastewater, release from cadmium batteries, and solid waste disposal (Muntau & Baudo, 1992; Nieder, 2018; Xiong et al., 2019) the most plausible sources of Cd in the area.

According to Kabete et al. (2012), the geology of the study area is dominated by basaltic and volcaniclastics together with gneisses. Rivera-Hernandez et al. (2021) have also attributed the source of Pb, As, Cr, and Mn to ultramafic rocks whose release is facilitated by mining activities. Thus, the source of the PTEs, such as As, Cu, Zn, Cr, and Mn, can be attributed to the chemical weathering of mafic–ultramafic rocks in the area, which is the main geological process controlling their enrichment in soils. Clay-dominated soils largely control Pb concentrations, while anthropogenic activities like commercial agricultural activities, and domestic and solid waste disposal are the most plausible cause of Cd concentration levels in the study area.

Factor analysis (FA) has been a useful approach over the years in characterizing and evaluating compositional data. This approach has been applied in various fields such as hydrochemical patterns, mineral exploration, and identification of sources of contamination by PTEs in soils (Abu et al., 2021; Lermi & Sunkari, 2019; Mvile et al., 2021; Kazapoe & Arhin, 2019; Sunkari et al., 2019, 2020, 2021; Yidana et al., 2018; Zango et al., 2020).

In this study, the extraction method of the FA of the samples was principal components analysis (PCA), and the significant (≥ 0.5) eigenvalue loadings were considered (Table 5). In the FA, 3 principal components (PC) accounted for 80% of the total variance based on the loading of the eigenvalues (Table 5). The 3 number of PCs can easily be seen in the scree plot (Fig. 2a). The first PC (PC1) accounted for 51.6% of the total 80% variance with elements: Cu, Zn,

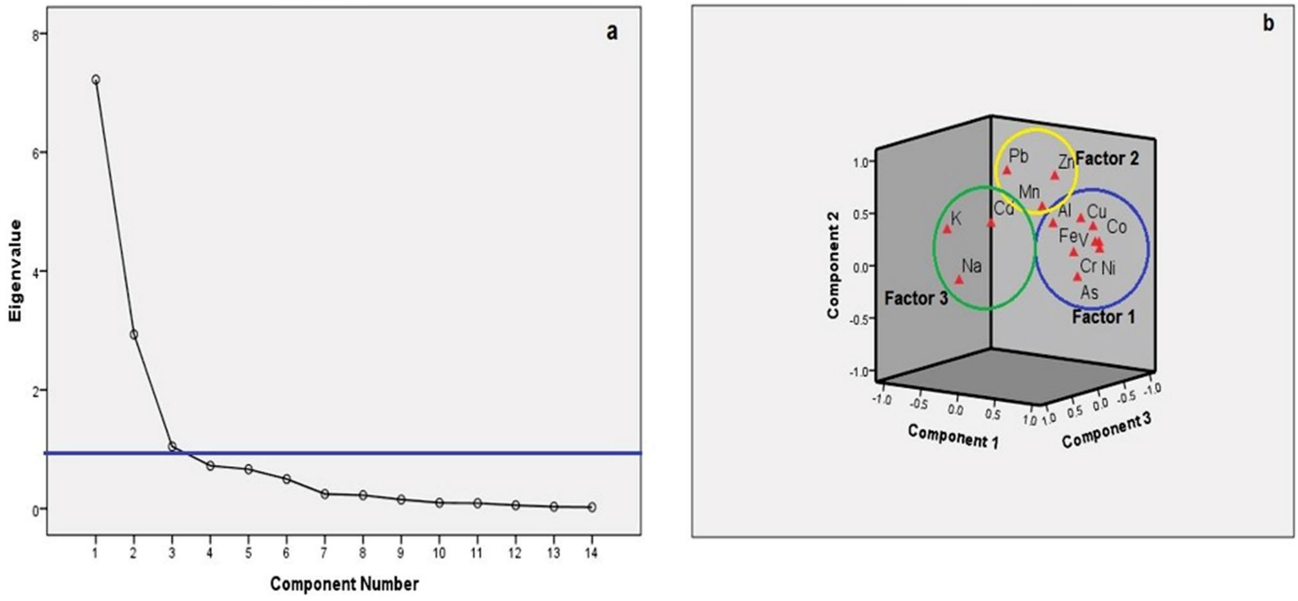

Fig. 2 The scree plot, **a**, and rotated factor loading plotted in space, **b** (with the number of points above the blue line which is on the 1 eigenvalue mark on the ordinate indicating the number factors)

Ni, Co, Mn, As, V, Cr, Al, and Fe (Table 5). PC2 accounts for 20.9% of the total variance with Pb, Cd, and K defining the composition of that component (Table 5). The third component PC3 accounts for 7.5% of the variance with Na as its component element (Table 5). The PCA has PTEs; Cu, Zn, Mn, As, and Cr in PC1. These have trace elements that are generally accepted to be of mafic–ultramafic origin (Ni, Co, V, and Fe) (Abu et al., 2021; Sakyi et al., 2019) together with them in the same PC1, suggesting their mafic–ultramafic source as interpreted from the analyzed correlation matrix. The PC2 grouped Pb, Cd, and, K together suggesting that Cd and Pb had the same source. From the FA, the Cd and Pb are of the same source, thus possibly of solid waste and mining waste disposal in the area.

Plots of the rotated loadings of the FA (Fig. 2b) have factor 1 (F1) having Cu, Fe, V, Cr, Co, Ni, As, and Al grouping closely together (Fig. 2b). Factor 1 (F2) has Pb, Zn, and Mn with factor 3 (F3) having Na, K, and Cd.

The geogenic source of Cu, Zn, Mn, As, and Cr has been clearly brought out by the factor analysis. From the FA, the composition of F2 is suggesting that Pb has a contribution from the same as Zn and Mn. The anthropogenic source of Cd is unequivocal from the FA, with its association with Na and K.

4.4 Spatial distribution of PTEs

The interpolations (by kriging techniques) and the resulting spatial distribution maps are presented in Fig. 3 where the high spots of As, Cr and Cu are located in the southern parts of the study area. Their concentration in this part could be attributed to mafic–ultramafic rocks, and the chemical weathering of these rocks could subsequently enriched the soils with these PTEs. Cadmium has an observable high spot in the easternmost part of the area (Fig. 3) and concentration could be to due anthropogenic activities including run-offs from fertilized agricultural farmlands and waste from mine sites according to Nieder (2018). Zinc is enriched in the northern half of the study area, whereas a hot spot of Pb is located in the southeastern part of the area. The RCCI indicates that anthropogenic activities disturb the geology and are responsible for the PTEs concentrations in soils from the southernmost and central-northern parts of the study area. The overall spatial distribution of the RCCI suggests that the whole area is worth monitoring. However, the individual PTEs such as As, Cd, Cr, Cu, Mn, Pb, and Zn at their various hotspots need to be given special attention and mitigation measures so as to ensure healthy public health in those parts.

4.5 Health implications

The PTEs considered in the study, As, Cr, Cd, and Mn have exceeded their standard limits in the area with the possibility of causing various health challenges, including asthma, kidney diseases as well as other hearth related complications (Senesi et al., 1999). Arsenic is particularly well known for its cancer risk in humans when exposed to them for longer periods. High Cd concentrations have a deleterious health effect on women and fetuses (Wang et al., 2015). Cadmium on prolonged exposure has carcinogenic

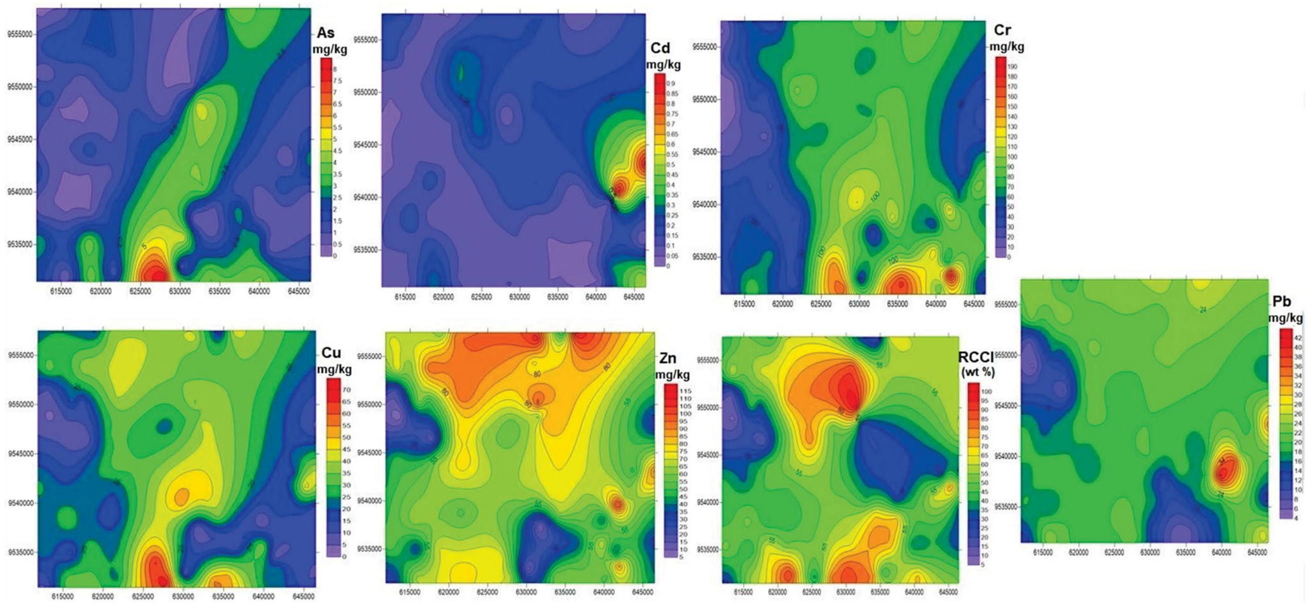

Fig. 3 Interpolation maps indicating the spatial distribution of the PTEs and RCCI

and noncarcinogenic health effects, including kidney-related diseases and cancers in extreme cases (Fu et al., 2008). Chromium has been reported (Sheehan et al., 1992) as a major cause of human respiratory carcinogenic diseases. In Tanzania maternal and child mortality, respiratory tract infections, and skin diseases are among the common and most important diseases in most districts including Tabora, Kahama, Kibaha, Handeni, etc., within the country (Magesa et al., 2001). The study area (Fig. 1) fall within the Tabora region and its adjoining districts; hence, these reported health issues in the study area could be attributed to the intake of food produced from PTEs, e.g., As, Cr, Mn, and Cd contaminated farmlands.

5 Conclusion

Based on the evaluation and characterization of the PTEs in soils in central Tanzania, the following conclusions can be drawn. The order of concentration of the PTEs of interest in the study area is Mn > Zn > Cr > Cu > Pb > As > Cd. Generally, their concentrations are within acceptable limits, except for 39 samples of As and 4 samples of Cr, which account for 52% and 5.3% of the total pollution, respectively, relative to Tanzania's Ministry of State's standards. Additionally, manganese levels are very high in the area and need attention. Assessment of pollution levels indicates that all the studied PTEs range from moderate to extremely polluted in the area. RCCI also shows that anthropogenic activities, such as mining and related activities that involve geology are the dominant cause of PTEs pollution in the area, with 70.6% of high to very high RCCI values. From the statistical analysis, Cu, As, Zn, Mn, and Cr have geogenic sources, while Cd concentrations in the soils are due to mining and related activities, and fertilizer run-off from cultivated lands, solid waste, and domestic wastewater disposal are the main source of Cd contaminations. Clay-dominated soils also contribute to Cu, As, Zn, Mn, and Zn contents in the studied soils. Factor analysis also reveals that Pb is sourced from the same source as Cd. The southern parts of the area have high spots of As, Cr, and Cu, while the northern half of the area has high Zn spots. Cd is associated with the eastern parts, and Pb is concentrated in a spot to the southeast. RCCI distribution is high in the northern and southern parts of the area.

Given the potential health risks associated with long-term exposure to As, Cr, and Cd, anthropogenic activities, especially mining, need to be monitored regularly. Effluent from mining waste must be checked to ensure that PTEs concentrations are within tolerable levels. Health-related issues such as cancer, kidney, heart, and reproduction are likely due to exposure to As, Cr, and Cd.

6 Recommendation

There is a need for periodic monitoring of these PTEs within the catchment area, especially the mining activities which appear to be the dominant anthropogenic activity releasing these PTEs into soils. Additionally, women with the tendency of eating clays should be cautioned on the possible effect of these PTEs on their lives and that of their unborn babies since clays are one of the major sources of the assessed PTEs.

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