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Analysis of environmental pollution and contamination linked to gold mining in the Agadez region: The case of the Tabelot and Emzegeur sites

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Abstract: In Niger, gold mining contributes to the income of rural populations. The use of chemicals such as cyanide, mercury, and acids (sulphuric and nitric) in gold mining has a significant impact on the environment and human health. The objective of this study is to determine the levels of soil, water, and plant pollution by trace metals, as well as pollution indices in the Emzegeur, Tabelot, and Agadez areas. This involves conducting a combined analysis of the spatial distribution of gold mining activities and the chemical composition of the soil. In the context of favourable gold prices, the number of artisanal mines has increased, making it relevant to focus on this issue, given that few studies have been conducted to date on gold mining in relation to soil degradation in the Agadez region. The soil samples were collected from various sites divided into three (3) categories: sites in the gold zone, sites in the peripheral zone, and one (1) site for the control sample. A total of twenty-one (21) soil samples, seventeen (17) water samples, and eleven (11) plant samples were collected. The results obtained indicate that the negative impacts of gold mining on the soil range from moderate to high, with pollution indices above 1. The borehole water samples enables that the aquifer has a high buffering capacity, which allows it to bind potentially toxic substances such as heavy metals. However, in the absence of adequate mitigation measures, soil degradation will be exacerbated, leading to a decrease in the aquifer's buffering capacity and the cross-mobilisation of heavy metals.

1. Introduction

With the acceleration of economic development, humans are increasingly responsible for environmental pollution. Anthropogenic toxic substances, particularly trace metals, are major problems facing the current population in the context of gold mining (Alassane et *al.,* 2025). Since the dawn of time, minerals have played a vital role in human life and in the economies of most countries worldwide. Niger is a Sahelian country in West Africa whose subsoil is rich in essential mineral resources. Certain substances are exploited industrially or artisanally: uranium, gold, coal, oil, limestone, gypsum, cassiterite and salt. As a result, the extractive industries play a significant place in the Nigerien economy (Tahirou et *al.,* 2024). The small-scale mining sector has the potential to make a significant contribution to economic and social development, provided it receives a minimum of support and assistance from the relevant institutions. This sector, which does not require large investments, employs a large workforce, and provides a significant production of ores and minerals for industry or export.

The constant movement of gold miners in search of richer sites causes the soil to be abandoned to gully erosion and intensive erosion processes, leading to the total destruction of the topsoil. These processes are virtually irreversible and can become catastrophic. Approximately 15 to 20% of the land is destroyed by abandoned sites camouflaged by stagnant water. The environment is undergoing unprecedented degradation, and the potential for acid mine drainage exists in all mining operations because sulphides present in mine tailings and waste rock can contaminate surface and groundwater during extraction and processing operations. Certain products, including hazardous and toxic ETMs that are harmful to human health and the environment, are leached by surface water (Amoakwah et *al.*, 2020). It should also be noted that there have been mass deaths of cattle attributed to cyanide effluents. Deforestation also leads not only to a huge loss of agricultural land but also to significant economic losses (Nyame 2010). Noise pollution from the use of explosives to destroy overburden rock affects both people and animals (Zakaria Ibrahim et al. (2019) et Tankari Dan-Badjo et *al.* (2019)). Boukari et *al.* (2022) stated that when humans consume food containing arsenic over a long period of time, it leads to poisoning called arsenicosis. High levels of Cr in the human body cause diseases (skin rashes, respiratory problems, weakened immune system, liver and kidney damage). Its content in the environment can be reduced by adding lime, phosphates and organic matter (Zakaria Ibrahim et *al.*, 2019). Inhalation of dust, vapours and mists containing copper salts can cause congestion of the nasal mucous membranes, sometimes fever, or nausea, stomach pain and diarrhoea. When the Cu content in the soil increases, the Cu content observed in the plant becomes critical depending on the plant species (appearance of phytotoxicity symptoms) (Gado, 2018). Mercury poisoning can occur through skin contact during the amalgamation process, during metal combustion, and through the consumption of contaminated water, food, and fish (tilapia and sardines) (Niane, 2014). This poisoning causes cases of psychopathological syndromes such as depression, gingivitis, muscle tremors and vomiting to appear within mining communities, and leads to deaths (Abdoulatif et al., 2019). Once absorbed by the digestive or respiratory tract, lead is distributed by the blood to various organs (liver, kidneys, spleen, bone marrow), where it inhibits haemoglobin synthesis and can cause anaemia due to the inhibition of enzymes involved in synthesis. Zinc can have toxic effects (physiological and gastrointestinal disorders in humans, complications in the respiratory system and skin conditions) at high concentrations. It enters the body through inhalation, contact or ingestion (Abdoulatif et al., 2019). In Niger, this sector is informal and often operates outside existing regulations, posing serious problems in terms of public health and safety, environmental damage (mineral resources, natural environment), and marketing control. These pollutants are highly toxic and have a harmful effect on human and animal health, as well as on plant growth (Alaqarbeh et *al.,* 2022; Goix et *al.,* 2014). Mining sites, particularly gold mining sites, have undergone remarkable development in recent years thanks to the efforts of the authorities and the multifaceted support and assistance of partners. These activities involve the use of chemicals and/or explosive substances. The environmental and safety contexts require rigorous supervision. Mining substances play an indispensable role in the economic development of several countries (Boukari et *al.,* 2022). Gold panning has become a vital activity for many people today. Although this activity has harmful consequences for the environment and the health of surrounding communities, it is becoming necessary to develop adaptation measures to live with it, while optimising it. Thus, the assessment of the level of contamination at mining sites is the subject of several research projects around the world (Djade et *al.,* 2020 ; Makhoukh et *al.,* 2011). Efforts are made to propose various processes to remove these heavy metals and other pollutants (Akartasse et *al.,* 2017; Errich et *al.,* 2021; Dagdag et *al.,* 2023; Saravanan et *al.,* 2025). Environmental management can be defined as the way we interact with the environment to ensure its protection, conservation, and sustainability.

Local communities are affected by environmental, social, and economic impacts, and it remains essential to take appropriate measures.

2. Materials and Methods

2.1. Site description

The study area, which is the Agadez region, is located in north-eastern Niger. In this area, there are enormous gold geochemical indices and anomalies. The village of Agadez is located between X=16°58'41.9'"; Y= 8°1'10.7"'. According to the latest general population census (INS, 2025), it covers an area of 157 km² with an estimated population of 156 024 people in 2024 **(Fig. 1)**. The Agadez region is rich in natural resources, particularly gold and copper, as well as forestry and wildlife resources (Tahirou et *al.,* 2024). Artisanal gold mining contributes significantly to the region's economy.

2.2. Preliminary work

The first step was to compile the available information, in particular the GIS database of the Agadez Regional Mines Directorate related to the topic (MME du Niger 2023; Tahirou et *al.,* 2024). This data served as the basis for fieldwork and digitisation. Transects were defined in advance.

2.3. Sampling and fieldwork

In the field, transects were surveyed using the Global Positioning System (GPS) through topographic sequences. Gold mining sites were located and characterised, as was the vegetation cover. A total of twenty-one (21) soil samples, seventeen (17) water samples and eleven (11) plant samples were collected in accordance with the guidelines of the Food and Agriculture Organisation of the United Nations (Canton, 2021). A portable LEVIBOND multiparameter device equipped with probes was used to measure temperature, pH and conductivity **(Fig. 2b).** The water and sediment samples were then packaged, labelled, and placed in a cooler for storage in the laboratory. The positions of the sampling points were recorded using a GARMIN global positioning system (GPS).

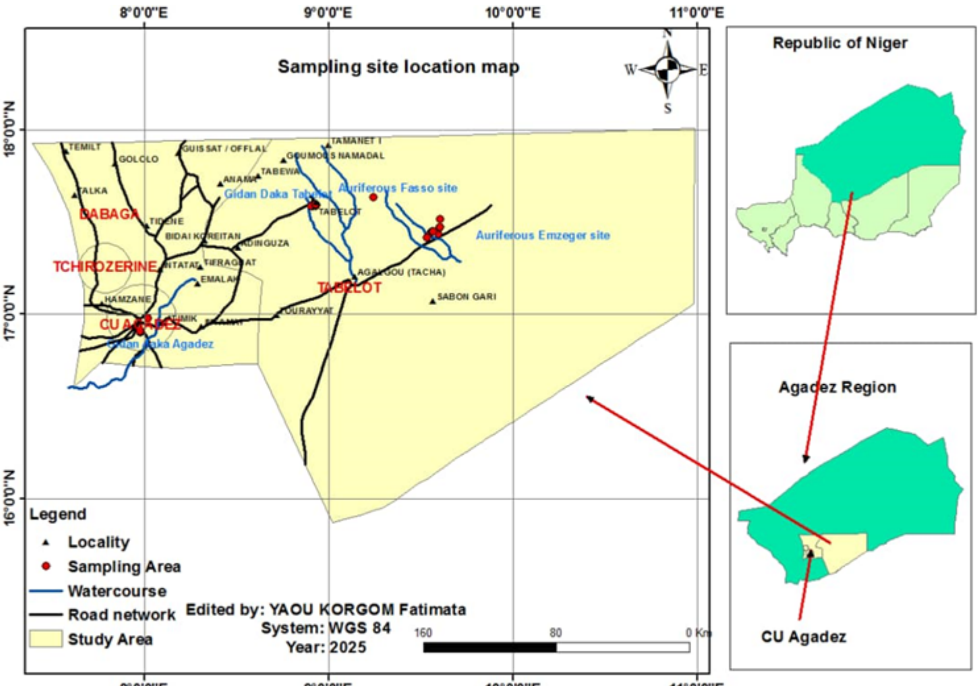

Figure 1: Location of the various sites and sampling points

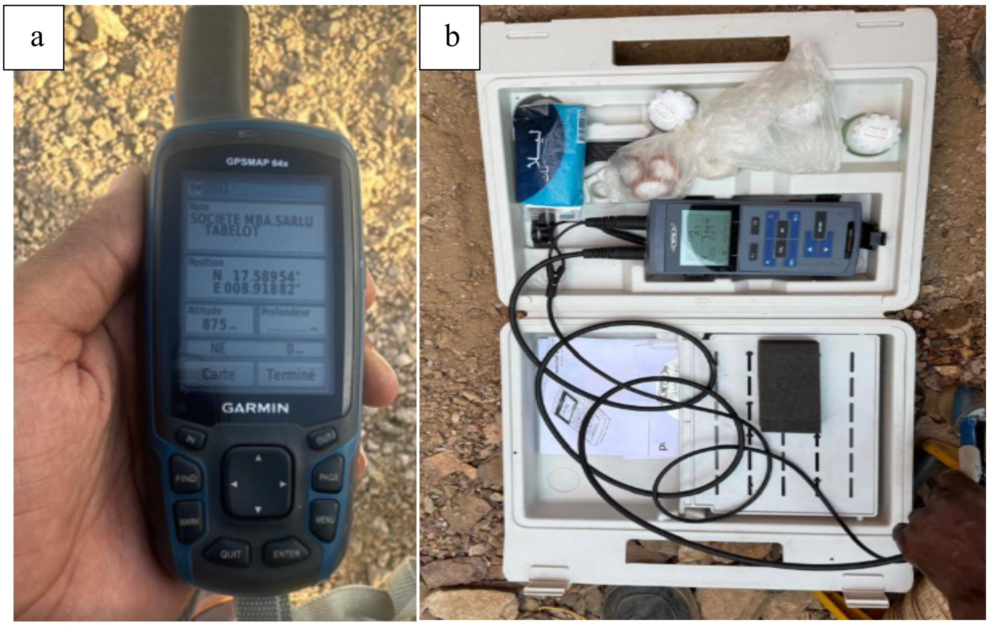

Figure 2: (a) multi parameter; (b) GPS

2.3.1. Soil sampling

During the field study campaign, soil samples were taken at various mining sites and surrounding areas. Soil samples were taken at several sites (Fig. 1). An auger was used to take samples at a depth of between 0 and 30 cm at each site, in a gradual manner. First, samples were taken from 0 to 15 cm and finally from the last 15 cm (from 15 to 30 cm). The sampling strategy was designed to assess the quantity of pollutants according to the soil profile. At each site, a composite sample (0.5 to 1 kg of soil) is collected. A clean plastic bag is clearly labelled and used to package this sample.

Figure 3: (a) Soil sampling using an auger; (b) soil samples packaged in plastic bags

2.3.2. Water sampling

For water samples, samples were collected from the various boreholes that are operational at each site visited. Throughout the sampling campaign, it should be noted that the bottles were sterilised before water sampling began, and the bottles were first rinsed three times with the water to be sampled. The bottles were filled to the brim (completely) and the caps screwed on to prevent any gas exchange with the atmosphere. For boreholes, sampling was carried out by placing the bottle under the pipe. A cooler containing ice cubes is prepared to keep the temperature of the water samples very low. Once in town, the samples are then stored in a refrigerator.

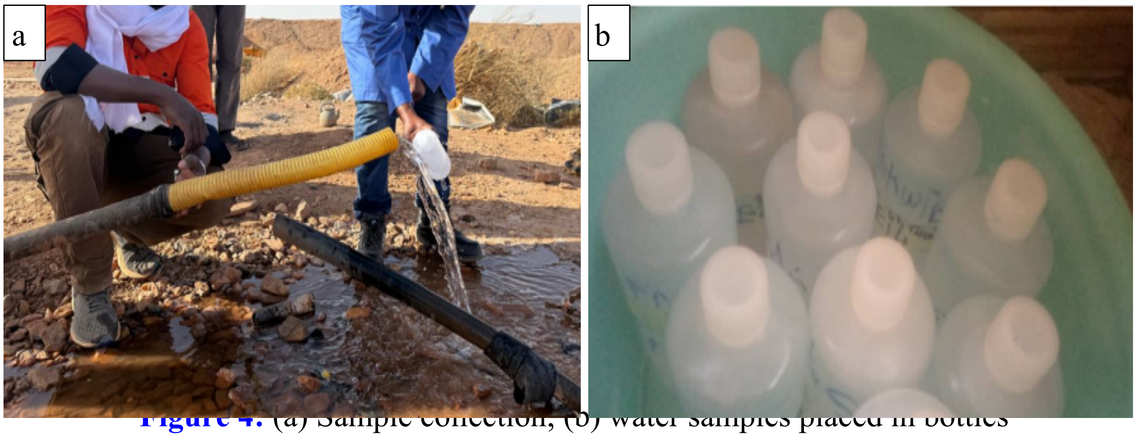

Figure 4: (a) Sample collection, (b) water samples placed in bottles

2.3.3. Sampling of plants

For plant samples, a few plants were collected based on their availability. The entire plant (root, stem, and leaf) was collected and placed on a sheet of white paper. Sediments were stored in plastic jars according to the sampling points at the study sites. Samples of locally grown vegetables (leaves, roots, and fruits), whether they are most frequently consumed by the local population, were taken to measure the residual chemical content. The sampling points are the gardens around the Tabelot treatment sites, preferably those close to the facilities. A 500 g portion of each type of vegetable is collected and packaged.

Figure 5: Samples of dried plants packaged in plastic bags

2.4. Laboratory tests

Analyses of soil samples, borehole water, mine tailings and plants were carried out at the Enval laboratory in Côte d'Ivoire to determine standard physical and chemical parameters: (i) as well as concentrations of cyanide (CN), copper (Cu), mercury (Hg), lead (Pb) and zinc (Zn) concentrations were determined by ICP OES (ii).

2.5. Analysis and mineralization

Prior to analysis using OES-type ICP spectrometry, all water samples were filtered using 45 µm diameter Whatman paper to remove unwanted particles. Sediment samples were dried in an oven at 80°C for 24 hours. They were then sieved to obtain a fine fraction with particles less than 200 µm in diameter. Dry mineralisation was carried out. This method begins with the calcination of a 5 g mass of sediment at 550°C in a muffle furnace until a whitish ash is formed. This ash is then attacked by acids (4 mL of 50% concentrated HNO_3 and 10 mL of 20% concentrated HCl) which are heated to reflux on a hot plate without boiling and covered with a watch glass according to the total digestion method recommended by the Quebec Centre of Expertise in Environmental Analysis. After cooling to ambient temperature, the mineral is filtered using Whatman filter paper, then adjusted to 100 mL with distilled water in a volumetric flask and analysed using ICP-OES spectrometry coupled with a computer. This is an inductively coupled plasma device for determining target heavy metals in liquid matrices. The analysis focused mainly on Fe, Cu, Cd, Pb and Hg.

2.6. Calculation of various pollution factors and indices

The extent of heavy metal contamination on the soil surface, particularly at mining sites, can be assessed either by comparing site-specific data with background reference data or by using pollution indices. To assess this factor and the overall toxicity of contaminated soils, the combination of contaminants rather than a single metal was considered. Thus, several authors (Chon et *al.*, 1998 ; Smouni et *al.*, 2010 ; Tankari Dan-Badjo et *al.*, 2013 ; Akanchise et *al.*, 2020) introduced and used the concept of soil pollution index (IP), geo-accumulation index (Igeo) and contamination factor (CF). The intensity of heavy metal contamination of water, sediments and soil at the sites studied was assessed using five indices: the geo-accumulation index, the water quality index, and the enrichment factor. These indices are based on comparing measured values with reference values such as the average shale content of the Earth's crust.

2.6.1. Soil pollution index

According to Chon et *al.* (1998), the average ratio of the limit values for metal concentrations in soil samples to the guideline limit values corresponds to the assumed tolerable levels in soil. Thus, the pollution index is calculated using the following **Eqn 1:**

$$IP = (([Cu]/100 + [Pb]/100 + [Hg]/1 + [CN]/18 + [Zn]/300)/5) \quad (1)$$

IP > 1 corresponds to soil contaminated by several metals.

2.6.2. Geo-accumulation index (Igéo)

To estimate the extent of elemental pollution in the soil, the geo-accumulation index is determined (Prechthai et *al.,* 2008). It was calculated using the following **Eqn 2:**

$$Igeo = \log_2(\frac{C_n}{1{,}5XB_n}) \qquad (2)$$

Cn is the measured concentration of the metal examined in the sample, Bn is the geochemical background concentration or reference value of the metal (n). The factor or constant 1.5 allows for the analysis of possible variations in background values for a given metal in the environment as well as very low anthropogenic influences (Barbieri, 2016). The value for Bn of metals in (mg/kg) was Cu = 15.75; Hg = 0.06; Pb = 4.5; Zn = 63. CN = 0.5 (Darko et *al.*, 2017).

2.6.3. Contamination facteur

The contamination factor (CF), which is the ratio of the concentration of a metal in the soil to background levels, was used to assess the extent of metal contamination. The CF was calculated using the following **Eqn 3:**

$$CF = \frac{Chm}{Ccrustal} \quad (3)$$

Where CF is the heavy metal contamination factor, Chm is the concentration of heavy metal in the sample, and Ccrustal is the concentration of heavy metal in the geochemical background (Barbieri 2016). According to (Boukari et *al.,* 2022), if CF <1, contamination is absent to low; 1≤ CF < 3, contamination is moderate; 3≤ CF< 6, contamination is considerable; and 6≤ CF, contamination is very high.

2.7. Data processing

The data obtained in this study were analysed using several software programmes. Microsoft Excel version 2019 was used for the descriptive analysis of the results for each chemical element. Origin 2022 software was used to create the graphs. The spatial distribution maps of the sample locations were created using ArcGIS mapping software.

3. Results and Discussion

3.1. Impact and description of gold panning activity on soils

Artisanal gold mining in the Agadez region began in 2014 and currently involves around 700 households, or approximately 3,000 people, who are putting pressure on the soil resources of the ecosystem in this area (Tahirou et *al.*, 2024). These activities consist of: (i) cutting and extracting ore, carried out manually using picks, shovels, hammers and chisels. The vein is traced, and pits and trenches are dug along its structure (**Fig. 6.a**). The ore is brought up using nylon rope connected to plastic bags or buckets. The waste rock is piled up along the pits and trenches (**Fig. 6.b**). Ore processing includes crushing, grinding, screening, and washing (**Fig. 6.c and Fig. 6.d**). The ore is generally washed and concentrated by gravity on handmade sluice tables in the processing area, which makes extensive use of wood for the construction of sheds. The use of cyanidation in the ore processing phase has been growing in the area for several years (**Fig. 6.e**). The heavy mineral concentrate is mixed with mercury for amalgamation (**Fig. 6.f**). The gold is recovered by heating in the open air without any protection or special precautions. Environmental problems are noted at every stage of the production chain. They are diverse and directly or indirectly affect soil resources.

3.2. Environmental consequences

There are many of them on the sites due to the influx of people into a fragile desert environment with no waste or wastewater management (lack of sanitation facilities, piles of plastic bottles and bags), but also and above all due to increasingly industrialised mining and processing methods. Groundwater is contaminated using toxic products. The land stripped bare by prospecting and the slag heaps around the wells release large amounts of dust that damage the vegetation cover and the scarce pastoral resources, not to mention the increased demand for charcoal for cooking, which is accelerating deforestation throughout the region (**Fig. 7.a and Fig. 7.b**). Poaching of wild animals has intensified and living creatures (goats and birds) have been contaminated by consuming cyanide-contaminated water (**Fig. 7.c and Fig. 7.d**). Finally, as the ore extracted from Tabelot and sometimes from the Aïr is partly processed in Arlit and Agadez, the municipalities have made land available to gold panners. Although located more than ten kilometres from the city centres, this has resulted in pollution due to the use of chemicals and an increase in dust emissions from the formation of slag heaps. In Agadez, this processing takes place on the outskirts of the city on the road to Zinder. The mayor denounces the poor management of the site, which is littered with cement bags and all kinds of rubbish, the pollution of the water, soil and air due to the use of cyanide and mercury, and the haphazard piling up of crushed rocks.

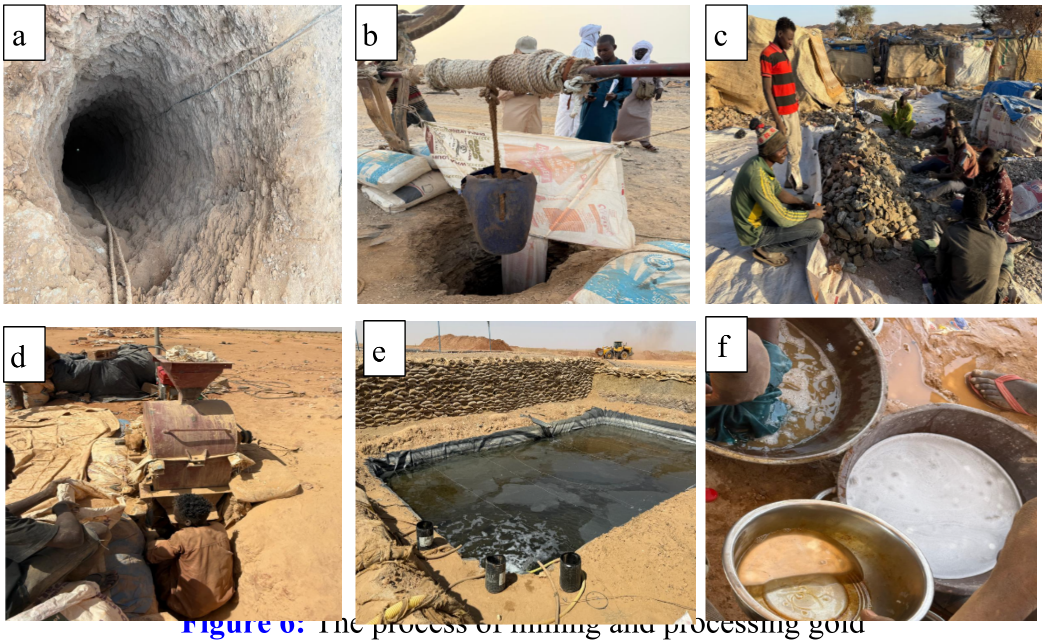

Figure 6: The process of mining and processing gold

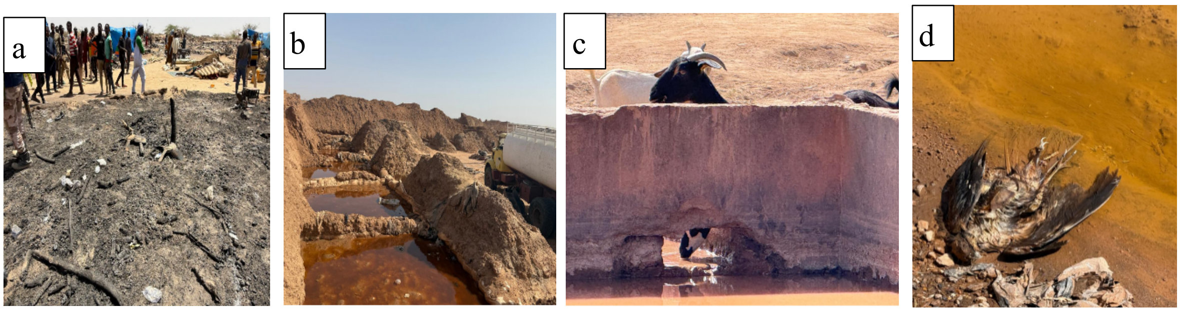

Figure 7: Soil degradation and contamination of living organisms

3.3. Average concentrations of heavy metals in the study matrices

3.3.1. Concentration analysis in water samples at the study sites

The average concentrations of heavy metals Cu, CN, Pb, Zn, and Hg measured at the various study sites are listed in Table 1 below. Table 1 above presents the results of the analysis of heavy metals present in water samples taken from the 17 sites in the study area. The heavy metals analysed were total cyanide, copper, mercury, lead, and zinc. After analysis, the total cyanide and zinc concentrations in all water samples were below the detection limits of the instrument, set at 0.020 µg/L and 50 µg/L respectively. For copper, the lowest value was recorded at the Moussa BABA TGC PE13 site with a value of 8.8 µg/L, and the highest value was recorded at the 3M Tabelot PE12 site with a value of 137 µg/L.

Table 1: Results of heavy metal concentration analysis in water samples

Water sampling sites	Heavy metals (µg/L)				(mg/L)
	CN totaux	Cu	Pb	Zn	Hg
Tazarjarat PE9	<0.020	33.10	37.70	<50	0.008
3M tabelot PE12	<0.020	137.00	338.00	<50	0.004
Faso forage chinois PE8	<0.020	12.00	14.30	<50	0.0003
Takwte PE15	<0.020	14.60	10.10	<50	0.0001
Abarchi jardin PE11	<0.020	13.00	18.00	<50	0.0001
Sos agadez	<0.020	13.00	16.90	<50	0.001
Takwte PE14	<0.020	15.50	9.50	<50	<0.0001
Emzgeur forage 200m PE3	<0.020	13.80	11.80	<50	0.0005
Faso nappe PE7	<0.020	47.00	12.10	<50	0.002
Big robinet PE5	<0.020	<50	11.50	<50	0.0003
FD4 traidung	<0.020	<50	11.20	<50	0.0008
345m PE2	<0.020	<50	13.10	<50	<0.0001
Abarchi PE10	<0.020	<50	9.61	<50	0.0003
Forage 320m PE1	<0.020	11.7	9.27	<50	0.0005
3M traiding rejet PE4	<0.020	13.2	74.7	<50	0.6
Moussa baba TGC PE13	<0.020	8.8	12.9	<50	0.001
Faso PE6	<0.020	87.4	36.8	<50	0.002
CIAPOL directive limit		**2000**	**500**	**2000**	**50**

Mercury was present in almost all water samples in trace amounts. The values recorded were practically below 0.001 mg/L, except for the 3M trading discharge PE4, where the value was 0.6 mg/L. This confirms the use and discharge of mercury at the various gold mining sites. Lead was detected in all water samples from the various sampling sites. The lowest value, 9.27 µg/L, was recorded at borehole PE1 at 320 m, and the highest value was obtained at site 3M Tabelot PE12, with a value of 338 µg/L. The presence of these heavy metals at these depths indicates that there is a transfer of contaminants to the peripheral areas of the gold mining areas, contaminating some locations. This can be explained by the topography of the area, which favours the transfer and deposition of heavy metals through a water network (watercourses) during the rainy season in the downstream part of the peripheral area (Akanchise et *al.*, 2020).

3.3.2. Concentration analysis in soil samples

Table 2 below presents the results of the analysis of heavy metals present in soil samples from the various sites. After analysing the table, the highest copper content exceeding the guideline value was recorded at the Tazarjarate Tabelot site with a content of 838.8 mg/kg, followed respectively by the Djibo site in terms of cyanidation residue discharge; PS 33 Bassins; PS Moctar 0-15 cm; Tazarjarate PS4 0-15 cm; Tazarjarate PS4 15-30 cm; PS Seydou 0-15 cm and PS Seydou 15-30 cm, with respective values of 755.95 mg/kg; 622.92 mg/kg; 600.36 mg/kg; 501.8 mg/kg; 495.25 mg/kg; 408.72 mg/kg; 342 mg/kg. The lowest value was recorded at the Agadez control site at 15-30 cm with a value of 4.67 mg/kg. For total cyanides, the highest value is 9.88 mgCN/kg recorded at the Moussa PS3 Cyanidation Residues site. However, the lowest value, which is 0.14 mgCN/kg, is obtained at the Emzegeur Moussa PS1 sub-surface site. For mercury, the PS Seydou d'Agadez 0-16 cm site recorded the highest value of

54.54 mg/kg, which is 27 times higher than the guideline value of 2 mg/kg, while 0.17 mg/kg is the lowest value recorded for the Abarchi Tabelot Koris PS8 0-15 cm site. For lead, the highest value was recorded at the Tazarjarate PS4 15-30 cm site, with a content of 1566 mg/kg. This value is significantly higher than the guideline value of 180 mg/kg. The lowest value, 5.37 mg/kg, was recorded at the Agadez 15-30 cm control site. For zinc, the highest value was recorded at the Moctar PS site (0-15 cm) with a value of 6027 mg/kg, which is 20 times higher than the guideline value of 300 mg/kg. The lowest zinc content (25.8 mg/kg) was recorded at the Moussa PS cyanidation residue site. The results obtained by the study of Ali (2013) et Tankari Dan-Badjo et *al.,* (2013) on the cyanidation site at Komabangou are significantly lower than our results (Tankari Dan-Badjo et *al.*, 2013). In addition, the proliferation of gold panners on the site has led to excessive use of chemicals in recent years.

Table 2: Results of heavy metal concentration analysis in soil samples

Soil sampling sites	**Heavy metals (mg/kg)**				**(mgCN/kg)**
	Cu	Hg	Pb	Zn	CN totaux
EMZGEUR MINING PS-6 Residus	84,2	0,47	11,16	32,66	0,24
OBEY MNT Bagaza PS9 15- 30 cm	87,55	**3,37**	**222,8**	**405,72**	0,17
Temoin AGADEZ 15-30 cm	4,67	0,27	5,37	50,41	0,19
SEYDOU Agadez PS 15-30 cm	**342,55**	**8,81**	**522,9**	164,49	0,71
EMZGEUR Moussa PS2 0- 20 cm	107,11	1,15	30,35	195,22	0,77
TAZARJARATE PS4-15-30 cm	**497,25**	**14,3**	**1566**	209,47	3,15
SEYDOU Agadez PS 0-15 cm	**408,72**	**54,54**	**439,2**	174,78	2,39
AGADEZ PS Residus Djibo Cyanuration	**755,95**	**4,46**	**977**	186,4	2
ABARCHI Tabelot PS8 15- 30 cm Koris	14,9	0,33	8,15	158,02	1
ABARCHI Tabelot PS8 0- 15 cm Koris	9,47	0,17	7,52	91,83	0,79
MOUSSA PS3 Residus Cyanuration CN	146,25	**32,79**	**219,1**	25,8	9,88
PS-33 Bassins	**622,92**	**2,17**	**663,3**	216,09	0,22
TAKWTE Tabelot PS10– 15-30 cm	12,36	0,42	10,64	183,16	7,14
TAZARJARATE PS4 0-15 cm	**501,8**	**13,26**	**1556**	153,17	0,82
TEMOIN Agadez 0-15 cm	7,68	0,76	7,19	55,61	0,23
OBEY Mont Bagzam PS-9-0-15 cm	220,2	**12,51**	**561,4**	159,49	0,21
MOCTAR PS 0-15 cm	**600,36**	**50,75**	**674,5**	**6027**	0,13
TAKWTE Tabelot PS10 0- 15 cm	18,73	1,29	11,29	102,27	0,3
MOCTAR Agadez 15-30 cm	178,56	**6,2**	61,739	**3785**	0,15
EMZEGEUR Moussa PS1 sub Surface	211,8	1,14	41,85	31,81	0,14
TAZARJARATE Tabelot PS7	**838,8**	**34,4**	**602**	84,42	0,17
DIRECTIVES NF U44-095	**300**	**2**	**180**	**300**	**18**

When the content is very high on the surface and then decreases rapidly with depth, it is most likely anthropogenic contamination (Mourato et *al.*, 2015). This variation is coupled with that of pH and organic matter (OM). The high Zn content is due to the use of zinc pellets in the process of recovering gold from acidic ore leaching solutions. Mercury, due to its volatility and solubility during the gold purification process, can easily be deposited on the sub-surface layer of the soil. The other elements (Cu, Pb, CN) are probably associated with contamination by trace elements from the zinc pellets

(Tankari Dan-Badjo et *al.,* 2014). The high Zn contents can be explained not only by the fact that Zn ores such as blende (ZnS) are closely associated with gold ores, but also using zinc chips for gold cementation, which are sometimes dumped on the ground at mining sites. This is partly consistent with the work of Zakaria Ibrahim et *al.* (2019) et Tankari Dan-Badjo et *al.* (2019). The presence of Pb at the two cyanidation sites (35.09) for site 1 and (9.57 mg/kg) for site 2 may be due to the presence of sulphide ore such as galena (PbS), which is sometimes associated with gold. In general, the high concentrations of heavy metals observed at the various sites, in addition to being influenced by organic matter, could also be related to the slightly neutral pH of the soil. At this pH, most trace elements are found in the soil in the form of oxides and are therefore bound to the solid phase of the soil. Analysis of the distribution of concentrations over the first five centimetres of depth clearly shows that this is the most heavily polluted part in terms of heavy metals. Table 3 presents the values and ranking of the geo-accumulation index calculated for soils at mining sites, peripheral sites, and sites outside the mining area. The ranking of the Igéo index (Soares et *al.,* 1999) is given in Table 4. Overall, the results in Table 3 indicate irregular fluctuations in the Igéo values of the ETMs at the different sites.

Table3: Values of IP pollution indices and soil geo-accumulations at different sites

Soil sampling sites	**Index Pollution**	**Geo-accumulation index**				
		Cu	CN	Hg	Pb	Zn
Emzgeur Mining ps-6 résidus	0,31	1,83	-1,64	2,38	0,73	-1,53
Obey mnt Bagazan ps9 15- 30 cm	1,57	1,89	-2,14	**5,23**	**5,04**	2,10
Temoin Agradez 15-30 cm	0,11	-2,34	-1,98	1,58	-0,33	-0,91
Seydou Agadez PS Seydou 15-30 cm	3,61	**3,86**	-0,08	**6,61**	**6,28**	0,80
Emzgeur Moussa PS2 0- 20 cm	0,64	2,18	0,04	**3,68**	2,17	1,05
Tazarjarate PS4-15-30cm	7,16	4,40	2,07	**7,31**	**7,86**	1,15
Seydou agadez PS Sedou 0-15 cm	12,75	4,11	1,67	**9,24**	**6,02**	0,89
Agadez PS residus Djibo cyanuration	4,50	5,00	1,42	**5,63**	**7,18**	0,98
Abarchi Tabelot PS8 15- 30 cm koris	0,23	-0,67	0,42	1,87	0,27	0,74
Abarchi Tabelot PS8 0- 15 cm koris	0,14	-1,32	0,07	0,92	0,16	-0,04
Moussa PS3 résidus cyanuration CN	7,42	2,63	3,72	**8,51**	**5,02**	-1,87
PS -33 bassins	3,15	4,72	-1,77	**4,59**	**6,62**	1,19
Takwte Tabelot PS10 - 15-30 cm	0,33	-0,93	**3,25**	2,22	0,66	0,95
Tazarjarate PS4 0-15 cm	6,88	**4,41**	0,13	**7,20**	**7,85**	0,70
Témoin Agradez 0-15 cm	0,22	-1,62	-1,71	**3,08**	0,09	-0,76
PS9-0-15 cm site Obey Mont Bagzam	4,17	3,22	-1,84	**7,12**	**6,38**	0,76
Moctar PS0-15 cm	16,72	4,67	-2,53	**9,14**	**6,64**	**5,99**
Takwte Tabelot PS10 0- 15 cm	0,39	-0,33	-1,32	**3,84**	0,74	0,11
Moctar Agadez 15-30 cm	4,25	2,92	-2,32	**6,11**	**3,19**	**5,32**
Emzegeur Moussa PS1 sub surface	0,76	**3,16**	-2,42	**3,66**	2,63	-1,57
Tazarjarate Tabelot PS7	9,82	**5,15**	-2,14	**8,58**	**6,48**	-0,16

According to Chon et *al.* (1998), when the IP index is greater than 1, sites are contaminated by multiple elements in the soil. This is the case, for example, in our study of the sites marked in blue in Table 3. Plant samples taken from mining sites and surrounding gardens are analysed. The results of the analyses are recorded in Table 3. The Igéo values for metals show moderate to extremely high contamination of these elements depending on the different sites. Igéo values between [0 and 1] indicate that the soil is moderately contaminated with metals. On the other hand, values above 3 indicate high to extremely high contamination. This contamination by trace metals is closely linked to the residues of chemicals used and their discharge without prior treatment. This confirms the results of the pollution index calculations. These results are similar to those reported by Akanchise et *al.* (2020) on the Asmakum dumps in Koumassi, Ghana, which found Igéo values for Cu up to (2.07) and Pb (1 to 2.62). However, the negative values for trace metals indicate insignificant contamination with these elements at each given site. Table 5 shows the results of soil contamination factors with trace metals at the various sites studied. The results recorded in Table 5 were obtained by calculating equation 3.

Table 4: Igéo index ranking

Classes	Geo-accumulation index	Soil contamination
0	Igéo ≤ 0	Uncontaminated
1	0 43 Igéo ≤ 1	Uncontaminated to moderately contaminated
2	1 < Igéo ≤ 2	Moderately contaminated
3	2 < Igéo ≤ 3	Moderately to heavily contaminated
4	3 < Igéo ≤ 4	Heavily contaminated
5	4 < Igéo ≤ 5	Heavily to extremely contaminated
6	Igéo >5	Extremely contaminated

Table 5: Contamination factor of different mining sites, peripheral areas, and control areas

Soil sampling sites	Contamination factor (CF)				
	Cu	CN	Hg	Pb	Zn
Emzgeur Mining ps-6 résidus	5.35	0.48	7.83	2.48	0.52
Obey mnt Bagazan ps9 15- 30 cm	5.56	0.34	56.17	49.51	6.44
Temoin Agradez 15-30 cm	0.30	0.38	4.50	1.19	0.80
Seydou Agadez PS Seydou 15-30 cm	21.75	1.42	146.83	116.20	2.61
Emzgeur Moussa PS2 0- 20 cm	6.80	1.54	19.17	6.74	3.10
Tazarjarate PS4-15-30 cm	31.57	6.30	238.33	348.00	3.32
Seydou agadez PS Sedou 0-15 cm	25.95	4.78	909.00	97.60	2.77
Agadez PS residus Djibo cyanuration	48.00	4.00	74.33	217.11	2.96
Abarchi Tabelot PS8 15- 30 cm koris	0.95	2.00	5.50	1.81	2.51
Abarchi Tabelot PS8 0- 15 cm koris	0.60	1.58	2.83	1.67	1.46
Moussa PS3 résidus cyanuration CN	9.29	19.76	546.50	48.69	0.41
PS -33 bassins	39.55	0.44	36.17	147.40	3.43
Takwte Tabelot PS10 - 15-30 cm	0.78	14.28	7.00	2.36	2.91
Tazarjarate PS4 0-15 cm	31.86	1.64	221.00	345.78	2.43
Témoin Agradez 0-15 cm	0.49	0.46	12.67	1.60	0.88
PS9-0-15 cm site Obey Mont Bagzam	13.98	0.42	208.50	124.76	2.53
Moctar PS0-15 cm	38.12	0.26	845.83	149.89	95.67
Takwte Tabelot PS10 0- 15 cm	1.19	0.60	21.50	2.51	1.62
Moctar Agadez 15-30 cm	11.34	0.30	103.33	13.72	60.08
Emzegeur Moussa PS1 sub surface	13.45	0.28	19.00	9.30	0.50
Tazarjarate Tabelot PS7	53.26	0.34	573.33	133.78	1.34

Analysis of Table 5 provides the results of the contamination factors for the various sites studied. Very high values are obtained for several elements at different sites, notably Cu, Hg, Pb and Zn, with contamination factors of 48 for the PS Djibo cyanidation residue site in Agadez, 909 for the Seydou Agadez PS 0-15 cm site; 348 for the Tazarjarate PS4-15-30 cm site; and 95.67 for the Moctar PS0-15 cm site. Their CFs are very high, indicating very high contamination at these sites. The high concentration of these heavy metals in soil samples from the cyanidation site is a major concern.

3.3.3. Concentration analysis in plants samples

Table 6 above shows the concentrations of heavy metals in the different species present at the various sampling sites. Table 6 shows that the highest concentration of cyanide is 281.73 mg/kg (Abarchi site) and the lowest is 0.31 mg/kg (Tazarjarate Tabelot). For mercury, the highest content is 51.12 mg/kg (Tazarjarate Mining site), while the lowest is 0.22 mg/kg (Tabelot fruit r*enzen* site). As for copper, its highest concentration is 74.53 mg/kg (Tazarjarate site) and the lowest is 2.56 mg/kg (Takwte site). For lead, the highest content is 125.56 mg/kg (Tazarjarate site) while the lowest is less than 2 mg/kg (Abarchi Garden site and Takwte *Oignon* site). Finally, the highest zinc content was observed at the Tazarjarate site (Ep3) with 74.73 mg/kg and the lowest at the Takwte *Oignon* site with 10.41 mg/kg. The results obtained show that the concentrations of CN, Pb and Zn in the species sampled are generally higher than those for Hg and Cu for the same sites. These results clearly demonstrate the impact of gold mining on the contamination of the surrounding vegetation. The concentrations of CN, Pb and Zn obtained in the rezin fruit and *toufafiya* leaf species collected were higher than those detected by (Barthwal et *al.*, 2008). However, the Hg concentrations detected in the leaves of Emzgeur Trainding and Tazarjarate EP3 *toufafiya* were higher than those obtained by Barthwal et *al.* (2008) in *Calotropis* leaves.

Table 6 : Résultat d'analyse des concentrations des métaux lourds dans les échantillons des plantes

Plant sampling sites	Heavy metals (mg/kg)				
	CN	Hg	Cu	Pb	Zn
Tazarjarate Tabelot Ep4	37.91	7.62	59.97	47.21	82.84
Tabelot site fruit renzen	158.63	0.22	4.3	2.62	16.58
Emzgeur Mining leaf *Toufafiya*	136.23	42.99	35.72	37.41	35.39
Tazarjarate Tabelot Ep5	0.31	7.02	29.97	<2	42.77
tazarjarate Ep3	22.96	7.08	74.53	125.56	74.73
Jardin Abarchi Ep6	51.52	0.31	44.33	<2	23.83
Tazarjarate Mining leaf *Toufafiya*	44.86	51.12	66.43	9.59	56.33
Moussa Baba TGC Ep8	44.09	8.8	49.08	53.47	52.69
Takwte Oignon	63.79	0.35	2.56	<2	10.41
Abarchi Mangue Ep7	281.73	0.26	13.14	2.54	24.48
Leaf de Cindonzgou	9.86	0.41	8.55	5.89	20.12
(OMS, 2004)	-	0.03	9	0.3	15
Regulation (UE 2023)	-	0,10-1		0.010-3	-

In fact, in general, samples taken from the gardens of Tabelot have higher cyanide levels (Abarchi *Mangue* site, Tabelot fruit *renzen* site, Takwte *Oignon* site and Abarchi garden site) except for the Emzgeur Mining site. This high content could be explained by the presence of high levels of these elements in the soil and irrigation water. All samples taken from chemical gold processing sites show very high levels of mercury, copper, and zinc. This may be due to the low mobility of these elements by transport agents (water and wind). Analysis of the samples shows high levels of cyanide (CN), mercury (Hg) and lead (Pb). Compared to the thresholds recommended by WHO standards for food plants (Oms et *al.*, 2010), The CN, Hg and Pb contents in all samples exceed the reference values. For mercury (Hg), the limit value is 0.03 mg/kg. All samples showed values above the normal limit. For lead (Pb), normal values vary according to species, i.e. 0.10 mg/kg for non-leguminous plants such as guava and 0.30 mg/kg for leguminous plants (cassava leaves). The results found are far above the standards, while the toxic nature of lead is well known, as are the dangers associated with food contamination by this metal (Mourato et *al.,* 2015). Compared to copper (Cu), the limit value is 9 mg/kg. The results showed levels below the normal limit in some samples: 2.56 mg/kg, 4.30 mg/kg, and 8.55 mg/kg. Regarding the maximum levels for certain contaminants (Hg and Pb) in foodstuffs defined by the European Commission (EU, 2024), some samples showed levels well above European regulations. Heavy metals absorbed by plants enter the food chain and cause bioconcentration at each step up the trophic ladder (Mishra et *al.*, 2023). Thus, the accumulation of heavy metals varied from one plant to another and from one element to another. This study clearly showed an increase in trace element concentrations near the gold mining site, suggesting a negative impact of this artisanal mine on environmental matrices. The accumulation of heavy metals in the environment can affect human and animal health (Mitra et *al.,* 2022). In high concentrations, they exhibit varying degrees of toxicity (Liu et *al.,* 2022). The heavy metals most often considered toxic to humans are lead, mercury, arsenic, and cadmium. Others, such as copper, zinc, and chromium, although necessary for the body in small quantities, can become toxic in larger doses (Mourato et *al.,* 2015). Trace elements in soil, water, and plants in many samples taken in gold-bearing areas exceeded the limit values, particularly for Pb and Zn. Investigations must continue to reduce environmental and health impacts, through the implementation of a programme to monitor and treat polluted soil and water. The presence of this metal in soil and plants can be explained by its sources of discharge and waste.

3.4. Field survey results

Figure 8 shows the different activities carried out in gold mining and the number of people per job. After analysis, we find that 18 people are involved in sinking and support work, 19 people are involved in deep extraction, 18 are involved in loading and transporting ore, 19 are involved in crushing ore and, finally, 11 are involved in screening. These survey results show the extent to which each phase of gold mining requires people to obtain the desired metal.

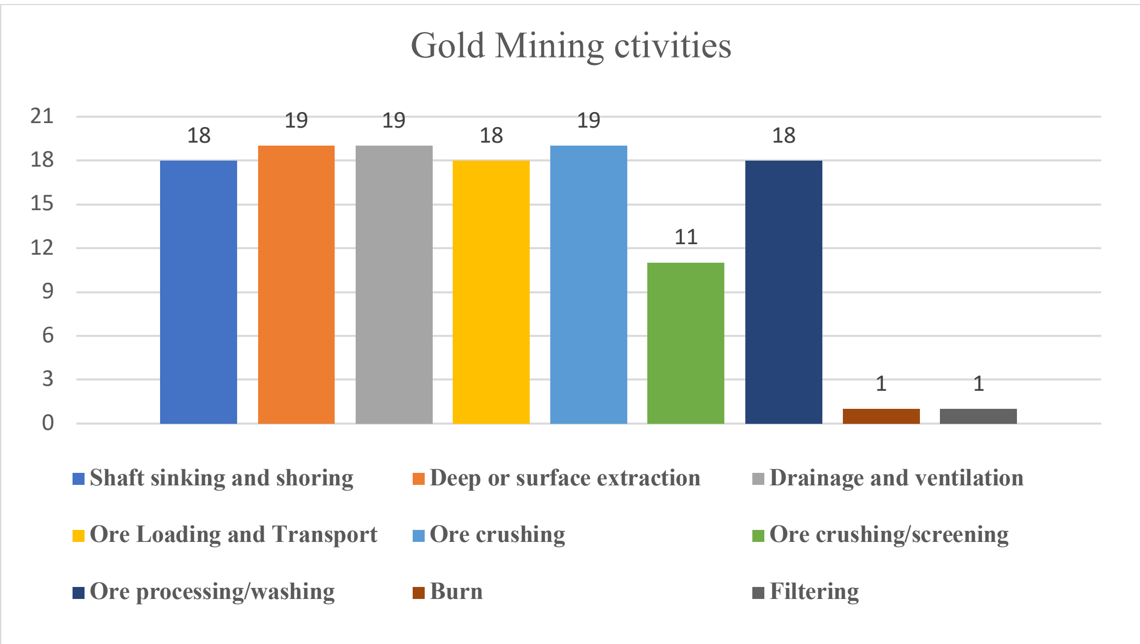

Figure 8: People surveyed by the different phases of gold mining in Tabelot

Conclusion

The objective of this study was to assess soil pollution levels in the Agadez region according to sampling depth and to calculate pollution factors and indices. It found that there were moderate concentrations of trace metals (copper, lead, mercury, cyanide, and zinc) in the Agadez area. The results of this study show that the water and sediments of the Agadez River, which flows through the town of Tabelot, are influenced by human activities in its immediate environment. The waters in the region are weakly mineralised. In addition, Cu, CN, Pb, Zn and Hg were all detected in the water and sediments at levels well above the values recommended by international standards. These high levels of metals in the environment in this region suggest contamination of anthropogenic origin. Analysis of the heavy metal content detected in the sediments showed that they are toxic in heavy metals, particularly CN, Pb and Zn, for burrowing organisms.

This indicates the presence of harmful effects due to heavy metals in the sediments. The extreme contamination of sediments and the degradation of water quality by the metal pollutants studied will therefore pose environmental and health risks that endanger local populations.

The pollution indices for certain sites are well above 1, revealing soil contamination by several elements. The risk indices for metals increased at the various sampling points, ranging from low risk to very high risk. This shows that the cocktail of metals in the soil in the Agadez area is a potential source of toxicity for flora, fauna, and inhabitants. For better ecological preservation, it would be necessary to monitor these sites.

Conflict of interest

The authors declare that they have no conflict of interest.

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