

Assessment of Soil Contamination and Human Health Risk around an Industrial Gold Mine in Côte d'Ivoire: The Case of Arsenic

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Abstract

The Tongon mine generates millions of tons of waste rock and tailings, which are stored in landfills in the vicinity of the mine. These tailings contain arsenic. The risk of soil contamination in this area is evident. This study assesses the arsenic contamination of soils around the mine and the health risks to the local population. Soil samples were taken from plastic bags and other materials used as working tools. Arsenic concentrations were determined by inductively coupled plasma mass spectroscopy, after the soil samples had been concentrated and digested. Metal contamination indices were used to assess the degree of soil contamination. The results obtained indicate that soils in the industrial zone of the Tongon gold mine have very high average concentrations, well above the world average for uncontaminated soils of 6 mg/kg arsenic. Geoaccumulation index values range from 1.28 to 3.40. These values highlight severe arsenic soil contamination. The human health risk assessment revealed that exposure risks are well above the critical limit of 1 and are, in descending order, children > adult women > adult men. These results indicate an ecological risk, requiring environmental monitoring, underpinned by the development of an effective remediation strategy to reduce local pollution and contamination.

Keywords

Industrial Mine, Tongon, Pollution, Arsenic, Soil

1. Introduction

The Tongon mine is Côte d'Ivoire's largest gold mine, producing seven tons of

gold a year [1]. However, the population of this gold mining region can be confronted with numerous health problems linked to the emergence of toxic elements, including heavy metals [2]. Environmental contamination by heavy metals in gold mining areas has been identified as one of the most serious environmental problems in many countries [1]. Mining, ore processing and tailings disposal are the operations that cause environmental contamination through the dispersion of heavy metals [2]. In gold mining areas, arsenic is one of the metals commonly encountered [3]. Arsenic is likely to be released into adjacent environmental media and can accumulate in the soil as a result of the mining process, leading to a relatively high concentration of arsenic in the soil around mining areas [4]. The impact of mining areas as sources of pollution is widely known, but the pollution levels of individual mines should be studied [5]. Rural populations use soils for agriculture. This can lead to arsenic accumulation by plants from contaminated soils, creating bioaccumulation in trophic chains. It is therefore necessary to assess the arsenic content of soils in mining areas, as they have been shown to be the main reservoirs of these contaminants [6]. At present, scientific investigations into the level of contamination arising from industrial gold mining activities in Côte d'Ivoire are inadequate. Most of the research work on soils around the Tongon mine has focused on the geochemical assessment of soils and water resources. These studies have shown that surface water heavily impacted by mining has been classified as Ca-SO₄ and Na-Cl with high pH values, while slightly contaminated groundwater has been classified as Ca-Mg-HCO₃, reflecting the influence of silicate and carbonate weathering [2]. The results of these studies show that the soil and water resources around the Tongon mine are vulnerable to mining operations [1] [2]. However, no study has taken into account soil contamination and human health risk assessment. The general aim of this study is to assess the level of arsenic contamination in soils in the area of the Tongon industrial gold mine, and the risks to human health.

2. Materials and Methods

2.1. Sediment Sampling

The Tongon industrial mine is located in northern Côte d'Ivoire (N9°57'-5°76' W5°42'-13°68'), approximately 628 km northeast of Abidjan, the economic capital.

Soil samples were collected using a hand dredge in and around the Tongon industrial mine area to assess the lateral dispersion of mining-related contaminants (Figure 1). The location of the respective sampling sites is shown in Figure 2.

The samples collected were packaged in plastic bags, labelled according to the sampling site. The samples were kept in a cool box for transport to the laboratory, where they were placed in a freezer at (-4°C) [7].

After drying in an oven (60°C) for 24 hours, the sample was pre-sieved on a



Figure 1. Soil sampling.

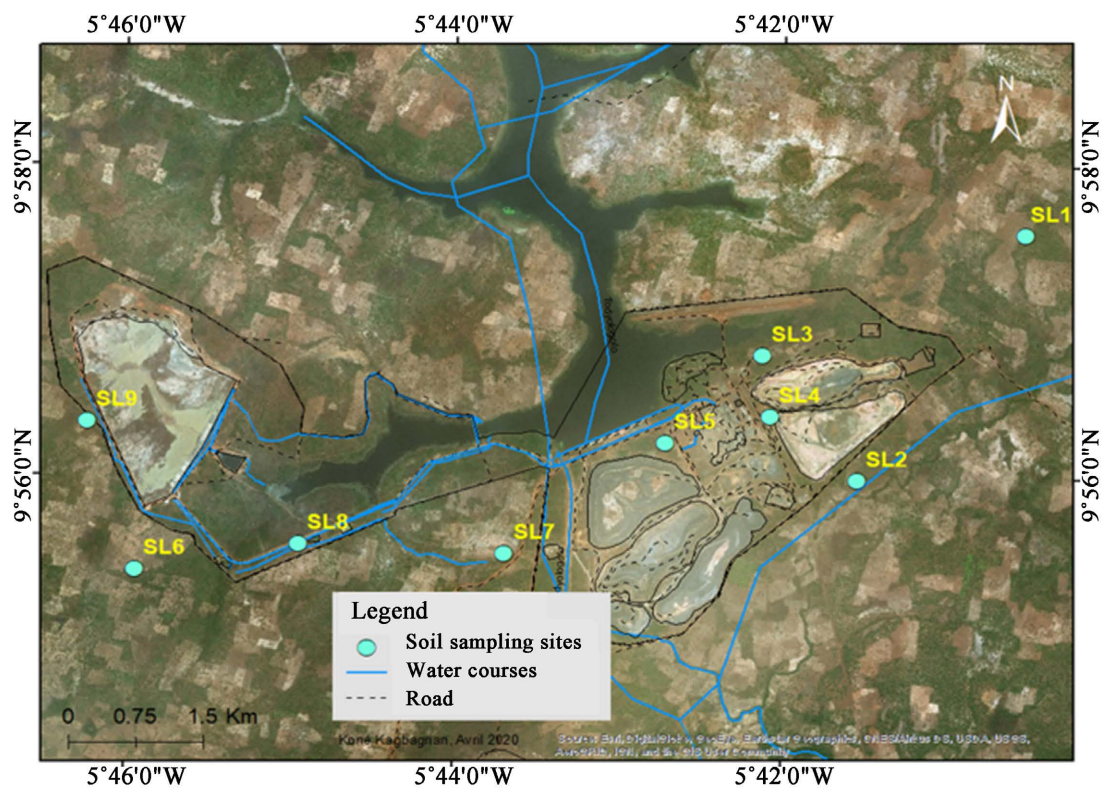


Figure 2. Soil sampling sites.

sieve to remove coarse elements such as pieces of shell, branches and leaves before being sieved using a sieve. Fractions smaller than 2 mm were kept in hermetically sealed plastic bottles to protect them from moisture, then stored in a

dark, cool (20 °C) cupboard for analysis.

2.2. Determination of Arsenic Concentrations in Soil Samples

The analyses to determine the total arsenic concentration in the soil samples required the synthesis of aqua regia. This aqua regia was synthesized from 65% pure concentrated nitric acid HNO₃ and 37% pure concentrated hydrochloric acid HCl at a ratio of 1/3 (v/v). A solution of hydrofluoric acid HF concentrated to 48% pure and a solution of boric acid H₃BO₃ prepared from distilled water were also used to determine the total arsenic concentration. The sediments were mineralized using a reference method for marine pollution studies [7]. The principle of this method is based on the total dissolution of sediments by hydrofluoric acid (HF) and aqua regia (HNO₃: HCl; 1:3, v/v) at high temperature. The use of HF is essential because it is the only acid that completely dissolves silicates and all metals [8]. 0.2 g of dry, homogeneous sediment or soil sample placed in a Teflon tube previously washed with acid underwent hot mineralization using 1 mL of aqua regia (HNO₃: HCl; 1:3, v/v) and 6 mL of concentrated HF (48%). Heating was carried out in a water bath at 120 °C for 2 hours 30 minutes. After cooling in ambient air, the residue was taken up in a boric acid solution (2.70 g in 20 mL of distilled water). The final volume was reduced to 50 mL and left to stand for 6 hours. After the samples had been concentrated and digested, arsenic concentrations were determined by inductively coupled plasma mass spectroscopy (NexION 2000 ICP-MS, USA). The minimum detection limit (MDL) for arsenic was 0.0005 mg/L.

2.3. Assessment of the Level of Arsenic Contamination in Soils

2.3.1. Metal Content of the Upper Continental Crust (UCC)

In this study, metal concentration values from the upper continental crust (UCC) were used as reference values (Table 1) [7], because they were shown to be the most appropriate for soils in the Côte d'Ivoire area [7].

2.3.2. Index of Geoaccumulation

The Index of Geoaccumulation (I_{geo}) is calculated using the following formula:

$$I_{geo} = \log_2 \left(\frac{[\text{metal}]_s}{1.5 \times [\text{metal}]_b} \right) \quad (1)$$

$[\text{m}^\text{t}al]_s$ is the concentration of metal in the soil samples in mg/kg;

$[\text{m}^\text{t}al]_b$ is the concentration of metal in UCC in mg/kg.

The index of geoaccumulation establishes a relationship between the measured concentration of a metal in the fine fraction of sediments and the geochemical background concentration chosen as a reference for the metal studied,

Table 1. Metal content of the upper continental crust (UCC).

Metal	As	Hg	Cr	Mn	Fe	Ni	Cd	Cu	Pb	Zn
Content (mg/kg)	2	0.056	35	527	30890	18.6	0.1	14.3	17	52

including a corrective factor (1.5) for lithological variations in the metal elements. I_{geo} values greater than 1 indicate moderate contamination of a sediment sample by the metal under study, while those greater than 3 indicate heavy contamination [7]. I_{geo} values can be used to define seven levels of contamination (Table 2).

2.3.3. Contamination Factor

The contamination factor (CF) is calculated using relationship 2:

$$CF = \frac{[As]_s}{[As]_b} \quad (2)$$

$[As]_s$ is the concentration of the metal in the soil in mg/kg;

$[As]_b$ is the concentration of metal in UCC in mg/kg.

The different levels of contamination according to CF values are shown in Table 3.

2.3.4. Human Health Risk Assessment

The health risk assessment for people exposed to arsenic-contaminated mine deposits was calculated for three groups: children, men and adult women. The average daily intake (ADI, mg element kg^{-1} body weight day^{-1}) was calculated using the following formula:

$$ADI = [As] \frac{IR \times EF \times ED \times 10^{-6}}{BW \times AT} \quad (3)$$

where $[As]$ is the total concentration of arsenic in the soil samples;

Table 2. Different classes of soil contamination.

Class	Value	Levels of contamination
0	$I_{geo} < 0$	Uncontaminated
1	$0 < I_{geo} < 1$	Uncontaminated to moderately contaminated
2	$1 < I_{geo} < 2$	From contaminated to moderately contaminated
3	$2 < I_{geo} < 3$	From moderately contaminated to severely contaminated
4	$3 < I_{geo} < 4$	Severely contaminated
5	$4 < I_{geo} < 5$	From severely contaminated to extremely contaminated
6	$5 < I_{geo}$	Extremely contaminated

Table 3. Contamination levels according to CF values.

CF value	Levels of contamination	Levels of contamination
	$CF < 1$	Low contamination
	$1 \leq CF < 3$	Moderate contamination
	$3 \leq CF < 6$	Considerable contamination
	$CF \geq 6$	high contamination

IR is the soil ingestion factor (children = 200 mg of dust per day; adults = 100 mg of dust per day);

EF is the exposure frequency (children = 350 days per year; adults = 250 days per year);

ED is the exposure duration (children = 6 years; adults = 25 years);

BW is body weight (children = 15 kg; adult men = 68 kg; adult women = 58 kg);

AT is the average exposure duration (6×365 days) = 2190 days; adults (25×365 days) = 9125 days;

10^{-6} is for unit conversion [8].

The Hazard quotient (HQ) was calculated as follows:

$$HQ = \frac{ADI}{RfD} \quad (4)$$

where, RfD is the oral reference dose (0.0003). HQ values > 1 indicate a higher probability of adverse health effects [8].

2.4. Quality of Analyses

The quality of the analyses was checked using blanks and duplicates. To prevent uncertain contamination, all the laboratory equipment used was washed with phosphate-free soap, rinsed twice with distilled water and soaked in 10% nitric acid for 24 hours. They were then rinsed twice with distilled water and dried at room temperature. The limits of detection (LOD) for the elements were calculated as follows:

$$LOD = 3 \times \frac{s}{m} \quad (5)$$

where “ s ” is the standard deviation of 10 blank measurements and “ m ” is the slope of the calibration curve obtained. The prepared blanks are analyzed at the same time as each batch of 10 samples.

2.5. Statistical Methods and Representations

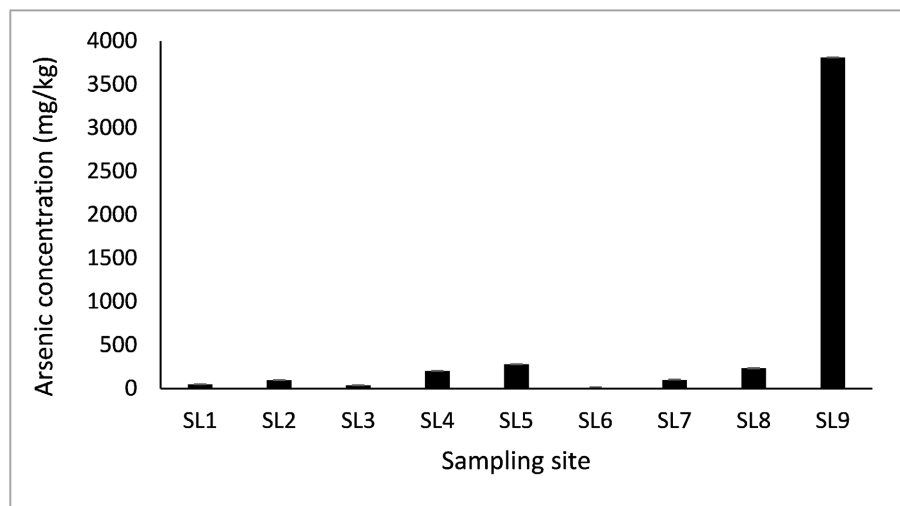
Analysis of variance (one-way ANOVA) was used to assess the difference between sampling sites. The difference was considered significant at $P < 0.05$. Whenever the difference was significant, Tukey’s test was performed to identify groups that were particularly different from each other. Person correlation analysis was used to establish a relationship between the heavy metal content of soils, suspended particles, sediments and water. The correlation coefficient is between -1 and 1 . The higher its absolute value (towards 1), the more the variables are correlated. On the other hand, the closer it is to 0 , the weaker the correlation. Statistical analyses (mean value, minimum, maximum, standard deviation, and analysis of variance and Pearson correlation) were carried out using STATISTICA 2005 software (version 7.1). Spatial distribution maps were produced using ArcGIS-10.2 software. 2.

3. Results and Discussion

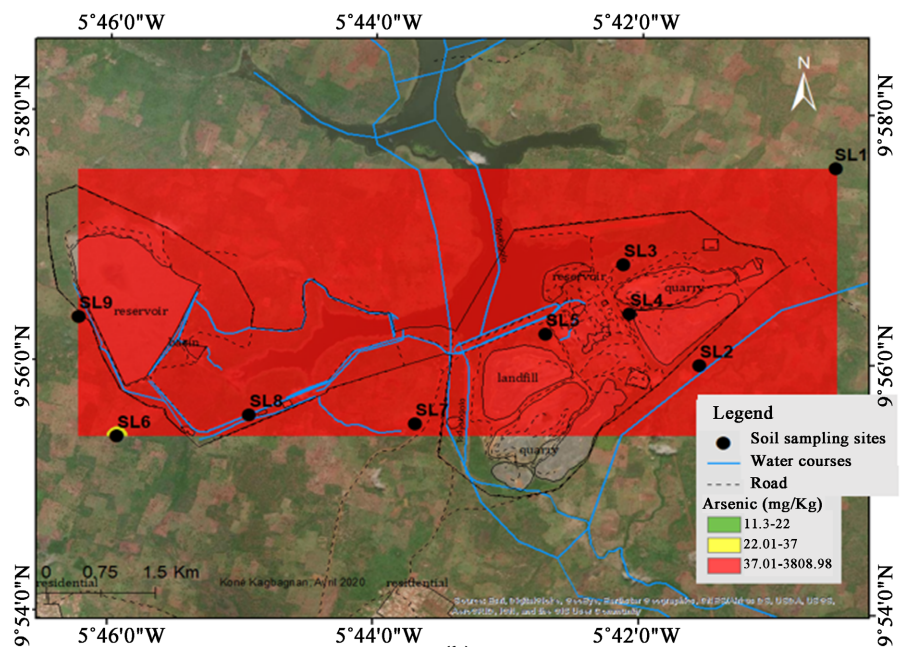
3.1. Spatial Distribution of Arsenic Concentrations in Soils in the Study Area

Figure 3 shows the spatial distribution of arsenic concentrations in soils in the Tongon mine area.

Average arsenic concentrations in soils range from 137.917 ± 0.046 mg/kg to 3808.987 ± 0.030 mg/kg (**Figure 3(a)**). These average concentrations are very high and well above the world average for arsenic-free soils, which is 6 mg/kg [9]. The reference values for arsenic-contaminated soils are set at 20 mg/kg and 29 mg/kg respectively by the environmental protection legislation of certain



(a)



(b)

Figure 3. Concentrations (a) and spatial distribution (b) of arsenic in soil in the Tongon industrial mine area.

European countries such as France, Italy and Holland [9]. The concentrations obtained are all above these standards. The overall average for the site was 534.929 ± 1166.267 mg/kg. They are higher than the concentrations determined in other studies on soil samples from gold mines in Côte d'Ivoire. In their studies of soil samples from certain gold mines in Côte d'Ivoire, the authors found arsenic concentrations of up to 278.6 mg/kg [2]. They also found concentrations of 294.38 ± 195.40 mg/kg at Afema and 7.38 ± 4.39 mg/kg at Bonikro in other industrial mines [3].

The high concentrations of arsenic in soils are thought to be due not only to naturally occurring levels in soils but also to their distribution, which often originates from mine tailings. Their wide distribution can be explained by the remobilization of arsenic from waste rock. Rainwater infiltrates the waste rock, leading to arsenic being distributed over large areas and accumulating in the soil [2].

3.2. Assessment of Arsenic Soil Contamination in the Tongon Mine Area

3.2.1. Index of Geoaccumulation

The geoaccumulation index (GEI) takes into account natural fluctuations in metal concentration. **Table 4** shows the geoaccumulation index values for the soil samples. The geoaccumulation index values range from 1.28 to 3.40. These values indicate that the soils belong to classes 1 to 3 according to Müller, indicating the severe arsenic contamination in the vicinity of the TSF or the reservoir (SL9) [7]. The arsenic enrichment shown by the geoaccumulation index in all areas could be linked to water run-off and the impact of the TSF, as well as mining activities such as crushing, leaching and storage of tailings, and the mechanical and chemical displacement of elements [9].

3.2.2. Contamination Factor

Table 5 summarizes the arsenic contamination factor (CF) values for the soil samples. Different levels of contamination were observed depending on the sampling sites. The CF values range from 2.23 to 224.06. These values are all greater than 1, indicating moderate to very high levels of arsenic contamination in the soil. It should be remembered that arsenic is a substance naturally present in the earth's crust and diffused in natural environments. It is important to

Table 4. Index of geoaccumulation of arsenic in soils.

Sampling site	SL1	SL2	SL3	SL4	SL5	SL6	SL7	SL8	SL9
Igeo	1.51	1.8	1.4	2.13	2.27	1.28	1.83	2.19	3.40

Table 5. FC values for soil samples.

Sampling site	SL1	SL2	SL3	SL4	SL5	SL6	SL7	SL8	SL9
CF	24.41	5.52	2.23	11.81	16.39	2.66	5.94	13.71	224.06

distinguish between organic and inorganic forms of arsenic, since inorganic arsenic is usually less toxic than organic arsenic [10]. In its pure state, arsenic is a grey metal, but it is rarely present in this form in the environment. It is generally associated with one or more elements such as oxygen, chlorine and Sulphur. Combined with these elements, it is called inorganic arsenic; combined with coal and hydrogen, it is called organic arsenic. Many substances containing arsenic (both inorganic and organic) are naturally occurring, but many more are the result of human activity. All soils contain a certain amount of arsenic [11]. At Tongon, the natural concentration of arsenic can reach a threshold of 17 parts per million (ppm) in the mining area (the quarry) and a threshold of 1.8 ppm in the areas around the mine declared gold-free. Although ore bodies account for a significant proportion of the arsenic introduced into the natural environment, arsenic contamination of the soil is mainly attributable to human activities (SL9). At Tongon, a large quantity of gold ore is contaminated with arsenic. We note that areas with a high gold content also have a high arsenic content, so we can state that the arsenic content is a function of the gold content of the area. This is why the highest contamination factor values are observed at point SL9 at the slurry farm and in the quarry. For copper, the CF values range from 1.83 to 5.41. These values range from 1 to 6, indicating moderate to considerable copper contamination in the soil. The presence of copper in these areas accompanies the gold ore [11]. The FC value for SL9 is just a little high because this is the slurry farm where there is an accumulation of metals from the ore and the addition of copper sulphate as a catalyst. Copper sulphate is used in the gold recovery process. The use of this catalyst in gold recovery could be the reason for the increase in the CF value of copper in this zone.

3.3. Human Health Risk Assessment

Figure 4 shows the health risks associated with exposure to arsenic-contaminated soil for children, adult men and adult women, respectively. For children, the mean value is 205.18 ± 52.47 . For adult men, the mean value is 16.16 ± 4.13 , and

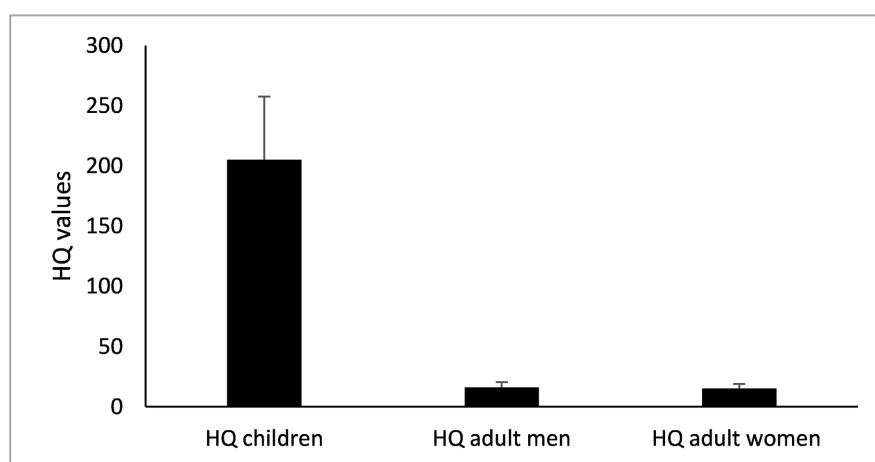


Figure 4. Health risks associated with exposure to contaminated soil.

for adult women, the mean value is 15.16 ± 3.88 . Human health risk assessment has shown that children are at the greatest disadvantage when it comes to exposure risks such as direct inhalation of dust [5]. The risks of exposure are well above the critical limit of 1 and are, in descending order, children > adult women > adult men. The risks are higher for children. Contaminated soil could be used as a passageway and playground for children, who could inhale, ingest and eat contaminated soil [8]. Soil ingestion by children is a primary exposure route of concern for contaminated soils [5]. Similarly, arsenic hazard quotients have been reported in other gold mining areas in Ghana [8]. These studies identified trends similar to those found in our study. Similarly, they found that higher levels of arsenic in the topsoil presented a potential health risk for children [8].

4. Conclusion

The study was carried out to assess the level of arsenic contamination in soils in the Tongon gold mine area and the health risks to the local population. The results indicate that the soil in the industrial zone of the Tongon gold mine has very high average concentrations, well above the world average for uncontaminated soil, which is 6 mg/kg. The geoaccumulation index values range from 1.28 to 3.40. These values indicate that the soils belong to classes 1 to 3 according to Müller, highlighting their severe arsenic contamination. The human health risk assessment showed that children are the most disadvantaged in terms of exposure risk. These results show that there is an ecological risk, hence the need for environmental monitoring, underpinned by the development of an effective remediation strategy to reduce local pollution and contamination.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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