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Screening of Native Plant Species in the Artisanal Gold Mining Sites of Doko, Guinea: Perspectives for Phytoremediation

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ABSTRACT

Artisanal gold mining in Doko, Guinea, has caused severe environmental degradation and soil contamination by potentially toxic metals. This study evaluated the phytoremediation potential of indigenous species growing on contaminated sites. Soil and plant samples (roots and shoots) were collected from six artisanal mining sites, selecting 12 dominant native species based on abundance and ecological relevance. In total, 358 samples were analyzed. Metal concentrations (As, Pb, Cu, Ni, Zn, Cd, Sb, Hg, and Fe) were measured by inductively coupled plasma mass spectrometry (ICP-MS). Phytoremediation efficiency was assessed using the bioconcentration factor (BCF), translocation factor (TF), and biological accumulation coefficient (BAC). Soils showed severe contamination, with arsenic and lead reaching 550 and 2300 mg/kg, exceeding WHO/FAO guidelines by 27- and 23-fold, respectively. Arsenic was the main ecological risk contributor. No species met hyperaccumulator criteria. However, several species exhibited promising phytoremediation traits. *Xanthocercis zambesiaca* showed a BCF > 1 for Pb, indicating phytostabilization potential. *Acacia ataxacantha*, *Hyptis suaveolens*, and *Mitragyna inermis* showed TF > 1 for several metals, suggesting effective translocation. Multivariate analysis highlighted *Mimosa pigra*, *X. zambesiaca*, and *Detarium senegalense* as influencing metal mobility. Overall, Doko's native flora shows strong potential for phytostabilization and assisted phytoextraction, offering a realistic nature-based solution for rehabilitating artisanal gold mining sites.

1 | Introduction

Artisanal and small-scale gold mining (ASGM) plays a significant role in the socioeconomic fabric of several West African countries, including the Republic of Guinea. Historically, gold mining activities in Guinea date back to the 11th century, well before the rise of the Mali Empire, with artisanal operations established in Bouré (Siguiri) [1]. Today, ASGM has expanded considerably across Upper Guinea, supported by the introduction of modern extraction techniques and chemical inputs. For a significant portion of the population in this region, artisanal mining provides essential income and contributes to improved livelihoods [1, 2]. In 2022, exports from artisanal mining reached approximately 63.5 t, generating over $55 million in revenues, while industrial and semi-industrial mining accounted for just 25.14 t [3]. Despite these economic contributions, ASGM is linked to extensive envi-

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ronmental damage and health risks, including the destruction of over 140 000 hectares of vegetation annually since 1965 [4]; soil and water pollution [5, 6]; abandonment of exploited pits without rehabilitation [7]; and the degradation of agricultural and pastoral lands [8, 9]. In such areas, heavy metal contamination is of particular concern [10, 11]. Nonbiodegradable elements such as lead (Pb), mercury (Hg), and cadmium (Cd) pose a critical global concern due to their persistence in the environment and potential to bioaccumulate in the food chain [12]. Several conventional remediation methods were developed, but they are often costly and may compromise soil fertility and ecosystem health [13, 14]. Biological approaches such as phytoremediation have emerged as promising alternatives due to their lower cost, environmental compatibility, and capacity for in situ application [15].

Phytoremediation is a green and cost-effective technique that uses the natural ability of plants, often in association with beneficial microbes, to absorb, stabilize, and detoxify contaminants in soil and water [16, 17]. This approach is particularly well suited to developing countries, offering the dual benefits of environmental restoration and biomass production for potential energy use [13]. However, degraded mining environments often present significant challenges for plant growth due to edaphoclimatic constraints [18, 19]. Several studies have highlighted the strong potential of indigenous plant species as valuable phytoresources for the remediation of heavy metal-contaminated sites, particularly gold mining environments [20–23]. The inventory and characterization of native plants are a crucial step for developing phytoremediation procedures. For instance, Petelka et al. [22] conducted an inventory of native and non-native flora at a gold mining site in Ghana, identifying 25 plant species capable of growing in soils polluted with arsenic, mercury, lead, and copper. Bansah and Addo [24] reported several species with the potential of Cu, Cd, and Pb phytoremediation at the AngloGold Ashanti site in Tarkwa, including *Pityrogramma calomelanos*, *Chromolaena odorata*, *Leucaena leucocephala*, and *Terminalia superba*. Furthermore, *Ceratopteris cornuta*, a native fern, was identified at the Obuasi Gold Mine in Ghana and accumulated up to 9.7 mg/kg of mercury in its aboveground tissues, highlighting its suitability for Hg phytoremediation. To date, no research has evaluated the phytoremediation potential of native plant species at gold mining sites in the Republic of Guinea. The present study constitutes the first systematic investigation in this context. Our study investigates the extent of heavy metal contamination at gold mining sites in Doko, Upper Guinea, and evaluates the potential of native plant species for phytoremediation. Specifically, the study aims to (i) characterize the physicochemical properties of soils affected by ASGM and assess the concentrations of heavy metals; and (ii) identify indigenous plant species with phytoremediation potential based on accumulation and translocation metrics.

2 | Materials and Methods

This research investigates phytoremediation using native plant species to reduce heavy metal mobility in mining-contaminated soils of Doko. Twelve dominant species were screened on the basis of their capacity to accumulate and translocate metals. Rhizospheric soils and plant tissues (roots and shoots) were sampled and digested, and metal concentrations were determined by inductively coupled plasma mass spectrometry (ICP-MS). Phytoremediation potential was assessed by calculating the bioconcentration factor (BCF), translocation factor (TF), and biological accumulation coefficient (BAC). Identifying metal-tolerant and metal-accumulating species is crucial for developing sustainable and cost-effective phytoremediation strategies in degraded mining environments, where conventional remediation methods are often impractical. To our knowledge, this study represents the first systematic assessment of the phytoremediation potential of native flora in the Doko artisanal gold mining area, thereby filling a major gap in knowledge for environmental management in Guinea.

2.1 | Description of Sampling Sites

Doko is a subprefecture in Guinea, part of the Siguiri prefecture, located at coordinates 11°47′ N, 8°58′ W (Figure 1). According to official demographic projections from the National Institute of Statistics of Guinea [25], the population of Doko was estimated at 83 133 inhabitants, compared to 86 782 recorded during the 2014 General Population and Housing Census (RGPH3, 2014). The locality lies approximately 838 km northeast of Conakry, the capital of Guinea, and about 172 km southwest of Bamako, the capital of Mali.

Doko is well known for its intensive artisanal and semi-industrial gold mining activities, which have historically shaped both the socioeconomic and environmental landscape of the region. The area belongs to the Siguiri gold district, one of the most productive in West Africa, located within the Birimian Greenstone Belt, a geological formation rich in auriferous quartz veins and sulfide-bearing schists [26, 27]. Gold mining in Doko dates back to the pre-colonial period, when traditional panning and manual extraction were the dominant techniques.

During the colonial era, French exploration missions identified the Siguiri basin as a promising gold province, leading to the first systematic surveys [28]. Since the 1990s, the expansion of ASGM has intensified due to economic liberalization and rising global gold prices. This activity constitutes the main source of income for a large proportion of the population in Doko, with seasonal influxes of miners from neighboring Mali and Burkina Faso [29].

However, this mining boom has also brought environmental challenges, including land degradation, deforestation, heavy metal contamination, and sedimentation of watercourses [30, 31]. The proliferation of artisanal mining sites has reshaped local ecosystems and created complex socio-environmental dynamics, making Doko a key site for studies on artisanal gold mining impacts and community resilience in Guinea.

Six artisanal gold mining sites were investigated in the Doko subprefecture and surrounding areas (Figure 2). The first site, the Doko Gold Panning Site, is located 6 km from the city center of Doko (11°46′28.852″ N, 008°53′59.788″ W; 430 m above sea level (a.s.l.)). It is characterized by degraded vegetation and lateritic soils. The mine is organized into two main zones: An extraction area and a processing area, where ore is washed manually without the use of mercury or other chemicals. Several nearby watercourses are dammed in places and show down-

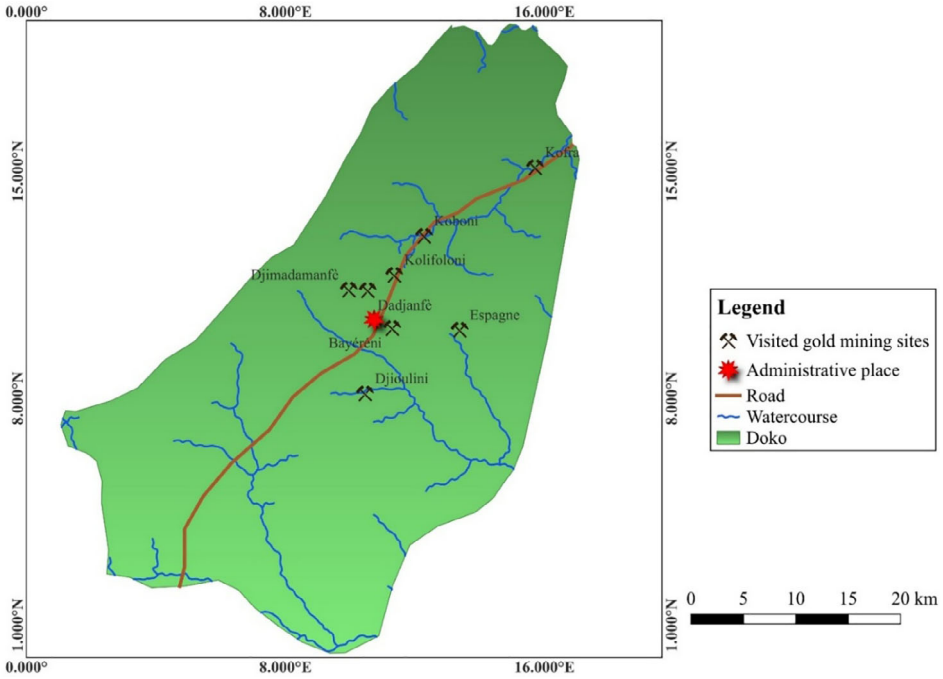


FIGURE 1 | Map of the study area shows artisanal gold mining sites.

stream pollution caused by drainage from ore washing. The Kolifoloni site lies in the Tomboko district, approximately 10 km from Doko (11°49′21.634″ N, 008°57′26.057″ W; 480 m a.s.l.). Its herbaceous vegetation develops during the rainy season but dries out completely during the dry season. This cover has been further degraded by human activities, particularly gold panning. The site is located close to a watercourse contaminated by drainage from mechanical ore washing, also carried out without chemical inputs. A total of 58 samples, including plant aboveground and root parts as well as soils, were collected at this site (Figure 2b). The Koboni site, situated in the Salla district about 12 km from Doko (11°51′24.455″ N, 008°55′51.899″ W; 348 m a.s.l.), is characterized by Sudanian-type savanna vegetation. Like the previous sites, it includes two distinct zones, one dedicated to ore extraction and the other to washing. From this site, 28 samples were collected, including both plant material and soil (Figure 2c). The Dadjanfè site, located 3 km from Doko (11°48′33.491″ N, 008°58′49.609″ W; 416 m a.s.l.), is another artisanal gold mining area. Local miners report that the groundwater table lies at a depth of 22–25 m. The site is organized into two main sectors: An extraction zone and a washing zone. In total, 38 samples of plants (aboveground and root parts) and soils were obtained (Figure 2d). Further downstream, the Banfelebougou site is located in the village of the same name within the Siguiri commune, on the right bank of the Niger River (11°25′24.848″ N, 009°04′34.417″ W; 340 m a.s.l.). The site is characterized by alluvial river soils and a gallery forest. Gold extraction occurs directly in the main riverbed, whereas ore washing is performed within the mining bed. From this location, 58 plant and soil samples were collected (Figure 2e). Finally, the Köfra site represents one of the largest artisanal gold mines in the region. It is located in Kouremalen, about 3 km from the village and over 20 km from Doko (11°55′00.523″ N, 008°50′02.011″ W; 336 m a.s.l.). Approximately 1000 miners, representing a total of about 1500 individuals, work at this site on a daily basis. The surrounding environment is dominated by Sud-Sudanian savanna vegetation, and the nearby Köfra River is strongly impacted by mining activities. A total of 58 samples, including plant aboveground and root parts and soils, were collected at this site (Figure 2f).

2.2 | Soil and Plant Sampling

Samples were collected from six artisanal gold mining sites: Banfelebougou, Espagne, Kolifoloni, Koboni, Dadjanfè, and Köfra, all located in the Siguiri prefecture. Twelve dominant plant species were selected and sampled (aboveground and root parts), with six replicates per species. Rhizospheric soils and soils near and at a distance (15 m) from the tailing deposits were also collected. The first step involved establishing relevels (vegetation plots), following the Braun-Blanquet method, which remains a cornerstone of phytosociology. Plots of uniform area 10 m × 10 m were laid out systematically across the sites [32]. In each plot, all plant species were recorded along with their cover-abundance using the modified Braun-Blanquet scale. This process resulted in a total of 358 samples, as detailed in Table 1. Samples were air-dried (30°C) for a week, then ground and prepared for further analyses.

2.2.1 | Plant Sample Mineralization

Plant samples are first dried thoroughly and then finely ground using an electric grinder. Up to 200 mg of the ground biomass is weighed and placed at the bottom of polytetrafluoroethylene (PTFE) tubes. Gradually, 1.5 mL of 69% concentrated HNO_3 is added in increments of 0.5 mL, allowing the solution to rest for approximately 15–20 min between each addition to prevent excessive reactions. The tubes are then sealed and placed in blocks at room temperature for 6 h. After this incubation period,



FIGURE 2 | Anthropogenic and mining activities in the studied sites: (a) Espagne; (b) Kolifoloni; (c) Koboni; (d) Dadjanfè; (e) Banfelebougou; and (f) Kofra.

TABLE 1 | Record of collected samples of soil and plants.

Plants		Soils		
Aboveground	**Root**	**Rhizospheric**	**Tailings**	**At 15 m from the tailing deposits**
96	96	96	10	10

1.5 mL of 37% concentrated HCl is added in small fractions of 0.5 mL, and the solution is heated for at least 6 h at 120°C. Following the heating, the mixture is allowed to cool for at least 1 h. Next, 1 mL of 30% concentrated H_2O_2 is added. The mixture is then heated again for 8 h at 120°C. Finally, after complete dissolution of the plant samples, the mixture was quantitatively transferred into a 10 mL tube and adjusted with distilled water.

2.2.2 | Soil Sample Mineralization

The soil samples were carefully dried and ground to obtain fine particles (<2 mm) before use. 50–100 mg of soil was weighed and placed into PTFE tubes. 2 mL of 69% concentrated HNO_3 is added and the mixture is incubated overnight at room temperature. Then, 1.5 mL of 37% concentrated HCl and 0.5 mL of 40%

concentrated hydrofluoric acid is added. The mixture is heated with the heating plates at 130°C with the caps tightly closed for 5 days. The tubes are cooled daily for 30 min and gently rotated to ensure droplets settle at the tube bottoms. They are then left open for about 10 min, stirred gently to release dissolved gases, and reheated. After 5 days, the mineralized solutions are transferred to 15 mL tubes, and a final volume of 10 mL is adjusted with distilled water.

2.2.3 | Determination of Metal Content

The concentrations of metals As, Cu, Ni, Cd, Sb, Zn, and Pb in soil and plant samples were determined using ICP-MS (inductively coupled plasma-mass spectrometry; Ultima2 JY, Horiba Company, Edison, NJ, USA) at the CEREGE-European Center for Research and Teaching in Environmental Geoscience according to Marguí et al. [33], with the white values deduced from the measurement.

2.2.4 | Measurement of Organic Matter (OM)

Soil OM was measured using the method described by Combs et al. [34]. Between 5 and 10 g of the soil sample were weighed using a precision balance and transferred to crucibles. The initial mass of the sample was recorded, and the crucibles were placed in an oven at 105°C for 4 h. After cooling for 45 min, the mass was measured ($M_{105°C}$). The crucibles were then incubated again at 400°C for 4 h. Following this, they were allowed to cool for at least 1 h and 30 min before the mass was reweighed ($M_{400°C}$). To measure the OM (M_o) content, the following equation is applied:

$$M_o = \frac{M_{105°C} - M_{400°C}}{M_{400°C}} \times 100 \quad (1)$$

2.2.5 | pH Measurement

The soil pH was determined on a 5:1 water/soil suspension. The mixture was stirred for 1 h using a magnetic stirrer, then left to settle for 30 min. The pH was measured directly in the supernatant using a pH meter (Bante210 Benchtop pH/mV Meter, Bante Instruments Co. LTD., Shanghai, China) [35].

2.2.6 | Soil Pollution Index (PI)

The soil PI is calculated by dividing the concentrations of metals in the soil (mg/kg) by the background metal concentration according to [36]. This background concentration corresponds to standard levels in uncontaminated soils [37]. Thus, the PI is calculated using the following equation:

$$PI = \frac{\left(\frac{[Fe]soil}{38} + \frac{[Ni]soil}{100} + \frac{[Cu]soil}{100} + \frac{[Zn]soil}{300} + \frac{[As]soil}{6} + \frac{[Cd]soil}{3} + \frac{[Sb]soil}{8.6} + \frac{[Hg]soil}{0.25} + \frac{[Pb]soil}{100}\right)}{9\,[metal]\,soil} \quad (2)$$

The PI is categorized as low (PI ≤ 1), moderate (1 ≤ PI ≤ 3), or high (PI > 3) according to the classification by Seklaoui et al. [38].

2.2.7 | Enrichment Factor (EF)

The EF is utilized to evaluate the impact of human activities on the natural environment. It is calculated using the following equation [39]:

$$EF = \frac{\left(\frac{C_i}{C_{réf}}\right) sample}{\left(\frac{C_i}{C_{ref}}\right) background} \quad (3)$$

where $(C_i/C_{réf})$ sample is the ratio between the content of the element of interest in the sample and its reference in the soil, and (C_i/C_{ref}) background is the ratio between the content of the reference metal in the sample and its natural background (average crust) [36]. In this study, aluminum (Al) is the reference metal.

Five contamination categories are generally recognized based on the EF [40]: EF < 1 (no enrichment); 1 ≤ EF < 10 (minimal enrichment); 10 ≤ EF < 100 (moderate enrichment); 100 ≤ EF < 1000 (significant enrichment); and EF > 1000 (extremely high enrichment).

2.2.8 | Ecological Risk Index (ERI)

The ERI quantifies the sensitivity of the biological community to a toxic substance and indicates the potential ecological risk resulting from overall contamination (Table 5) [41]. It is the sum of the individual E_i values for each heavy metal, where E_i represents the individual risk factor associated with the heavy metal:

$$ERI = \sum E_i \quad (4)$$

To determine the ERI, the initial step is to calculate the accumulation coefficient (C_f), which compares the concentration of a metallic element in a soil sample (C_i) to the reference concentration found in the average crust (C_b):

$$C_f = \frac{C_i}{C_b} \quad (5)$$

Then, calculate the potential ecological risk coefficient (E_i), which is determined by multiplying the accumulation coefficient (C_f) by the toxic response factor (T_i) of a metallic element according to Hakanson [42]:

$$E_i = C_f \times T_i \quad (6)$$

The potential ecological risk E_i is categorized into five classes: E_i < 40 (weak); 40 ≤ E_i < 80 (moderate); 80 ≤ E_i < 160 (considerable); 160 ≤ E_i < 320 (high); and E_i > 320 (very high) [43]. The ERI was categorized into four classes: ERI < 150 (weak); 150 ≤ ERI < 300 (moderate); 300 ≤ ERI < 600 (high); and ERI ≥ 600 (very high) [44].

2.2.9 | BCF, TF, and BAC

To evaluate the metal enrichment characteristics of different plant species, three factors were calculated.

The BAC is defined as the concentration of metals in the aboveground parts of plants divided by the concentration of metals in rhizospheric soils [45]. It is calculated using the following equation:

$$\text{BAC} = \frac{[\text{Metal}]\,\text{aerial part}}{[\text{Metal}]\,\text{rhizospheric soil}} \quad (7)$$

The TF is the ability of the metal to transfer from the root part to the aboveground parts of plants [46]. It is calculated using the following equation:

$$\text{TF} = \frac{[\text{Metal}]\,\text{aerial part}}{[\text{Metal}]\,\text{root}} \quad (8)$$

The BCF is obtained by dividing the metal concentration in plant roots by the metal concentration in rhizospheric soils [46]. This factor indicates the roots' accumulation capacity from the soil. It is calculated using the following equation:

$$\text{BCF} = \frac{[\text{Metal}]\,\text{root}}{[\text{Metal}]\,\text{rhizospheric soil}} \quad (9)$$

2.3 | Statistical Analyses

Differences in metal concentrations in aboveground and root parts among the 12 species were studied using one-way ANOVA. This analysis was performed separately for each metal in both aboveground and root parts. To identify significant differences between species for each metal concentration, Tukey HSD post hoc tests were used to establish homogeneous groups.

To investigate the relationships between metal concentrations in the aboveground and root parts of the studied species, a principal component analysis (PCA) was conducted using Xlstat. The data matrix contains the average values (5 replicates) of each metal in the shoots and roots of each species. Similarity between species in their metal accumulation capacity in aboveground and root parts was studied using hierarchical cluster analysis (HCA) with STATISTICA 10 (StatSoft Inc., Tulsa, OK, USA).

3 | Results and Discussion

3.1 | Soil Properties and Metal Concentrations

The soils from the artisanal gold mining sites under study exhibited a slightly alkaline pH, ranging from 8.04 to 8.92 (Table 2), indicating mildly basic conditions.

This alkalinity is likely shaped by a combination of lithological factors and human activities, particularly the dispersion of metallic dust and the disruption of soil horizons caused by mining activities. As noted by Tchassanti et al. [47], such variability often reflects spatial differences in soil composition, mining intensity, and local environmental interactions. Soil pH is a critical parameter influencing nutrient availability, microbial dynamics, and metals mobility [48] and thus directly affects vegetation establishment and persistence in contaminated areas.

TABLE 2 | Variations in pH and organic matter (OM) by sites.

Sites	pH	OM (%)
Espagne	8.26–8.47	1.89–10.17
Kolifoloni	8.6–8.87	3.21–3.37
Koboni	8.04–8.82	4.47–5.81
Dadjanfè	8.47–8.9	1.7–6.09
Kofra	8.53–8.92	0.73–3.39
Banfelebougou	8.25–8.9	2.36–10.45

The OM content varied widely, from 0.73% to 10.45% (Table 2). Using the fertility classification of Dabin (1956), cited in Tchassanti et al. [47], approximately 85% of samples fall within the "very high" fertility range (OM > 2.36%). OM plays a critical role in the formation of both soluble and insoluble metal complexes, thereby influencing metal mobility in the soil [49]. In addition to promoting plant growth, it stimulates soil microbial activity [50, 51]. However, Yassir and Sana [52] showed that elevated concentrations of heavy metals can suppress microbial activity and reduce populations of soil macrofauna, such as earthworm organisms, which are essential for nutrient cycling and the mineralization of OM.

Table 3 summarizes the concentrations of heavy metals (Fe, Ni, Cu, Zn, As, Cd, Sb, Hg, and Pb) measured at six artisanal gold mining sites (Espagne, Koboni, Kolifoloni, Dadjanfè, Banfelebougou, and Kofra), both within tailing deposits and at a distance of 15 m. The results reveal exceptionally high metal concentrations, indicating severe soil contamination directly linked to artisanal gold exploitation. Fe, As, Sb, and Pb exhibit particularly elevated levels. The Espagne site shows the highest degree of contamination, with Fe and As levels reaching 132 132.54 and 6430.70 mg/kg, respectively, in tailing soils far exceeding natural geochemical baselines. Although iron constitutes approximately 4.06% of the Earth's crust [53], the concentrations observed here greatly surpass lithogenic background values, reflecting strong anthropogenic enrichment. Arsenic levels are also notably high, consistent with the oxidation of arsenic-bearing minerals such as arsenopyrite commonly associated with gold ores [54, 55]. Substantial concentrations of Cu, Zn, Pb, and Sb further indicate the direct influence of mining residues. At 15 m from disposal areas, metal levels generally decrease, suggesting attenuation with distance. Nevertheless, persistently high values, particularly for Fe, Pb, and Sb, highlight potential mobility and dispersion through wind erosion and surface runoff, as previously noted by Quinton and Catt [56]. Clear spatial heterogeneity is evident across sites. Espagne and Dadjanfè exhibit the highest level of heavy metals, reflecting intensive mining activity and direct soil exposure to tailings. Conversely, Kolifoloni, Koboni, and Banfelebougou display comparatively lower but still elevated concentrations relative to background levels, confirming diffuse and widespread contamination in the study area. These findings align with previous studies reporting heavy metal enrichment in

TABLE 3 | Variations in the concentrations of heavy metals (mg/kg) in the soil samples.

Sites			Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb
Tailings											
Espagne	Concentrations in the soil (mg/kg)	Min	110 955.30	112.79	279.12	224.44	6238.88	0.41	118.02	0.10	175.97
		Max	132 132.54	140.60	301.36	272.52	6430.70	0.88	134.89	0.38	221.77
Koboni		Min	14 863.85	97.38	165.13	225.87	223.52	0.35	8.79	0.02	79.53
		Max	18 116.38	167.93	233.23	273.92	369.49	0.81	14.35	0.14	150.25
Kolifoloni		Min	111 933.41	78.10	444.79	301.83	257.20	0.34	9.12	0.10	21.82
		Max	132 132.54	127.30	450.58	364.07	283.72	0.49	10.75	0.16	29.07
Dadjanfè		Min	60 317.15	322.19	172.00	217.06	13.73	0.45	115.69	0.17	20.19
		Max	76 604.71	361.88	197.88	255.10	17.24	0.51	139.81	1.00	28.52
Banfelebougou		Min	20 175.46	306.93	517.00	964.35	31.21	0.68	71.55	0.09	13.17
		Max	34 086.83	378.98	598.36	1444.42	33.39	0.79	79.03	0.23	16.24
Kofra		Min	2484.03	79.73	110.01	1617.04	71.97	0.23	81.71	0.13	13.46
		Max	4750.56	103.87	126.73	1846.87	77.54	0.53	98.85	0.39	20.48
15 m from the tailing deposits											
Espagne	Concentrations in the soil (mg/kg)	Min	2204.03	236.98	256.98	314.21	1308.86	0.58	22.59	0.06	147.16
		Max	6907.84	295.79	319.88	389.46	1783.06	0.90	30.67	0.35	190.56
Koboni		Min	35 024.52	202.64	265.68	403.86	796.01	0.55	15.77	0.26	200.18
		Max	56 329.04	224.82	269.29	478.29	862.17	0.86	21.48	0.57	262.84
Kolifoloni		Min	13 464.33	79.95	269.84	155.78	158.38	0.67	32.60	0.17	21.48
		Max	17 282.15	86.41	280.89	160.48	188.60	0.95	37.88	0.23	28.48
Dadjanfè		Min	14 063.85	59.25	479.01	721.21	22.39	0.65	33.23	0.11	11.64
		Max	149 036.07	67.94	536.30	952.24	25.94	0.79	38.62	0.20	17.00
Banfelebougou		Min	2598.54	141.71	569.40	408.58	139.56	0.54	115.73	0.24	19.10
		Max	3226.46	165.48	610.46	459.37	164.71	0.68	196.99	0.39	29.86
Kofra		Min	56 329.04	107.47	103.40	908.82	66.46	0.30	53.67	0.08	18.81
		Max	59 712.54	129.66	127.09	957.26	78.12	1.63	56.83	0.19	25.17

mining-impacted regions across Africa. Fereja et al. [57] reported high Fe, As, and Pb concentrations around the abandoned Laga Dambi gold mine in Ethiopia, whereas Rasulov et al. [58] documented extreme Cd, Pb, Cu, Zn, Ni, Co, Cr, and Fe values in polluted industrial soils. Likewise, Mununga Katebe et al. [59] quantified pollution levels of soils, irrigation waters, and vegetables by As, Cd, Cr, Cu, Pb, Co, and Zn in urban gardens of Lubumbashi, Democratic Republic of the Congo.

The presence of such elevated concentrations of toxic metals substantially exceeding internationally accepted soil quality thresholds poses considerable ecotoxicological and public health risks. These contaminants may impair soil microbial functions, bioaccumulate in vegetation, leach into groundwater systems, and enter the food chain. Therefore, urgent intervention is required, including stabilization of mine residues, erosion control, and phytoremediation strategies to mitigate environmental and human health hazards associated with artisanal gold mining.

3.2 | PI and EFs

Table 4 presents the PI and EF calculated for soils collected from artisanal gold mining tailings and at a distance of 15 m from the deposits. The results clearly demonstrate severe anthropogenic disturbance and metal input into the soil environment. The PI values within the tailings indicate extreme levels of pollution, ranging from 6.34 (Koboni) to 120.27 (Espagne), highlighting intense contamination across all sampled locations. Although PI values decreased at 15 m from the tailings, they remained significantly elevated, with values between 3 (Kofra) and 30.01 (Espagne). According to the classification of Seklaoui et al. [38], these sites fall within the highly polluted to extremely polluted categories, reflecting the strong influence of artisanal and small-scale mining activities on soil quality.

The EF values reveal distinct patterns of metal enrichment. On the basis of the criteria of Liu et al. [40], no enrichment

TABLE 4 | Pollution index and soil enrichment factor studied.

Sites			Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb	PI
Tailings												
Espagne	Enrichment Factor	Min	152.25	0.21	0.34	0.41	41.23	0.09	8.82	0.06	0.36	**120.27**
		Max	443.63	0.59	1.09	1.18	138.78	0.15	26.76	0.07	0.99	
Koboni		Min	7.36	0.08	0.09	0.15	0.74	0.02	0.30	0.00	0.07	**6.34**
		Max	8.81	0.09	0.10	0.18	0.83	0.03	0.33	0.01	0.09	
Kolifoloni		Min	32.22	0.04	0.11	0.12	0.38	0.01	0.15	0.01	0.01	**6.41**
		Max	107.51	0.10	0.42	0.38	1.37	0.03	0.50	0.02	0.03	
Dadjanfè		Min	32.38	0.23	0.09	0.15	0.04	0.02	3.52	0.01	0.02	**2.09**
		Max	40.41	0.25	0.10	0.18	0.05	0.02	4.18	0.08	0.02	
Banfelebougou		Min	19.74	0.29	0.34	1.10	0.11	0.04	11.16	0.02	0.01	**3.19**
		Max	55.46	1.11	1.39	3.47	0.48	0.17	12.32	0.04	0.05	
Kofra		Min	2.82	0.08	0.07	1.44	0.26	0.02	3.32	0.02	0.02	**3.58**
		Max	2.85	0.12	0.12	2.43	0.46	0.03	5.32	0.03	0.02	
15 m from the tailing deposits												
Espagne	Enrichment Factor	Min	2.85	0.25	0.20	0.33	6.41	0.05	1.12	0.01	0.17	**30.01**
		Max	4.46	0.36	0.29	0.47	8.35	0.06	1.47	0.03	0.24	
Koboni		Min	6.28	0.03	0.03	0.07	0.53	0.01	0.14	0.01	0.04	**17.1**
		Max	13.42	0.10	0.10	0.20	1.70	0.02	0.34	0.02	0.11	
Kolifoloni		Min	36.45	0.24	0.58	0.44	2.21	0.19	4.53	0.06	0.08	**3.02**
		Max	47.56	0.37	0.93	0.72	3.11	0.22	6.53	0.07	0.11	
Dadjanfè		Min	59.43	0.10	0.60	1.44	0.17	0.07	2.52	0.03	0.03	**17.19**
		Max	171.73	0.31	1.87	3.78	0.50	0.08	7.54	0.06	0.07	
Banfelebougou		Min	0.49	0.03	0.09	0.09	0.14	0.01	1.70	0.01	0.01	**6.21**
		Max	1.00	0.07	0.21	0.21	0.30	0.02	2.52	0.01	0.01	
Kofra		Min	24.25	0.06	0.05	0.51	0.18	0.03	1.31	0.01	0.01	**3**
		Max	51.36	0.15	0.09	1.09	0.34	0.06	2.78	0.01	0.02	

or only background levels were recorded for Ni, Cu, Zn, Cd, Sb, and Pb at most sites, both within tailings and at 15 m distance. In contrast, moderate to high enrichment of As was observed particularly at the Espagne, Kolifoloni, and Dadjanfè sites, confirming that arsenic is a key contaminant mobilized during artisanal gold extraction. Notably, Fe displayed extremely high enrichment, especially at Espagne and Kolifoloni, suggesting either ore-derived contribution or the presence of Fe-rich parent lithology altered by mining activities. These findings are consistent with previous research in ASGM environments. Akoto et al. [60] reported elevated Fe and As enrichment around gold mining tailings in Nangodi, Ghana, emphasizing the release of As associated with arsenopyrite-rich mineral assemblages during ore crushing and amalgamation. Similarly, Compaore et al. [61] recorded moderate enrichment and geo-accumulation indices for As in mining soils of the Youga region in southern Burkina Faso, reaching concentrations of 286.55 ± 12.50 mg/kg. Such enrichment patterns reflect both geogenic factors (presence of As-bearing sulfides in ore veins) and anthropogenic drivers, primarily linked to mercury-based gold recovery techniques that further mobilize As during ore oxidation [62, 63]. Overall, the elevated PI and EF values confirm that artisanal gold mining is a major source of soil contamination, creating persistent metal-enriched environments with substantial ecological and human health implications. The persistence of elevated indices at 15 m distance suggests active dispersion mechanisms driven by runoff and wind, underscoring the urgent need for mitigation measures, including environmental monitoring, controlled waste disposal, and nature-based remediation strategies such as phytostabilization.

3.3 | Ecological Risk Index

The ERI showed pronounced spatial and site-specific variability across the study locations (Table 5). The highest ERI value was recorded at Espagne (9459.73) at the tailing source, indicating *extreme ecological risk*. This elevated risk substantially decreased at 15 m from the dumps (2469.28) yet remained within a level suggesting serious ecological threat, reflecting the strong persistence and mobility of contaminants, particularly arsenic and associated trace metals.

TABLE 5 | Ecological risk index of the sites.

Sites	Ecological risk index (ERI)	
	Tailings	15 m from the tailing deposits
Espagne	9459.73	2469.28
Koboni	568.11	1470.73
Kolifoloni	537.26	207.62
Dadjanfè	214.93	1472.88
Banfelebougou	297.27	444.22
Köfra	267.72	268.19

At Koboni, the ERI was lower at the tailings (568.11) but increased at 15 m (1470.73), implying potential lateral dispersion or secondary contamination pathways. Kolifoloni followed a similar attenuation trend, with ERI declining from 537.26 to 207.62, indicating reduced ecological pressure away from the source zone. Dadjanfè showed moderate ERI at the tailings (214.93) but a marked rise at 15 m (1472.88), suggesting contaminant accumulation downslope or in depositional zones. Banfelebougou demonstrated a gradual decline from 297.27 to 444.22, remaining in a moderate-to-considerable risk category. Köfra showed relatively stable ERI values between the two sampling points (267.72 vs. 268.19), reflecting limited contaminant dispersion but consistent pollution pressure.

Overall, ERI patterns generally decreased with distance from tailing deposits, consistent with expected dilution and dispersion processes; however, exceptions at Koboni and Dadjanfè highlight complex transport dynamics likely influenced by soil texture, hydrology, and artisanal mining disturbance. These findings align with the observations of Obiora et al. [64] and Merem et al. [65], who emphasized that elevated ERI values near mining areas represent substantial ecological and public health concerns.

In summary, despite some attenuation with distance, the measured ERI values indicate that soils in proximity to artisanal gold tailings remain significantly impacted by toxic metals. These conditions underscore the need for continuous monitoring and targeted remediation interventions, while also highlighting the potential role of metal-tolerant native vegetation for ecological stabilization and phytomanagement in these degraded landscapes.

3.4 | Identification of Plant Species Occurring at Artisanal Gold Mining Sites

A floristic inventory was conducted at various gold mining sites, identifying 12 dominant native species across six surveyed locations (Table 6, Figure 3). These species predominantly belong to the Fabaceae family. Additionally, as noted by Cissé [1], these species are part of five key woody plant families recorded in the Siguiri area: Fabaceae, Rubiaceae, Lamiaceae, Caesalpiniaceae, *and* Combretaceae.

3.5 | Heavy Metal Concentration in Plants

The levels of various metals in the aboveground and root parts of abundant native plants from the studied mining sites are indicated in Table 7, along with the phytotoxic and hyperaccumulation thresholds defined by Krämer [66]. The BCFs, TF, and BAC are presented in Table 8.

3.5.1 | Iron (Fe)

The concentrations of iron in the aboveground parts and roots differed significantly depending on the species (Table 7). The highest Fe concentration in the roots was observed in *Mimosa*

TABLE 6 | Abundant native species were identified.

Sites	Plant species	Families	Vernacular names
Espagne	*Detarium senegalense*	Caesalpiniaceae	Tamba or Tambanibaly
	Prosopis africana	Fabaceae	Gbéléni
	Acacia ataxacantha	Fabaceae	Solokawanin
Koboni	*Mitragyna inermis*	Rubiaceae	Djoun
Dadjanfè	*Detarium senegalense*	Caesalpiniaceae	Tamba or Tambanibaly
	Combretum glutinosum	Combretaceae	Demba
Kolifoloni	*Sarcosephalus latifolius*	Rubiaceae	Bady
	Cassia sieberiana	Fabaceae	Sindjan
	Hyptis suaveolens	Lamiaceae	Soukoura
Köfra	*Detarium senegalense*	Caesalpiniaceae	Tamba or Tambanibaly
	Pteleopsis suberosa	Combretaceae	Ternie
	Mimosa pigra	Fabaceae	Tri or Kali
Banfelebougou	*Copaifera salikounda*	Fabaceae	Djékoun
	Mitragyna inermis	Rubiaceae	Djoun
	Xanthocercis zambesiaca	Fabaceae	Kissa

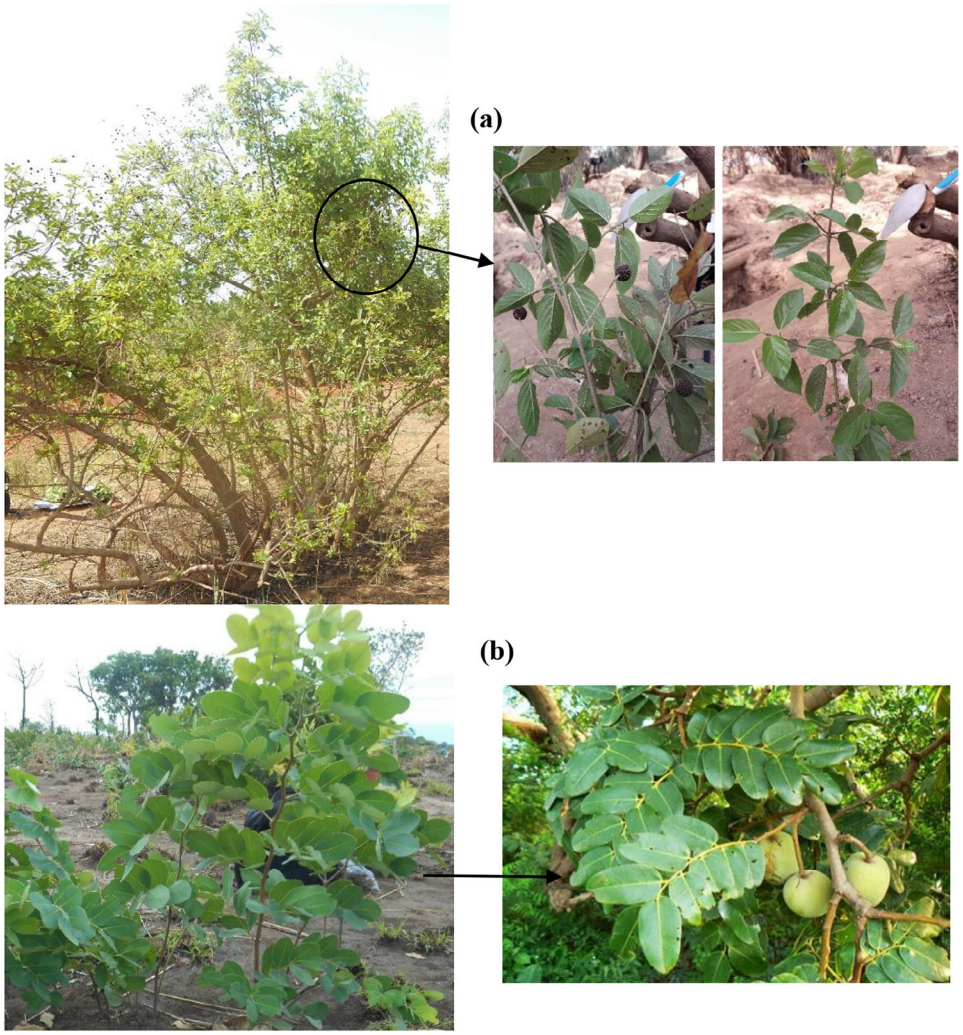


FIGURE 3 | Example of sampled species: (a) *Mitragyna inermis* and (b) *Detarium senegalense*.

pigra, with a value of 21 517.27 mg/kg DW. In contrast, the lowest concentration in the roots was recorded in the unidentified species preceding *Sarcosephalus latifolius*, with a value of 543.19 mg/kg DW. In the aboveground parts, the lowest Fe concentration was observed in Koboni in *Mitragyna inermis*, with 250.23 mg/kg DW. Conversely, *Hyptis suaveolens*, *M. pigra*, and *Pteleopsis suberosa* exhibited the highest concentrations in the aboveground parts, with *H. suaveolens* reaching 3872.05 mg/kg DW. The toxicity threshold of Fe varies depending on the plant type and environmental conditions [67, 68]. This variation is partly due to the fact that Fe is very abundant in soils, making it difficult to distinguish between normal and "excessive" accumulation levels compared to less common metals [69]. Fe is an essential element in plant metabolism and plays a crucial role in the production of proteins and enzymes, particularly those involved in chlorophyll synthesis and those necessary for major physiological processes such as respiration, photosynthesis, and macronutrient assimilation. Most plants have evolved efficient regulatory mechanisms to limit Fe uptake and avoid toxicity [70]. These homeostatic mechanisms operate at several levels (root uptake, chelation, transport, distribution, and storage) and help prevent Fe levels from rising to harmful concentrations [70].

Regarding the threshold for Fe hyperaccumulation in plants, there is still no scientific consensus on a precise threshold value, although some studies suggest a threshold of approximately 10 000 mg/kg in leaves [71]. Accordingly, none of the studied species reached this threshold in aboveground tissues, indicating that although some species are capable of significant Fe uptake, they do not qualify as Fe hyperaccumulators. It is important to note that hyperaccumulation is a relatively rare phenomenon and that the majority of hyperaccumulator species known to date are Ni accumulators [72].

The BCF, BAC, and TF were evaluated to assess the potential for metal accumulation, phytostabilization, and/or phytoextraction of plants [16]. According to Malik et al. [73]; Nazir et al. [45]; Sudmoon et al. [74], BCF, TF, and BAC are decisive factors for choosing species-specific strategies for the remediation of heavy metals in the environment. Among the studied species, three exhibited a TF greater than 1, namely, *H. suaveolens* (3.32) and *M. inermis* (Koboni site: 1.12), suggesting effective Fe translocation from roots to shoots (Table 8). However, our results revealed that eleven species had a BCF < 1 and twelve had a BAC < 1. These results indicate that none of the twelve plant species have the

TABLE 7 | Differences between heavy metal concentrations in pairs (mg/kg) in the shoots and roots of plants collected from the studied sites in the Doko area (Siguiri, Guinea).

Sites	Species	Parts	Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb
Banfel ebougou	*Xanthocercis zambesiaca*	Above-ground	(870 ± 37.95)^{ab}	(16.42 ± 0.94)^{e}	(21.46 ± 1.28)^{abc}	(42.70 ± 3.13)^{ab}	(2.90 ± 0.12)^{ab}	(0.09 ± 0.01)^{abcd}	(0.16 ± 0.17)^{ab}	(0.05 ± 0.00)^{c}	(3.01 ± 0.44)^{a}
		Root	(3870.25 ± 47.52)^{cd}	(11.82 ± 1.26)^{abcde}	(7.96 ± 0.30)^{a}	(27.34 ± 2.28)^{a}	(2.09 ± 0.21)^{ab}	(0.13 ± 0.01)^{bcde}	(0.07 ± 0.01)^{a}	(0.01 ± 0.00)^{ab}	(143.88 ± 45.47)^{b}
	Copaifera salikounda	Above-ground	(624.02 ± 55.57)^{ab}	(16.18 ± 2.23)^{de}	(25.26 ± 3.30)^{abc}	(59.34 ± 8.28)^{ab}	(5.82 ± 0.55)^{ab}	(0.08 ± 0.01)^{abc}	(0.06 ± 0.01)^{a}	(0.03 ± 0.00)^{abc}	(3.44 ± 1.22)^{a}
		Root	(1316.99 ± 61.96)^{ab}	(9.65 ± 0.54)^{abcde}	(10.42 ± 0.43)^{abc}	(32.70 ± 2.53)^{a}	(1.81 ± 0.21)^{ab}	(0.14 ± 0.02)^{cde}	(0.10 ± 0.01)^{a}	(0.01 ± 0.00)^{abc}	(36.75 ± 7.00)^{a}
	Mitragyna inermis	Above-ground	(451.93 ± 23.82)^{ab}	(14.29 ± 1.12)^{abcde}	(12.02 ± 1.36)^{abc}	(42.64 ± 5.82)^{ab}	(0.65 ± 0.05)^{ab}	(0.14 ± 0.02)^{abcd}	(0.07 ± 0.03)^{a}	(0.02 ± 0.00)^{bc}	(3.85 ± 0.68)^{a}
		Root	(2227.67 ± 148.46)^{ab}	(6.42 ± 0.61)^{a}	(14.12 ± 1.43)^{abc}	(44.84 ± 4.96)^{a}	(4.85 ± 1.15)^{ab}	(0.11 ± 0.01)^{abcd}	(0.15 ± 0.03)^{a}	(0.02 ± 0.00)^{abc}	(5.18 ± 0.51)^{a}
Koboni	*Mitragyna inermis*	Above-ground	(250.23 ± 23.71)^{a}	(8.61 ± 1.26)^{abcd}	(13.41 ± 2.09)^{abc}	(34.94 ± 6.63)^{a}	(0.41 ± 0.06)^{ab}	(0.03 ± 0.00)^{a}	(0.05 ± 0.02)^{a}	(0.01 ± 0.00)^{abc}	(1.42 ± 0.31)^{a}
		Root	(5136.49 ± 190.89)^{cd}	(30.80 ± 2.86)^{e}	(88.27 ± 7.26)^{bcd}	(158.84 ± 20.48)^{ab}	(47.95 ± 19.79)^{b}	(0.17 ± 0.02)^{de}	(0.53 ± 0.12)^{abc}	(0.08 ± 0.02)^{abc}	(14.22 ± 2.15)^{a}
Espagne	*Detarium senegalense*	Above-ground	(446.47 ± 81.46)^{a}	(5.69 ± 0.58)^{abcd}	(11.64 ± 1.07)^{abc}	(33.66 ± 2.15)^{a}	(3.57 ± 1.14)^{ab}	(0.07 ± 0.01)^{a}	(0.07 ± 0.03)^{a}	(0.02 ± 0.00)^{abc}	(4.46 ± 0.94)^{a}
		Root	(715.93 ± 99.75)^{cd}	(7.92 ± 1.53)^{e}	(6.91 ± 0.52)^{bcd}	(17.00 ± 1.50)^{ab}	(1.31 ± 0.25)^{b}	(0.24 ± 0.04)^{de}	(0.08 ± 0.01)^{abc}	(0.01 ± 0.00)^{abc}	(9.88 ± 0.82)^{a}
	Prosopis africana	Above-ground	(519.04 ± 64.96)^{a}	(10.18 ± 1.45)^{abcde}	(12.80 ± 1.50)^{abc}	(67.53 ± 4.59)^{ab}	(2.37 ± 0.42)^{ab}	(0.07 ± 0.02)^{ab}	(0.08 ± 0.02)^{a}	(0.04 ± 0.00)^{abc}	(5.01 ± 0.99)^{a}
		Root	(875.55 ± 65.90)^{ab}	(6.91 ± 0.69)^{abc}	(9.31 ± 0.72)^{abc}	(31.81 ± 2.08)^{a}	(1.55 ± 0.40)^{ab}	(0.06 ± 0.01)^{ab}	(0.11 ± 0.03)^{a}	(0.01 ± 0.00)^{ab}	(4.43 ± 0.40)^{a}
	Acacia ataxacantha	Above-ground	(915.78 ± 44.16)^{ab}	(6.48 ± 0.77)^{abcde}	(11.86 ± 0.49)^{abc}	(33.83 ± 3.06)^{a}	(10.07 ± 0.36)^{ab}	(0.06 ± 0.02)^{ab}	(0.14 ± 0.02)a	(0.02 ± 0.00)^{abc}	(5.02 ± 1.09)^{a}
		Root	(927.39 ± 57.87)^{ab}	(5.48 ± 0.45)^{ab}	(8.46 ± 1.34)^{ab}	(23.56 ± 3.51)^{a}	(2.65 ± 1.05)^{ab}	(0.07 ± 0.01)^{abc}	(0.09 ± 0.03)^{a}	(0.01 ± 0.00)^{ab}	(4.72 ± 1.31)^{a}
	Acacia ataxacantha in tailing deposits	Above-ground	(466.91 ± 58.84)^{ab}	(11.45 ± 1.21)^{abcde}	(11.25 ± 0.84)^{abc}	(35.76 ± 3.05)^{a}	(2.63 ± 0.32)^{ab}	(0.06 ± 0.01)^{ab}	(0.07 ± 0.01)^{a}	(0.05 ± 0.01)^{abc}	(4.75 ± 0.84)^{a}
		Root	(543.19 ± 21.11)^{ab}	(5.87 ± 0.93)^{ab}	(6.37 ± 0.89)^{ab}	(31.21 ± 4.62)^{a}	(1.55 ± 0.50)^{ab}	(0.07 ± 0.01)^{abc}	(0.07 ± 0.01)^{a}	(0.01 ± 0.00)^{ab}	(6.17 ± 1.46)^{a}

(Continues)

TABLE 7 | (Continued)

Sites	Species	Parts	Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb
Kolifoloni	*Sarcos-ephalus latifolius*	Above-ground	(482.45 ± 64.50)^{a}	(14.27 ± 2.20)^{cde}	(19.05 ± 3.21)^{abc}	(44.96 ± 2.70)^{ab}	(4.97 ± 0.67)^{ab}	(0.06 ± 0.02)^{ab}	(0.06 ± 0.02)^{a}	(0.02 ± 0.00)^{abc}	(4.58 ± 0.88)^{a}
		Root	(721.44 ± 42.71)^{ab}	(7.47 ± 1.22)^{abc}	(7.60 ± 1.18)^{ab}	(24.88 ± 4.12)^{a}	(1.15 ± 0.26)^{ab}	(0.06 ± 0.01)^{ab}	(0.07 ± 0.01)^{a}	(0.01 ± 0.00)^{a}	(3.04 ± 0.63)^{a}
	Cassia sieberiana	Above-ground	(756.92 ± 13.29)^{ab}	(13.31 ± 1.53)^{bcde}	(16.37 ± 1.56)^{abc}	(48.85 ± 5.92)^{ab}	(7.49 ± 0.77)^{a}	(0.06 ± 0.01)^{ab}	(0.10 ± 0.01)^{a}	(0.02 ± 0.00)^{abc}	(2.42 ± 0.57)^{a}
		Root	(890.95 ± 48.05)^{ab}	(6.11 ± 0.79)^{ab}	(7.65 ± 0.92)^{a}	(46.34 ± 2.23)^{ab}	(6.08 ± 1.07)^{ab}	(0.10 ± 0.01)^{abcde}	(0.10 ± 0.01)^{a}	(0.01 ± 0.00)^{a}	(4.00 ± 0.61)^{a}
	Hyptis suaveolens	Above-ground	(3872.05 ± 623.68)^{cd}	(8.26 ± 0.92)^{abcde}	(25.33 ± 2.87)^{abc}	(64.94 ± 5.35)^{ab}	(43.07 ± 4.27)^{d}	(0.05 ± 0.01)^{a}	(0.50 ± 0.14)^{d}	(0.03 ± 0.01)^{abc}	(4.25 ± 0.69)^{a}
		Root	(1166.77 ± 108.33)^{ab}	(5.55 ± 1.52)^{abc}	(14.42 ± 2.83)^{abc}	(66.33 ± 12.02)^{ab}	(4.07 ± 1.00)^{ab}	(0.08 ± 0.02)^{abcd}	(0.09 ± 0.03)^{a}	(0.01 ± 0.00)^{abc}	(2.70 ± 0.72)^{a}
Dadjanfè	*Detarium senegalense*	Above-ground	(440.50 ± 45.13)^{a}	(10.41 ± 1.89)^{abcd}	(20.71 ± 2.51)^{abc}	(43.05 ± 4.11)^{a}	(0.87 ± 0.13)^{ab}	(0.03 ± 0.01)^{a}	(0.08 ± 0.01)^{a}	(0.01 ± 0.00)^{abc}	(1.77 ± 0.49)^{a}
		Root	(22745.86 ± 296.63)^{cd}	(10.98 ± 3.18)^{e}	(9.12 ± 3.07)^{bcd}	(38.69 ± 8.19)^{ab}	(3.01 ± 1.00)^{b}	(0.04 ± 0.01)^{de}	(0.12 ± 0.05)^{abc}	(0.01 ± 0.00)^{abc}	(3.85 ± 0.47)^{a}
	Combretum glutinosum	Above-ground	(529.54 ± 1.094)^{a}	(10.62 ± 1.24)^{abcde}	(21.52 ± 2.29)^{abc}	(43.17 ± 3.42)^{ab}	(1.18 ± 0.12)^{ab}	(0.08 ± 0.01)^{abc}	(0.09 ± 0.02)^{a}	(0.02 ± 0.00)^{abc}	(1.81 ± 0.38)^{a}
		Root	(3598.26 ± 119.40)^{d}	(8.59 ± 0.25)^{abcd}	(11.17 ± 1.89)^{abc}	(68.16 ± 5.63)^{ab}	(1.54 ± 0.51)^{ab}	(0.13 ± 0.02)^{bcde}	(0.24 ± 0.05)^{abc}	(0.01 ± 0.00)^{a}	(10.28 ± 0.38)^{a}

(Continues)

TABLE 7 | (Continued)

Sites	Species	Parts	Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb
Kofra	*Mitragyna inermis*	Above-ground	(908.10 ± 75.73)^{ab}	(8.50 ± 2.90)^{abcde}	(23.02 ± 8.86)^{abc}	(40.27 ± 10.80)^{ab}	(5.16 ± 1.65)^{ab}	(0.05 ± 0.01)^{abcd}	(0.09 ± 0.01)^{a}	(0.06 ± 0.03)^{bc}	(2.02 ± 0.21)^{a}
		Root	(809.25 ± 75.32)^{ab}	(3.60 ± 0.24)^{a}	(7.83 ± 0.38)^{abc}	(23.65 ± 0.93)^{a}	(2.07 ± 0.22)^{ab}	(0.05 ± 0.00)^{abcd}	(0.09 ± 0.01)^{a}	(0.01 ± 0.00)^{abc}	(2.12 ± 0.33)^{a}
	Pteleopsis suberosa	Above-ground	(1671.69 ± 77.08)^{ab}	(53.85 ± 3.00)^{h}	(50.53 ± 2.34)^{d}	(235.25 ± 37.78)^{b}	(2.77 ± 0.34)^{ab}	(0.61 ± 0.06)^{g}	(0.24 ± 0.05)^{abc}	(0.13 ± 0.01)^{f}	(12.80 ± 1.68)^{a}
		Root	(3397.92 ± 277.17)^{cd}	(34.48 ± 2.60)^{f}	(35.21 ± 3.16)^{c}	(90.73 ± 14.28)^{d}	(4.73 ± 0.55)^{ab}	(0.22 ± 0.03)^{f}	(0.30 ± 0.06)^{bc}	(0.05 ± 0.00)^{c}	(17.18 ± 1.27)^{a}
	Mimosa pigra	Above-ground	(2596.52 ± 54.24)^{ab}	(54.30 ± 1.43)^{h}	(94.00 ± 1.40)^{e}	(318.92 ± 22.43)^{e}	(5.88 ± 0.23)^{ab}	(0.16 ± 0.03)^{e}	(0.36 ± 0.03)^{c}	(0.07 ± 0.00)^{e}	(7.02 ± 0.52)^{a}
		Root	(21 517.27 ± 425.01)^{e}	(43.08 ± 2.09)^{g}	(108.45 ± 4.01)^{e}	(166.70 ± 10.92)^{c}	(29.69 ± 1.45)^{c}	(0.25 ± 0.04)^{f}	(0.91 ± 0.09)^{e}	(0.06 ± 0.00)^{e}	(13.80 ± 1.90)^{a}
Toxicity of metal concentration	ND	10–50	20–30	100–300	2–80	0.1–3	2	ND	0.6–28		
Hyperaccumulation threshold	ND	>1000	>1000	>10000	>1000	>100	>1000	>10	>1000		

Note: The values in the table represent the mean concentrations of heavy metals in the aboveground and roots of each plant species. Mean values followed by the same letter are not significantly different each other.

TABLE 8 | Phytoremediation factors (biological accumulation coefficient [BAC], translocation factor [TF], and bioconcentration factor [BCF]) of the studied plant species.

Sites	Species	Factors	Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb
Banfelebougou	*Xanthocercis zambesiaca*	BAC	0.37	0.10	0.19	0.11	0.01	0.09	0.09	0.27	0.04
		TF	0.22	**1.39**	**2.70**	**1.56**	**1.39**	0.67	2.46	**4.32**	0.02
		BCF	**1.66**	0.07	0.07	0.07	0.01	0.13	0.04	0.06	**1.70**
	Coepaifera salikounda	BAC	0.15	0.05	0.11	0.11	0.02	0.08	0.02	0.15	0.03
		TF	0.47	**1.68**	**2.42**	**1.81**	**3.21**	0.53	**0.65**	**2.27**	0.09
		BCF	0.32	0.03	0.05	0.06	0.01	0.16	0.04	0.06	0.33
	Mitragyna inermis	BAC	0.05	0.03	0.04	0.09	0.00	0.11	0.02	0.05	0.03
		TF	0.20	**2.23**	0.85	0.95	0.13	**1.22**	0.44	**1.13**	0.74
		BCF	0.26	0.01	0.05	0.09	0.02	0.09	0.04	0.05	0.04
Koboni	*Mitragyna inermis*	BAC	0.01	0.03	0.06	0.08	0.01	0.07	0.00	0.35	0.02
		TF	**1.12**	**2.36**	**2.94**	**1.70**	**2.49**	**1.09**	0.97	**5.40**	0.95
		BCF	0.01	0.01	0.02	0.04	0.00	0.06	0.00	0.06	0.02
Espagne	*Detarium senegalense*	BAC	0.01	0.02	0.05	0.04	0.01	0.09	0.00	0.07	0.03
		TF	0.62	0.72	**1.69**	**1.98**	**2.72**	0.28	0.87	**2.22**	0.45
		BCF	0.02	0.03	0.03	0.02	0.00	0.33	0.01	0.03	0.06
	Prosopis africana	BAC	0.01	0.03	0.04	0.09	0.00	0.07	0.00	0.09	0.02
		TF	0.59	**1.82**	**1.38**	**2.12**	**1.53**	**1.20**	0.70	**4.43**	**1.13**
		BCF	0.02	0.02	0.03	0.04	0.00	0.06	0.01	0.02	0.02
	Acacia ataxacantha	BAC	0.01	0.02	0.03	0.03	0.01	0.04	0.01	0.05	0.02
		TF	0.99	**1.18**	**1.40**	**1.44**	**3.79**	0.82	**1.52**	**2.07**	**1.06**
		BCF	0.01	0.01	0.02	0.02	0.00	0.05	0.00	0.02	0.02
	Acacia ataxacantha in tailing deposits	BAC	0.01	0.03	0.03	0.06	0.01	0.10	0.01	0.18	0.02
		TF	0.86	**1.95**	**1.77**	**1.15**	**1.70**	0.87	**1.07**	**6.91**	0.77
		BCF	0.01	0.02	0.02	0.05	0.00	0.11	0.01	0.03	0.03
Kolifoloni	*Sarcosephalus latifolius*	BAC	0.01	0.07	0.08	0.11	0.00	0.10	0.00	0.09	0.03
		TF	0.67	**1.91**	**2.51**	**1.81**	**4.31**	**1.11**	0.87	**3.47**	**1.51**
		BCF	0.01	0.04	0.03	0.06	0.00	0.09	0.00	0.03	0.02
	Cassia sieberiana	BAC	0.23	0.07	0.10	0.14	0.01	0.13	0.01	0.28	0.03
		TF	0.85	**2.18**	**2.14**	**1.05**	**1.23**	0.63	**1.07**	**2.70**	0.61
		BCF	0.27	0.03	0.04	0.13	0.01	0.20	0.01	0.10	0.04
	Hyptis suaveolens	BAC	0.06	0.02	0.04	0.11	0.01	0.07	0.02	0.13	0.03
		TF	**3.32**	**1.49**	**1.76**	0.98	**10.57**	0.55	**5.29**	**4.58**	**1.57**
		BCF	0.02	0.01	0.02	0.11	0.00	0.13	0.00	0.03	0.02
Dadjanfè	*Detarium senegalense*	BAC	0.01	0.04	0.09	0.05	0.00	0.03	0.00	0.04	0.01
		TF	0.15	0.95	**2.27**	**1.11**	0.29	0.71	0.65	**1.93**	0.46
		BCF	0.08	0.04	0.04	0.04	0.01	0.05	0.01	0.02	0.03
	Combretum glutinosum	BAC	0.01	0.04	0.11	0.12	0.00	0.14	0.00	0.06	0.01
		TF	0.15	**1.24**	**1.93**	0.63	0.76	0.61	0.37	**2.19**	0.18
		BCF	0.09	0.04	0.06	0.19	0.00	0.23	0.01	0.03	0.08

(Continues)

TABLE 8 | (Continued)

Sites	Species	Factors	Fe	Ni	Cu	Zn	As	Cd	Sb	Hg	Pb
Kofra	*Detarium senegalense*	BAC	0.00	0.03	0.05	0.08	0.00	0.05	0.00	0.06	0.01
		TF	0.05	0.28	0.15	0.22	0.01	0.17	0.10	0.19	0.10
		BCF	0.08	0.12	0.34	0.35	0.10	0.31	0.02	0.33	0.07
	Pteleopsis suberosa	BAC	0.16	0.30	0.29	0.41	0.01	0.77	0.04	0.88	0.11
		TF	0.49	**1.56**	**1.44**	**2.59**	0.58	**2.73**	0.82	**2.91**	0.75
		BCF	0.33	0.19	0.21	0.16	0.02	0.28	0.04	0.30	0.14
	Mimosa pigra	BAC	0.06	0.18	0.29	0.68	0.01	0.22	0.01	0.48	0.04
		TF	0.12	**1.26**	0.87	**1.91**	0.20	0.64	0.39	**1.34**	0.51
		BCF	0.46	0.14	0.34	0.36	0.04	0.34	0.04	0.36	0.08

potential to be used for Fe phytoextraction. In contrast, *Xanthocercis zambesiaca* showed potential for Fe phytostabilization with limited translocation (TF = 0.22) and strong Fe accumulation ability in roots (BCF = 1.66; BAC = 0.37).

3.5.2 | Nickel (Ni)

In the present study, the highest concentrations of Ni in roots were observed in *M. pigra* (43.08 mg/kg DW), followed by *P. suberosa* (34.48 mg/kg DW), Koboni (unidentified species) (30.80 mg/kg DW), and *X. zambesiaca* (11.82 mg/kg DW) (Table 7). For the aboveground parts, the lowest Ni accumulation was found in *Detarium senegalense* (5.69 mg/kg DW), whereas the highest concentration was observed in *M. pigra* (54.30 mg/kg DW), followed closely by *P. suberosa* (53.85 mg/kg DW) and *X. zambesiaca* (16.42 mg/kg DW). Other species with notable Ni accumulation include *S. latifolius* (14.27 mg/kg DW) (Table 7).

These results are lower than those reported by Kahangwa et al. [75], who found Ni concentrations of up to 3126 mg/kg DW in the aboveground parts and 4464 mg/kg DW in the roots of *L. leucocephala* growing in artisanal gold-mining areas of Tanzania. This high accumulation is attributable to the local abundance of Ni, whereas the lower Ni levels observed at our study sites likely reflect the distinct geological characteristics of the area. According to Krämer [66], none of the plants sampled from the different sites exceeded the phytotoxic Ni concentrations. This is due to the low concentration of Ni in the soil [18]. Furthermore, Reeves [76] found that none of the studied plants exceeded the threshold of Ni hyperaccumulation (10 000 mg/kg DW).

None of the plants collected from the different sites had a BCF > 1 (Table 8). However, eleven plant species have TFs greater than 1, namely, *Copaifera salikounda* (1.68), *X. zambesiaca* (1.39), *M. inermis* (Banfelebougou and Koboni, sites) (2.23 and 2.36, respectively), *Prosopis africana* (2.04), *Acacia ataxacantha* (Espagne and Doko sites: TF = 1.18 and 1.95, respectively), *S. latifolius* (1.91), *Cassia sieberiana* (2.18), *H. suaveolens* (1.49), *Combretum glutinosum* (1.24), *P. suberosa* (1.56), and *M. pigra* (1.26) (Table 8). These plants have a good capacity to translocate Ni from roots to shoots [77]. BAC values ranged from 0.02 in *D. senegalense* and *H. suaveolens* to 0.18 in *M. pigra*. On the basis of these results, none of the studied plant species showed potential for phytostabilization (BCF > 1 with BAC and TF < 1) or phytoextraction (BCF, TF, and BAC > 1) of Ni [78].

3.5.3 | Copper (Cu)

Among the analyzed plant species, Cu accumulation in roots ranged from 6.37 mg/kg DW in *A. ataxacantha* to 108.45 mg/kg DW in *M. pigra*, whereas the Cu concentration in the aboveground parts ranged from 10.62 mg/kg DW in *D. senegalense* to 94.00 mg/kg DW in *M. pigra*. As already concluded by Nkansah and Belford [79], Cu accumulation differs immensely with plant species. This variation is regulated by several factors such as soil physicochemical and climatic conditions, the efficiency of Cu uptake from the soil, and their subsequent translocation to aboveground plant tissues [80–82].

Cu TF was higher than one (TF > 1) in eleven plant species, namely: *C. salikounda* (2.42), *X. zambesiaca* (2.70), *M. inermis* (Koboni site: 2.94), *D. senegalense* (1.54; 2.27), *P. africana* (1.38), *Cassia ataxacantha* (1.40–1.77 depending on site), *S. latifolius* (2.51), *C. sieberiana* (2.14), *H. suaveolens* (1.76), *C. glutinosum* (1.93), and *P. suberosa* (1.44) (Table 8). These species therefore demonstrated efficient mobility of Cu from roots to shoots.

However, none of the 12 plant species possessed BACs and BCF greater than 1 (Table 8). Only *M. pigra* and *P. suberosa* accumulated Cu above the reported level of phytotoxicity (20–30 mg/kg DW; [66]) in plant tissues, suggesting tolerance at high Cu concentrations. None of the studied plants exceeded the threshold for copper hyperaccumulation (>1000 mg/kg in aboveground biomass [83]). As Mganga [82] explains, plants with translocation and bioaccumulation values below one are excluded and are not suitable for heavy metal extraction from soils. Consequently, none of the plant species analyzed in the present study are good candidates for Cu-phytoextraction or Cu-phytostabilization.

3.5.4 | Zinc (Zn)

Zinc accumulation in roots ranged from 17.00 mg/kg DW in *D. senegalense* to 166.70 mg/kg DW in *M. pigra* (Table 7). In aboveground tissues, *M. pigra* also showed the highest Zn concentration

(318.92 mg/kg DW), followed by *P. suberosa* (235.25 mg/kg DW), both sampled at the Köfra site. The Zn content of the aboveground parts of *P. suberosa* and *M. pigra* reached or exceeded the phytotoxicity threshold of 100–300 mg/kg DW reported by Kabata-Pendias and Mukherjee [84], suggesting that these species are Zn-tolerant under field conditions (Table 7).

High Zn accumulation in plant tissues growing on contaminated substrates has been reported in several studies. Mkumbo et al. [85] recorded 1000 mg/kg DW of Zn in the roots of *Erato polymioides* from a gold mining area in southern Ecuador. Chamba-Eras et al. [86] found 1510.33 mg/kg DW of Zn in the roots of *Stylochaeton natalensis*, 664.35 mg/kg DW in the aboveground part of *Pteridium aquilinum* (L.) Kulm, and 13.13 mg/kg DW of Zn in the aboveground parts of *Celosia trigyna* (L.) from a Tanzanian gold mine. Similarly, Cruzado-Tafur et al. [87] have detected high Zn concentrations in leaves of *Baccharis alnifolia* (172 mg/kg DW), *Achyrocline alata* (267 and 198 mg/kg DW), *Chusquea scandens* (153 mg/kg DW), and *Nicotiana thyrsiflora* (635 mg/kg DW). In other research, the Zn concentration in aerial parts reached 2008 mg/kg DW in Ecuador, 303–517 mg/kg DW in Chile, and 15–3414 mg/kg DW in Spain [88–90]. Such variations are primarily linked to the heterogeneity of metal concentrations in soils and to soil physicochemical properties.

The BCF ranged from 0.07 (*X. zambesiaca*, *D. senegalense*, and *A. ataxacantha*) to 0.36 (*M. pigra*) (Table 8). Ten plant species had a TF value superior than 1, including *Copaifera africana* (1.56), *X. zambesiaca* (1.56), *M. inermis* (Koboni) (1.70), *D. senegalense* (Espagne (1.98) and Dadjanfè (1.11)), *P. africana* (2.12), *A. ataxacantha* (1.15–1.44 depending on site), *S. latifolius* (1.81), *C. sieberiana* (1.05), *P. suberosa* (2.59), and *M. pigra* (1.91) (Table 8), which indicated their ability to translocate Zn. None of the studied species had a BAC greater than 1. The highest BAC (0.68) was recorded in *M. pigra*, whereas the lowest (0.04) was found in *A. ataxacantha* (Espagne–Doko extraction area). In addition, no species met the hyperaccumulation criterion for Zn (>10 000 mg/kg DW in aboveground biomass), as defined by Baker and Brooks [91]. The combined analysis of BCF, TF, and BAC values therefore indicates that none of the investigated plant species present potential for Zn phytoextraction or Zn phytostabilization.

3.5.5 | Arsenic (As)

The total arsenic (As) concentrations in roots and aboveground parts of the sampled plant species are presented in Table 7. *M. pigra* and *D. senegalense* recorded the highest As concentrations in the roots (29.69 and 47.95 mg/kg DW, respectively), whereas *S. latifolius* showed the lowest value (1.15 mg/kg DW). In aboveground tissues, *H. suaveolens* accumulated the highest concentration (43.07 mg/kg DW), while the lowest was observed in *D. senegalense* at the Köfra site (0.41 mg/kg DW). As previously discussed, the level of heavy metal accumulation in plant organs depends on both the metal and the plant species involved [79, 92]. Similar findings have been reported in other mining contexts. Kahangwa et al. [75] reported As concentrations of 45.56 mg/kg DW in the aboveground parts of *Lantana camara* and 68.61 mg/kg DW in the roots of *L. leucocephala* growing in artisanal gold-mining areas in Tanzania. Petelka et al. [22] also reported As concentrations ranging from 20.75 to 40.25 mg/kg DW in plant species from the Damang gold mine in Ghana. The search for and characterization of efficient As-hyperaccumulating species in their natural habitats is still a key step towards the successful phytoremediation of this metal [16].

In the present study, 9 of the 12 plant species exhibited TF > 1, indicating their efficiency in translocating As from roots to aboveground parts. These include *H. suaveolens* (10.57), *C. sieberiana* (1.23), *S. latifolius* (4.31), *A. ataxacantha* (3.79), *P. africana* (1.53), *D. senegalense* (2.72), *M. inermis* (2.49), *X. zambesiaca* (1.39), and *C. africana* (3.21). However, none of the plant species examined reached the As hyperaccumulation threshold [93] or the phytotoxicity threshold defined by Krämer [66]; all had BAC and BCF values below 1 (Table 8). In our study, none of the studied plants were suitable for As phytostabilization or phytoextraction.

3.5.6 | Cadmium (Cd)

Cadmium (Cd) concentrations in roots ranged from 0.04 mg/kg DW in *D. senegalense* to 0.25 mg/kg DW in *M. pigra* (Table 7). In the aboveground parts, *P. suberosa* recorded the highest Cd concentration, followed by *M. pigra*. Comparable Cd concentrations in plant shoots from mining environments have been documented previously, including 11 mg/kg DW in *Erato polymnoides* from an artisanal mining site in Ecuador [80]; 9 mg/kg DW in *Aerva lanata* (L.) at a gold-mine tailings site in northern Mara, Tanzania [82]; 21 mg/kg DW in *Ludwigia stolonifera* from the same region [92]; 3–6 mg/kg DW in *Taraxacum officinalis*, *Coriaria thymifolia*, *Erythraea quitensis*, and *Panicum agrostoides* from South America [88]. Three plant species had Cd concentrations between 0.1 and 3 mg/kg DW (phytotoxicity threshold) (Table 7). According to the present study, *C. sieberiana, P. suberosa*, and *M. pigra* are considered Cd-tolerant species.

The BCF for Cd ranged from 0.09 (*C. glutinosum*) and 0.26 (*M. inermis*) to 0.34 (*M. pigra*) (Table 8). Four species showed a TF (TF > 1), indicating their ability to transport Cd from roots to shoots: *M. inermis* (1.22 and 1.09 in Banfelebougou and Koboni, respectively), *P. africana* (1.20), *S. latifolius* (1.11), and *P. suberosa* (2.73) (Table 8). However, all species displayed BAC < 1, ranging from 0.02 (*S. latifolius*) to 0.77 (*P. suberosa*), indicating a limited capacity to transfer Cd from soil to plant tissues. Consistent with earlier research [94–97], Cd concentrations were generally higher in roots than in aerial tissues, which reduces the efficiency of phytoextraction. On the basis of hyperaccumulation threshold defined by Kabata-Pendias and Mukherjee [84], none of the plants gathered are Cd hyperaccumulators nor do they have sufficient potential for Cd phytoextraction or phytostabilization [98].

3.5.7 | Antimony (Sb)

Antimony (Sb) concentrations in the roots and aboveground parts of the sampled plant species are presented in Table 7. Sb concentrations in roots ranged from 0.07 mg/kg DW in *A. ataxacantha* and *S. latifolius* to 0.91 mg/kg DW in *M. pigra*. In aboveground tissues, *D. senegalense* exhibited the lowest Sb concentration (0.05 mg/kg DW), whereas *H. suaveolens* showed

the highest (0.50 mg/kg DW) (Table 7). As highlighted by Feng et al. [99], elevated Sb levels in soils do not necessarily result in proportional Sb accumulation within plant tissues. Sb uptake and internal redistribution depend on several factors, including Sb bioavailability in soils, its chemical speciation, and the presence and interactions of coexisting ions such as calcium (Ca) and phosphorus (P) [99]. Our findings are similar to those of Wang et al. [100], who observed similarly low Sb uptake in plants growing in metal (loid)-contaminated soils from a Carlin-type gold mining area in southwestern China.

In the present study, none of the plant species examined reached either the phytotoxicity threshold of Sb (5–10 mg/kg DW) or the Sb hyperaccumulation threshold (1000 mg/kg DW) defined by Kabata-Pendias and Mukherjee [84] and Krämer [66]. All the collected plant species exhibited BCF values of less than 1 (Table 8). However, four species showed a TF > 1, namely, *X. zambesiaca* (2.46), *A. ataxacantha* (1.52), *C. sieberiana* (1.07), and *H. suaveolens* (5.29), revealing the ability of these species to translocate Sb from roots to aboveground parts. The BACs for all species were <1 (Table 8). According to the criteria defined by Ghazaryan et al. [101] and Siyar et al. [98], none of the 12 plant species were suitable for the phytostabilization or phytoextraction of Sb. Nonetheless, the notably high TF recorded for *H. suaveolens* suggests that this species could be explored further for assisted phytoextraction strategies to manage Sb fractions in contaminated soils.

3.5.8 | Mercury (Hg)

Mercury (Hg) concentrations in plant roots ranged from 0.01 mg/kg DW in almost all species to 0.08 mg/kg DW in *D. senegalense*. In the aboveground parts, Hg concentrations varied from 0.01 mg/kg DW in *D. senegalense* at the Dadjanfè and Köfra sites to a maximum of 0.07 mg/kg DW in *M. pigra* (Table 7). Comparable studies have reported higher Hg concentrations in plant species from gold-mining environments. Durante-Yánez et al. [102] found 4.99 mg/kg DW of Hg in *Clidemia sericea*, whereas Chamba-Eras et al. [86] identified 13 mg/kg DW of Hg in the roots *of E. polymioides*, and Petelka et al. [22] detected 0.00035 mg/kg DW of Hg in *Elaeis guineensis* and 0.00120 mg/kg DW of Hg in *Stachytarpheta cayennensis* at a gold mine in Ghana. None of the plant species examined surpassed the 10 mg/kg DW accumulation threshold in their aboveground parts, as defined by Kabata-Pendias and Mukherjee [84], indicating that none of the collected plants qualified as Hg hyperaccumulators. According to Ghazaryan et al. [101] and Siyar et al. [98], phytoremediation strategies are based on BCF, TF, and BAC values. The TF values for all species exceeded 1, except for *D. senegalense*, which had a TF < 1 at the Köfra site. The BAC and BCF of the sampled species were less than 1 (Table 8), demonstrating that none of the studied plant species were suitable for the phytostabilization or phytoextraction of Hg.

3.5.9 | Lead (Pb)

The concentrations of Pb in the roots of the plants varied from 2.12 to 107.48 mg/kg DW in *M. inermis* and *X. zambesiaca*, respectively (Table 7). The Pb concentration in *X. zambesiaca* was significantly higher ($p < 0.05$) than that in the other plant species. Moreover, in four plant species, the Pb content in the roots was higher than that in the aboveground parts, indicating a low translocation rate in *C. africana, X. zambesiaca, D. senegalense*, and *C. glutinosum*. Various studies have documented Pb levels in different plant species growing in soils affected by artisanal gold mining. Some studies have shown that in other gold mining sites, Pb concentrations were found to be particularly high, reaching 1786 mg/kg DW in the roots of *E. polymnoides* and 189 mg/kg DW in the leaves of *Axonopus compressus* [80]. Chamba-Eras et al. [86] reported a Pb concentration of 31.57 ± 3.37 mg/kg DW of Pb in *C. sericea* D. Kahangwa et al. [75], in gold extraction areas in Tanzania, found 738.9 mg/kg DW of Pb in the aboveground biomass and 757.8 mg/kg DW of Pb in the root part of *Sporobolus pyramidalis* and 351 mg/kg DW of Pb in the roots of *Melinis repens*. These values surpassed those observed in the roots of *X. zambesiaca* (107.48 mg/kg DW) collected at the Banfelebougou site and were significantly higher than those found in *C. glutinosum* collected at Köfra. The differences in Pb accumulation in the roots of *X. zambesiaca* and *C. glutinosum* may be attributed to variations in the physicochemical properties of the alluvial and sandy-gravelly soils.

In the aboveground parts, Pb concentrations ranged from 1.42 mg/kg DW in *D. senegalense* to 12.80 mg/Kg DW in *P. suberosa* (Table 7). The Pb content of *P. suberosa* was significantly higher than that of *M. inermis* and the other plants (Table 7). All the plants studied showed Pb concentrations above the phytotoxic concentration (0.6–28 mg/kg DW) defined by Kabata-Pendias and Mukherjee [84], indicating their tolerance to this metal.

The BAC was less than 1 (BAC < 1) for all species studied (Table 8). For BCF, only *X. zambesiaca* recorded values greater than 1 (Table 8). The TF of four species was greater than 1, namely, *P. africana* (1.13), *A. ataxacantha* (Espagne extraction zone) (1.06), *S. latifolius* (1.51), and *H. suaveolens* (1.57). On the basis of these results, none of the 12 plant species were suitable for Pb phytoextraction; however, *X. zambesiaca* (BCF = 1.27, TF = 0.04, and BAC = 0.05) showed potential for Pb phytostabilization due to its strong accumulation in roots and limited translocation to shoots.

3.6 | Polymetallic Accumulation (PCA)

PCA was performed to assess polymetallic accumulation patterns in different plant tissues (Figure 4). PCA of aboveground tissue concentrations explained 91.26% of the variance ($F1$ = 78.62%, $F2$ = 12.64%) (Figure 4a). $F1$, which explained 78.62% of the total inertia, reflected the species' ability to concurrently accumulate various PTEs in shoots. A positive correlation was observed between *X. zambesiaca* and Pb accumulation in this study. *M. pigra* was associated with the simultaneous accumulation of As, Sb, and Cu, whereas *P. suberosa* correlated with Cd, Ni, and Fe accumulation (Figure 4a). This suggests that species-specific accumulation patterns are driven by metal availability.

Root PCA explained 88.86% of the variance ($F1$ = 60.95%, $F2$ = 27.91%) (Figure 4b). A positive correlation was observed between *H. suaveolens* and root accumulation of Sb, Fe, and As, whereas *P. suberosa* was positively correlated with Cd, Ni, Pb, and

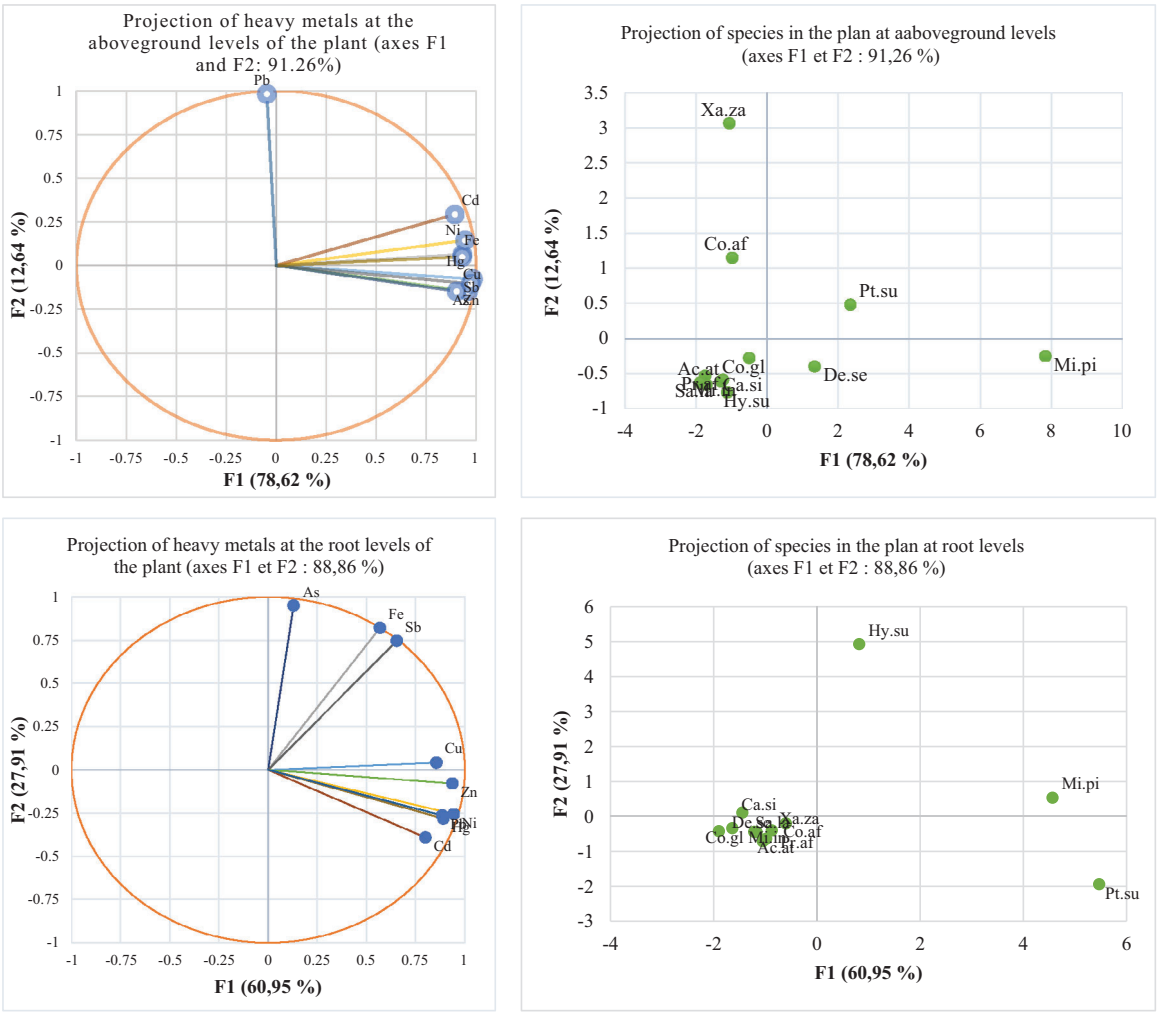


FIGURE 4 | Plotting the *F*1 and *F*2 axes of the principal component analysis (PCA) on the average metal concentrations separately in the aboveground (a) and root (b) parts for the studied species. Co.af: *Copaifera salikounda*, Xa.za: *Xanthocercis zambesiaca*, Mi.in: *Mitragyna inermis*, De.se: *Detarium senegalense*, Pr.af: *Prosopis africana*, Ac.at: *Acacia ataxacantha*, Sa.la: *Sarcosephalus latifolius*, Ca.si: *Cassia sieberiana*, Hi.su: *Hyptis suaveolens*, Co.gl: *Combretum glutinosum*, Pt.su: *Pteleopsis suberosa*, and Mi.pi: *Mimosa pigra*.

Zn. A positive correlation was also observed between *M. pigra* and root Cu accumulation.

4 | Conclusion

This study demonstrates that artisanal gold mining in Doko (Siguiri Prefecture) has caused severe soil contamination by potentially toxic elements, particularly Fe, As, Pb, and Cd, with clear anthropogenic origins. Although soils exhibit variable physicochemical properties, contamination levels remain high enough to threaten soil biodiversity and ecosystem functioning.

Among the twelve indigenous plant species assessed, none can be classified as a true hyperaccumulator; however, several show promising phytoremediation traits. *X. zambesiaca* is identified as a suitable candidate for Pb phytostabilization, whereas *H. suaveolens* and *M. inermis* display effective translocation capacities for multiple metals, supporting their potential use in phytoextraction strategies. Multivariate analysis further confirms distinct species-specific accumulation patterns.

Overall, the use of selected native species represents a low-cost and sustainable option for the ecological rehabilitation of mining-impacted soils in West Africa while also providing additional socio-environmental benefits for local communities.

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Ethics Statement

The authors state that this research was conducted in accordance with ethical standards.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets used in the study are available upon request.

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