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Heavy Metal Concentrations and Ecological Risk Assessment of the Mine Tailings around Moanda Manganese Mining areas of Gabon

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Abstract

This study aimed to assess the concentrations of trace elements and the associated ecological risk in tailings collected around the manganese mining area of Moanda in Gabon. The contents of trace elements in the mining tailing samples determined using the XRF analysis were significantly higher than their average concentrations in the upper continental crust (UCC), indicating a polymetallic contamination in the following order: Mn>Cu>Zn>Ni>Co>Cr>Pb>Zn. The Mn more concentrated in tailing samples would accumulate in the edible parts of plants cultivated around the manganese mine of Moanda. The values of geoaccumulation index (Igeo) and contamination factor (CF) indicate a moderate contamination in Co, Cu, and Cr, and a high contamination by Mn, Cu, Ni, and As. Results indicate a very high ecological risk (Ri) to the local biocenosis. These results highlight the need to implement strategies to mitigate environmental impacts and develop systems to protect local ecosystems and communities from the adverse effects of mining activities in the region of Moanda.

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Heavy metals, manganese mine, tailing, ecological risk, Moanda, Gabon

Introduction

In recent years, numerous studies have reported widespread concern regarding elevated levels of heavy metals originating from mining operations, particularly around mine sites and, more specifically, at mine tailings disposal areas (Kayika et al., 2017; Chileshe et al., 2020). These concerns have prompted efforts to assess heavy metal contamination in soils at tailings disposal sites and in surrounding mining areas as a critical first step toward mitigating potential risks to surrounding ecosystems and human health (Nazir et al., 2015; Van Nguyen et al., 2016; Abdul-Wahab and Marikar, 2012).

Open-pit mining operations can have severe environmental consequences, including air, water, and soil pollution, as well as adverse effects on surrounding wildlife due to the release of heavy metals (Kitula, 2006). In developing countries such as Gabon, several regions have been impacted by mining activities, notably the Moanda region, where manganese mining generates substantial quantities of tailings and results in chronic exposure to heavy metals through soil, water, and vegetation (Ndala and Moussone, 2011). Intensive manganese exploitation in Moanda since 1962 by the Compagnie Minière de l'Ogooué (COMILOG) positioned Gabon as the world's second-largest manganese producer in 2010, accounting for approximately 25% of global demand (Ndala and Moussone, 2011; Clarke and Upson, 2017).

Manganese extraction by COMILOG has produced large mine tailings piles composed of fine ore particles with diameters less than 8 mm, which were for an extended period directly discharged into the surrounding environment (Boupassia, 2004; Lebas, 2010; Boulamatari et al., 2017). In the vicinity of manganese-bearing plateaus exploited in Gabon, these tailings have led to elevated concentrations of manganese and other trace metals in ferruginous soils, reaching levels as high as 333,600 ppm (Bekoung Assoume et al., 2024). However, heavy metals are non-biodegradable and toxic to flora and fauna in ecosystems where their concentrations exceed permissible thresholds (Benjamin and Mwashote, 2003; Ikem et al., 2003; Krissanakriangkrai et al., 2009).

Certain heavy elements such as copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), and lead (Pb) are essential micronutrients for plant and animal growth. Nevertheless, excessive concentrations are harmful and considered pollutants for non-tolerant plant species, as they inhibit growth and development (Cheng, 2003). For instance, manganese is an essential micronutrient involved in numerous metabolic processes in living organisms; however, at elevated levels, it becomes toxic to plant growth and development (Ollagnier and Prévot, 1955; Bénac, 1976).

In the Haut-Ogooué province of Gabon, several studies conducted in the Moanda mining area have reported adverse effects of manganese toxicity on crops cultivated near manganese mining plateaus. These effects include foliar chlorosis in roselle (*Hibiscus sabdariffa* L. var. *sabdariffa*) (Ontod Tshi-Tshi et al., 2013), reduced growth in groundnuts (*Arachis hypogaea* L.) (Nzengué et al., 2019), and growth inhibition in sweet potatoes (*Ipomoea batatas*). Such adverse effects may also impact human health, as evidenced in Kabwe, Zambia, where harmful health outcomes have been reported following exposure to high concentrations of lead (Pb) and zinc (Zn) (Ikenaka et al., 2010; Burga and Saunders, 2019). Furthermore, a study in South Africa reported cattle mortality due to chronic copper (Cu) intoxication (Taylor et al., 2020; Gummow et al., 1991).

Consequently, the detrimental impacts of mining waste, particularly tailings, on ecosystems, biodiversity, and the health of populations residing near these disposal sites have raised serious concerns (Chileshe et al., 2020; Olobatoke and Mathuthu, 2008). Studies assessing heavy metal pollution levels in soils and tailings, as well as their environmental impacts in the Moanda region, remain scarce. Nevertheless, Ondo et al. (2012) demonstrated significant accumulation of Al, Zn, and Mn in plants cultivated on soils surrounding the Moanda mine, thereby posing potential risks to human health.

To address these existing knowledge gaps, the primary objective of this study is to analyze the concentrations of eight heavy metals (Cd, Cr, Cu, Mn, Ni, Pb, As, and Zn) and to assess their potential ecological and human health risks in tailings deposits surrounding the Moanda manganese mine in Gabon. Ultimately, ecological pollution due to heavy metals will be characterized using the geo-accumulation index (Igeo), contamination factor (CF), degree of contamination, and potential ecological risk index (RI) (Müller, 1969; Hakanson, 1980). This study aims to establish baseline data on heavy metal pollution in mine tailings covering the soils of Moanda, thereby contributing to future research and development strategies for the management of toxic mining waste and the protection of ecosystems surrounding mining areas in the Republic of Gabon.

Materials and Methods

Geographical Location and Description of the Study Area

The Moanda manganese mine is located in southeastern Gabon, approximately 50 km west of Franceville, within the Haut-Ogooué Province. It is the largest manganese mine in Gabon and is operated by the Compagnie Minière de l'Ogooué (COMILOG), a subsidiary of the ERAMET Group (63.71% ownership), with a 28.7% stake held by the Gabonese State. The produced ore is of high grade, ranging between 45% and 50% Mn, and is extracted by open-pit mining using hydraulic excavators that remove an overburden layer averaging 4–5 m in thickness.

With a production of 7.409 million tonnes of manganese ore in 2023, Gabon was ranked as the world's leading manganese producer (Lelementarium, 2024). As of January 2024, proven reserves were estimated at 250 million tonnes of ore with an average manganese content of 44.3%. The manganese mineralization is hosted within manganese-enriched carbonate series interbedded with black shales, which constitute the protore responsible for the secondary manganese concentrations currently exploited. This protore corresponds to Formation B of the Francevillian Basin series, specifically the upper FB1c unit deposited along the margin of a shallow continental shelf (Gauthier-Lafaye and Weber, 2003; Préat et al., 2011; Ossa Ossa et al., 2018). These manganese-rich carbonates were subsequently enriched through supergene alteration processes.

The Moanda region is characterized by herbaceous to shrubby savanna vegetation, with localized forested areas along valley bottoms. The climate is transitional equatorial, with an annual rainfall ranging from 1,800 to 2,000 mm and average temperatures between 23 and 34 °C (Guichard and Tercinier, 1979). During frequent and intense rainy seasons, mining residues such as tailings and waste rock are transported and deposited onto soil surfaces and into watercourses through runoff processes. Mining residues often contain elevated levels of heavy metals and are generally considered a significant environmental threat (Ritcey, 1989). Their physicochemical properties depend largely on the nature of the ore and the extraction techniques employed (Fashola et al., 2016).

Sample Preparation and Chemical Characterization

The material used in this study consisted of manganese mining residues collected from tailings deposits surrounding the Bangombé manganese plateau in the Moanda region, Gabon. This manganese-exploited plateau is located between latitudes 1°25′ and 1°35′ S and longitudes 13°10′ and 13°15′ E, at an average elevation of 571 m.

For each tailings sample collected directly from piled residues on the soil surface, the material was homogenized and sieved to a particle size of 850 µm. Samples collected from the left side of the mine toward the lake were designated **GL**, while those collected toward the Moulili River were designated **ML**.

Concentrations of trace metal elements (Cr, Mn, Co, Ni, Cu, Zn, As, and Pb) were determined using X-ray fluorescence (XRF) analysis with a portable E-max heavy-metal analyzer. The limits of quantification (ppm) were 0.2 for As, 0.5 for Cu and Zn, 0.8 for Pb, 1 for Ni and Co, and 5 for Cr and Mn.

Pollution Indices Calculation

Several indicators—including the geo-accumulation index (Igeo), contamination factor (CF), degree of contamination (DC), and potential ecological risk index (RI)—were applied for the first time to manganese mine tailings from Moanda in order to assess the pollution status of tailings sediments by trace metal elements. The selected indices are described below.

Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) was proposed by Müller (1969) to quantify the intensity of environmental pollution and is calculated using the following equation:

$$I_{geo} = \log_2 \left(\frac{C_i}{1.5 \times C_b} \right)$$

where *Ci* is the measured concentration of the metal in the sample, *Cb* is the background concentration of the metal in the Upper Continental Crust (UCC) (Rudnick and Gao, 2003), and 1.5 is a correction factor accounting for lithological variations.

According to Müller (1969), Igeo values are classified as follows:

Igeo ≤ 0 (unpolluted);
0 < Igeo ≤ 1 (unpolluted to moderately polluted);
1 < Igeo ≤ 2 (moderately polluted);
2 < Igeo ≤ 3 (moderately to strongly polluted);
3 < Igeo ≤ 4 (strongly polluted);
4 < Igeo ≤ 5 (strongly to extremely polluted);
Igeo > 5 (extremely polluted).

Contamination Factor (CF) and Degree of Contamination (DC)

The contamination factor (CF) and degree of contamination (DC) are commonly used to assess heavy-metal contamination in sediments. The CF describes contamination by toxic elements and represents the ratio between the measured metal concentration and its geochemical background value (Hakanson, 1980). It is calculated as:

$$CF = \frac{C_i}{C_b}$$

Due to the lack of site-specific background values for heavy metals in sediments dominated by lithologies such as pelites, jaspers, and sandstones, average reference values for sedimentary rocks reported by Rudnick and Gao (2003) were used as background concentrations.
According to Hakanson (1980), CF values are interpreted as follows: CF < 1 (low contamination); 1 ≤ CF < 3 (moderate contamination); 3 ≤ CF < 6 (considerable contamination); CF ≥ 6 (very high contamination).

The degree of contamination (DC) is defined as the sum of contamination factors for all analyzed elements:

$$DC = \sum CF$$

where n is the number of analyzed elements. DC values are classified as follows (Hakanson, 1980): DC < 8 (low contamination); 8 ≤ DC < 16 (moderate contamination); 16 ≤ DC < 32 (considerable contamination); DC ≥ 32 (very high contamination indicating severe anthropogenic pollution).

Potential Ecological Risk Index (RI)

The potential ecological risk index (RI) evaluates the ecological risk posed by heavy metals in sediments and is calculated according to Hakanson (1980) and Yi et al. (2011):

$$RI = \sum E_r^i \quad \text{with} \quad E_r^i = T_r \times CF$$

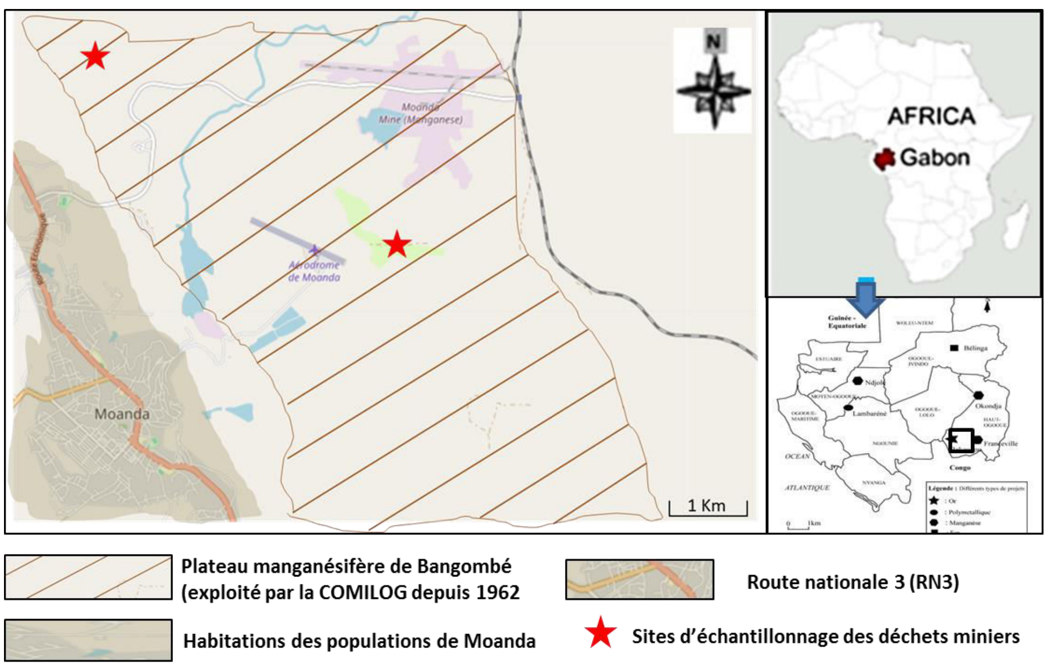
where *Er* represents the potential ecological risk factor for each metal, *Tr* is the toxic response factor, and *CF* is the contamination factor. The toxic response factors (*Tr*) for the studied trace elements (Co, Cr, Cu, Mn, Ni, Pb, Zn, As) according to Hilton et al. (1985) are 5, 2, 5, 1, 6, 5, 1, and 10, respectively.

The ecological risk is interpreted as follows (Hakanson, 1980): RI < 95 (low ecological risk); 95 ≤ RI < 190 (moderate risk); 190 ≤ RI < 380 (considerable risk); RI ≥ 380 (very high ecological risk).

Statistical Analyses

Analysis of variance (ANOVA) was used to test for significant differences in trace metal concentrations between the two sampled tailings deposits. Relationships among the studied trace metal elements were evaluated using Principal Component Analysis (PCA). These relationships were statistically tested using Pearson's correlation coefficient at a significance level of $p < 0.05$. All statistical analyses were performed using R cmdr software, version 4.4.3.

Figure 1. Location of the Moanda mining area



Results and Discussion

Concentrations of Trace Metal Elements in Mining Residues

The concentrations of trace metal elements (TMEs) measured in the mining residues are presented in Table 1. In these residues derived from two waste dumps (GL and ML) located near the Moanda manganese mine, the mean concentrations ranged from 132.33 to 157.67 mg·kg^{-1} for chromium (Cr), 267,078 to 305,090 mg·kg^{-1} for manganese (Mn), 284 to 302 mg·kg^{-1} for cobalt (Co), 391 to 403.4 mg·kg^{-1} for nickel (Ni), 436.33 to 468.07 mg·kg^{-1} for copper (Cu), 401.67 to 445.93 mg·kg^{-1} for zinc (Zn), 48.40 to 50 mg·kg⁻¹ for arsenic (As), and 61.07 to 77.33 mg·kg⁻¹ for lead (Pb), expressed on a dry-weight basis.

For all trace metal elements, no statistically significant differences were observed between the GL and ML sites ($p > 0.05$). The concentrations of each element were of the same order of magnitude at both sampling sites. However, for all TMEs analyzed, the mean concentrations recorded in all waste dump samples were far higher than the geochemical background values of the Upper Continental Crust (UCC) (Table 1). Furthermore, for each element investigated in this study, the concentrations exceeded the standard sediment guideline values established by the USEPA (1999).

Overall, the mean concentrations of trace metals in the mining residues from Moanda followed the decreasing order:

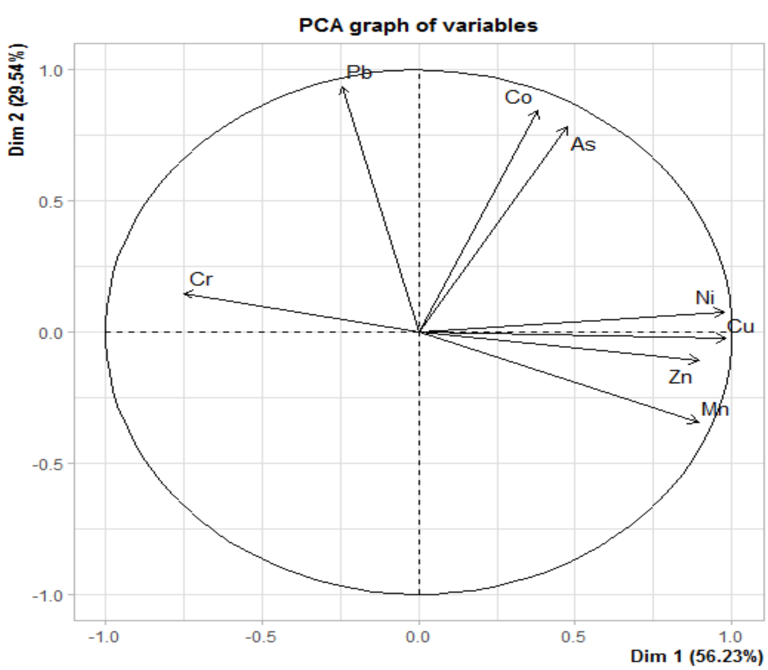
Mn > Cu > Zn > Ni > Co > Cr > Pb > As.

Table.1 Concentrations of trace metal elements ($mg \cdot kg^{-1}$) in mining residues.

Sites		Concentrations of Trace Metal Elements (mg·kg⁻¹) in Mining Residues							
		Cr	Mn	Co	Ni	Cu	Zn	As	Pb
GL	max.	151,00	354411,00	327,00	485,00	551,00	529,00	57,00	69,20
	Mean	**132,33**	**305090,00**	**284,00**	**403,40**	**468,07**	**445,93**	**48,40**	**61,07**
	mini.	101,00	274775,00	232,00	328,00	401,00	385,00	39,00	50,00
	Standard Deviation (SD)	27,30	43085,89	48,14	78,68	76,25	74,51	9,03	9,93
ML	max.	176,00	344918,00	316,00	446,00	476,00	509,00	54,00	88,00
	Mean	**157,67**	**267078,00**	**302,00**	**391,00**	**436,33**	**401,67**	**50,00**	**77,33**
	mini.	128,00	186070,00	277,00	315,00	365,00	329,00	44,00	71,00
	Standard Deviation (SD)	25,93	79471,37	21,70	67,98	61,91	94,88	5,29	9,29
	UCC[1]	92	1000	17,3	47	28	67	4,8	17
	USEPA[2]	25	30	40	16	16	110	-	40

[1]**UCC:** Geochemical background concentrations in sedimentary rocks according to Rudnick and Gao (2003). [2]**Sediment quality standards:** United States Environmental Protection Agency (USEPA, 1999).

Figure.2 Principal Component Analysis (PCA) of mining residues from Moanda, based on trace metal element (TME) concentrations at the different studied sites..



The relationships among the investigated TMEs were examined using Principal Component Analysis (PCA) and Pearson correlation analysis. PCA identified two significant factors, Dim 1 and Dim 2, explaining 56.23% and 29.54% of the total data variance, respectively (Figure 2). Together, these two components accounted for 85.77% of the total variance.

Nickel, copper, zinc, and manganese concentrations were strongly and positively correlated with Dim 1, whereas chromium showed a strong negative correlation with Dim 1. In contrast, cobalt, arsenic, and lead were strongly and positively correlated with Dim 2 (Figure 2). Pearson correlation analysis revealed strong positive relationships between Mn and Zn (r = 0.945), Zn and Ni (r = 0.87), and Zn and Cu (r = 0.799). These four elements (Ni, Cu, Zn, and Mn) showed no significant correlation with Cr, As, and Pb. Conversely, strong positive correlations were observed among Co, As, and Pb, namely Co vs. As (r = 0.73), Co vs. Pb (r = 0.65), and As vs. Pb (r = 0.60).

Degree of Trace Metal Contamination in Mining Residues

Geo-accumulation Index (Igeo)

The geo-accumulation index (Igeo) values for trace metals in the waste dump sediments collected near the Moanda manganese mine are shown in **Figure 3**. Mean Igeo values for each element were similar at both sites. However, certain elements exhibited significant accumulation, resulting in moderate to high pollution levels in the mining residues.

Specifically, for Cr, Ni, Zn, and Pb, Igeo values were < 1, indicating unpolluted sediments. For Co and Cu, Igeo values ranged between 1 and 2, corresponding to moderately polluted sediments. In contrast, Mn exhibited Igeo values > 2, indicating strong pollution by manganese in the sediments (Figure 3).

Contamination Factor (CF) and Degree of Contamination (DC)

The contamination factor (CF) and degree of contamination (DC) values are summarized in Table 2. For all elements, CF values were greater than 1. Specifically, CF values ranged from 1.1 to 1.9 for Cr, 186 to 354 for Mn, 13 to 18 for Co, 7 to 10 for Ni, 13 to 19 for Cu, 5 to 8 for Zn, 8 to 12 for As, and 3 to 5 for Pb.

According to the classification proposed by Hakanson (1980), the sediments exhibited moderate contamination (1 < CF < 3) for Cr, considerable contamination (3 < CF < 6) for Pb and Zn, and very high contamination (CF > 6) for Mn, Cu, Ni, and As. CF values were comparable for each trace metal between the GL and ML sites (Table 2).

The degree of contamination (DC) values ranged from 327 to 428 at the GL site and from 247 to 411 at the ML site (Table 2). These results indicate that sediments at both sites exhibit a very high degree of trace metal contamination (DC > 32), reflecting severe anthropogenic pollution.

Potential Ecological Risk of Contaminated Mining Residues

Potential Ecological Risk Factor (Er) for Individual Trace Metals

The potential ecological risk factor (Er) values for the mining residues are presented in Figure 4. The results show that Er values were well below 40 (Er < 40) for Cr (2.2–3.8), Zn (4.9–7.9), and Pb (14.7–25.9), indicating a low potential ecological risk for these elements.

In contrast, Ni, Co, Cu, and As exhibited moderate to considerable ecological risk levels (40 < Er < 160). Finally, manganese showed high potential ecological risk values (160 < Er < 360) across all analyzed samples (Figure 4).

Table.2 Contamination factor (CF) and degree of contamination (DC) of mining residues by trace metal elements

Sites	Contamination Factor (CF)								CD= ∑ CFi
	Cr	Mn	Co	Ni	Cu	Zn	As	Pb	
GL	1,4± 0,3	305,1± 43,1	16,4 ± 2,8	8,6 ± 1,7	16,6 ± 2,7	6,6 ± 1,1	10,1 ± 1,9	3,6 ± 0,6	368,6± 52,6
ML	1,7± 0,3	267,1± 79,5	17,5 ± 1,2	8,3 ± 1,4	15,6 ± 2,2	6,0 ± 1,4	10,4 ± 1,1	4,5 ± 0,5	331,1± 82,2

Figure.3 Geo-accumulation Index (Igeo) of trace metal elements in the mining residues.

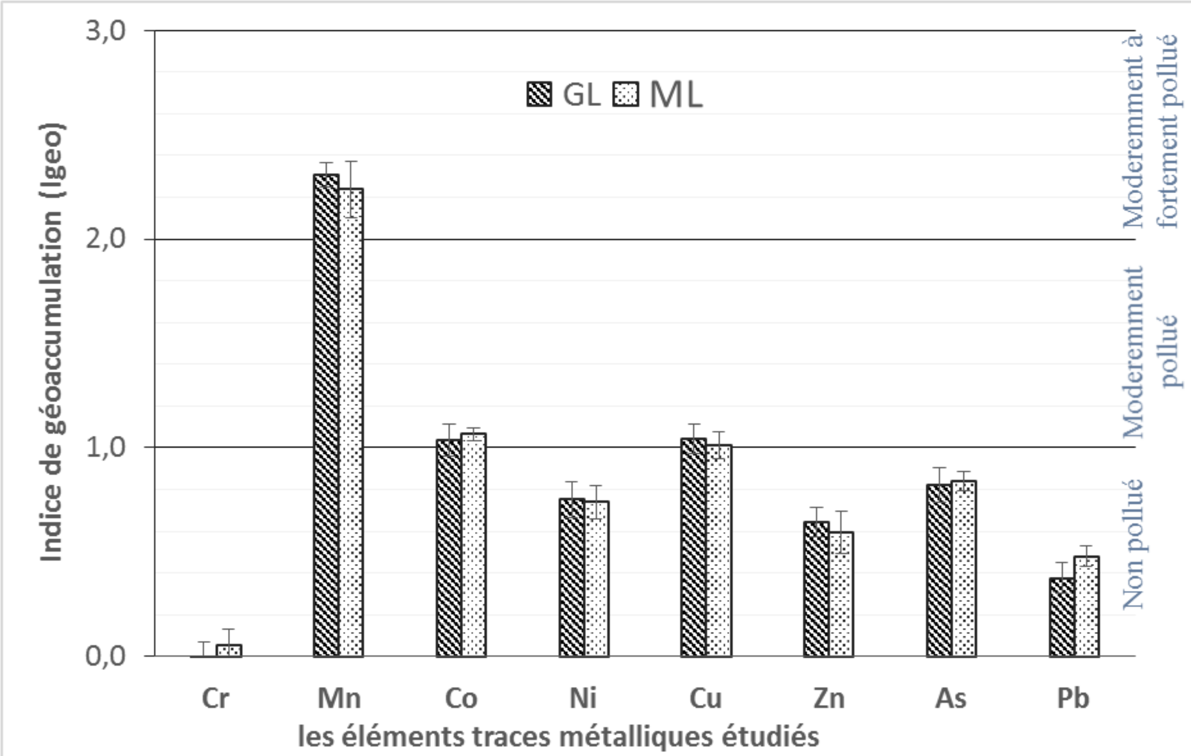
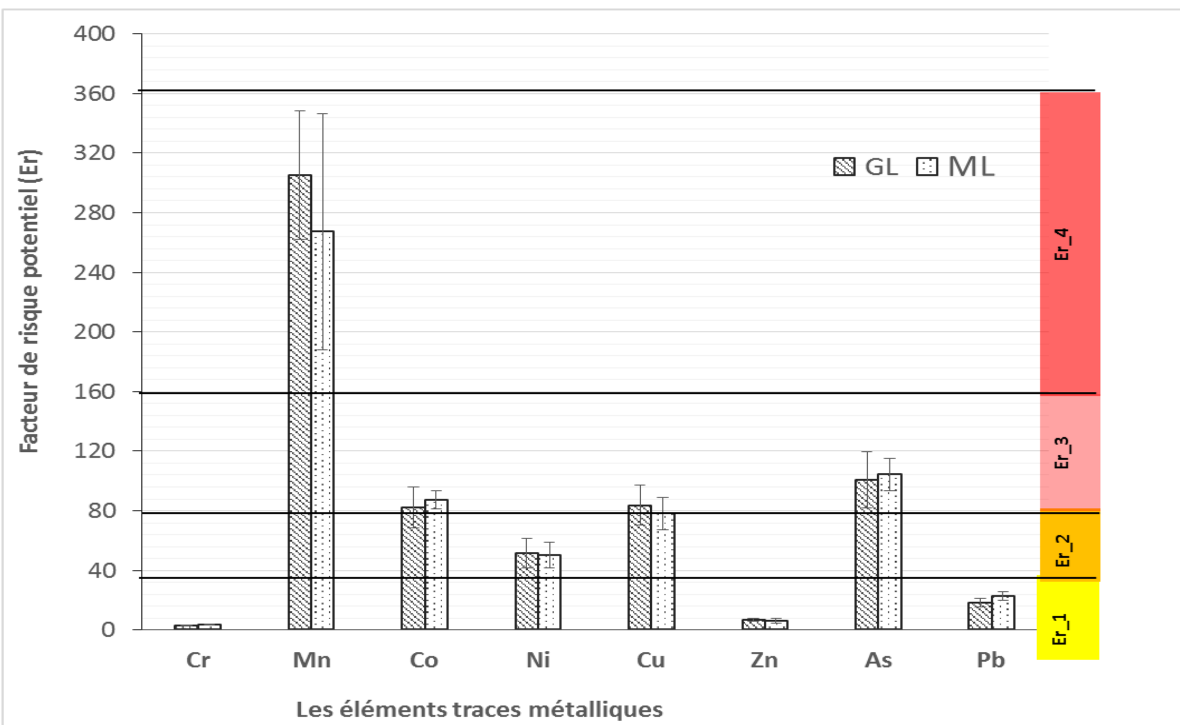
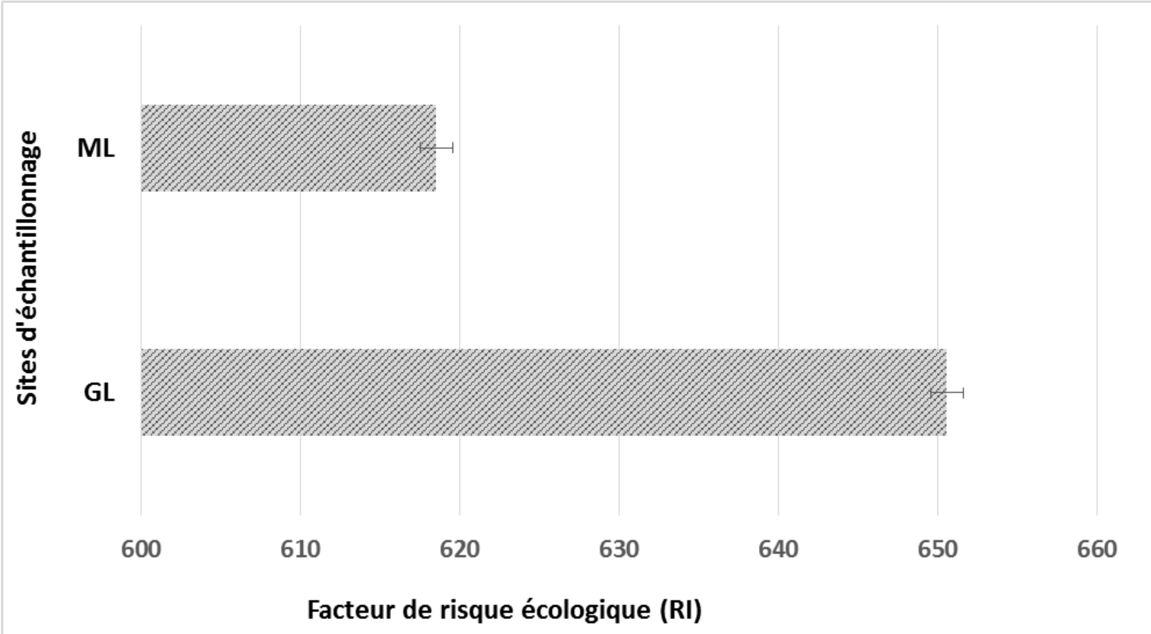


Figure.4 Potential ecological risk (Er) of trace metal elements in mining residues:



Er₁: low risk, **Er₂:** moderate risk, **Er₃:** considerable risk, **Er₄:** high risk.

Figure.5 Ecological Risk Index (RI) of Trace Metal Elements (TMEs) in Mining Residues



Overall Ecological Risk Index (RI)

The ecological risk index (RI) values by site are shown in Figure 5. RI values ranged from 560 to 757 at the GL site and from 529 to 706 at the ML site. For all investigated mining residues, RI values were substantially higher than the threshold value of 190, which indicates a very high ecological risk according to Hakanson (1980).

These results clearly demonstrate that the areas where mining residues are stored around the Moanda manganese mine are subject to a very high ecological risk, posing serious threats to the surrounding environment.

As discussion of the present study results includes, the concentrations of trace metal elements (TMEs) measured in the mining waste dumps from the manganese exploitation area of Moanda, Gabon, follow the order:

Mn >> Cu > Zn > Ni > Co > Cr > Pb > As.

For all samples, the mean concentrations ($mg \cdot kg^{-1}$) are substantially higher than the geochemical background values of the Upper Continental Crust (UCC). Furthermore, TME concentrations exceed the sediment quality guideline limits established by the USEPA (1999). Each TME has a predominant origin and specific environmental and health impacts, as discussed below.

Arsenic (As) is a metalloid naturally present in soils at very low concentrations, primarily originating from the weathering of arsenic-bearing minerals such as arsenopyrite (FeAsS). It is widely recognized as a potential source of soil and water pollution (Sodhi et al., 2019). Arsenic can accumulate in the edible parts of plants, thereby posing a serious risk to human health (Fashola et al., 2016).

Lead (Pb) is a metal extensively used by humans and naturally occurs in parent rocks. However, industrial activities significantly increase its concentration in soils. Mining activities, in particular, promote Pb accumulation and its transformation into more bioavailable and toxic chemical forms (Goyer, 1990). Lead poisoning is known to cause severe neurological effects, including cognitive impairment and developmental delays in children (Naja and Volesky, 2009).

Chromium (Cr) naturally occurs in minerals such as chromite and can become relatively stable in air and water following oxidation. Elevated Cr concentrations are generally associated with surface pollution sources, including mining activities, which increase its bioavailability, mobility, and toxicity (Abdul-Wahab and Marikar, 2012). At high concentrations, chromium exposure may lead to asthma and severe respiratory and neurological disorders (Tchounwou et al., 2012).

Nickel (Ni) naturally exists in various chemical forms, and its concentration in soils depends on the parent material and pedogenetic processes. Anthropogenic activities, such as industrial waste disposal and the use of phosphate fertilizers, significantly increase Ni levels in soils. At elevated concentrations, nickel can be absorbed by humans through inhalation or ingestion, potentially causing pathological effects such as pulmonary fibrosis and respiratory tract cancers (Cempel and Nikel, 2006).

Zinc (Zn) is abundant in the environment and is an essential micronutrient, playing a vital role in immune system function and enzymatic processes. However, excessive Zn concentrations are commonly associated with anthropogenic and industrial wastes, including mining residues and agricultural fertilizers. Human exposure to Zn occurs through ingestion, inhalation, and dermal absorption, with potential toxic effects at high concentrations (Wuana and Okieimen, 2011).

Copper (Cu) is naturally present in the Earth's crust, particularly in mafic and intermediate rocks. Some Cu species are weakly soluble and relatively mobile compared to other TMEs. Copper is released into the environment through soil weathering, industrial emissions, and domestic waste disposal (WHO, 1998). Although Cu is an essential trace element, excessive concentrations may disrupt plant physiology and human neurological functions (Crichton, 2016).

Our results indicate that the studied mining residues pose a significant risk of TME contamination to the underlying soils. The mine tailings generated by manganese extraction in Gabon, which are often directly deposited into the surrounding environment, strongly contribute to soil pollution by TMEs, particularly Mn, reaching extremely high concentrations (Boupassia, 2004; Bekoung Assoume et al., 2024). Pearson correlation analysis revealed strong positive correlations among Ni, Cu, Zn, and Mn ($r > 0.799$), suggesting a common source related to manganese mining activities in Moanda. In contrast, elements such as Co, As, and Pb likely originate from different sources.

Regarding contamination indices and associated ecological risks, the mean geo-accumulation index (Igeo) values indicate no pollution by Cr, Ni, Zn, and Pb (Igeo < 1). However, the residues are moderately polluted by Co and Cu (1 < Igeo < 2) and strongly polluted by Mn (Igeo > 2), according to Hakanson (1980). Although not all TMEs indicate pollution, contamination factor (CF) values reveal moderate to significant contamination by Cr, Pb, and Zn, and very high contamination by Mn, Cu, Ni, and As. These findings are consistent with previous studies reporting high TME contamination, particularly Mn, in areas surrounding manganese mines in Gabon (Boupassia, 2004; Bekoung Assoume et al., 2024).

Furthermore, the similar degrees of contamination observed at both study sites (GL and ML) confirm a common origin of the mine tailings derived from manganese extraction. The sediments exhibit a very high degree of contamination (DC > 32) according to Hakanson (1980). In all studied mining residues, the ecological risk index (RI) indicates a very high ecological risk in the areas where manganese mining wastes are stored.

Several studies have demonstrated that manganese accumulates at high concentrations in edible plants such as roselle (*Hibiscus sabdariffa* L. var. *sabdariffa*) and groundnut (*Arachis hypogea* L.) cultivated near the Moanda manganese mine in the Haut-Ogooué Province, Gabon (Ondo et al., 2012; Ontod Tshi-Tshi et al., 2013; Nzengué et al., 2019). Therefore, the risk of TME exposure through consumption of crops grown near the Moanda manganese mine is substantial. Under humid tropical climatic conditions, mining residues are easily transported into surface waters via runoff, leading to chemical contamination and sedimentation of rivers. These processes pose serious threats to aquatic ecosystems and human health. Consequently, appropriate mitigation measures are urgently required to balance mining activities in Moanda with environmental protection and public health preservation.

In Conclusion, this study presents, for the first time, detailed data on trace metal element concentrations in mine tailings and the associated ecological risks to the biocenosis surrounding the Moanda manganese mine in the Haut-Ogooué Province, Gabon. The mean concentrations of Cr, Mn, Co, Ni, Cu, Zn, As, and Pb are approximately 2, 305, 17, 9, 17, 7, 10, and 4 times higher, respectively, than the UCC geochemical background values, indicating significant contamination. These concentrations exceed USEPA sediment guideline limits by factors ranging from 2 to 17.

Manganese is the most accumulated element and is likely responsible for toxic effects observed in crops cultivated near the Moanda manganese mine. Based on Igeo values, the mine tailings are moderately polluted by Co and Cu and strongly polluted by Mn. Contamination factor (CF) values further confirm moderate contamination by Cr, significant contamination by Pb and Zn, and very high contamination by Mn, Cu, Ni, and As. This contamination pattern is consistent across both study sites, which exhibit an overall very high degree of contamination (DC).

Ultimately, the ecological risk index (RI) indicates a very high ecological risk for all analyzed mining residues. These mine tailings constitute a major source of polymetallic contaminants capable of polluting surface waters and cultivated soils through runoff and wind transport. This study highlights the urgent need for monitoring and management strategies around manganese mine tailing storage areas in Moanda to prevent severe polymetallic environmental contamination, particularly by arsenic, which threatens water quality and ecosystem integrity in the region.

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