

# Determination, Speciation and Bioavailability of Trace Metals Elements in Sabodala Mine Tailings

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## Abstract

The risk of ecotoxicity from mine tailings depends on the bioavailable fraction of heavy metals in the soil, which is closely related to the biological and physico-chemical environment of the soils. The behavior, bioavailability and toxicity of heavy metals in soil depend essentially on their chemical composition. This paper seeks to quantify trace metal elements (TMEs) in mine tailings and to estimate the bioavailability and speciation of TMEs in mine tailings from the Sabodala mine using Tessier sequential extraction. The high metal levels found in the mine tailings revealed clear metallic contamination, with significant enrichment in certain elements such as arsenic (408.1 ppm), antimony (79.46 ppm), nickel (156.42 ppm) and Cd (4.16 ppm). These levels are well above the local geochemical background. This large difference is the result of human mining activity, mainly due to the geological nature of the rocks mined. Speciation studies revealed that 95% of the antimony is retained in the residual fraction, reflecting the limited toxicity of this metalloid. The average concentrations of arsenic, nickel and cadmium in the residual fractions are significant (61%, 51% and 52% respectively). This is followed by the sulphide phase, the carbonate phase, the iron and manganese oxide phase and finally the exchangeable phase. These last four phases, representing the labile fraction, contain relatively high levels of metallic elements, likely to contaminate the water and plants in the region. This labile fraction results in a high potential for mobility if conditions become more acidic. The potential mobility factors for arsenic and antimony are 5% and 2% respectively. These two metalloids (As, Sb) associated with crystalline and non-crystalline oxide, hydroxide or sulphide minerals, are considered immobile and have a low risk of polluting groundwater. Cadmium and nickel can be considered the most mobile ele-

ments in mine tailings, as around 12% and 10% respectively are found in the exchangeable and carbonate fractions.

## Keywords

Tailings, Contamination, Trace Metals Elements, Sabodala Gold Operations

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## 1. Introduction

Trace metals occur naturally in varying concentrations in soils, rocks and water. Despite this, human activities, particularly mining, contribute to an increase in their concentrations in soils, forming stocks of pollutants that are potentially toxic for the environment. These pollutants cause major disturbances to the soil fauna [1]-[3], but can also affect surface and groundwater in the vicinity. However, the total concentrations of metal contaminants in the soil are not a sufficient condition for toxic effects on biotic or abiotic organisms. The toxicity of a metal or metalloid is not just linked to its total concentration, it depends also on its 'speciation', in other words its valency, and its environment. Chemical speciation is a fundamental parameter that controls the migration, bioavailability and toxicity of chemical elements in environmental matrices. Investigating the mobility, fate and transfer of ETMs is extremely important. The mobility of TMEs, as well as their bioavailability, is highly dependent on their chemical speciation in soils.

This paper aims to determine the total levels of trace metals (TMEs) such as arsenic, antimony, cadmium and nickel, as well as their chemical speciation in mine tailings, *i.e.* their geochemical distribution in the various fractions making up these tailings, and their bioavailability in the tailings from the Sabodala mine. A sequential extraction scheme [4] is used to fractionate TMEs with different mobilities.

## 2. Materials and Method

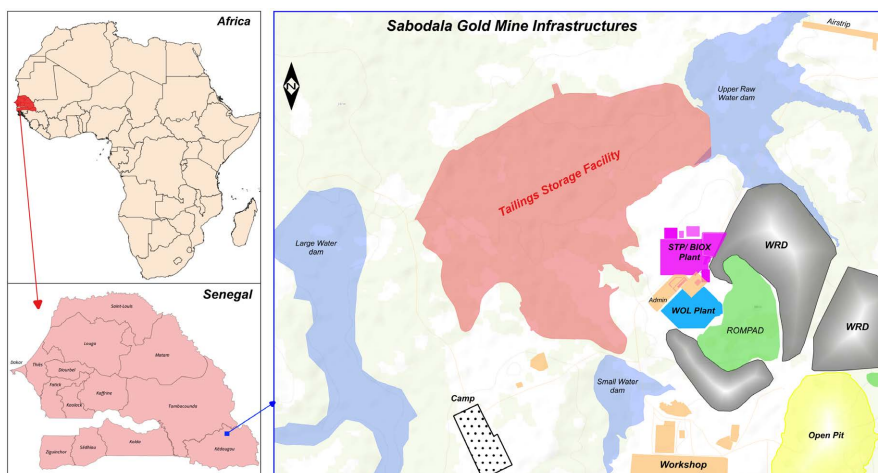
### 2.1. Study Area

The Sabodala mine site is located in the Kedougou region, in the south-eastern of Senegal, approximately 700 km from the capital Dakar (**Figure 1**). In this gold complex, ore is extracted from open-pit mines and processed through a conventional crushing-crushing-cyanide leaching cycle at the Sabodala Processing plant. In addition, in April 2024, the mine began commissioning a Bio-oxidation plant (STP / BIOX) to treat refractory ore from one of these large deposits.

The tailings storage facility studied is the first tailings storage facility on the Sabodala site, covering an area of around 388 ha. Following the last dam raise (in 2020), the maximum storage capacity increased to 48.8 Mm<sup>3</sup>, of which 35 Mm<sup>3</sup> was already occupied by tailings in February 2024.

This tailings management facility (**Figure 2**) is located next to the water basins (Large water dam, small water dam, Upper raw water dam) that the mine uses for workers' consumption and for ore processing. In this context, it is urgent to mon-

itor the concentration and bioavailability of metals elements in the Sabodala TSF to protect the surrounding water resources.



**Figure 1.** Geographical location of the Sabodala-Massawa mine.



**Figure 2.** Aerial view of the Sabodala tailings storage facility.

## 2.2. Methodology

### 2.2.1. Tailings Sampling

Tailings samples were collected from the Sabodala tailings facility in February 2024. The samples collected were air-dried and then homogenised by manual mixing. The samples were finely ground ( $<63\ \mu\text{m}$ ) and then digested with a mixture of three acids (perchloric, nitric and hydrofluoric acids). Trace metals were analysed by ICP-AES.

### 2.2.2. Sequential Extraction of TMEs from Mine Tailings

In order to study the affinities of heavy metals with the different soil phases, sequential extractions have been carried out according to the procedure of [4]. The method is based on the use of a set of chemical reagents to release the metals (**Table 1**). The extraction process was carried out in Erlenmeyer flasks using 1.0 g of

the initial dried sample and a precise volume of acid mixture. After stirring, the solution is filtered. The waste is washed with distilled water. The extracts are stored in expensive tubes. In general, the pH of the supernatant from each successive extraction was reduced by 0.5 ml of HNO<sub>3</sub> (63%). Trace metals in extracts are analysed using ICP-AES.

**Table 1.** Metal extraction procedure of [4].

Fraction	Extraction solvent	Stirring time	Temp (°)	Phase
F1	8 ml 1M of MgCl <sub>2</sub> (pH = 7)	1 h	25	Exchangeable fraction
F2	8ml 1M CH <sub>3</sub> COONa pH = 5 avec CH <sub>3</sub> COOH	5 h	25	Carbonate-bound fraction
F3	20 ml 0.04 M hydroxylamine NH <sub>2</sub> OH.HCl in 25% (v/v) CH <sub>3</sub> COOH, pH2	5 h	96	Iron and manganese oxides fraction
F4	3 ml 0.02 M HNO <sub>3</sub> ; 5 ml H <sub>2</sub> O <sub>2</sub> 30%, pH 2 with HNO <sub>3</sub> at 85°C for 3 h, then 5 ml CH <sub>3</sub> OONH <sub>4</sub> in 20% (v/v) HNO <sub>3</sub> , diluted in 20 ml, stirring for 30 mins.	3 h	85	Sulphide and organic fraction
F5	10 ml HF + 2 ml HClO <sub>4</sub> + 2 ml HCl 12 N		100	Residual fraction

The extractions were carried out in five successive stages (50 ml batch, on 1g of the granulometric fraction smaller than 0.63 mm of a dried and finely ground soil sample). Extracted fractions are as follows:

- ✓ Fraction (F1) ('exchangeable'): possible solubility of metals during sorption-desorption processes. Extracted with 8 ml 1M MgCl<sub>2</sub>, pH7; after shaking for 1 hour.
- ✓ Fraction (F2) ('carbonate-bound'): results from solubilisation when the pH is changed by 8 ml of 1M CH<sub>3</sub>COONa, pH 5 with CH<sub>3</sub>COOH; stirring for 5 hours;
- ✓ Fraction (F3) ('easily reducible'): liberation of metals bound to Mn oxides and Fe hydroxides: this corresponds to dissolving these oxides and hydroxides in the presence of a moderate reducing agent, in this case hydroxylamine NH<sub>2</sub>OH. HCl 0.04 M in 25% (v/v) CH<sub>3</sub>COOH at 96°C for 6 h;
- ✓ Fraction (F4) ('bound to organic matter and sulphides'): resulting from possible solubility during changes in redox conditions (oxidation) (3 ml of 0.02 M HNO<sub>3</sub>; 5 ml H<sub>2</sub>O<sub>2</sub> 30%, pH 2 with HNO<sub>3</sub> at 85°C for 3 h, then 5 ml CH<sub>3</sub>OONH<sub>4</sub> in 20% (v/v) HNO<sub>3</sub>, diluted in 20 ml, stirring for 30 min);
- ✓ Fraction (F5) ('tailing' or 'clay fraction'; metals closely linked to the structure of the crystals, some of which may be well-crystallised sulphide crystals).
- ✓ These different methods of extracting metals provide a better understanding of their potential mobility and bioavailability.

### 2.2.3. Potential Mobility of TMEs in Mine Tailings

The order of mobility of ETMs according to their abundance in the different fractions follows the following order: exchangeable > bound to carbonate > bound to

Fe-Mn oxide > bound to organic matter or sulphides > residual fraction [4]. Exchangeable elements are a measure of the elements that are most easily released into the environment under acidic conditions and can be considered the most dangerous for the environment [5]. Changes in ionic composition, influencing adsorption-desorption reactions or lowering the pH, could lead to remobilisation [6] [7], and [8]. Determination of the mobility of the TMEs in the tailings is based on the relative quantity of metal in the exchangeable fraction (T1) containing the mobile forms and in the carbonate-bound fraction (T2) containing the easily mobilised phases. The TME mobility index is calculated by the mobility factor (MF) based on the following equation (1) from [9] [10], and [11]:

$$MF = \frac{T1+T2}{T1+T2+T3+T4+T5} \quad (1)$$

As a result, the value of the mobility factor determines the relative mobility and biological availability of the TMEs in the soil.

### 3. Results and Discussion

#### 3.1. Determination of TMEs Levels

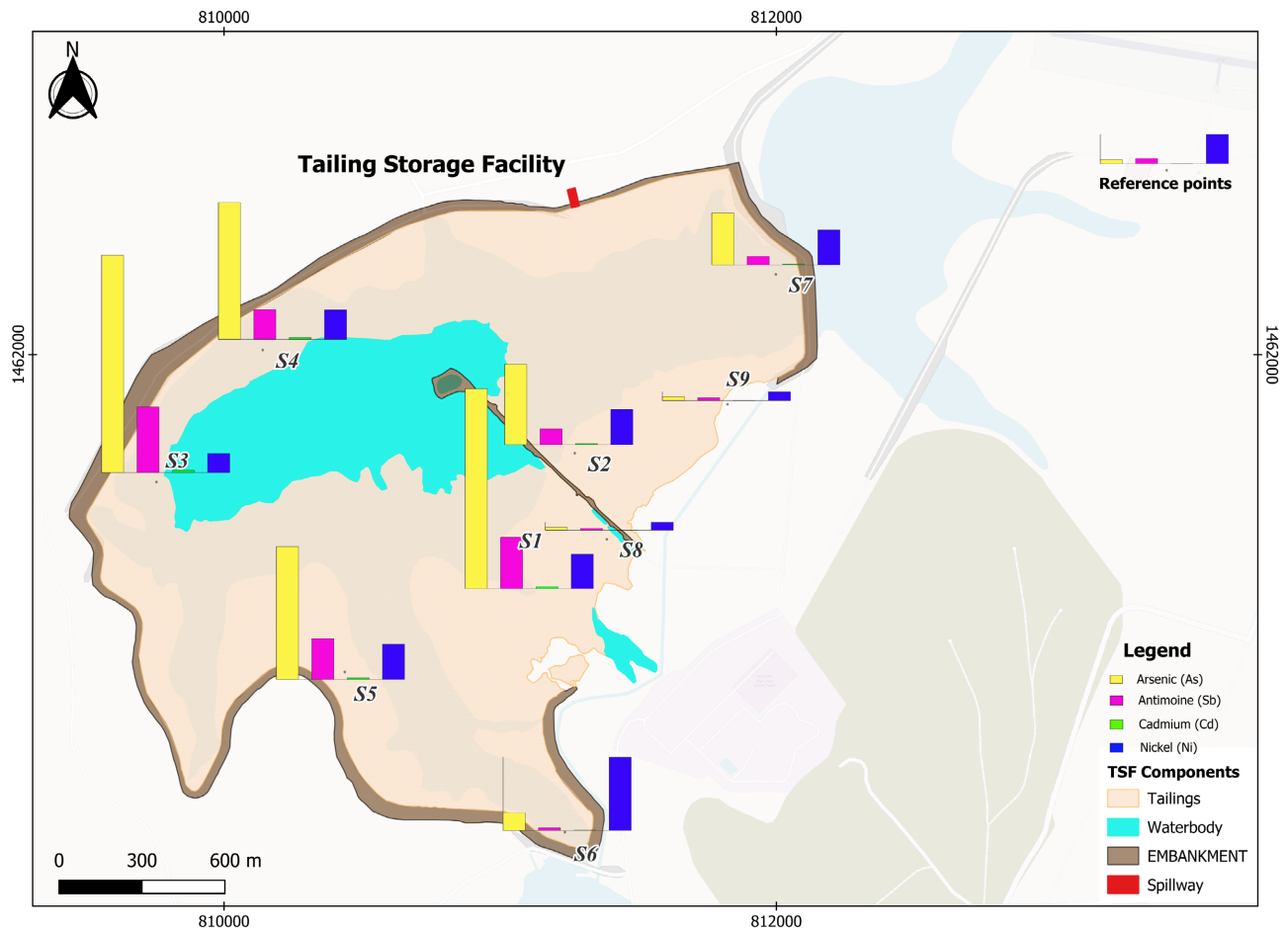
The average levels of trace elements in mine tailings are 408.1, 79.46, 4.16 and 156.42 ppm respectively for arsenic, antimony, cadmium and nickel. The distribution of these elements in the TSF is presented in **Figure 3**. These values are very high compared with the local background (reference points), where the levels are 12.9, 16.64, 0.54 and 92.35 ppm for arsenic, antimony, cadmium and nickel respectively. The data assembled in **Table 2** are classified according to the average concentrations of the trace elements studied in mine tailings from five mines around the world. ETM concentrations in our study area exceed UCC standard values [12].

The data presented in **Figure 3** are compared on the basis of their average concentration with the levels of the trace elements studied in the tailings of five mines around the world. The Sabodala mining area, which is the study area, has much lower levels of arsenic, antimony and cadmium than the Tourtit and Ichoumellal mines in central Morocco [13]. The Sabodala mine tailings show greater accumulation than the tailings from mines in Tunisia [14] and Iran [15]. Compared with the Iranian gold mine, the high arsenic and antimony content of the tailings shows that Sabodala's gold is associated with arsenopyrite and stibine (**Table 2**).

##### 3.1.1. Pollution Index (PI) of Tailings and Surrounding Soils

The pollution indices for the tailings and surrounding soils are shown in **Table 3**.

The results obtained show that the pollution index values for mine tailings are greater than unity, with the exception of stations S8 and S9. These values indicate polymetallic contamination of mine tailings (**Figure 4**). The potential risk factor of these metals for the environment (mobility) increases considerably with the combined effect of arsenic, antimony and cadmium. These pollution indices are lower than those found in the Moroccan mines of Mibladen (PI: 34.7) and Zeida (PI: 20.52) [18].



**Figure 3.** Distribution of TMEs in Sabodala mine tailings.

**Table 2.** Comparative table of average concentrations of trace metals in mine tailings from the study area with ETM concentrations in the earth’s crust (UCC: [12]), the local geochemical background and with five mines in the world. (Und: Undetermined value).

Country	Context	TME Concentration				Exploitable Mineral Substances	References
		As	Sb	Ni	Cd		
<b>Senegal</b>	Tailings Storage Facility	408.1	79.46	156.42	4.16	Au	This Study
	Local geochemical background	12.9	16.64	92.35	0.54	Und	This study
<b>Italy</b>	Tailings Storage Facility	319.25	Und	Und	8.75	Cu	[16]
<b>Iran</b>	Tailings Storage Facility	28.6	7.5	15.5	Und	Au	[15]
<b>Morocco</b>	Tailings Storage Facility	3783.24	34220.92	30.26	24.11	Sb	[13]
<b>Tunisia</b>	Tailings Storage Facility	85.8	32.1	36.7	0.64	Pb-Zn	[14]
<b>Morocco</b>	Tailings Storage Facility	101	0.7	14.2	0.4	Fe-S	[17]
<b>Und</b>	Upper Continental Crust (UCC)	30	UV	50	2	Und	[12]

**Table 3.** Variation in pollution index values.

Stations	PI	Status
<b>S1</b>	18	PI > 1
<b>S2</b>	19.04	Polymetallic contamination

Continued

S3	20	
S4	12.90	
S5	12.5	PI > 1
S6	2.41	Polymetallic contamination
S7	5.05	
S8	0.60	No polymetallic pollution
S9	0.69	No polymetallic pollution

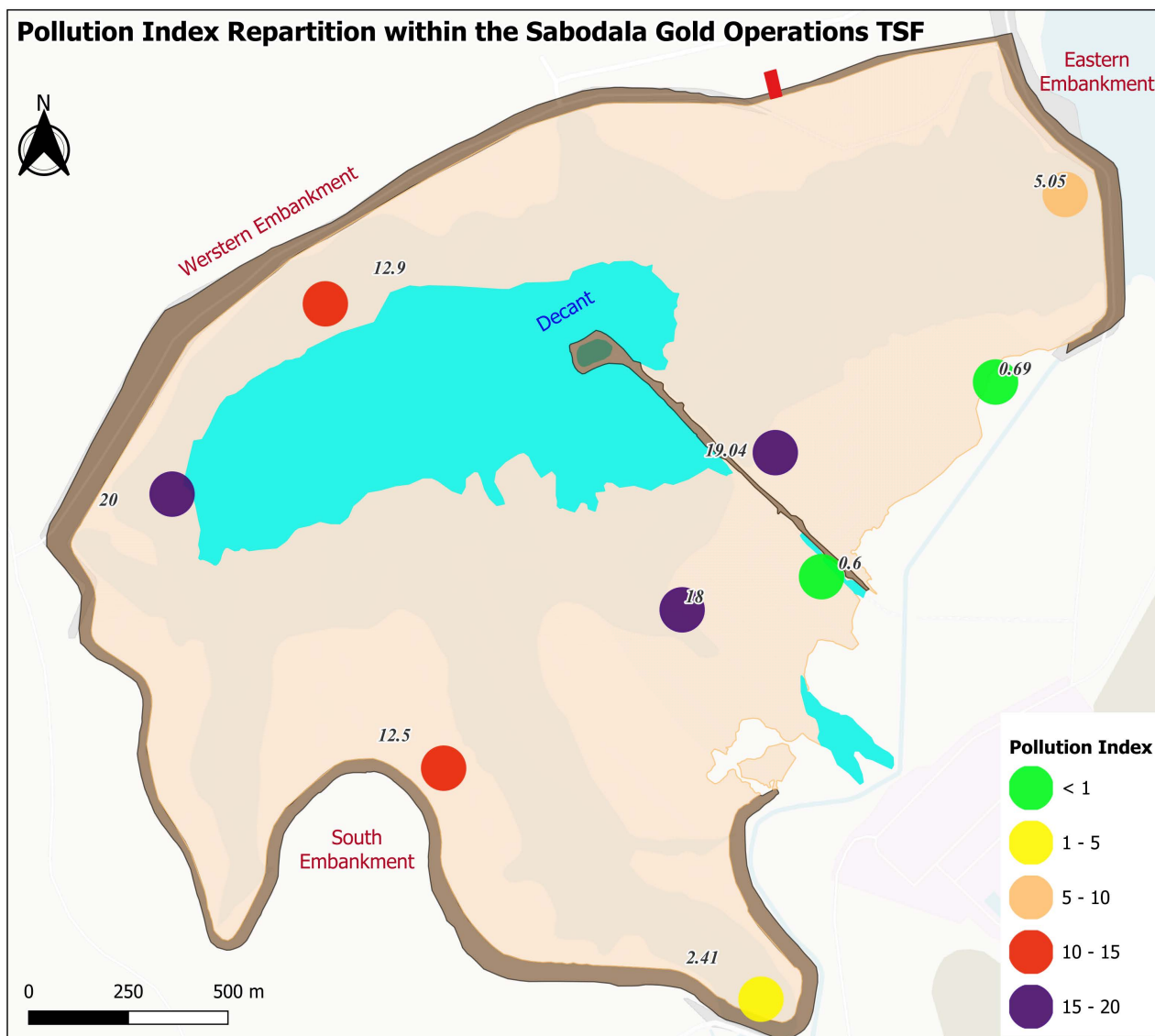


Figure 4. Spatial variation of the pollution indices (PI) in the Sabodala Tailings pond.

### 3.1.2. Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) was applied to gain a better understanding of the geochemical associations characterizing the study area and the possi-

ble origins of metal contaminants in mine tailings. After applying the VARIMAX rotation, two main factorial axes were selected for statistical analysis (Figure 5).

- ✓ The first factor accounts for around 88.9 % of the total variance, influenced mainly by metalloids (As and Sb) and cadmium, and is linked to the minerals arsenopyrite and stibine. This association between stibine and arsenopyrites has been noted in the work of [19] and [20]. This geochemical association contains impurities such as cadmium [21]. The presence of the metals As, Sb and Cd is linked to anthropogenic activities. This association is noted by strong correlations between arsenic-antimony (86%), arsenic-cadmium (82%) and antimony-cadmium (94%).
- ✓ The second factor accounts for around 7,6 % of the total variance, dominated by nickel, and is probably linked to nickel-bearing rocks. Unlike metals (As, Sb and Cd), mining activity has little influence on nickel levels in soils. This assertion is confirmed by the variations in nickel content in mine tailings and the reference site (Figure 3).

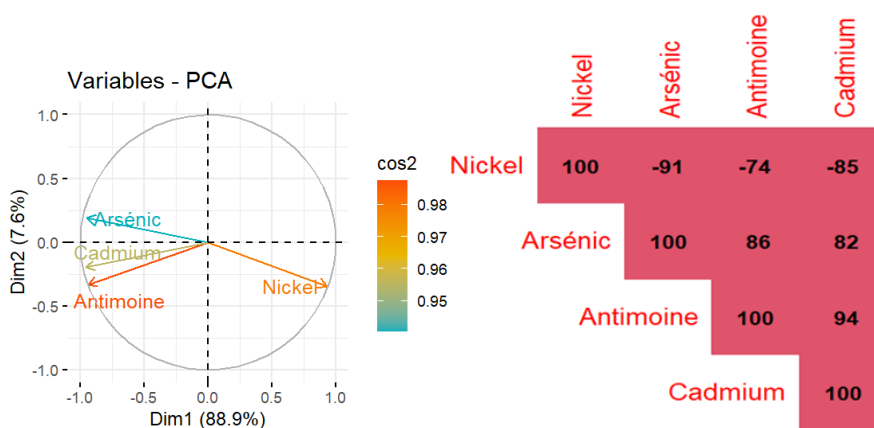


Figure 5. PCA analysis applied to trace metals.

### 3.2. Speciation

Speciation is defined as the determination of a specific form (monoatomic or molecular) or the configuration in which an element can be present in a group of atoms corresponding to different matrices [22].

Chemical methods are commonly used to determine the speciation of metallic elements in soils. They were used here to complement the physical data obtained and to clarify the potential mobility of metallic elements in the samples studied. The use of chemical extractions is much debated due to certain limitations encountered as a result of (1) refixation phenomena of extracted metallic elements on the solid fraction, (2) the non-selectivity of reagents, (3) the relative efficiency of the extractant depending on the nature of the element and (4) the multitude of protocols proposed. Despite all these limitations, chemical extractions are often used as they provide sufficient information to discuss the relative mobility of metallic elements. In addition, some of the stated limitations can be controlled by

returning to the solid residue analysis [23]. To minimize errors, determination using this procedure is carried out three times and then averaged.

Chemical fractionation shows that antimony is preferentially bound to the residual fraction (95%). This close bond was demonstrated by [24]. The proportion of antimony in the sulphide-bound fraction is of the order of 3% (Figure 6). The association of this element with carbonates is relatively low (2%).

Arsenic is found mainly in the residual fraction, with levels of 61%. This is followed by the sulphide fraction (27%), the iron and manganese oxide fraction (7%), the carbonate fractions (4%) and finally the exchangeable fraction (1%). These results confirm the role of iron and manganese oxides in arsenic retention [25].

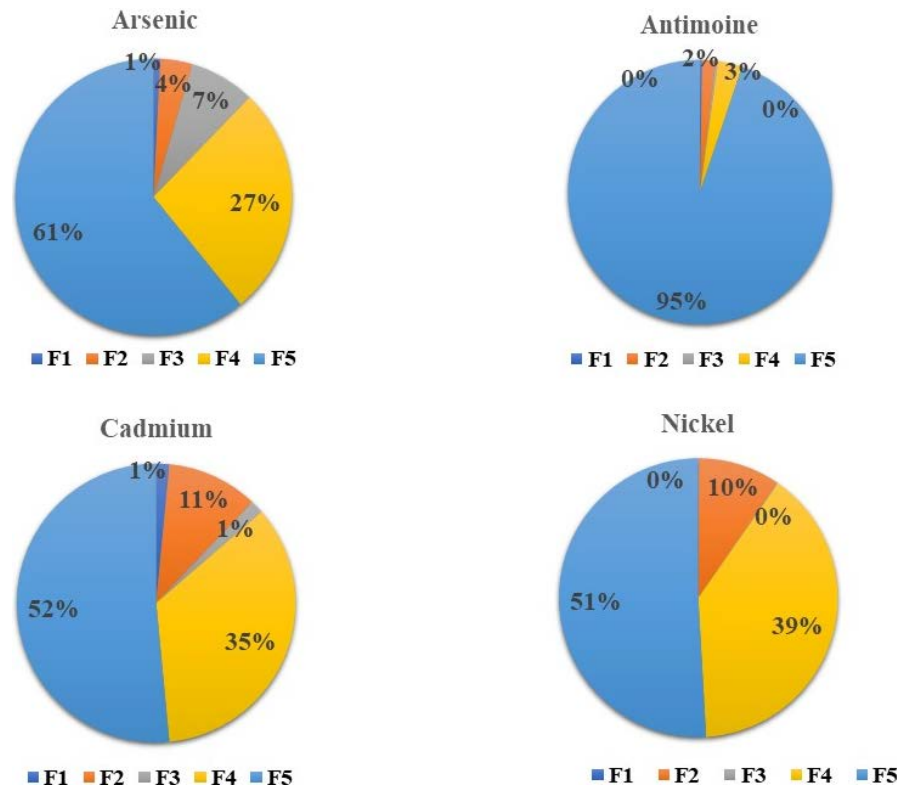
Cadmium exists in soils at very low levels, yet it is the most feared element because of its toxicity. Cadmium is mobile, easily bio-available and could either pass into the food chain via plants or migrate deep down to contaminate groundwater. Cadmium is preferentially associated with the residual phase (52%), the sulphide phase with a percentage of around 35% and the carbonate phase with 11%. The exchangeable fractions and those linked to oxides and sulphides are 1% each. This preferential accumulation of cadmium with the residual and sulphide phases was noted in the work of [26].

Nickel is preferentially associated with the residual fraction (Figure 6), with an average rate of around 51%. This association has been highlighted by several authors [27] [28].

### 3.3. Bioavailability

Bioavailability refers to the capacity of a quantity of an element present in the soil to be absorbed by a living organism [29]. Bioavailability is a tool for assessing toxicity and the risk of pollution. The risk of ecotoxicity by heavy metals does not result solely from the total concentrations found in polluted waste, but also from their mobile fraction [30] [31]. In soils, concentrations of soluble and exchangeable metals are indicators of a potential risk of contaminant transfer to the various environmental compartments [32] [33]. In this study, nickel is the most bioavailable metal, with a 49% share. It was followed by cadmium (48%), arsenic (39%) and antimony (5%) (See Figure 4). Metals in form (water-soluble, exchangeable carbonate-bound) are highly mobile and can easily be absorbed and accumulated by living organisms or leached down the soil profile to groundwater [34], while those embedded in the crystal lattice are relatively immobile and can have little or no harmful impact on living organisms and the environment [35]. Based on the classification described by [36], if the metal content released into the F1 and F2 fractions of the soil is less than 1% of the total metal, the soil presents no risk to the environment. Values between 1 and 10% reflect a low risk, 11 to 30% a medium risk and 31 to 50% a high risk. Above 50%, the soil presents a very high risk and is considered hazardous, so that TMEs accumulate along the food chain, more in humans than in species lower down the chain [37]. The F1 and F2 fractions of cadmium and nickel in root soil are 12% and 10% respectively, showing a low risk

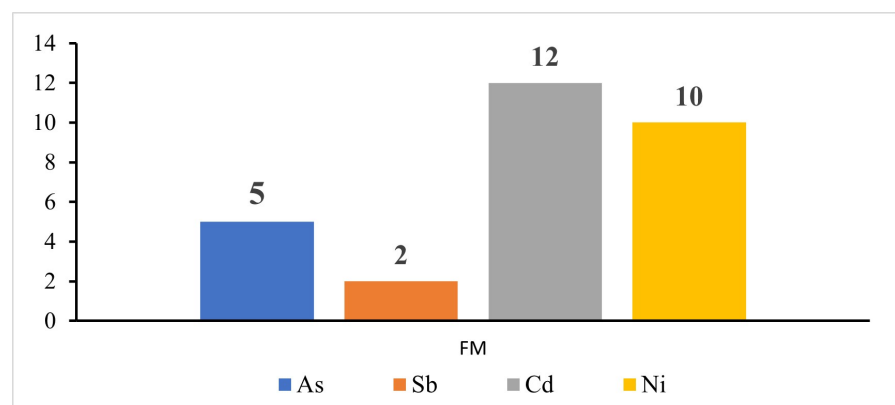
of contamination of groundwater by leaching or of plants by root uptake. Arsenic and antimony show a low risk to the environment.



**Figure 6.** Distribution of arsenic, antimony, cadmium and nickel levels in the various fractions of mining tailings. F1: Exchangeable fraction, F2: Carbonate bound fraction, F3: Fe-Mn oxides bound fraction, F4: Organic bound fraction, F5: Residual fraction.

### 3.4. Mobility Factor

Equation (1) is used to calculate the mobility factor for metals and metalloids. **Figure 4** shows the variations in mobility factors.



**Figure 7.** Potential mobility of potentially toxic elements (As, Sb, Cd and Ni).

Cadmium and nickel can be considered the most mobile elements in mine tail-

ings, as around 12% and 10% respectively are found in the exchangeable and carbonate-bound fractions. This suggests that a substantial proportion of cadmium and nickel is contained in minerals such as calcite and ferrodolomite. The results are in line with those obtained by [38] and [39]. The potential mobility factor for arsenic is 5%. Arsenic is considered to be a rather immobile element because most of this metalloid is bound to the residual mineral fraction. The chemistry of precipitation-dissolution and adsorption-desorption of arsenic is complex and depends on the load of the water, especially when there is a high presence of iron in the water. The potential mobility factor for antimony is 2%. As with arsenic, the distribution of Sb in the tailings indicates that this element was rather immobile and was largely present in the residual fraction. In a recent study on the sequential extraction of antimony from contaminated soils, [24] [40] and [41] found that a large amount (up to 90%) of the antimony was associated with the residual fraction. In general, there are a number of similar general trends in the fractionation of arsenic and antimony in soil. Metalloids (As, Sb) are associated with crystalline and non-crystalline oxide and hydroxide minerals and are often considered immobile [42].

#### **4. Conclusion**

In recent years, the management policy for polluted mining sites has focused mainly on assessing the chemical speciation, mobility and bioavailability of TMEs in order to predict their impact and toxicity on the environment. The mine tailings studied show a tendency to be highly enriched in potentially toxic elements. Total TME concentrations showed that the order of abundance of the TMEs studied in the samples was As > Ni > Sb > Cd. The results show that trace metals are mainly associated with the residual fraction. Most of these metallic elements are found in a form that is not easy to migrate and transform. The risk of contamination of groundwater and neighbouring plants by these trace metals is low. The mobility of metallic elements is essentially linked to the presence of carbonates in the soil, which favours an increase in pH, and a precipitation of metallic elements with a reduction in the bioavailability of metals is foreseeable. A decrease in pH and a variation in the redox potential in the environment caused by exogenous factors can release metals associated with mine tailings and impact the environment.

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#### **Conflicts of Interest**

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

#### **References**

- [1] Collon, P. (2003) Evolution de la qualité de l'eau dans les mines abandonnées du

- bassin ferrifère lorrain. De l'expérimentation en laboratoire à la modélisation in situ. Doctorat, Institut National Polytechnique de Lorraine-INPL.
- [2] Lghoul, M., Kchikach, A., *et al.* (2012) Etude géophysique et hydrogéologique du site minier abandonné de Kettara (région de Marrakech, Maroc): Contribution au projet de réhabilitation. *Hydrological Sciences Journal*, **57**, 370-381.  
<https://doi.org/10.1080/02626667.2011.637495>
- [3] Bussi re, B., Aubertin, M., Zagury, G.J., *et al.* (2005) Principaux d fis et pistes de solution pour la restauration des sites miniers abandonn s g n rateurs de drainage minier acide. *2e symposium sur l'environnement et les mines*, Rouyn-Noranda, 15 May 2005. <https://publications.polymtl.ca/24336/>
- [4] Tessier, A., Campbell, P. and Bosson, M. (1979) Sequential Extraction Procedure for Speciation of Particulate Trace Elements. *Analytical Chemistry*, **51**, 844-851.  
<https://doi.org/10.1021/ac50043a017>
- [5] Stone, M. and Marsalek, J. (1996) Trace Metal Composition and Speciation in Street Sediment: Sault Ste. Marie, Canada. *Water, Air, & Soil Pollution*, **87**, 149-169.  
<https://doi.org/10.1007/BF00696834>
- [6] Ure, A.M. and Davidson, C.M. (2001) Chemical Speciation in the Environment. 2nd Edition, Blackwell Science Ltd. <https://doi.org/10.1002/9780470988312.ch10>
- [7] Marin, B., Valladone, M., Polve, M. and Monaco, A. (1997) Reproducibility Testing of a Sequential Extraction Scheme for the Determination of Trace Metal Speciation in a Marine Reference Sediment by Inductively Coupled Plasma-Mass Spectrometry. *Analytica Chimica Acta*, **342**, 91-112.  
[https://doi.org/10.1016/S0003-2670\(96\)00580-6](https://doi.org/10.1016/S0003-2670(96)00580-6)
- [8] Sutherland, A. (2000) Comparison between Non-Residual Al, Co, Cu, Fe, Mn, Ni, Pb and Zn Released by a Three-Step Sequential Extraction Procedure and a Dilute Hydrochloric Acid Leach for Soil and Road Deposited Sediment. *Applied Geochemistry*, **17**, 353-365. [https://doi.org/10.1016/S0883-2927\(01\)00095-6](https://doi.org/10.1016/S0883-2927(01)00095-6)
- [9] Kabala, C. and Singh, B.R. (2001) Fractionation and Mobility of Copper, Lead and Zinc in Soil Profiles in the Vicinity of a Copper Smelter. *Journal of Environmental Quality*, **30**, 485-492. <https://doi.org/10.2134/jeq2001.302485x>
- [10] Narwal, R.P., Singh, B.R. and Salbu, B. (1999) Association of Cadmium, Zinc, Copper, and Nickel with Components in Naturally Heavy Metal-Rich Soils Studied by Parallel and Sequential Extractions. *Communications in Soil Science and Plant Analysis*, **30**, 1209-1230. <https://doi.org/10.1080/00103629909370279>
- [11] Salbu, B., Krekling, T. and Oughton, D.H. (1998) Characterization of Radioactive Particles in the Environment. *Analyst*, **123**, 843-849.  
<https://doi.org/10.1039/a800314j>
- [12] Rudnick, R.L. and Gao, S. (2003) Composition of the Continental Crust. *Treatise on Geochemistry*, **3**, 1-64. <https://doi.org/10.1016/B0-08-043751-6/03016-4>
- [13] Ahmedat, C., Dabi, S. and Zahraoui, M., *et al.* (2018) Spatial Distribution of Stream Sediment Pollution by Toxic Trace Elements at Tourtit and Ichoumellal Abandoned Mining Areas (Central Morocco). *Arabian Journal of Geosciences*, **11**, Article No. 55.  
<https://doi.org/10.1007/s12517-018-3390-0>
- [14] Ayari, J., Barbieri, M., Agnan, Y., Sellami, A., Braham, A., Dhaha, F. and Charef, A. (2021) Trace Element Contamination in the Mine-Affected Stream Sediments of Oued Rarai in North-Western Tunisia: A River Basin Scale Assessment. *Environmental Geochemistry and Health*, **43**, 4027-4042.  
<https://doi.org/10.1007/s10653-021-00887-1>

- [15] Siahcheshm, K., Orberger, B., & Wagner, C. (2022). Bioavailability and Heavy Metals Speciation Assessment in the Contaminated Soils of Doustbaglu Mineralized Area, NW Iran. *Environmental Earth Sciences*, **81**, 34. <https://doi.org/10.1007/s12665-021-10162-2>
- [16] Benvenuti, M., Mascaro, I. and Corsini, F., *et al.* (1997) Mine Waste Dumps and Heavy Metal Pollution in Abandoned Mining District of Boccheggiano (Southern Tuscany, Italy). *Environmental Geology*, **30**, 238-243. <https://doi.org/10.1007/s002540050152>
- [17] El Amari, K., Valera, P., Hibti, M., Pretti, S., Marcello, A., & Essarraj, S. (2014). Impact of Mine Tailings on Surrounding Soils and Ground Water: Case of Kettara old Mine, Morocco. *Journal of African Earth Sciences*, **100**, 437-449. <https://doi.org/10.1016/j.jafrearsci.2014.07>
- [18] El Hachimi, M.L., Fekhaoui, M., El Abidi, A. and Rhoujatti, A. (2014) Contamination des sols par les métaux lourds à partir de mines abandonnées: Le cas des mines Aouli-Mibladen-Zeïda au Maroc. *Cahiers Agricultures*, **23**, 213-219. <https://doi.org/10.1684/agr.2014.0702>
- [19] Diouf, A.F. (2020) Contribution à l'amélioration de la connaissance de la qualité des ressources en eaux souterraines et de surface en zone de socle: Cas du périmètre d'exploration aurifère Kanoumba, Kédougou-Sénégal. Mémoire de master. Cheikh Anta Diop de Dakar (Institut des sciences de l'environnement).
- [20] Bondu, R. (2017) Origine et distribution de l'arsenic dans l'eau souterraine de l'aquifère rocheux fracturé du bouclier canadien en Abitibi-Témiscamingue. Phd, Université du Québec en Abitibi-Témiscamingue. <https://depositum.uqat.ca/id/eprint/704/>
- [21] Plante, B. (2010) Évaluation des principaux facteurs d'influence sur la prédiction du drainage neutre contaminé. Phd, Université du Québec à en Abitibi-Témiscamingue. <https://depositum.uqat.ca/id/eprint/31/>
- [22] Hetland, S., Martinsen, I., Radzuk, B. and Thomassen, Y. (1991) Species Analysis of Inorganic Compounds in Workroom Air by Atomic Spectroscopy. *Analytical Sciences*, **7**, 1029-1032. [https://doi.org/10.2116/analsci.7.Supple\\_1029](https://doi.org/10.2116/analsci.7.Supple_1029)
- [23] Quevauviller, P., Rauret, R., Rubio, G., Lopez Sanchez, J.F., Ure, A.M., Bacon, J.R. and Muntau, H. (1997) Certified Reference Materials for the Quality Control of EDTA- and Acetic Acid-Extractable Contents of Trace Elements in Sewage Sludge Amended Soils (CRMs 483 and 484). *Fresenius' Journal of Analytical Chemistry*, **357**, 611-618. <https://doi.org/10.1007/s002160050222>
- [24] He, M.C. (2007) Distribution and Phytoavailability of Antimony at an Antimony Mining and Smelting Area, Hunan, China. *Environmental Geochemistry and Health*, **29**, 209-219. <https://doi.org/10.1007/s10653-006-9066-9>
- [25] Gabteni, N. (1986). Géochimie analytique et expérimentale des éléments traces dans les sols. Application aux sols calcaires de la Tunisie du Nord. These de Doctorat. Faculte des Sciences. Tunis, 136 p.
- [26] Sebei, A., Chaabani, F. and Ouerfelli, M.K. (2005) Impacts des rejets miniers sur le sol et les plantes de la région de Boujaber (NO. Tunisie) Fractionnement chimique des métaux lourds dans les sols. *GEO-ECO-TROP*, **29**, 37-50.
- [27] Added, A. (1981) Etude géochimique et sédimentologique des sédiments marins du Delta du Rhône. Doctoral Thesis. Université Pierre et Marie Curie (Paris).
- [28] Lopez-Sanchez, J.F., Rubio, R., Samitier, C. and et Rauret, G. (1996) Trace Metal Partitioning in Marine Sediments and Sludges Deposited of the Coast of Barcelona (Spain). *Water Research*, **30**, 153-159. [https://doi.org/10.1016/0043-1354\(95\)00129-9](https://doi.org/10.1016/0043-1354(95)00129-9)

- [29] Newman, M., Jagoe, C., Newman, M.C. and Jagoe, C.H. (1994) Ligands and the Bioavailability of Metals in Aquatic Environments. *Bioavailability: Physical, Chemical and Biological Interactions*, CRC Press, 39.
- [30] Adriano, D.C. (2001) Trace Elements in Terrestrial Environments: Biogeochemistry, Bioavailability, and Risks of Metals. Springer-Verlag, 867 p.
- [31] Jansen, B., Nierop, K.G.J. and Verstraten, J.M. (2003) Mobility of Fe(II), Fe(III) and Al in Acidic Forest Soils Mediated by Dissolved Organic Matter: Influence of Solution pH and Metal/Organic Carbon Ratios. *Geoderma*, **113**, 323-340. [https://doi.org/10.1016/S0016-7061\(02\)00368-3](https://doi.org/10.1016/S0016-7061(02)00368-3)
- [32] Lavazzo, P., Adamo, P., Boni, M., Hillier, S. and Zampella, M. (2012) Mineralogy and Chemical Forms of Lead and Zinc in Abandoned Mine Wastes and Soils: An Example from Morocco. *Journal of Geochemical Exploration*, **113**, 56-67. <https://doi.org/10.1016/j.gexplo.2011.06.001>
- [33] Jeannot, R., Lemiere, B., Chiron, S., Augustin, F. and Darmendrail, D. (2000) Guide méthodologique pour l'analyse des sols pollués. BRGM/RP-50128-FR. <https://infoterre.brgm.fr/rapports/RP-50128-FR.pdf>
- [34] Chopin, E.I.B., Black, S., Hodson, M.E., Coleman, M.L. and Alloway, B.J. (2003) A Preliminary Investigation into Mining and Smelting Impacts on Trace Element Concentrations in the Soil and Vegetation around Tharsis, SW Spain. *Mineralogical Magazine*, **67**, 279-288. <https://doi.org/10.1180/0026461036720099>
- [35] Ogundiran, O. and Osibanjo, M.B. (2009) Mobility and Speciation of Heavy Metals in Soils Impacted by Hazardous Waste. *Chemical Speciation & Bioavailability*, **21**, 59-69. <https://doi.org/10.3184/095422909X449481>
- [36] Singh, K.P., Mohan, D., Singh, V.K. and Malik, A. (2005) Studies on Distribution and Fractionation of Heavy Metals in Gomti River Sediments—A Tributary of the Ganges, India. *Journal of Hydrology*, **312**, 14-27. <https://doi.org/10.1016/j.jhydrol.2005.01.021>
- [37] Jain, C.K. and Ran, D. (2004) Metal Fractionation Study on Bed Sediments of River Yamuna, India. *Water Research*, **38**, 569-578. <https://doi.org/10.1016/j.watres.2003.10.042>
- [38] Kapusta, P., Szarek-Łukaszewska, G. and Stefanowicz, A.M. (2011) Direct and Indirect Effects of Metal Contamination on Soil Biota in a Zn-Pb Post-Mining and Smelting Area (S Poland). *Environmental Pollution*, **159**, 1516-1522. <https://doi.org/10.1016/j.envpol.2011.03.015>
- [39] Vaněk, A., Borůvka, L., Drábek, O., Mihaljevič, M. and Komárek, M. (2005) Mobility of Lead, Zinc and Cadmium in Alluvial Soils Heavily Polluted by Smelting Industry. *Plant, Soil and Environment*, **51**, 316-321. <https://doi.org/10.17221/3592-PSE>
- [40] Tighe, M., Lock wood, P. and Wilson, S. (2005) Adsorption of Antimony (V) by Flood-Plain Soils, Amorphous Iron (III) Hydroxide and Humic Acid. *Journal of Environmental Monitoring*, **7**, 1177-1185.
- [41] Denys, S., Tack, K., Caboche, J. and Delalain, P. (2008) Bioaccessibility, Solid Phase Distribution, and Speciation of Sb in Soils and in Digestive Fluids. *Chemosphere*, **74**, 711-716. <https://doi.org/10.1016/j.chemosphere.2008.09.088>
- [42] Fillela, M. (2011) Antimony Interactions with Heterogeneous Complexants in Waters, Sediments and Soils: A Review of Data Obtained in Bulk Samples. *Earth-Science Reviews*, **107**, 325-341. <https://doi.org/10.1016/j.earscirev.2011.04.002>