

Original Article

Geochemical Fractionation of Heavy Metals Under Three Land-Use Types in Gold Mining Areas, Côte d'Ivoire (West Africa)

Kakou Charles Kinimo,^{1*} N'Guessan Louis Bérénger Kouassi,¹ Koffi Marcellin Yao,² Doubi Bi Irié Hervé Gouré,¹ Albert Trokourey³

¹Department of Mathematical Physics and Chemistry, University Peleforo GON COULIBALY, Korhogo, Côte d'Ivoire

²Oceanologic Research Center, Treichville-Vridi, Abidjan, Côte d'Ivoire

³Department of Sciences of Material Structure and Technology, University Félix Houphouët Boigny, Abidjan, Côte d'Ivoire

Article history:

Received: October 12, 2025

Revised: November 25, 2025

Accepted: December 3, 2025

ePublished: June 29, 2026

***Corresponding author:**

Kakou Charles Kinimo,
Email: nkinimo01@gmail.com

Abstract

Introduction: This study investigated the mobility and bioavailability potential risk of heavy metals in sediments affected by land use types in a gold mining environment.

Methods: The study employed the modified Community Bureau of Reference (BCR) sequential extraction method to assess the mobility of arsenic (As), cadmium (Cd), and mercury (Hg) in sediments from gold mining areas in Côte d'Ivoire. Concentrations of these metals in surface sediment samples (n=45) were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES), and the Risk Assessment Code (RAC) was applied to evaluate the potential risk associated with these metals.

Results: It was found that the metals were primarily associated with the residual fraction, comprising 44–58% of the total concentration. The BCR method indicated that 41–56% of these metals were prone to leaching into the water column. Pearson correlation analysis revealed positive relationships among the extracted fractions but no correlation with pH or TOC across the three land-use types. Principal component analysis (PCA) showed high positive loadings for As and Cd on component 1, and for Hg on component 2, suggesting a geogenic influence for Hg and mixed sources for As and Cd. The RAC indicated low risk for As and medium risk for Cd and Hg across the sediments of the studied land-use types.

Conclusion: The sediments exhibit a dominantly geogenic distribution with localized anthropogenic enrichment of Cd and As, and moderate ecological risk was mainly associated with Cd and Hg mobility in the three land-use types.

Keywords: Heavy metals, Sequential extraction, Bioavailability, Gold mining, Sediments, Côte d'Ivoire

Please cite this article as follows: Kinimo KC, Kouassi NGLB, Yao KM, Doubi BIHG, Trokourey A. Geochemical fractionation of heavy metals under three land-use types in gold mining areas, Côte d'Ivoire (West Africa). J Adv Environ Health Res 2026;14(2):123-131. doi:10.34172/jaehr.1466

Introduction

Wetlands contribute in diverse ways to the livelihoods of millions of people in Africa and are of huge economic importance.¹ They contain a multitude of ecological niches and supports a wide variety of flora and fauna with different ecological functions.² Wetlands around gold mine sites of different scales (large, small, and illegal) are seriously threatened by wet and dry emissions from smelters and by runoff waste accumulating in sediments.³ Thus, sediments become a sink where heavy metals tend to accumulate and persist because they are not biodegradable. In unpolluted sediments, heavy metals exist in various chemical forms and can bind to silicates and primary minerals, which form relatively immobile

species, whereas in polluted sediments, heavy metals are generally more labile and bound to other sediment phases. Trace metals in sediments serve as key indicators of metal pollution in aquatic systems, particularly in contaminated areas like gold mining.⁴ Their partitioning is influenced by sediment properties, such as pH, and organic matter and chemical interactions, such as sorption.⁵ Understanding the binding sites and associations of trace metals is crucial for evaluating their mobility and toxicity.⁶ Sequential extraction, involving various chemical reagents, facilitates the analysis of these interactions, revealing insights into the metal's geochemical behavior and potential environmental risks under changing conditions (e.g pH and Eh).⁷



© 2026 The Author(s); Published by Kurdistan University of Medical Sciences. This is an open-access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The Community Bureau of Reference (BCR) sequential extraction procedure was developed to standardize previously inconsistent methodologies for determining trace metal fractionation, thereby facilitating reliable comparisons across studies.⁸ This widely adopted protocol is now applied to various environmental solid samples, such as sediments, soils, and sewage sludge.⁸

The first three fractions (water-soluble, exchangeable, and acid-soluble) constitute the most mobile, active, accessible pool of heavy metals in sediment, also called the effective available pool. The trace metals associated with these fractions can be remobilized by different reactions such as water solubilization, ionic exchange, and acid dissolution. Trace metals present in the reducible and oxidizable fractions are important for evaluating the amount of transferable metals from sediments to aquatic organisms and plants and represent the potentially available pool, while those associated with the residual fraction are considered immobile.⁹

Arsenic (As), cadmium (Cd), and mercury (Hg) are highly toxic metals with minimal essential biological functions, linked to numerous health issues such as cancers and cardiovascular problems.^{6,10,11} Various extraction methods exist for their identification in soils and sediments, but differences in sequences and procedures complicate data comparisons.¹² Moreover, the absence of suitable reference materials hinders independent result validation across laboratories. To address these challenges, the European Community Bureau recommended (BCR) sequential extraction method, which categorizes trace metals in sediments into four fractions based on their solubility and mobility, with the first two fractions being more active and mobile, and the fourth being inert and non-mobile.¹³

Trace metal pollution in the environment has been investigated in Côte d'Ivoire, but these studies concerned Ebrié lagoon water, sediments, and gastropods.^{14,15} These studies reported that urban samples were more contaminated by heavy metals than rural samples. Thus, despite the development of gold mining activities in developing countries in general and particularly in Côte d'Ivoire this last decade, no study has been conducted on the impact of gold mining and smelting on sediments in wetlands and on crops grown around active or abandoned gold mines. Therefore, information on the distribution of toxic metals such as Cd, As, and Hg is still lacking. The main objective of this study was (i) to investigate the mobility of As, Cd, and Hg in sediment from three distinct land uses; (ii) to evaluate the ecological risk posed by these metals based on their bioavailability in the vicinity of a gold mine.

Materials and Methods

Study Area

The present research focused on three wetland sites affected by gold mining activities in Côte d'Ivoire (7.54°N, 5.54°W), West Africa (Figure 1). The country's geology consists mainly of Paleoproterozoic formations, making

it rich in mineral deposits. Two sites in south-central Côte d'Ivoire - Bonikro and Agbaou (6.38°N – 5.21°N) - and one in the southeast - Afema (5.41°N, 2.92°N) were selected. Bonikro and Agbaou are about 230 km from Abidjan, with mining operations beginning in 2008 and 2012, respectively. These sites feature granodiorite intrusions into mafic volcanic basalts from the upper Birimian series, with deposits stretching 1000 m long and up to 300 m wide.¹⁶ The area experiences an equatorial climate with yearly rainfall reaching 1305 mm. The Afema mine, located 42 km east of Aboisso and 160 km from Abidjan, operated briefly from 1994 to 1998.¹⁷ This region has a sub-equatorial climate, with temperatures ranging from 21 °C to 33 °C and annual rainfall between 1400 and 2500 mm. Like the other sites, Afema's geology features Birimian formations, primarily metavolcanic and metasedimentary rocks that extend into neighboring Ghana.¹⁷ While Afema sits in the Ehanian River basin (a Tanoe River tributary), Bonikro and Agbaou are within the Bandama River watershed.

Sample Collection and Analysis

Between March and November 2015, surface sediment samples (0-5 cm depth) were collected from wetlands around all the three sites. At each location, 15 samples were gathered: 5 from industrial mining areas, 5 from artisanal mining zones, and 5 from unmined control areas. A small Van Veen stainless steel grab sampler (0.02 m² area) was used to collect roughly 300 g of sediment per sample, and 5 sub-samples were combined to account for local variation. Samples were kept on ice during transport, were frozen until processing, and were then air-dried at room temperature. After being ground with an agate mortar and sieved to 63 µm mesh, the homogenized samples were stored in sealed bags before being shipped to the COBRA Laboratory at the University of Rouen in France for analysis.

BCR Sequential Extraction Procedure

Various methods have been tried by scientists to analyze how metals bind to sediments and soils, but there is still no universally agreed-upon approach.¹⁸ In most methods, the easily removable metals are extracted first using water and salt solutions. Then, reducing and oxidizing agents are used to remove metals bound to iron and manganese compounds and organic matter. Finally, strong acids are used to break down the most stubborn minerals where metals are trapped in the sediment's crystal structure.¹⁹ In this study, the distribution of As, Cd, and Hg across four different fractions of sediment samples was examined: exchangeable (F1: Exch), reducible (F2: Red), oxidizable (F3: Org), and residual (F4: Res). The European Commission's Standard Measurements and Testing Program (formerly BCR) protocol was used to analyze these metals.¹² The process involves three main steps: First, acetic acid was used to extract the easily removable metals. Next, hydroxylamine hydrochloride was used to extract the reducible fraction. Finally, hydrogen peroxide

and ammonium acetate were used to extract the oxidizable fraction. An extra step using nitric and hydrochloric acids was added to dissolve the remaining residual fraction. For each extraction, 1 g of heated, powdered sample was placed in a centrifuge tube. After being mixed with the appropriate chemical, the liquid was separated from the solid by centrifuging. The liquid was analyzed, and the remaining solid was washed with ultra-pure water before the next step was carried out. The final solid residue was used to determine the residual fraction through acid digestion. The operational details are presented in Table 1.

Risk Assessment Code (RAC)

The RAC is a widely used method to evaluate the potential bioavailability and mobility of heavy metals.²⁰ It is based on the fraction of metal that is weakly bound to sediment and could become more rapidly bioavailable. According to Perin et al.,²¹ the RAC classification is as follows: <1% = no risk; 1–10% = low risk; 11–30% = medium risk; 31–50% = high risk; and 51–100% = very high risk.

Control Quality and Method Efficiency

Replicate samples and analytical blanks were analyzed for each sample, and the analytical error was within 6%. The accuracy of the analytical procedures was evaluated through the analysis of the certified reference material CRM CNS 301-04-050 (Sigma-Aldrich; Missouri, USA) for freshwater sediment. The percentage recovery was calculated for each element in each extraction step by dividing the measured concentrations by the certified concentration values. The accuracy of the BCR extraction procedure was assessed by comparing the sum of the four fractions with the total metal content. The recoveries were in the ranges: 84–118% for As, 104–119% for Cd, and 82–117% for Hg.

Statistical Analysis

Pearson's correlation analysis was employed on raw data to explore the relationship between trace metal concentrations in the different sequential fractions and physicochemical parameters in sediments such as pH and

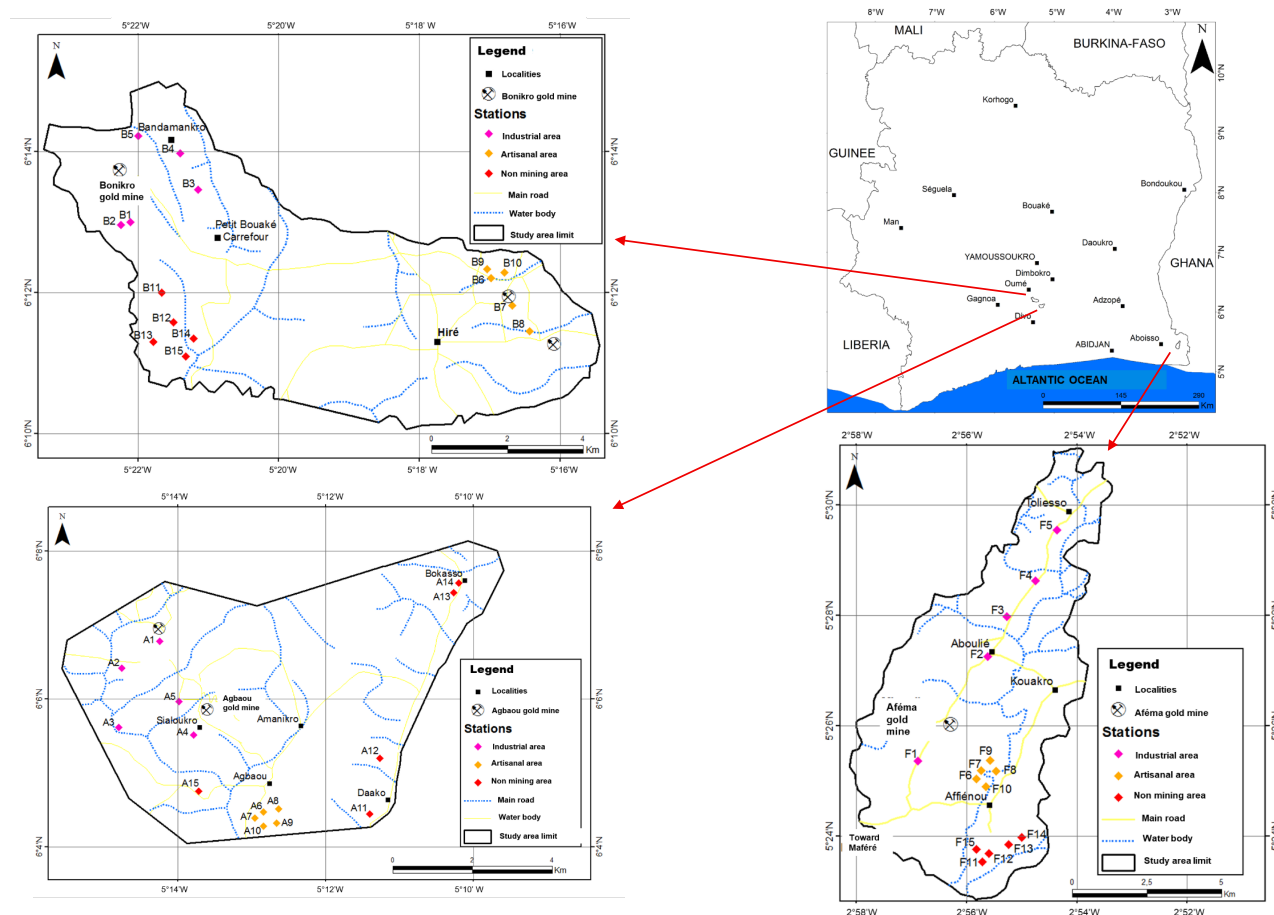


Figure 1. Study Area and Sampling Point Localization

Table 1. BCR Three-Stage Sequential Extraction Scheme

Extraction step	Reagents	Nominal target phases
1	HOAc (0.11 mol/L)	Carbonate exchangeable fraction (Exch)
2	NH ₂ OH, HCl (0.1 mol/L)	Reducible fraction (Red)
3	H ₂ O ₂ (8.8 mol/L) then NH ₄ OAc (0.1 mol/L) at pH 2	Organic bound fraction (Org)
Residual	HCl/HNO ₃ + HF	Residual fraction (Res)

total organic carbon (TOC). Principal component analysis (PCA) was applied to the average metal concentrations obtained from stations, which were pooled according to land use to explore their similarities. Statistical analyses were performed using SigmaPlot (version 12.0).

Results and Discussion

As, Cd, and Hg Fractionations

Table 2 and Figure 2 present the concentrations and distribution of As, Cd, and Hg in surface sediments from industrial, artisanal, and non-mining areas. Arsenic fractionation revealed the following order of decrease: Res-As > Red-As > Oxi-As > Exch-As. Overall, As content was found to be preferentially associated with the residual fraction of the sediments in the industrial and artisanal mining areas, as well as in the non-mining area. At industrial stations, on average, As content accounted for $54.1 \pm 14.7\%$ in the residual, $32.9 \pm 9.25\%$ in the reducible, $6.59 \pm 3.95\%$ in the oxidizable, and $6.49 \pm 3.95\%$ in the exchangeable fraction. At artisanal stations, the As content accounted for $57.8 \pm 11.8\%$ in the residual, $32.8 \pm 10.5\%$ in the reducible, $5.14 \pm 2.09\%$ in the oxidizable, and $4.31 \pm 2.16\%$ in the exchangeable fractions. At non-mining stations, the corresponding values were $55.3 \pm 6.05\%$ in the residual, $33.6 \pm 5.75\%$ in the reducible, $4.68 \pm 1.48\%$ in the oxidizable, and $6.45 \pm 2.63\%$ in the exchangeable fraction. No significant differences ($P > 0.05$) were observed in the heavy metal content of the different fractions, regardless of the land-use type.

Cd partitioning showed the decreasing order: Res-Cd > Org-Cd > Exch-Cd > Red-Cd in the three land-use types. On average, cadmium was predominantly associated with the residual fraction: $57.8 \pm 7.62\%$ in the residual, $17.3 \pm 7.03\%$ in the oxidizable, $14.6 \pm 3.83\%$ in the exchangeable, and $10.4 \pm 3.67\%$ in the reducible fraction at industrial stations. At artisanal stations, the distribution was $58.5 \pm 6.18\%$ in the residual, $17.1 \pm 6.18\%$ in the oxidizable, $13.9 \pm 4.76\%$ in the exchangeable, and $10.5 \pm 4.02\%$ in the reducible fraction. At non-mining stations, it was $58.2 \pm 6.63\%$ in the residual, $18.6 \pm 8.21\%$ in the oxidizable, $13.0 \pm 3.73\%$ in the exchangeable, and $10.1 \pm 3.15\%$ in the reducible fraction. The ANOVA indicated that there were no significant differences ($P > 0.05$) among the different Cd fractions in sediments from the three studied land-use types. Hg fractionation in sediments from industrial, artisanal, and non-mining areas followed the order: Res-Hg > Org-Hg > Red-Hg > Exch-Hg. This study reveals that the chemical fractionation of Hg in the sediments was predominantly associated with the residual fraction, regardless of the land-use type. At industrial stations, on average, the percentage of Hg bound to the different sediment fractions was $48.9 \pm 11.9\%$ in the residual, $13.3 \pm 5.12\%$ in the reducible, $27.5 \pm 9.15\%$ in the oxidizable, and $10.2 \pm 4.63\%$ in the exchangeable fraction. At artisanal stations, the pattern was $43.7 \pm 15.1\%$ in the residual, $30.4 \pm 11.8\%$ in the oxidizable, $11.7 \pm 2.65\%$ in the reducible, and $14.1 \pm 8.82\%$ in the exchangeable fraction. At non-mining stations, the distribution was $44.3 \pm 14.4\%$

Table 2. Average Concentration and Mathematic Sum of the Most Labile of As, Cd, and Hg in Different Fractions in Surface Sediments From the Three Land-Use Types (n = 15)

	Mean	Σexch + Red + Org	CV (%)	UCC ²²
Industrial				
Exch-As	4.12	37.4 ± 57.4	172	2.00
Red-As	29.9		160	
Org-As	3.32		146	
Res-As	68.3		180	
Exch-Cd	0.46	1.43 ± 1.19	90.7	0.102
Red-Cd	0.38		98.6	
Org-Cd	0.59		89.4	
Res-Cd	1.90		86.1	
Exch- Hg	0.01	0.07 ± 0.08	105	0.06
Red- Hg	0.02		113	
Org-Hg	0.04		100	
Res-Hg	0.06		100	
Artisanal				
Exch-As	0.18	1.13 ± 1.82	215	2.00
Red-As	0.97		120	
Org-As	0.18		191	
Res-As	1.44		86.4	
Exch-Cd	0.41	1.22 ± 0.38	36.0	0.102
Red-Cd	0.30		39.0	
Org-Cd	0.51		50.3	
Res-Cd	1.71		20.1	
Exch- Hg	0.01	0.04 ± 0.02	75.2	0.06
Red- Hg	0.01		41.0	
Org-Hg	0.02		60.6	
Res-Hg	0.03		55.0	
No-mining				
Exch-As	1.00	7.98 ± 11.83	222	2.00
Red-As	6.37		199	
Org-As	0.62		237	
Res-As	8.18		201	
Exch-Cd	0.78	2.58 ± 1.67	56.7	0.102
Red-Cd	0.57		48.9	
Org-Cd	1.22		96.2	
Res-Cd	3.42		50.2	
Exch- Hg	0.01	0.03 ± 0.01	68.6	0.06
Red- Hg	0.01		52.9	
Org-Hg	0.01		71.9	
Res-Hg	0.02		60.7	

in the residual, $30.3 \pm 13.6\%$ in the oxidizable, $14.2 \pm 2.54\%$ in the reducible, and $11.3 \pm 5.96\%$ in the exchangeable fraction.

No significant difference ($P > 0.05$) was observed between the percentages of Hg bound to the different fractions of the sediments. It is well known that heavy metals found in the residual fraction are strongly bound to the crystalline structures of the minerals present in the sediment matrix, and studies have proven that these

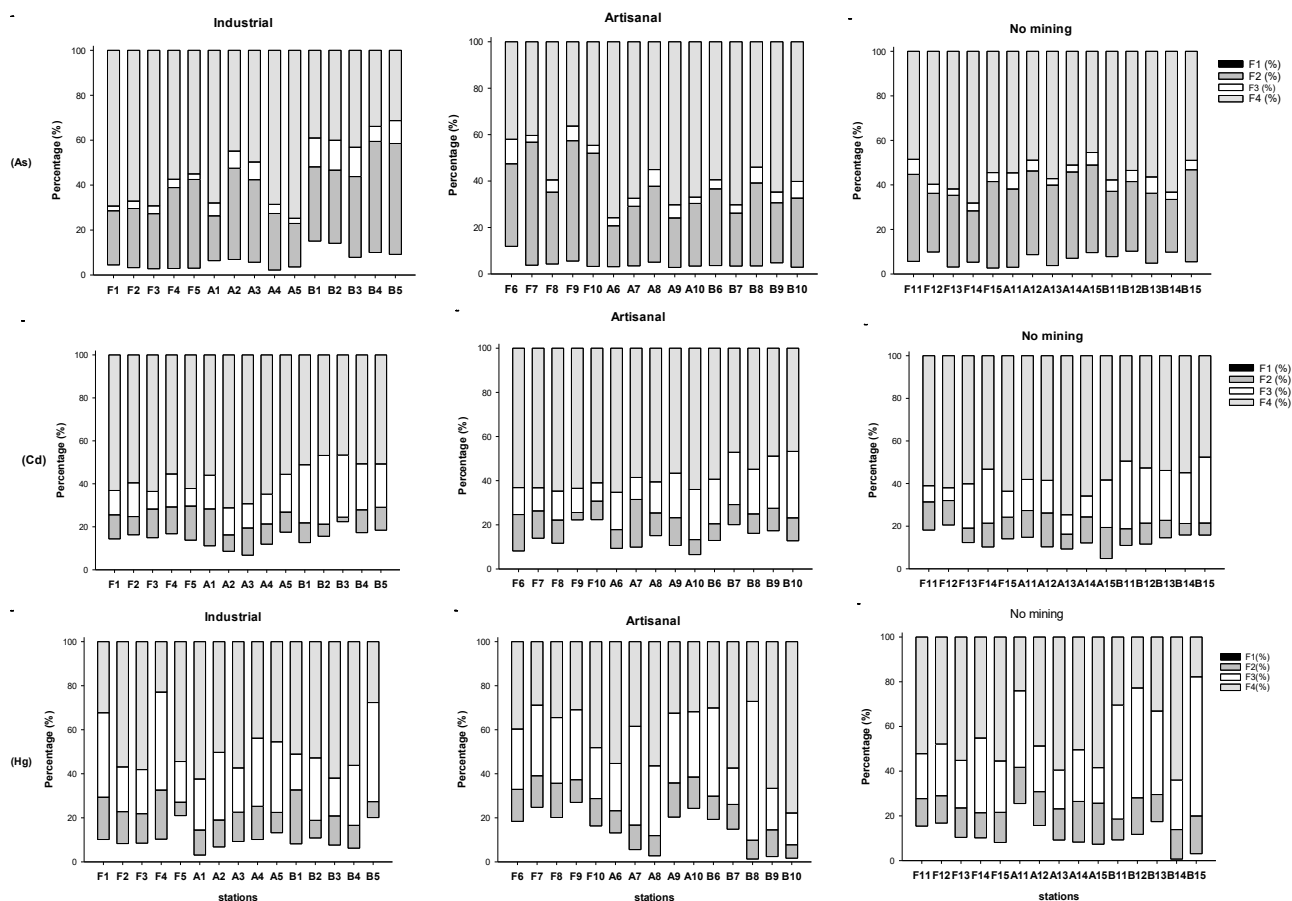


Figure 2. Chemical Speciation of As, Cd, and Hg in Sediments from Industrial, Artisanal, and No-Mining Areas

metals are not labile.²³ As Figure 2 shows, all metals were predominantly associated with the residual fraction in sediments from the three land-use types. No significant difference ($P > 0.05$) was observed in the partitioning of As, Cd, and Hg among sediments from industrial, artisanal, and non-mining areas. This result indicates that these metals were strongly bound to the minerals and resistant components of the sediment matrix. Thus, the similar partitioning behavior in sediment fractions may be due to the proximity of non-mining sites used for agricultural purposes to gold mining areas. Moreover, extensive agricultural practices, such as the application of pesticides and excess nutrients, affect metal leaching.²⁴ Previous studies have reported similar distribution patterns for Cd, As, and Hg extracted from soil or sediment samples by the BCR sequential extraction method.²⁵

Correlation Analysis

Table 3 presents the Pearson correlation matrix for As, Cd, and Hg contents in the sequential extraction fractions and the physicochemical characteristics of the sediment data sets. Weak correlations were observed between the sediment physicochemical characteristics (pH and TOC) and the heavy metal contents in the extraction fractions, indicating that pH and TOC have little influence on the binding behavior of As, Cd, and Hg in the three types of sediments. In contrast, strong positive correlations existed ($P < 0.05$) among the concentrations of As, Cd,

and Hg in all sediment fractions from the three land-use types. This suggests the possibility of shared sources and transformation pathways for these metals.

Principal Component Analysis (PCA)

Two PCs with eigenvalues > 1 were extracted, explaining 68.64, 59.4, and 79.3% of the total variance for industrial, artisanal, and non-mining sites, respectively, as shown in Table 4. All extracted fractions of As and Cd were positively correlated with PC1 in the three land-use types, while Hg had a high positive loading on PC2 in the artisanal and non-mining sites. The sediment properties (pH and TOC) were weakly correlated with the two components. The high positive loadings between the extracted fractions of the selected metals and PC1 indicated that they share the same source of anthropogenic inputs, which could be derived from mixed natural and anthropogenic sources such as gold mining and agricultural practices.²⁶ The main explanation for this is the high percentage of the studied metals in the residual fraction (F4). This result was confirmed by the Pearson correlation analysis for the selected elements.

Mobilizable Concentration of As, Cd and Hg in Sediment Fractions

It is assumed that the extractability (potential mobility) of a metal is directly related to its proportion in the first three fractions (acid-soluble/exchangeable

Table 3. Pearson Correlation Between Chemical Fractionation Concentration of As, Cd, Hg, TOC and pH in Sediments

Industrial	Exch-As	Red-As	Org-As	Res-As	Exch-Cd	Red-Cd	Org-Cd	Res-Cd	Exch-Hg	Red-Hg	Org-Hg	Res-Hg	pH	TOC
Exch-As	1													
Red-As	0.93	1												
Org-As	0.89	0.96	1											
Res-As	0.98	0.97	0.95	1										
Exch-Cd	-0.29	-0.33	-0.31	-0.30	1									
Red-Cd	-0.27	-0.31	-0.29	-0.28	0.74	1								
Org-Cd	-0.36	-0.44	-0.39	-0.39	0.92	0.75	1							
Res-Cd	-0.32	-0.37	-0.35	-0.33	0.81	0.94	0.82	1						
Exch-Hg	-0.12	-0.07	-0.14	-0.11	-0.31	-0.35	-0.38	-0.37	1					
Red-Hg	-0.02	0.00	-0.02	-0.01	-0.30	-0.30	-0.30	-0.32	0.84	1				
Org-Hg	-0.06	-0.04	-0.07	-0.05	-0.26	-0.29	-0.31	-0.32	0.94	0.93	1			
Res-Hg	-0.21	-0.22	-0.22	-0.20	-0.21	-0.19	-0.21	-0.23	0.84	0.90	0.87	1		
pH	0.01	-0.19	-0.22	-0.10	0.11	0.04	0.16	-0.04	-0.06	-0.28	-0.09	-0.13	1	
TOC	-0.50	-0.50	-0.56	-0.51	0.14	-0.09	0.21	0.11	-0.19	-0.24	-0.24	-0.22	-0.01	1
Artisanal	Exch-As	Red-As	Org-As	Res-As	Exch-Cd	Red-Cd	Org-Cd	Res-Cd	Exch-Hg	Red-Hg	Org-Hg	Res-Hg	pH	TOC
Exch-As	1													
Red-As	0.95	1												
Org-As	0.98	0.94	1											
Res-As	0.97	0.93	0.97	1										
Exch-Cd	-0.35	-0.33	-0.35	-0.40	1									
Red-Cd	0.08	-0.04	0.07	0.13	-0.05	1								
Org-Cd	-0.32	-0.49	-0.32	-0.32	0.38	0.13	1							
Res-Cd	-0.28	-0.34	-0.29	-0.24	0.34	0.21	0.48	1						
Exch-Hg	0.24	0.39	0.21	0.28	0.30	-0.18	-0.07	0.23	1					
Red-Hg	0.34	0.43	0.33	0.42	0.41	0.21	0.05	0.21	0.77	1				
Org-Hg	0.04	0.10	0.06	0.02	0.24	0.13	-0.05	0.13	0.03	0.34	1			
Res-Hg	0.04	-0.02	0.03	0.04	0.66	0.17	0.41	0.10	0.30	0.59	0.03	1		
pH	-0.32	-0.48	-0.28	-0.29	0.02	0.51	0.55	0.26	-0.49	-0.24	0.25	0.11	1	
TOC	0.32	0.33	0.29	0.29	0.21	0.15	-0.26	0.49	0.55	0.39	-0.12	0.09	-0.44	1
No mining	Exch-As	Red-As	Org-As	Res-As	Exch-Cd	Red-Cd	Org-Cd	Res-Cd	Exch-Hg	Red-Hg	Org-Hg	Res-Hg	pH	TOC
Exch-As	1													
Red-As	0.72	1												
Org-As	0.98	0.59	1											
Res-As	0.99	0.78	0.96	1										
Exch-Cd	0.62	0.58	0.61	0.66	1									
Red-Cd	0.57	0.28	0.64	0.57	0.69	1								
Org-Cd	0.90	0.75	0.87	0.92	0.73	0.63	1							
Res-Cd	0.65	0.45	0.68	0.67	0.87	0.84	0.76	1						
Exch-Hg	-0.32	-0.38	-0.29	-0.35	-0.47	-0.16	-0.43	-0.45	1					
Red-Hg	-0.35	-0.01	-0.45	-0.33	-0.61	-0.51	-0.35	-0.58	0.48	1				
Org-Hg	0.05	0.55	-0.12	0.11	-0.11	-0.38	0.09	-0.30	0.17	0.65	1			
Res-Hg	-0.39	-0.40	-0.39	-0.40	-0.57	-0.40	-0.40	-0.40	0.34	0.66	0.01	1		
pH	0.30	0.12	0.37	0.27	0.29	0.64	0.19	0.39	0.47	-0.21	-0.11	-0.31	1	
TOC	0.19	0.13	0.15	0.16	-0.04	0.03	0.07	0.08	0.26	0.21	0.15	-0.02	0.25	1

(In bold significant correlation at 0.05 level).

Table 4. Varimax-Rotated Loadings of Heavy Metals in Sediments From the Three Land-Use Types

Fractions	Industrial		Artisanal		No-mining	
	PC 1	PC 2	PC 1	PC 2	PC1	PC2
Exch-As	0.694	0.612	0.960	-0.05	0.90	0.283
Red-As	0.745	0.594	0.960	-0.05	0.68	0.623
Org-As	0.717	0.615	0.986	-0.04	0.90	0.124
Res-As	0.721	0.614	0.951	-0.07	0.91	0.32
Exch-Cd	-0.755	0.155	0.951	-0.03	0.85	-0.149
Red-Cd	-0.717	0.185	-0.326	0.77	0.77	-0.33
Org-Cd	-0.825	0.122	0.007	0.19	0.91	0.25
Res-Cd	-0.791	0.173	-0.486	0.40	0.87	-0.232
Exch-Hg	0.443	-0.805	-0.3	0.60	-0.46	0.154
Red-Hg	0.48	-0.752	0.412	0.66	-0.59	0.699
Org-Hg	0.454	-0.784	0.451	0.79	-0.11	0.882
Res-Hg	0.306	-0.842	0.0319	0.24	-0.59	0.185
pH	-0.185	0.056	0.07	0.72	0.38	-0.17
TOC	-0.485	-0.159	-0.505	-0.01	0.08	0.359
Eigenvalue	5.458	4.152	5.858	3.05	6.94	2.317
Explained variance (%)	38.986	29.659	39.05	20.33	49.56	16.55
Cumulative variance (%)	38.986	68.645	39.05	59.38	49.56	66.119

In bold significant loading at 0.05 level (2-tailed).

+ reducible + oxidizable) of sequential extraction.²⁷ Based on the average of the mathematical sum of the first three fractions, the extractability decreased in the order: As (industrial) 45% > As (non-mining) 44% > As (artisanal) 42% for As; Cd (industrial) 42% > Cd (non-mining) 41% ≈ Cd (artisanal) 41% for Cd; and Hg (artisanal) 56% > Hg (non-mining) 55% > Hg (industrial) 51% for Hg (Figure 3). Except for Hg, the concentrations of these metals bound to the non-residual fractions were 4 to 25 times higher than UCC values for As and Cd in the three land-use types. This trend could be due to the high concentrations of As and Cd previously reported in sediments from industrial and non-mining sites at Aféma, Bonikro, and Agbaou.²⁸ Our results are consistent with those of Danga et al²⁹ in sediments from the Meiganga gold district, Cameroon.

RAC Analysis

Figure 4 illustrates the results of the risk factor analysis, with values given as percentages of the metal soluble in acid (% F1) for the three metals according to land-use type. In general, medium risks were observed for Cd and Hg, with average RAC values higher than 11%, indicating a substantial risk of remobilization from sediment across the three land-use types studied, while As presented a low risk (RAC < 11%). It is assumed that variations in environmental conditions, such as pH or salinity, could increase the availability of the elements to the aquatic system. Similarly, medium risks were observed for Cd in sediments from a polymetallic mining region in China.³⁰

Conclusion

This study focused on the geochemical fractionation of As, Cd, and Hg in sediments from industrial and artisanal

gold mining areas and adjacent non-mining lands near the Aféma, Agbaou, and Bonikro gold mining sites in southeastern and mid-western Côte d'Ivoire. A total of forty-five surface sediment samples were collected from March to December 2015. According to the BCR sequential extraction procedure, the distribution of As, Cd, and Hg among the exchangeable, carbonate-bound, Fe/Mn oxide-bound, organic matter-bound, and residual fractions did not vary significantly across the three land-use types. Pearson correlation analysis revealed no correlation between the extracted fractions and the sediment properties (pH and TOC) in the three land-use types. PCA revealed high positive loadings on PC1 for all extracted fractions (F1–F4) of the selected metals at the three sites, suggesting that the elements originate from both anthropogenic inputs and geogenic sources. The mobility assessment revealed that more than 41% of the total metal concentrations are preferentially associated with the more labile fractions (F1 + F2 + F3), and the average equivalent concentrations were higher than UCC values. These findings may serve as indicators of inputs from anthropogenic sources in gold mining and non-mining areas. The RAC values indicated that Cd and Hg posed a medium risk to sediments from the three land-use types and that they could easily be transferred to water and plants through the mobile phase.

Acknowledgements

We appreciate the support of the director of the Centre de Recherche Océanologique (CRO). We are also thankful to the staff of the Laboratoire de Chimie Organique et Bioorganique, Réactivité et Analyse (COBRA), Université de Rouen, France, for the ICP-OES sample analyses.

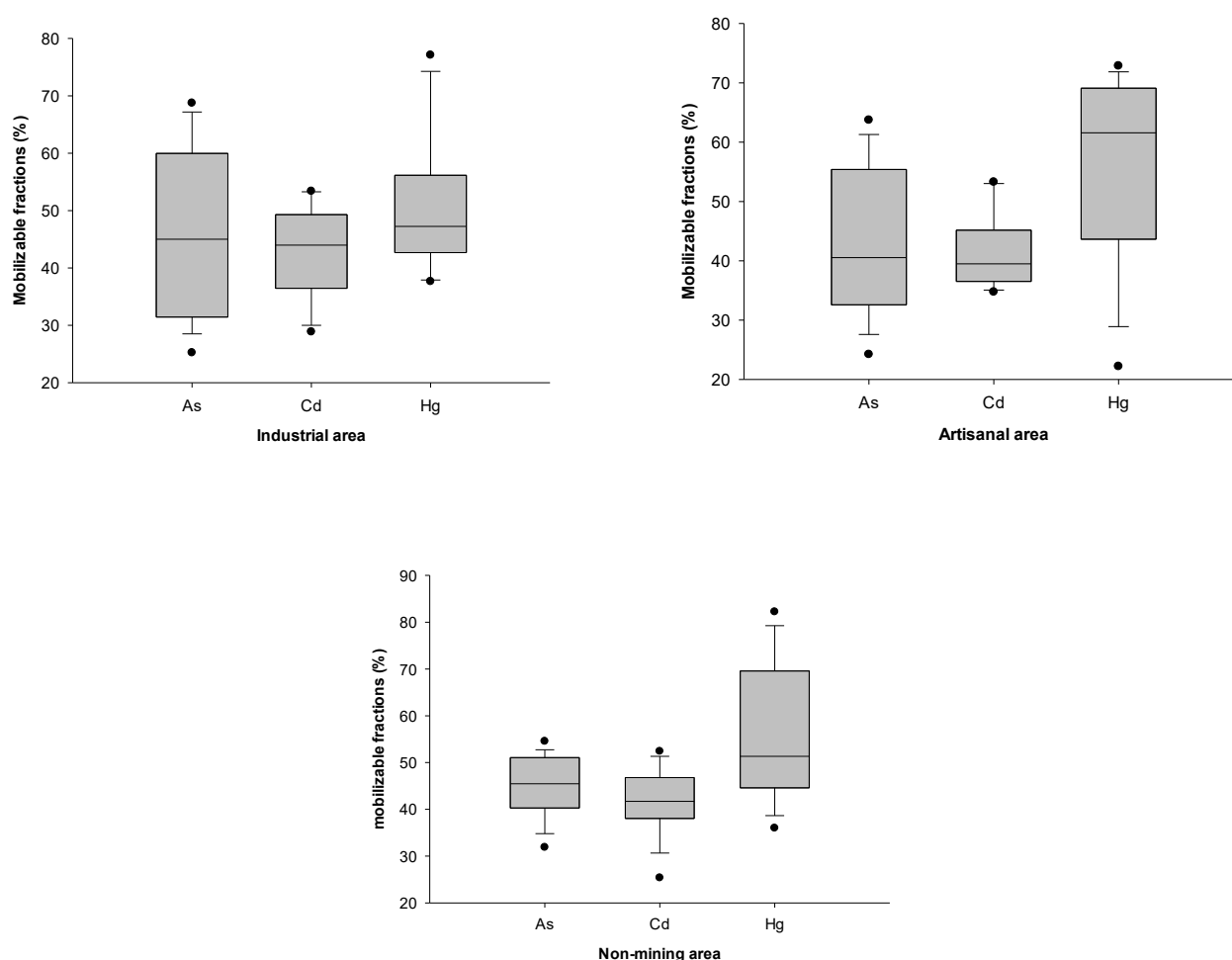


Figure 3. Mobile Fractions of As, Cd, and Hg in Surface Sediments from Industrial, Artisanal Gold Mining, and Non-Mining Areas

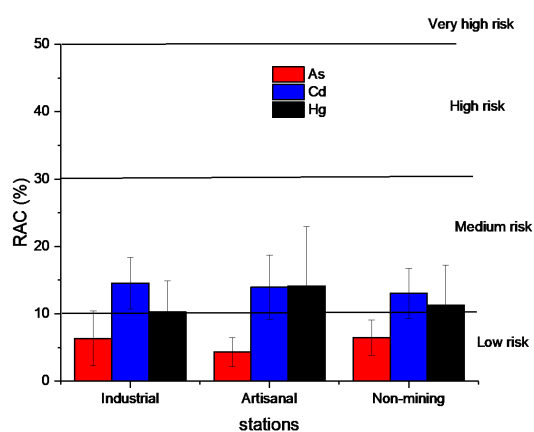


Figure 4. RAC for As, Cd, and Hg in Surface Sediments from Industrial, Artisanal, and Non-Mining Areas

Authors' Contribution

Conceptualization: Koffi Yao, Kakou Kinimo, N'Guessan Kouassi
 Data Curation: Kakou Kinimo
 Investigation: Koffi Yao, Kakou Kinimo, N'Guessan Kouassi
 Methodology: Koffi Yao, Kakou Kinimo
 Writing—Original Draft: Kakou Kinimo
 Writing—Review & Editing: Kakou Kinimo, N'Guessan Kouassi, Doubi Gouré, Albert Trokourey

Competing Interests

The authors confirm that there is no competing interest in this research.

Ethical Approval

Not applicable.

Funding

There was no funding for this study.

References

1. Zaynab M, Al-Yahyai R, Ameen A, Sharif Y, Ali L, Fatima M, et al. Health and environmental effects of heavy metals. *J King Saud Univ Sci* 2022;34(1):101653. doi:10.1016/j.jksus.2021.101653
2. Lecce SA, Pavlowsky RT. Floodplain storage of sediment contaminated by mercury and copper from historic gold mining at Gold Hill, North Carolina, USA. *Geomorphology* 2014;206:122-32. doi:10.1016/j.geomorph.2013.10.004
3. Taka M, Sillanpää N, Niemi T, Warsta L, Kokkonen T, Setälä H. Heavy metals from heavy land use? Spatio-temporal patterns of urban runoff metal loads. *Sci Total Environ* 2022;817:152855. doi:10.1016/j.scitotenv.2021.152855
4. Swain CK. Environmental pollution indices: a review on concentration of heavy metals in air, water, and soil near industrialization and urbanisation. *Discov Environ* 2024;2(1):5. doi:10.1007/s44274-024-00030-8
5. Modabberi S, Tashakor M, Rajabian N, Khorasanipour M, Esmaeilzadeh E, Ambrosino M, et al. Characterization and chemical fractionation of potentially toxic elements in soils of a pre-mining mineralized area; an evaluation of mobility and environmental risk. *Environ Geochem Health* 2023;45(7):4795-815. doi:10.1007/s10653-023-01537-4
6. N'goran KP, Diabate D, Kouassi NL, Yao KM, Kinimo KC, Ouattara AA, et al. Geochemical speciation and distribution of trace metals in sediments around industrial and artisanal

- gold mining areas in northern Côte d'Ivoire. *Environ Earth Sci* 2022;81(12):333. doi:10.1007/s12665-022-10447-0
7. Nabuyanda MM, Kelderman P, Sankura MG, Rousseau D, Irvine K. Investigating the effect of Eh and pH on binding forms of Co, Cu, and Pb in wetland sediments from Zambia. *J Environ Manage* 2022;319:115543. doi:10.1016/j.jenvman.2022.115543
 8. Ali J, Tuzen M, Shaikh Q, Jatoi WB, Feng X, Sun G, et al. A review of sequential extraction methods for fractionation analysis of toxic metals in solid environmental matrices. *Trends Analyt Chem* 2024;173:117639. doi:10.1016/j.trac.2024.117639
 9. Bouazizi N, Baraud F, Lemoine M, Leleyter L. Shortened sequential extraction procedure: an effective and time-saving determination of trace metals over sediments. *Soil Sediment Contam* 2024;33(7):1087-101. doi:10.1080/15320383.2023.2293879
 10. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Arsenic, Metals, Fibres and Dusts. Lyon, FR: International Agency for Research on Cancer; 2012. (IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, No. 100C.) Available from: <https://www.ncbi.nlm.nih.gov/books/NBK304375/>.
 11. Charkiewicz AE, Omeljaniuk WJ, Nowak K, Garley M, Nikliński J. Cadmium toxicity and health effects-a brief summary. *Molecules* 2023;28(18):6620. doi:10.3390/molecules28186620
 12. Ruan T, Li P, Wang H, Li T, Jiang G. Identification and prioritization of environmental organic pollutants: from an analytical and toxicological perspective. *Chem Rev* 2023;123(17):10584-640. doi:10.1021/acs.chemrev.3c00056
 13. Matabane DL, Godeto TW, Mampa RM, Ambushe AA. Sequential extraction and risk assessment of potentially toxic elements in river sediments. *Minerals* 2021;11(8):874. doi:10.3390/min11080874
 14. Marcellin YK, Bernard SM, Trokourey A, Yobou B. Assessment of sediments contamination by heavy metals in a tropical lagoon urban area (Ebrié lagoon, Cote d'Ivoire). *Eur J Sci Res* 2009;34(2):280-9.
 15. Koné M, Dramane D, Sory TK, Ardjouma D, Valentin HP. Comparison of trace element contamination levels (Cu, Zn, Fe, Cd and Pb) in the soft tissues of the gastropods *Tympanotonus fuscatus* and *Tympanotonus fuscatus radula* collected in the Ebrié lagoon (Côte d'Ivoire): evidence of the risks linked to linked to lead and. *Afr J Biotechnol* 2008;7(6):811-20. doi:10.4314/ajb.v7i6.58548
 16. Endeavour Mining. Projects - Endeavour Mining plc (LSE: EDV/TSX: EDV). Available from: <https://www.endeavourmining.com/our-portfolio/projects/>. Accessed May 24, 2026.
 17. Assie KE. Lode Gold Mineralization in the Paleoproterozoic (Birimian) Volcano Sedimentary Sequence of Afema Gold District, Southeastern Côte D'Ivoire [dissertation]. Papierflieger; 2008. Available from: https://dokumente.ub.tu-clausthal.de/servlets/MCRFileNodeServlet/import_derivate_00000405/db108905.pdf. Accessed May 24, 2026.
 18. Sungur A, İşler M. Geochemical fractionation, source identification and risk assessments for trace metals in agricultural soils adjacent to a city center (Çanakkale, NW Turkey). *Environ Earth Sci* 2021;80(8):299. doi:10.1007/s12665-021-09611-9
 19. Yiika LP, Tita MA, Suh CE, Mimba ME, Jean-Lavenir NM. Heavy metal speciation by Tessier sequential extraction applied to artisanal gold mine tailings in Eastern Cameroon. *Chem Afr* 2023;6(5):2705-23. doi:10.1007/s42250-023-00652-0
 20. Mukherjee P, Das PK, Ghosh P. The extent of heavy metal pollution by chemical partitioning and risk assessment code of sediments of sewage-fed fishery ponds at East Kolkata wetland, a Ramsar site, India. *Bull Environ Contam Toxicol* 2022;108(4):731-6. doi:10.1007/s00128-021-03447-6
 21. Perin G, Craboledda L, Lucchese M, Cirillo R, Dotta L. Heavy metal speciation in the sediments of northern Adriatic Sea: a new approach for environmental toxicity determination. 1985. Available from: <https://iris.unive.it/handle/10278/8149>. Accessed May 24, 2026.
 22. Taylor SR, McLennan SM. The geochemical evolution of the continental crust. *Rev Geophys* 1995;33(2):241-65. doi:10.1029/95RG00262
 23. Gabarrón M, Zornoza R, Martínez-Martínez S, Muñoz VA, Faz Á, Acosta JA. Effect of land use and soil properties in the feasibility of two sequential extraction procedures for metals fractionation. *Chemosphere* 2019;218:266-72. doi:10.1016/j.chemosphere.2018.11.114
 24. Yun SW, Kim DH, Kang DH, Son J, Lee SY, Lee CK, et al. Effect of farmland type on the transport and spatial distribution of metal(loid)s in agricultural lands near an abandoned gold mine site: confirmation of previous observations. *J Geochem Explor* 2017;181:129-37. doi:10.1016/j.gexplo.2017.07.004
 25. Klein P, Gunkel-Grillon P, Juillot F, Feder F, Kaplan H, Thery G, et al. Behavior of trace metals during composting of mixed sewage sludge and tropical green waste: a combined EDTA kinetic and BCR sequential extraction study in New Caledonia. *Environ Monit Assess* 2023;195(5):589. doi:10.1007/s10661-023-11151-7
 26. Fagbenro AA, Yinusa TS, Ajekigbe KM, Oke AO, Obiajunwa EI. Assessment of heavy metal pollution in soil samples from a gold mining area in Osun state, Nigeria using proton-induced X-ray emission. *Sci Afr* 2021;14:e01047. doi:10.1016/j.sciaf.2021.e01047
 27. Tokaloğlu Ş, Kartal Ş. Multivariate analysis of the data and speciation of heavy metals in street dust samples from the Organized Industrial District in Kayseri (Turkey). *Atmos Environ* 2006;40(16):2797-805. doi:10.1016/j.atmosenv.2006.01.019
 28. Kinimo KC, Yao KM, Marcotte S, Kouassi NL, Trokourey A. Distribution trends and ecological risks of arsenic and trace metals in wetland sediments around gold mining activities in central-southern and southeastern Côte d'Ivoire. *J Geochem Explor* 2018;190:265-80. doi:10.1016/j.gexplo.2018.03.013
 29. Danala Danga S, Ekengele Nga L, Tiki D, Mamdem LE, Djangué Moustapha B, Ibrahim BA, et al. Speciation and bioavailability of potentially toxic element in soils and sediments of mining areas in Meiganga Adamawa plateau (Cameroon). *Environ Geochem Health* 2025;47(9):398. doi:10.1007/s10653-025-02716-1
 30. Liu G, Tao L, Liu X, Hou J, Wang A, Li R. Heavy metal speciation and pollution of agricultural soils along Jishui River in non-ferrous metal mine area in Jiangxi province, China. *J Geochem Explor* 2013;132:156-63. doi:10.1016/j.gexplo.2013.06.017