The University of Tehran Press

Pollution

https://jpoll.ut.ac.ir/

Print ISSN: 2383-451X
Online ISSN: 2383-4501

Scalp Hair Analysis Using µ-PIXE for Screening Toxic Elements Accumulation in Gold Miners

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Article Info

Article type:
Research Article

Article history:
Received: 2 September 2024
Revised: 24 November 2024
Accepted: 19 January 2025

Keywords:
Artisanal gold miners
Biomonitor
Gold miner
Human tissue
µ-PIXE

ABSTRACT

Artisanal mining is an expanding sector of the mining industry in various parts of the world. Workers in this field often lack protective safety gear and are exposed to mining pollutants that can adversely affect their health and well-being. Given the limited availability of occupational biomonitoring studies in the mining industries of countries like Sudan, this study aimed to investigate the effectiveness of a micro Particle Induced X-ray Emission (µ-PIXE) approach to biomonitor human tissue—specifically hair samples—obtained from artisanal gold miners for the presence of toxic metals, including iron (Fe). Gold miners from the region in Sudan voluntarily provided hair samples, which were subsequently analyzed using the PIXE technique. The analysis revealed a range of elements, including sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), bromine (Br), strontium (Sr), and lead (Pb). However, some essential elements, such as silicon (Si) and chromium (Cr), were notably absent. All samples contained elevated levels of sulfur, phosphorus (P), and chlorine, with some samples indicating the presence of lead (Pb).

Additionally, only six out of the nineteen samples contained lead, and its absence can result in metabolic issues and hinder tissue growth. Furthermore, all analyzed hair samples exhibited low levels of essential elements like zinc, which is vital for plant disease resistance, photosynthesis, cell membrane integrity, protein synthesis, and pollen formation.

Cite this article: Eisa, M., Cloete, K., Mtshali, Ch., Mongwaketsi, N., Salih, M., & Maaza, M. (2025). Scalp Hair Analysis Using µ-PIXE for Screening Toxic Elements Accumulation in Gold Miners. *Pollution*, 11(2), 497-509. https://doi.org/10.22059/poll.2024.381741.2537

DOI: https://doi.org/10.22059/poll.2024.381741.2537

INTRODUCTION

The increasing problem of illegal mining in Africa has garnered significant attention due to the health risks associated with such activities (Ahmed El Tohami, 2018). These mining operations can have adverse effects on human health due to the chemicals used in processing minerals, leading to water and soil contamination (Cortes Toro et al., 1993). For example, soil is a natural source of nutrients that plants and crops require to grow and produce good yields. It contains varying levels of minerals, organic matter, and water, which are essential for the growth and yields of crops (Zaichick et al., 2008). Nutrients such as nitrogen (N), phosphorus

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(P), potassium (K) (major/macronutrients), sulfur (S) (secondary-nutrient), zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), and boron (B) (micronutrients) are crucial for crops, but excessive amounts can be harmful to human health (Čargonja et al., 2023)**.** For instance, an excess of iron (Fe) in the soil can lead to vomiting, diarrhea, hepatocellular necrosis, fibrosis, and even carcinoma. Heavy metal pollution in terrestrial ecosystems is a significant environmental concern due to the potential absorption of metal pollutants by plants or their leaching into water, posing harm to plants and humans through the food chain. Additionally, some of these pollutants are non-biodegradable and can cause diseases such as multiple sclerosis, Alzheimer's disease, Parkinson's disease, muscular dystrophy, and cancer (Čargonja et al., 2023)(Amaral et al., 2008).

The presence of minerals, such as gold, in large quantities in Sudan, along with increased poverty, has driven many people to engage in illegal mining (Arifin et al., 2020). These small-scale artisanal gold mining activities have significantly increased across the arid and semi-arid areas of Sudan, leading to notable environmental and socioeconomic impacts (Ahmed El Tohami, 2018). There is limited research on the effects of these activities in this region. In recent years, there has been growing interest in using nuclear science and technology for biomonitoring and risk assessment due to the sensitivity of these techniques compared to other analytical and imaging methods, such as x-ray fluorescence (XRF) (Simon et al., 2024)(Spanu et al., 2024)(Vivek Kumar Singh , Jun Kawai, 2022)(Noreen et al., 2020)(Kumakli et al., 2017).

This research investigates the elemental content in human hair collected from areas associated with illegal mining activities in Sudan. The study area contains gold and mineral mines, with precious metals like gold, silver, and platinum, base metals like copper, zinc, and lead, and strategic minerals such as iron, manganese, and chromium. It also includes industrial metals like calcium carbonate, salt, talc, kaolin, silicon, zircon, and building stones in the Butana area of east Sudan. We used the nuclear analytical technique called particle-induced x-ray emission (μ-PIXE) at the 3 MV Tandetron accelerator of iThemba LABS in Cape Town, South Africa. Previous researchers have also used this technique to study the elemental composition of various substances**.** μ-PIXE was chosen because it offers several advantages, including multi-elemental determination, non-destructive analysis, small sample requirement, and very low detection limit. The technique is based on the ionization of atoms from the sample by a beam of protons from the accelerator and the subsequent emission of characteristic X-rays. The number of characteristic X-rays determines the amount of the element detected as part per million (ppm).

This study aims to analyze the elemental composition of human hair samples collected from regions linked to illegal mining activities in Sudan. The study area encompasses gold and mineral mines that yield precious metals like gold, silver, and platinum, as well as base metals such as copper, zinc, and lead, and strategic minerals like iron, manganese, and chromium. Additionally, it includes industrial metals such as calcium carbonate, salt, talc, kaolin, silicon, zircon, and various building stones found in the Butana region of eastern Sudan.

MATERIALS AND METHODS

Sampling

Hair samples were collected from 22 volunteer miners in the Butana region. Several mining areas within a geographical area of about 10,000 km2 in the center of Butana, Gadaref State, eastern Sudan were randomly selected. The sampling area is shown in Figure 1(Ibrahim, 2015) and is outside the control of organized mining by official companies and the government (Biology et al., 2014)(Ahmed El Tohami, 2018)

Sample preparation

Each person›s hair was sampled by removing a 2 cm long hair shaft, which was then cleaned with de-ionized water. The hair samples were embedded in wax and thin cross sections of about

5 µm were cut using a microtome. Block sections of the hair were also prepared for ion beam analysis. Prior to µ-PIXE analysis, the samples were carbon-coated to prevent charging during irradiation.

PIXE analysis

Proton-induced X-ray emission (µ-PIXE) analysis was conducted on all the hair samples**.** The measurement was done using a 3 MeV focused proton beam of about ~1.5 × 1.5 µm^2 spot size. The beam was raster scanned on a hair surface area (cross-sectional and longitudinal) using an electrostatic scanning coil in a square pattern of up to a maximum of 128 × 128 pixels, with a dwell time of 10 ms/pixel. The beam current was kept below 100 pA to avoid the evaporation of elements due to the intense beam. The PIXE spectrum, for each sample, was acquired in an event-by-event mode, using a Si (Li) X-ray detector, positioned at an angle of 135^o with ∼∼160 eV resolution. The experimental setup was coupled with a proton backscattering detector (at 176^o scattering angle) and a 125 µm Beryllium (Be) and 155 µm Kapton filters that were used interchangeably to shield the X-ray detector and reduce the count rate. The PIXE count rate was kept below 1000 counts/s to avoid pulse pile-up and to achieve satisfactory counting statistics. The accumulated PIXE spectra were analyzed using GeoPIXE II software (Mtshali et al., 2024) (Minnis-Ndimba et al., 2015) (Ryan et al., 2002)**.** Beryllium is used as an X-ray filter due to its smooth X-ray transmission curve, and research-grade foils commonly used for this application have manufacturer-stated purities of 99.8–99.9%(McGarry et al., 2014). Also because of its excellent radiation resistance, Kapton is frequently used in high-radiation environments where a flexible insulating material is required. In outer space, Kapton is used both alone and in combination with other materials for applications that require radiation resistance at minimum weight(Megusar, 1997)(Ecology, 2012).

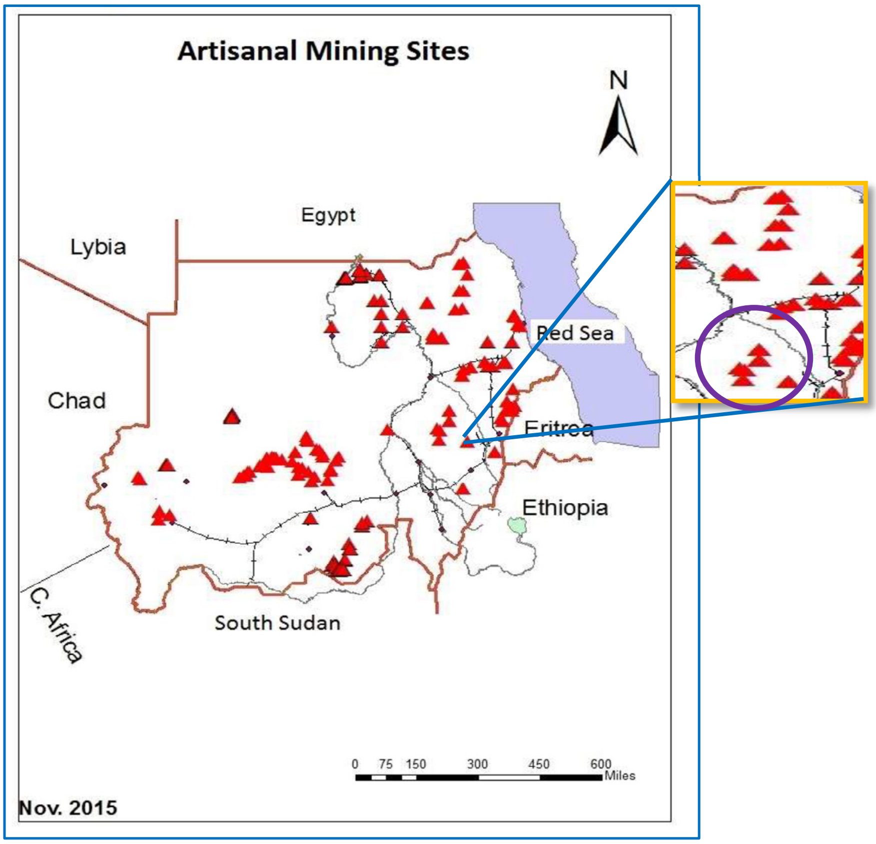

Fig. 1. Geographical distribution of artisanal-scale gold mining activities.

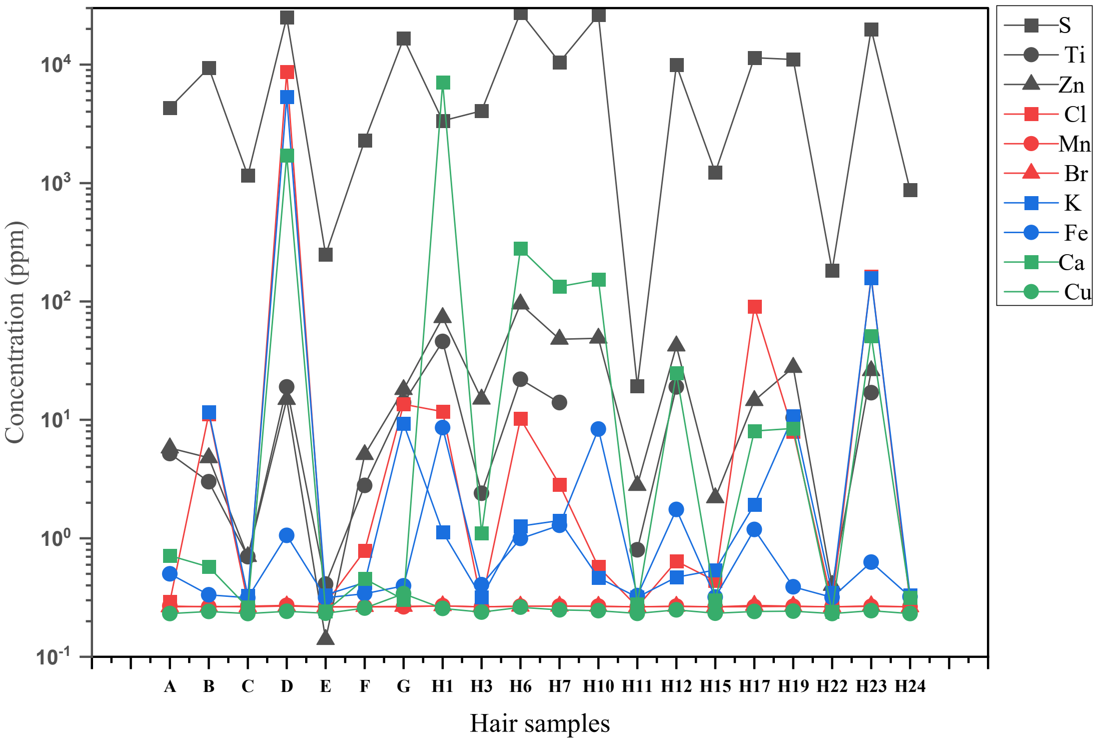

Fig. 2. Concentration of the detected elements as a function of the volunteers samples

RESULTS AND DISCUSSION

To avoid the influence of diet and other factors like environment, habits, etc. on the hair samples, all the subjects studied were chosen mostly from rural areas with a minimum socially accepted level of standard of living and hailing from the same region. All the patients were newly diagnosed, un-medicated and non-smokers(Pradeep et al., 2014)

The elemental compositions of hair samples are presented in Tables 1 and 2. Table 1 presents the elemental concentrations of hair obtained using a 125 µm Be filter while the ones obtained using a 155 um Kapton filter are presented in Table 2. All the concentrations of the identified elements are expressed in parts per million (ppm). The analysis has shown the presence of various elements (S, Cl, K, Ca, Ti, Mn, Fe, Cu, Zn, Br, Sr, and Pb) however, some essential elements such as Si, and Cr were not found. In all the hair samples, the detected elements vary in concentrations from miner to miner as can be observed in Tables 1 and 2. All samples contained high amounts of S, P and Cl, with some samples showing the presence of Lead (Pb), especially in Table 2. This observation highlights the significance of using various filters for such a study, especially in this case, the Be filter is good for X-rays from lower Z elements while Kapton allows a higher count rate and is good for X-rays from higher Z elements.

The concentration plot of the detected elements as a function of the volunteer›s samples is shown in Figure 2. This plot indicates that there is a variation of elemental accumulation of these miners.

Table 3 presents the mean values of the elemental concentration of the selected elements with certified and reference values concertation from the IAEA (International Atomic Energy Agency, 1994)[44]. In some cases, the obtained data is above that of the IAEA-certified values, while in others, it is below. For instance, K, Ti, and Fe values are higher than the certified values while the values of the other elements are below. This means that these miners risk developing

Table 1. Elemental concentration of hair using 125 µm Be filter(ppm)

Code	S	Cl	K	Ca	Ti	Mn	Fe	Cu	Zn	Br	Sr	Pb L
A	4324±126	55±3	24±4	67±3	5.2±0.9	10±2	101±9	n.d	5.8±0.8	n.d	n.d	n.d
B	9400±633	1931±99	787±40	54±6	3.0±0.9	n.d	12.7±0.7	2.2±0.5	4.8±0.7	5±1	n.d	n.d
C	1157±44	44±9	9±5	7±2	0.7±0.4	8±0.7	0.4±16	n.d	0.7±0.2	n.d	n.d	n.d
D	25016±610	5362±188	2123±53	530±18	19±2	15±4	264±16	2.6±0.5	14.9±0.8	9±1	5±1	n.d
E	248±8	33±2	12.8±1	2.5±0.1	0.41±0.06	n.d	0.45±0.05	0.4±0.06	0.14±0.03	n.d	n.d	n.d
F	2281±19	564±7	65±1	40.1±0.7	2.8±0.3	n.d	17.7±0.3	6.3±0.3	5.1±0.2	3.2±0.4	n.d	4.8±0.6
G	16576±201	2031±104	738±12	164±5	14±1	n.d	51±2	23±2	18±1	5.3±0.8	n.d	33±3
H1	1840±45	106±6	19±2	24±1	2.2±0.6	1.1±0.3	29±1	2.7±0.5	4.3±1	nd	n.d	n.d
H1	33483±72	1956±49	279±5	614±7	46±2	11±2	721±15	6±1	73±3	12±3	n.d	n.d
H3	2356±33	n.d	11±0.2	37.3 ±0.2	1.7±0.1	0.5±0.1	18.8 ±0.6	0.29±0.07	5.2±0.2	n.d	n.d	n.d
H6	27527±161	1884±11	304±8	422±3	22±1	6.7±0.9	251±5	7.2±0.6	95±3	8±1	n.d	n.d
H7	1.05%±485	0.123%±99	328±15	378±26	14±1	8.4±0.8	307±7	4.2±0.5	48±1	6±0.5	n.d	n.d
H10	26297±198	400±22	86±2	386±2	n.d	6±1	715±11	3.3±0.8	49±3	5±1	8±2	8±3
H11	16.4±0.5	n.d	2.3±0.2	10.8±0.2	0.8±0.1	0.2±0.1	9±0.2	0.15±0.09	2.8±0.2	n.d	n.d	n.d
H12	15405±64	976±23	104±4	264±4	11.9±0.6	5.8±0.8	97±2	2.5±0.2	25.8±0.8	5.2±0.4	2.4±0.4	n.d
H17	11445±209	3010±40	395±8	211±4	n.d	2.6±0.7	290±4	2.4±0.5	14.6±0.9	15±1	n.d	n.d
H22	183±13	40±3	21.4±0.8	2.3±0.3	n.d	0.21±0.06	1.9±0.1	n.d	0.4±0.1	n.d	n.d	n.d
H23	19874±98	3310±46	1355±23	321±5	17±1	5±1	151±5	3.2±0.6	26±2	11±1	nd	n.d
H24	872±21	45±3	9.6±0.7	18.3±1	n.d	0.4±0.1	5±0.2	n.d	n.d	n.d	n.d	n.d

n.d=not detected by

Table 2. Elemental concentration of hair using 155µm Kapton filter (ppm)

Code	S	Cl	K	Ca	Ti	Mn	Fe	Cu	Zn	Br	Sr	Pb L
A	1.78%±822	271±22	135±7	464±11	10.6±0.9	8±0.7	147±3	3.9±0.5	58±1	2±0.5	3.2±0.337	47±1
B	14133±205	3707±69	1845±11	210±4	7.1±1	3.8±0.7	84±2	2.8±0.5	16.4±0.8	14±1	n.d	3.8±0.9
C	15873±279	1308±35	130±5	327±2	11.9±0.5	5.4±0.4	150±5	10.6±0.7	41±2	7.5±0.8	n.d	17±1
D	12082±384	3139±45	1694±19	447±8	17.5±1	11.8±0.7	215±4	29±1	26.8±0.7	11±1	2.9±0.8	39±0.046
E	12541±346	2021±50	877±10	308±7	8.2±0.9	4.8±0.7	71±1	59±2	17.2±0.7	7±1	20±0.184	65±3
F	2977±146	699±15	64±3	55±2	1.7±0.5	0.9±0.2	22.7±0.5	5±0.3	7.4±0.4	4.3±0.9	n.d	10±1
G	12987±407	2295±45	884±14	212±7	17.8±0.6	3.6±0.5	75.1±0.9	35.6±0.8	25.5±0.5	6.8±0.5	n.d	47±1
H1	8964±155	802±27	118±4	146±3	16±3	3.1±0.8	126±4	3±0.7	39±1	5±1	n.d	n.d
H3	4066±175	39±6	20±2	93±2	2.4±0.7	1.7±0.4	55±1	1.5±0.4	15±1	0	n.d	n.d
H6	510±29	49±2	8.8±0.4	12.4±0.4	0.4±0.1	0.22±0.06	8.9±0.4	0.27±0.07	3.5±0.2	n.d	n.d	n.d
H7	10501±538	1228±63	328±15	378±10	14±1	8.4±0.9	307±7	4.2±0.6	48±2	6±1	n.d	n.d
H11	16.4±0.5	n.d	2.3±0.2	10.8±0.2	0.8±0.1	0.2±0.1	9±0.2	0.15±0.09	2.8±0.2	n.d	n.d	n.d
H12	0.99%±103	459±37	87±2	278±4	19±0.7	7.3±0.7	374±4	4.1±0.2	42.1±0.2	3.9±0.6	3.2±0.3	n.d
H15	1228±30	260±5	118.3±0.9	15.4±0.7	n.d	0.29±0.09	3.2±0.2	0.34±0.08	2.2±0.2	0.8±0.2	n.d	n.d
H19	11061±191	1754±31	771±6	214±2	10.4±0.8	5.1±0.5	46.5±1	2.8±0.4	27.8±0.9	8±1	n.d	4±1
H22	184±13	40±3	21.5±0.8	2.4±0.3	n.d	0.12±0.1	2±0.1	n.d	0.2±0.1	n.d	n.d	n.d
H23	10317±395	2321±103	1115±6	271±7	10.4±0.4	6.9±04	164±1	3.8±0.3	30±0.6	9.9±0.5	2±0.5	n.d
H24	838±21	43±3	9.4±0.7	18.5±1	n.d	0.4±0.138	5±0.2	n.d	2.9±0.3	n.d	n.d	n.d

n.d=not detected by

Table 3. Mean vales of the elemental concentration of the selected elements with certified and reference values concertation

Elements	Mean Analyzed values(Be)	Mean Analyzed values(Kapton)	Reference Value(Mikulewicz et al., 2013)		Certified 1 (Zaichick, 2010)	Certified 2(Gellein et al., 2008)	Certified 3 (Skalny et al., 2015)	Certified 4 (Zeisler, 1998)	Certified 5 (Bleise AR, Heller-Zeisler SF, 2000)	Certified 6 (H. Faghihian, 2002)	IAEA 1993(International Atomic Energy Agency, 1994)	IAEA 1985(Chatt et al., 1985)
			Lower	Upper			-	-	-			
S	8362.02	10399.57	-	-		46900	-	-	-	0.2%	53090±4505	48707 ± 150
Cl	1050.19	1140.56	-	-	2270	-	-	-	-	360	1664±1415	2265.29 ± 478.28
K	334.62	453.78	-	-	9.2	11.8	-	-	-	2.43%	213±T95 3	9.21 ± 5.15
Ca	156.20	234.97	120 160	365 1460	522	1090		1120	929	1.56%	512±383	522.03 ± 160.22
Ti	6.74	10.46				-						3.32 ± 0.55
Mn	3.87	4.64	0.04 0.002 0.1 0.03	0.77 0.91 0.6 0.75	0.85	2.94	3.83	9.6	8.8	98	5.96±6.19	0.85 ± 0.25
Fe	136.70	187.19	5.9 7 3.66	36.8 21 17.3	23.7	78.9	160	123	79.3		49.5 ±26.3	23.7 ± 9.7
Cu	3.56	9.29	7.2 9.1 8 10.1	82.7 59.7 36 46.6	-	25	33.6	17.6	16.8	3.7	14.2±3.6 8	10.23 ± 3.17
Zn	15.92	26.28	64 96.9 30 150	2228 329.2 130 327	174	189	191	167	163	179	205 ±86.9	174.09 ± 31.58
Br	4.019	5.21			-	-	-	-	-	-	9.83±23.2	4.16 ± 2.09
Sr	0.82	5.46	0.31 1.11	3.65 12.72	0.82	4.19	-	-	-	-	1.98 ±1.47	-
Pb	0.8	9.29	1 0.23	19.8 3.03		7.2	-	-	-	-	5.92±6.36	-

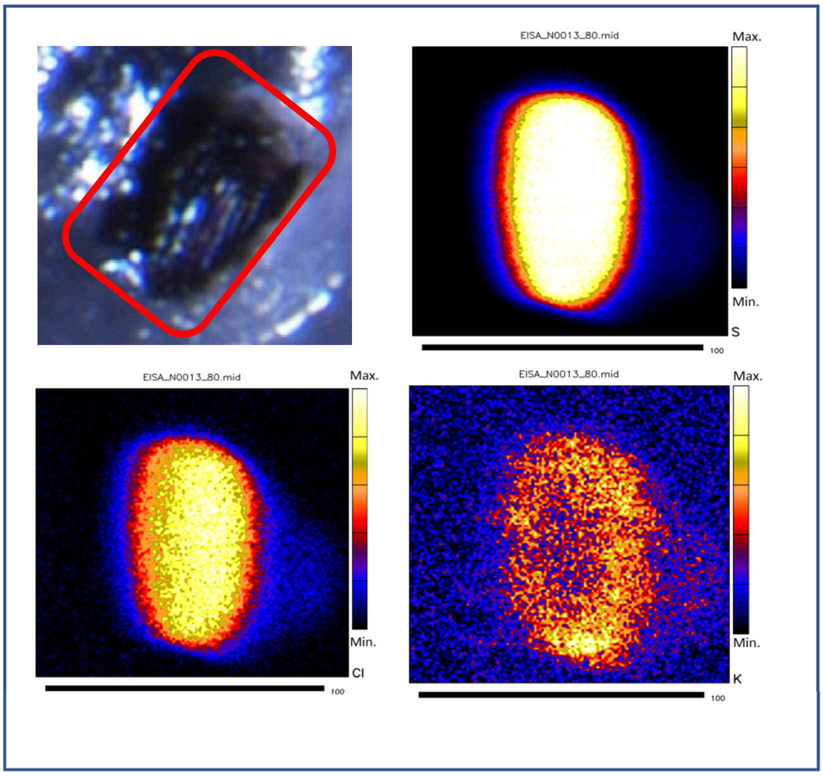

Fig. 3. Maps of the detected elements displaying S, Cl and K as analyzed cross-sectional using 125 µm Be.

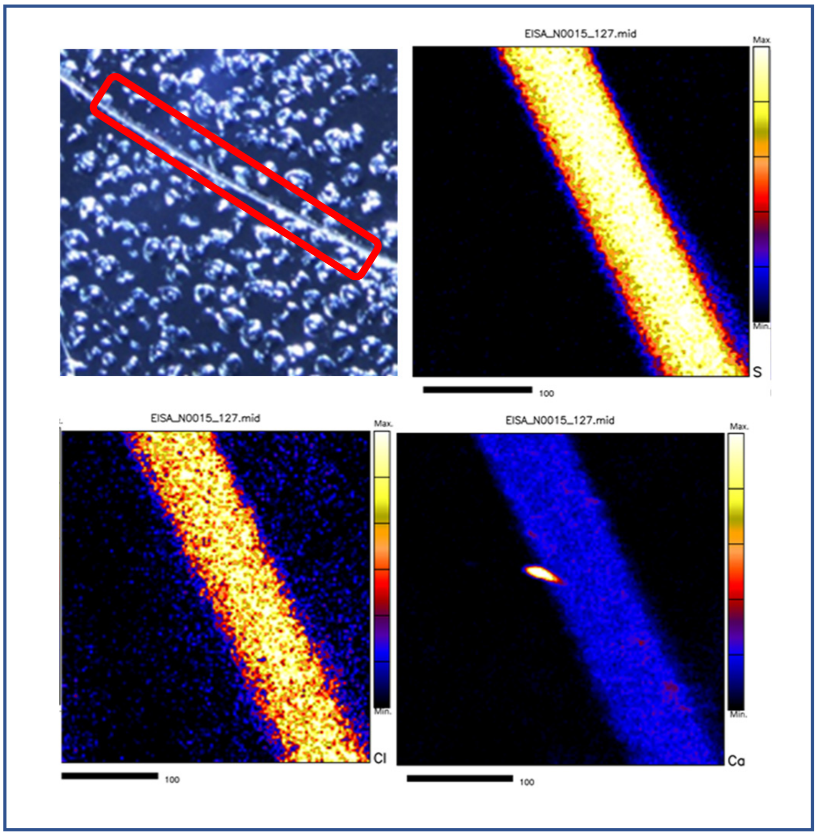

Fig. 4. Maps of the detected elements displaying S, Cl and Ca as analyzed longitudinal using 125 µm Be.

diseases associated with a high amount accumulation of these elements if the situation is left unattended.

The role of each detected element in plant crops and their concentrations are discussed in the section below:

Sulfur (S)

The average element S concentration was found to be ranging from 16.4±0.5to 1.78%±485 ppm. Sulfur is essential for synthesizing proteins, chlorophyll, enzymes, and vitamins, and it also influences general metabolic and photosynthetic mechanisms. S deficiency may compromise these processes. A high amount may result in intestinal problems, including: Diarrhea. Inflammatory bowel disease(Dordevic et al., 2023)

Potassium (K)

The concentration of K in all the samples ranged from 2.3±0.2 to 2123±53 ppm. Potassium (K) plays a crucial role as a regulator within the plant system. It is involved in osmoregulation, membrane potential regulation, transport of sugars, and stress adaptation. K deficiency may compromise these processes. A high amount may result in damage your heart, make you feel palpitations and even cause a heart attack (D'Elia, 2024).

Calcium (Ca)

The concentration of Ca ranged from 2.3±0.3to 614±7 ppm. Calcium plays a crucial role in maintaining the structure of bones and promoting cell cohesion. The absence of calcium can impede the development of bone tissue. A high amount may result in reducing the risk of breast cancer and contribute to the reduced rate of bone loss and fracture incidence in elders(Pu et al., 2016).

Titanium (Ti)

The concentration of Ti ranged from 0.41±0.06ppm to 46±2 ppm. Titanium enhances the nutritional status of plants, boosts enzymatic activity, facilitates nutrient uptake, increases photosynthesis, contributes to protein and chlorophyll synthesis, and helps in controlling plant diseases. Ti deficiency may compromise these processes. A high amount may result in slight changes in the lungs.(Tibau et al., 2019)

Manganese (Mn)

The concentration of Mn ranged from 0.12±0.1to 15±4 ppm. Manganese (Mn) plays a significant role in various processes of a plant's life cycle, including photosynthesis, respiration, scavenging of reactive oxygen species (ROS), pathogen defense, and hormone signalling. Mn deficiency may compromise these processes. A high amount may result in serious side effects, including poor bone health and symptoms similar to Parkinson disease, such as tremors (Keen et al., 2012)

Iron (Fe)

The concentration of Fe ranged from 1.9±0.1 to 715±11 ppm. Fe is an essential micronutrient for almost all living organisms because it plays a critical role in metabolic processes such as DNA synthesis, respiration, and photosynthesis. Iron deficiency in plants leads to changes in gene expression levels, and high iron levels in plants lead to protein degradation. A high amount may result in cellular changes, such as damage to the plasma membrane leading to cell death (Sousa et al., 2020).

Copper (Cu)

The concentration of Cu varied from 0.15±0.09 to 35.6±0.8ppm. Cu is essential for various plant functions, including photosynthetic and respiratory electron transport chains, ethylene sensing, cell wall metabolism, oxidative stress protection, and biogenesis of molybdenum cofactor. A copper deficiency can lead to the disruption of vital plant metabolic functions, while an excess can lead to phytotoxicity through the formation of reactive oxygen radicals that damage cells, or by interfering with proteins, disrupting key cellular processes, inactivating enzymes, and affecting protein structure. A high amount may result in damage the kidneys, inhibit urine production, and cause anemia due to the rupture of red blood cells (hemolytic anemia) and even deat(Barceloux, 1999)

Bromine (Br)

The concentration of Br varied from 0.8±0.2to 15±1 ppm. Br does not have any known essential function in plant metabolism and its phytotoxicity is generally low. Br deficiency may compromise these processes. A high amount may result in dizziness, nausea, coughing, and irritation of the skin, eyes, or throat. In severe cases, it could potentially lead to difficulty breathing or even coma. (National Research Council (US) Committee on Acute Exposure Guideline Levels., 2010).

Strontium (Sr)

The concentration of Sr varied from 2±0.5to 20±0.184ppm. Sr does not have any known essential function in plant metabolism and its phytotoxicity is generally low. Sr deficiency may compromise these processes. A high amount may result children, high levels of stable strontium can impair bone growth. High levels of radioactive strontium can cause anemia or cancer..(Ru et al., 2024)

Lead (Pb)

The concentration of Pb varied from 3.8±0.9 to 65±3 ppm. Pb does not have any known essential function in plant metabolism and its phytotoxicity is generally low. Pb deficiency may compromise these processes. A high amount may result in disrupts ionic processes and causes oxidative stress, causing enzyme and protein malfunction(Collin et al., 2022).

Furthermore, upon analysis, it was observed that all samples lacked P, an essential element for photosynthesis, sugar metabolism, energy storage and transfer, and plant growth. This deficiency can significantly impact anorexia, anemia, proximal muscle weakness, skeletal effects (bone pain, rickets, and osteomalacia), increased infection risk, paresthesias, ataxia, and confusion26]. Additionally, only six out of nineteen samples contained Pb, the absence of which can lead to metabolic issues and interfere with tissue growth. Furthermore, all analyzed hair samples indicated low levels of essential elements such as Zn, which is crucial for plant resistance against disease, photosynthesis, cell membrane integrity, protein synthesis, and pollen formation.

The distribution of identified elements in the soil samples was recorded using the GeoPixe II software to create elemental maps, as depicted in Figures 3 and 4 below displaying the maps of the S, Cl, K and Ca cross-sectional and longitudinal respectively. Silicon and aluminum were the primary components found in the samples. Silicon, aluminum, and sulfur were evenly distributed, while iron, rubidium, and zirconium were concentrated in specific areas.

CONCLUSION

This study sheds light on the significant occupational health risks faced by artisanal miners in Sudan, particularly regarding their exposure to toxic elements. Using Proton Induced X-ray Emission (PIXE) analysis on hair samples submitted voluntarily by gold artisanal miners, the research aimed to biomonitor the presence of harmful metals and evaluate the potential health implications. The analysis revealed a diverse array of elements in the samples, including sulfur, chlorine, potassium, calcium, titanium, manganese, iron, copper, zinc, bromine, strontium, and lead. However, some critical essential elements, such as silicon and chromium, were notably absent. High concentrations of S, phosphorus, and chlorine were consistently found across all samples, which could indicate exposure to environmental pollutants associated with mining activities. The lack of phosphorus in all samples is particularly concerning, as this element plays a vital role in various biological processes, including photosynthesis, energy metabolism, and overall plant growth. A deficiency in phosphorus could have broader implications not only for the miners' health but also for the surrounding ecosystem, potentially affecting the sustainability of the environment in which these miners operate. Additionally, while only six out of nineteen samples showed the presence of lead, the intermittent occurrence of this toxic metal raises alarms about the potential for metabolic disruptions and adverse effects on tissue growth among miners. The low levels of zinc found in all analyzed hair samples further amplify the health risks, as zinc is essential for various physiological functions, including disease resistance, protein synthesis, and maintaining cell membrane integrity. This study emphasizes the critical need for ongoing biomonitoring in the artisanal mining sector, particularly in regions with limited occupational safety regulations. The findings from this study not only highlight the importance of using PIXE as a tool for assessing occupational exposure to toxic elements but also call for increased awareness and intervention strategies to enhance worker safety. Addressing these health risks is essential for protecting the well-being of artisanal miners and ensuring the sustainability of their livelihoods and the environments in which they operate.

ACKNOWLEDGMENT

The authors extend their appreciation to the Deanship of Scientific Research, Northern Border University, Arar, Kingdom of Saudi Arabia for funding this research work, IAEA, Vienna and Mr. Ibrahim Abdallah for his help in samples collection.

GRANT SUPPORT DETAILS

This work carried out as a part of the project number NBU-FFR-2024-52-03, supported by Northern Border University, KSA

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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