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Comprehensive Assessment of Environmental Behavior of Mine Tailings for Sustainable Waste Management and Mitigation of Pollution Risks

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Abstract: The substantial volumes of tailings produced during ore beneficiation present significant challenges for sustainable management due to potential public health hazards, particularly from metal leaching. The risk associated with tailings varies greatly depending on their mineralogical composition and climatic conditions. If tailings are classified as a non-hazardous by-product, they may serve as secondary raw materials, offering a sustainable alternative to the reliance on non-renewable primary resources. In this study, the recycling feasibility of tailings from an active copper mine was assessed through mineralogical characterization, environmental tests (e.g., static, kinetic, and leaching tests), and geochemical modeling. This multi-faceted approach aimed to predict the geochemical behavior and reactivity of tailings under varying conditions. Results from the static tests indicated that the tailings were non-acid generating. Weathering cell tests revealed circumneutral pH conditions (6.5–7.8), low sulfide oxidation rates, and low instantaneous metal concentrations (<1 mg/L), except for copper (0.6–3.5 mg/L) and iron (0.4–1.4 mg/L). These conditions are attributed to the low abundance of sulfide minerals, such as pyrite, chalcopyrite, bornite, covellite (<0.1 wt.%), and chalcocite (0.2 wt.%), which are effectively encapsulated within gangue minerals. Additionally, the presence of neutralizing minerals, specifically dolomite (27.4 wt.%) and calcite (2.4 wt.%), further stabilizes pH and promotes metal sequestration in secondary mineral forms. The Toxicity Characteristic Leaching Procedure (TCLP) test confirmed low leachability, classifying the tailings as non-hazardous.

Keywords: sustainable waste management; water pollution risk assessment; geochemical behavior; mine tailings; neutral mine drainage; safe recycling assessment; static and kinetic tests; geochemical modeling

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1. Introduction

People rely heavily on mineral resources and mining operations to supply the materials essential for modern life and the transition to sustainable energy systems [1]. In response to this demand, the mining industry produced 22.7 billion tons of energy resources, metals, and critical non-metallic minerals in 2018, with a total output value of USD 5.9 trillion, accounting for 6.9% of global GDP [2]. Consequently, the mining and metallurgical industry is continuously engaged in research to meet the rising demand for critical resources, especially those vital to the energy transition, such as copper, lithium, and rare earth elements [3]. However, the mining sector is the world's largest producer of waste, generating billions of tons annually, primarily in the form of waste rocks, tailings, and slags [4,5]. Tailings, the fine-grained residues generated from ore processing and beneficiation, represent a substantial portion of this waste [6]. According to recent data from the Global Tailings Review, approximately 46% of all tailings are generated by copper production alone [7,8]. These huge quantities of tailings are stored in specialized structures known as tailings storage facilities (TSFs), which, in most cases, are abandoned without adequate environmental management [9,10]. These tailings often contain diverse minerals, particularly sulfide minerals, which can pose serious environmental challenges especially on surface and groundwater if not properly managed [11–14]. Thus, implementing advanced and precise waste management strategies not only mitigates environmental risks but also unlocks economic potential from these by-products, supporting the circular economy principles crucial to a sustainable energy future. It is well established that sulfide minerals in unmanaged tailings undergo abiotic and biotic reactions with water and air, resulting in significant environmental issues, including Acid Mine Drainage (AMD) [15–19]. When the neutralization potential (NP) of neutralizing minerals (e.g., carbonates and silicates) within the tailings is sufficient to buffer the acidity produced by AMD, contaminated neutral drainage (CND) may also develop [20,21]. This occurs when one or more heavy metals or metalloids are leached at levels exceeding regulatory standards, despite maintaining neutral pH values [22–27]. Both AMD and CND contribute to environmental issues that can persist for decades, if not millennia [28–30]. The primary environmental risks associated with AMD stem from its extremely low pH (typically below 3) and high concentrations of sulfates and toxic metal ions [31–34]. These conditions present significant threats, especially to water resources, which might be contaminated by acidic water (AW) [35–38]. Acidic waters generated by sulfide-rich tailings increase the solubility of metal(loid)s, facilitating their transport through runoff and enabling their spread into surrounding areas [39,40]. This dispersion leads to severe pollution of soils, surface water bodies, and even groundwater [41,42]. As a result, contamination from AMD poses serious hazards to drinking water quality, public health, and local crop growth on a global scale [42,43]. To mitigate the substantial impacts of AMD and the related heavy metal dispersion, integrated tailings management is essential and serves as a key strategy for reducing, if not entirely eliminating, these risks [44,45].

Integrated mine tailings management has seen the proposal of several sustainable practices aimed at reducing environmental impact and enhancing resource recovery. Key practices include tailings dewatering [46], which significantly limits water infiltration and minimizes leaching, alongside environmental desulfurization to reduce AMD generation [47,48]. Furthermore, co-disposal with mine backfill materials has been recognized for its double benefit in securing TSFs and optimizing material reuse [49,50]. Moreover, the reprocessing of tailings to extract remaining valuable resources presents an additional strategy, allowing for the recovery of valuable metals and minerals that would otherwise be lost, thus diminishing the ecological footprint of mining operations and enhancing sustainable reprocessing and valorization [51,52]. Furthermore, converting mine waste into economically viable materials, the management and valorization of tailings contribute meaningfully to a circular economy and reduce environmental risk [53–55]. Moreover, a comprehensive evaluation of the geochemical properties of tailings is essential for accurately classifying them into desirable or undesirable categories [56], facilitating the selection of optimal management approaches tailored to specific tailing characteristics.

To evaluate the geochemical behavior of mine tailings, a variety of predictive techniques are available, broadly classified into two categories [54,57]: (i) static tests and (ii) kinetic tests [58,59]. Static tests are primarily employed to assess the acid-generating potential of mine tailings [60–62], with Acid–Base Accounting (ABA), Net Acid Generation (NAG) tests, and paste pH analysis being the most widely used methods [61,63,64]. Conversely, kinetic tests are designed to replicate the natural weathering processes of waste under laboratory conditions, allowing for a more dynamic understanding of tailings behavior. Among the kinetic methods, the weathering cell (WC) test is considered the most effective due to its expedited assessment and reduced sample requirements compared to other kinetic tests [65,66]. Additionally, the Toxicity Characteristic Leaching Procedure (TCLP) serves as a standard operational approach for distinguishing hazardous from nonhazardous wastes by simulating pollutant leaching in landfill environments [66–68].

The Bleïda copper mine tailings pond was selected for this study due to its large volume of tailings, generated by one of Morocco's major copper producers. Additionally, with the mine located in an arid region with limited water resources, the mine's tailings may impact these resources if they are stored without a hazard assessment. Assessing the geochemical and environmental behavior of tailings is essential for developing reclamation strategies tailored to their physical, chemical, mineralogical, and environmental properties. Such a detailed analysis enables the identification of the most effective approaches for tailings recovery and conversion into economically viable materials. Thus, the objectives of this study are as follows: (i) to conduct a comprehensive characterization of the tailings and evaluate their contaminant drainage potential through static testing; (ii) to examine the long-term geochemical behavior of the tailings using weathering cell tests; and (iii) to classify the tailings based on their hazardousness using the TCLP.

2. Materials and Methods

2.1. Bleïda Mine Site

The Bleïda copper mine is located in the southeastern part of the Bou Azzer-El Graara inlier within Morocco's central Anti-Atlas region, approximately 80 km from the city of Zagora (Figure 1a). This area is characterized by a semi-desert climate, with winter temperatures ranging from 7 °C to −1 °C and summer temperatures reaching up to 40 °C. Annual rainfall is low, averaging around 60 mm, while evaporation rates are high, ranging between 2000 and 3000 mm per year. Evidence of mining at Bleïda dates back to the Middle Ages, as indicated by numerous trenches and the remains of ancient furnaces found east of the site. Modern mining operations were conducted intensively from 1971 to 1997, after which the site saw periods of inactivity due to reserve depletion. Mining resumed in 2008 and has continued to the present. The geological sequence at Bleïda comprises four main units: (i) stromatolitic limestone and quartzite, (ii) basalt, (iii) shale, and (iv) sandy shale (Figure 2) [67]. Copper is primarily hosted in sulfide minerals (including bornite, chalcopyrite, pyrite, and chalcocite), carbonate minerals (such as malachite and azurite), oxide minerals like cuprite, and silicate minerals like chrysocolla.

Copper ore extracted from various deposits in the mining district is then processed using the froth flotation technique. It undergoes first multiple stages of crushing to reduce its size to below 8 mm, after which it is conveyed to a ball mill for grinding to the required liberation size. The ground material is then classified by a hydrocyclone, which separates particles based on a specified cut-off diameter. The underflow (UF) is recirculated back to the ball mill, while the overflow (OF) is directed to the flotation unit, which consists of two circuits for sulfide and carbonate minerals, respectively. After the beneficiation process, two main products are obtained: a filtered and dried copper concentrate and a tailings slurry, which is transported via a pipeline to the surrounding tailings pond.

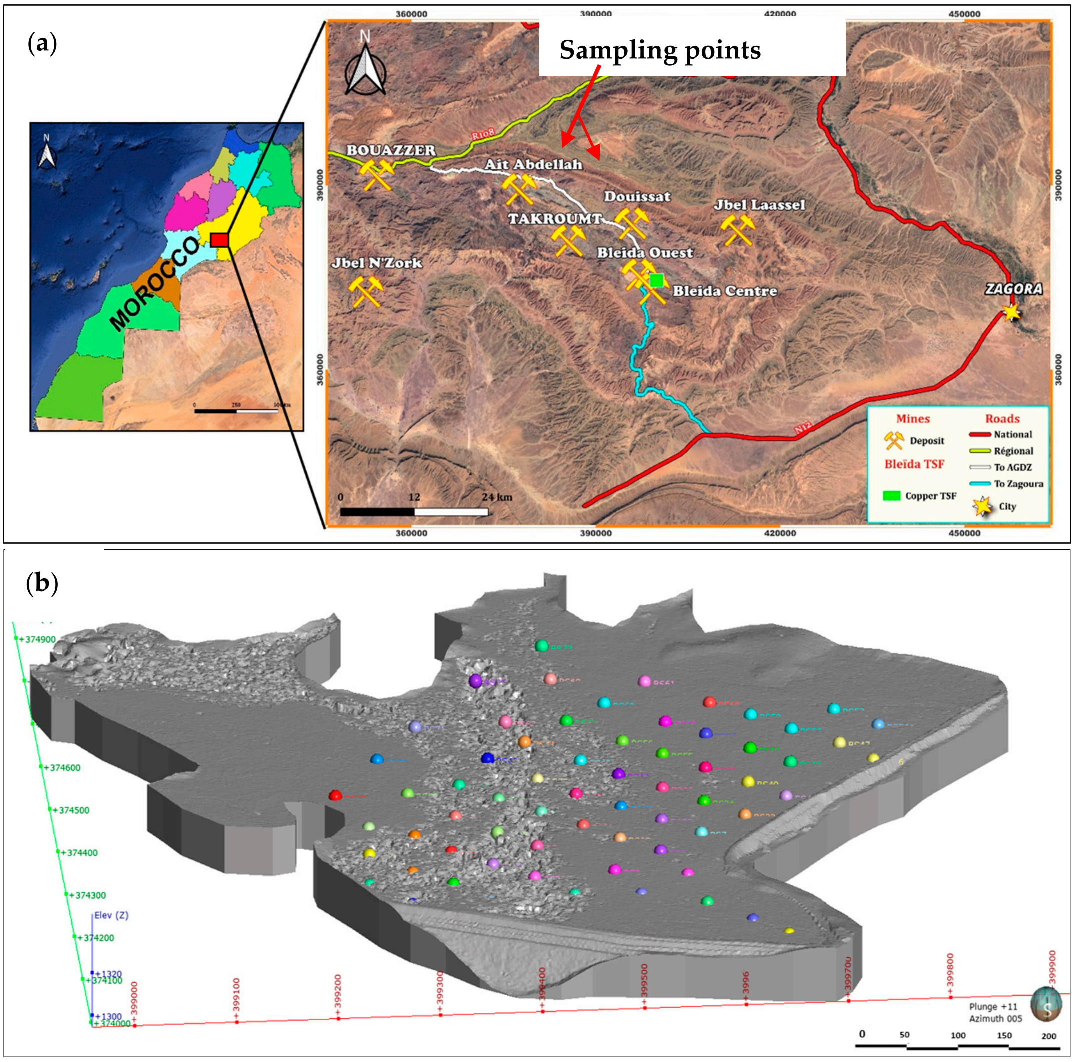


Figure 1. (**a**) Satellite imagery depicting the location of Bleïda Mining District, and (**b**) Bleïda TSF 3D model and localization of sampling points..

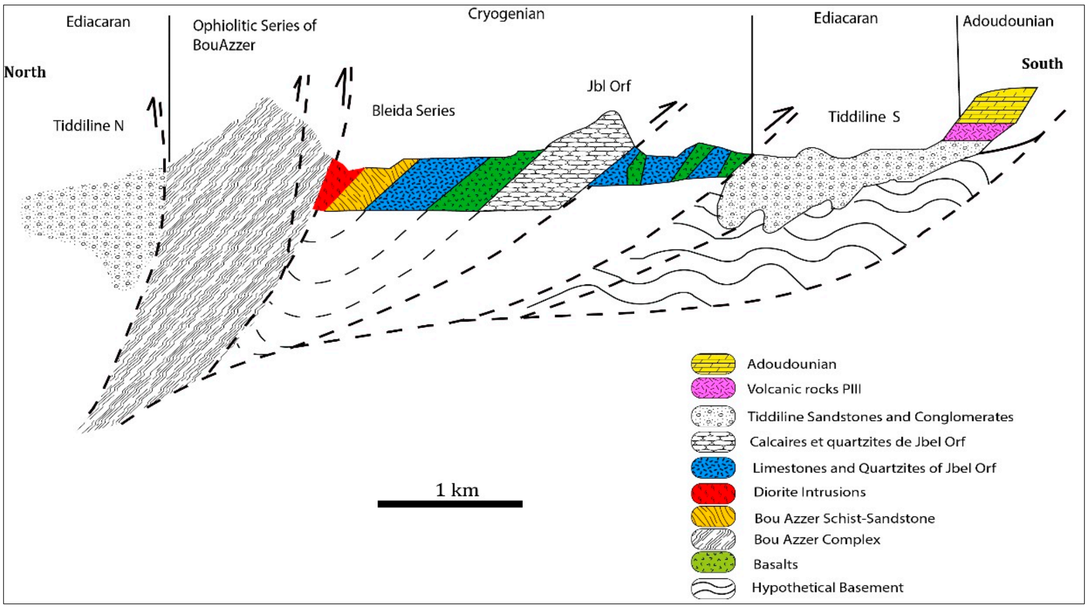


Figure 2. North–South geological section illustrating the arrangement of the different Precambrian series in the Bleïda district [67].

2.2. Sampling and Sampling Method

Sampling consists of selecting a subset from the entire population as measuring the full population is impractical. In this study, sampling points were chosen using a systematic approach based on a representative grid design (Figure 1b). A total of 73 samples were collected via the tubing method at depths between 1.5 m and 1.8 m. Samples were obtained from the non-oxidized residue, following the removal of the superficial, likely oxidized, weathered layer. Each sample was placed in a polyethylene plastic bag to maintain its original state and prevent oxidation upon exposure to atmospheric oxygen. The labeled bags were then transported to the laboratory, where samples were dried, homogenized, and divided to create composite samples.

2.3. Chemical and Physical Characterization

The bulk chemical composition of 42 elements in various solid samples was determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES), following method CR/AN/MO/102.00. Sulfur content (wt.% S) was analyzed by ICP-AES after digestion in a four-acid solution (HNO_3, Br_2, HF, and HCl). In this process, Br_2 oxidizes sulfur, while HCl and HF dissolve silicate minerals. A blank was analyzed every 20 samples. Standards were analyzed every 20 samples, duplicates were analyzed every 10 samples, and the instrument was recalibrated every 50 samples. Total sulfur content (wt.% S) was also measured using an ELTRA CS-2000 induction furnace, with a detection limit of 0.09% and a precision range of ±0.1 to 0.5%. Total carbon content (wt.% TC) was similarly measured, achieving a precision of ±0.6 to 1.1%. Particle size distribution (PSD) of the tailings was measured using a laser grain size analyzer (Malvern Mastersizer 2000, Ver. 6.00). The specific density of the tailings was measured with an Anton Paar Ultrapyc 5000 gas pycnometer, utilizing helium gas at a pressure of 10 psi and a temperature of 20 °C.

2.4. Mineralogical Characterization

The mineralogical composition of the samples was initially determined by X-ray diffraction (XRD) using a Bruker AXS Advance D8, equipped with a cobalt anode, scanning over a range of diffraction angles (2θ). Optical microscopy (OM) was employed to identify various sulfide minerals in the samples and examine their textures. Scanning electron microscopy (SEM) further complemented the mineralogical analysis, allowing for the identification of different mineral phases and associations, particularly highlighting sulfide mineral hosts and gangue minerals. Automated quantitative mineralogy (AQM) was conducted using a ZEISS Sigma VP microscope paired with Bruker EDS X-flash 30/60 spectrometers. Mineralogical data were processed with specialized software, and AQM analyses provided fully quantified modal mineralogy along with textural information, including copper deportment, elemental distribution, and the liberation degree of sulfide and non-sulfide minerals.

2.5. Geochemical Behavior Assessment

2.5.1. Static Tests

pH Paste Test

The pH paste test is used to assess the acid generation potential of the studied tailings [68]. This test consists of mixing 20 g of residue with a particle size of less than 250 μm with 20 mL of deionized water in a polyethylene tube, creating a solid/liquid (S/L) ratio of 2:1. The mixture is stirred to form a paste, and the pH of the paste is measured using a pH meter inoLab® 7110 Series, which is calibrated with standard buffer solutions, usually pH 4 and pH 7, prior to each pH measurement in order to guarantee the precision of results.

Classification is based on the measured pH: a paste pH above 7 indicates the presence of reactive carbonates, while a paste pH below 5 suggests acidity. The pH paste test is recommended as a complementary analysis to other static tests [56,61].

Acid–Base Accounting

The Acid–Base Accounting (ABA) test is one of the most commonly used static tests for predicting acid-generating potential (AGP) [69–71]. In this study, ABA was conducted following the original Sobek method [63], with modifications as outlined in [72]. This test measures the balance between the acid-producing potential (AP) and the neutralizing potential (NP) of Bleïda Mine Tailings (BMT) samples. Acid-generation potential was calculated using the sulfur sulfide content, following formula (1). Meanwhile, the carbonate neutralization potential (CNP) was determined based on total carbon content (C), using formula (2), with the assumption that organic carbon in fresh waste rock samples is negligible [20,73,74].

$$\mathrm{AP} = 31.25 \times \mathrm{wt\%}\ \mathrm{S}_{\mathrm{sulfide}} \tag{1}$$

$$\mathrm{NP} = 83.3 \times \mathrm{wt\%}\ \mathrm{C}_{\mathrm{carbonate}} \tag{2}$$

The net neutralization potential (NNP) was calculated by subtracting the acid potential (AP) from the neutralization potential (NP), with NNP = NP − AP. Samples with an NNP value greater than 20 kg $CaCO_3$/t were classified as non-acid-generating, while those with an NNP below −20 kg $CaCO_3$/t were classified as acid-generating. Values between −20 and 20 kg $CaCO_3$/t defined an uncertainty zone [75]. For materials within this zone, the neutralization potential ratio (NPR = NP/AP) was calculated per NNP standards. Samples were categorized as acid-generating if $NPR < 1$, uncertain if $1 < NPR < 2.5$, and non-acid-generating if $NPR > 2.5$ [76–78].

2.5.2. Kinetic Test

The geochemical behavior of the samples was studied using the weathering cell (WC) kinetic test, a streamlined version of the standard humidity cell (HC) test. Results from WC are closely comparable to those from HC [79,80]. In the WC test, 67 g of dry sample is placed in a 100 mm diameter Buchner funnel fitted with a glass fiber filter. The sample undergoes weathering twice a week with 50 mL of deionized water [81]. Each cycle involves two days of flushing, followed by two to three days of exposure to ambient air. After three hours of contact with the tailings, the leachate is recovered by applying light suction to a filtering flask [82]. WC tests are widely used for their advantages: rapid results (15–20 weeks) and minimal sample requirements [82]. Each recovered leachate was immediately filtered through a 0.45 µm filter. A 10 mL portion of the filtered leachate was acidified with 2% nitric acid (HNO_3, 65% concentration) in a glass flask to prevent metal precipitation and ensure metal solubilization.

The chemical quality of leachates from the WC test was analyzed using Visual Minteq 4.1 software to calculate the saturation indices (SI) of potential secondary minerals. The SI is calculated as the difference between the logarithm of the ionic activity product (log IAP) and the solubility constant (log K_s). A negative index ($IAP < K_s$) indicates undersaturation, suggesting that mineral formation is unlikely, whereas a positive index ($IAP > K_s$) indicates saturation or oversaturation, implying that mineral species may precipitate. Ks typically refers to the solubility constant or equilibrium constant for the dissolution of a substance in a solvent, while Ksp is a specific type of equilibrium constant that applies to the dissolution of sparingly soluble ionic compounds in water.

The SI was calculated using equilibrium calculations, with the resulting value expressed according to the following Equation (3):

$$SI = \log \frac{AIP}{Ksp} \tag{3}$$

where AIP represents the ion activity in the solution, and Ksp denotes the solubility product of the solid components.

2.5.3. Toxicity Characteristic Leachate Procedure (TCLP)

The Toxicity Characteristic Leaching Procedure (TCLP) was conducted following the guidelines in [83] to evaluate the leachability of environmentally regulated contaminants, including cyanide (CN^-), arsenic (As), mercury (Hg), lead (Pb), and selenium (Se) in the sample [83]. This test is designed by the United State Environmental Protection Agency (US EPA) to assess the hazard level of the material. The TCLP procedure begins by selecting an appropriate extraction fluid based on a preliminary assessment, as detailed in [84]. The leaching container was then securely placed in a rotary reactor, which was rotated at 30 ± 2 rpm for 18 h. After the test, the leachate was analyzed for various heavy metals, and the results were compared to US EPA regulatory limits.

3. Results

3.1. *Physical and Chemical Characteristics*

The laser particle size analysis generated a semilogarithmic curve (Figure 3), allowing for the determination of several key parameters that describe the material's properties. The D80 of the sample is 92.87 μm, closely aligning with the liberation size used in the copper ore grinding operation, where D80 = 100 μm. The D50, or median diameter, is 27.12 μm, indicating a relatively fine median particle size. The uniformity coefficient (Cu = D60/D10 = 9.18) suggests a broad particle size distribution, while the curvature coefficient (Cc = $(D30)^2/(D10 \times D60)$ = 0.75) indicates a fairly uniform distribution with minimal variation. Grain size was classified using the Soil Textural Triangle from [84]. The analysis revealed an average composition of 0.77% clay, 69.8% silt, and 29.43% sand (Table 1), classifying the material as silty loam, as illustrated in Figure 4.

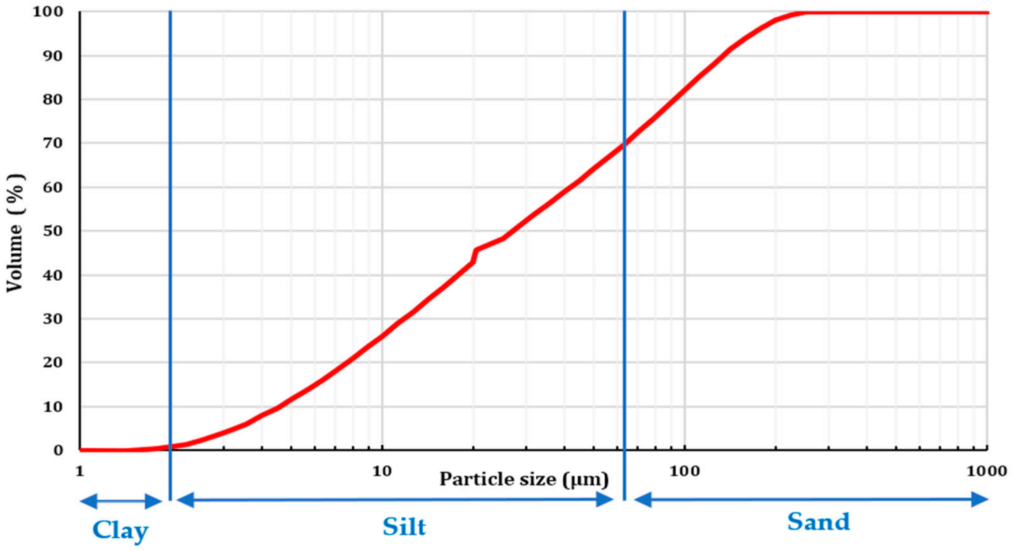


Figure 3. Particle size distribution of Bleïda mine tailings.

Table 1. Chemical, physical composition of BMT.

Characterization	Parameter	Unit	Average	Value $_{min}$	Value $_{max}$
Chemical properties	Si	%	19.89	16.42	25.49
	Al		4.72	3.22	5.46
	Fe		1.35	0.8	1.8
	Ca		8.19	7.06	10.81
	Mg		5.27	4.10	6.21
	K		1	0.75	1.17
	C		3.21	4.54	0.41
	S		0.14	0.23	0.11
	Ba		0.21	0.55	1.2
	Cu		0.22	0.13	0.5
	Zn		0.01	0.003	0.05
Physical properties	D10	µm	4.57		
	D30		11.83		
	D50		27.12		
	D60		41.95		
	D80		92.87		
	D90		134.21		
	Coefficient of uniformity		9.17		
	Coefficient of curvature		0.73		
	Sand sized > 63 µm	%	29.43		
	Silt sized 2–63 µm		69.8		
	Clay sized < 2 µm		0.77		
	Specific Surface Area	m^2/g	0.48		
	Apparent density	g/cm^3	1.3		

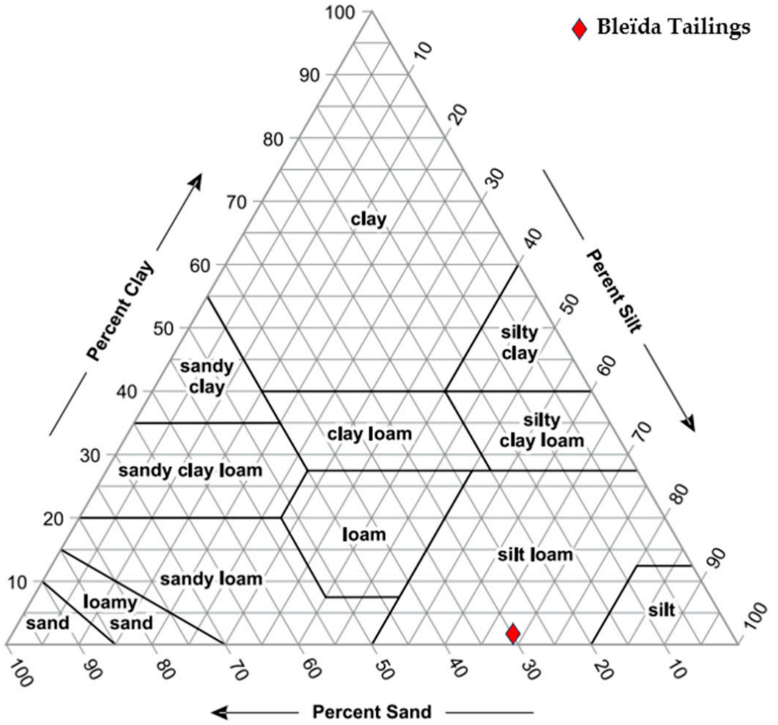


Figure 4. Positioning of Bleïda tailings on the Soil Texture Triangle [84].

The results of the chemical analyses are summarized in Table 1, presenting the average, minimum (Value min), and maximum (Value max) values for the 73 samples analyzed. Element concentrations are expressed as mass fraction (w), with all values in the table given as percentages (%). The data reveal that the primary chemical constituents are Si, Al_{3+}, Ca_{2+}, Mg_{2+}, Fe_{2+}, and K_{+}, with average concentrations of approximately 19.89%, 8.19%, 5.27%, 4.72%, 1.83%, and 1%, respectively. Other metals and metalloids are present in low quantities (below 0.001%).

3.2. Mineralogical Characteristics

The results of the mineralogical characterization by X-ray diffraction (XRD) are shown in Figure 5. The sample primarily consists of quartz (29%), dolomite (31%), and calcite (5%). Identified silicate minerals include clinochlore (10%), phlogopite (3%), albite (3%), and microcline (2%). Sulfide minerals were not detected in this analysis, suggesting their concentrations in the tailings are very low.

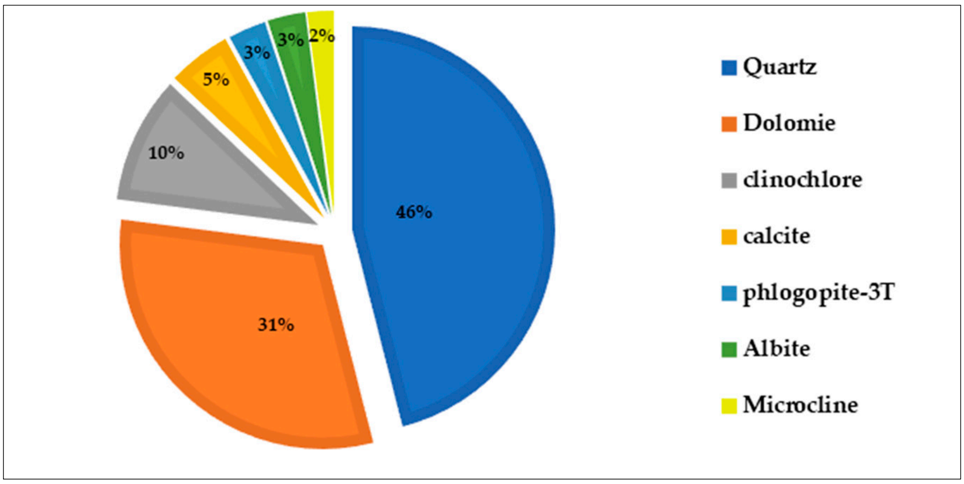


Figure 5. XRD results for BMT.

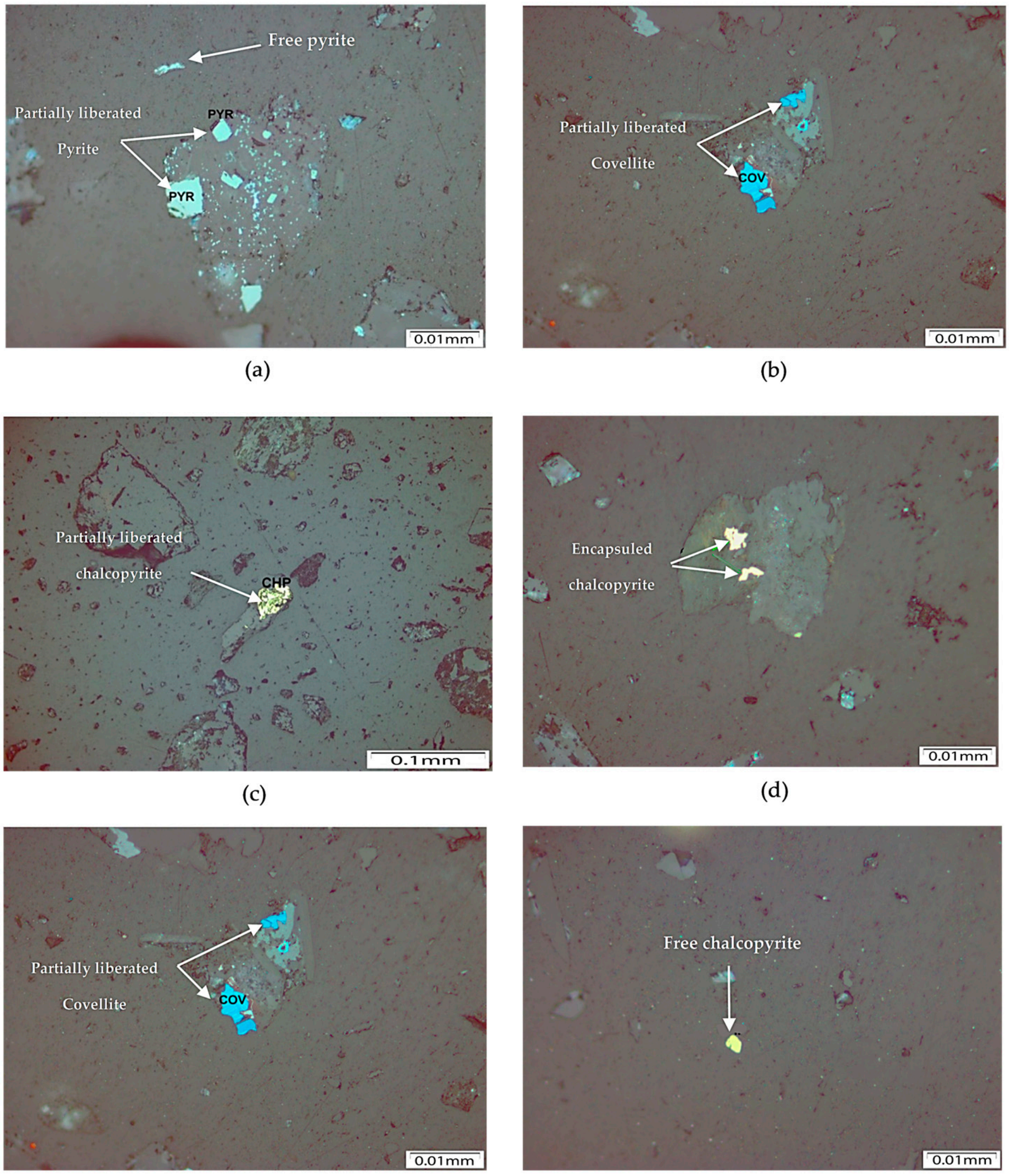
Automated quantitative mineralogy (AQM) provided a more detailed identification of minerals not detected by XRD. The analysis confirmed the presence of iron sulfides (pyrite) and copper sulfides (chalcopyrite, bornite, chalcocite, and covellite). The BMT also contains chlorite (12.4 wt.%), muscovite (11.5 wt.%), biotite (9.5 wt.%), orthoclase (3.6 wt.%), and kaolinite (2.1 wt.%). Additionally, trace amounts (less than 0.1 wt.%) of oxide minerals, including Fe-Cu-Mn oxides, were identified (Table 2).

Polished sections were examined primarily using an optical microscope with reflected light to verify the presence of acid-generating sulfide minerals. The analysis confirmed the presence of sulfides, including pyrite, chalcopyrite, covellite, and chalcocite. These sulfides were observed in three main exposure states: encapsulated (Figure 6d), partially liberated, with boundaries shared with non-sulfide gangue (NSG) minerals (Figure 6a,c,e,f), and as free sulfides with no shared boundaries with other minerals (Figure 6a,f). The scarcity of free sulfide minerals is attributed to the high recovery of sulfides during ore processing, which exceeds 95%.

Table 2. Mineralogical composition by AQM mineralogic analysis.

	Minerals	**Chemical Formula**	**Weight% (wt.%)**
Mineralogical composition by AQM analysis (wt.%)	Chalcopyrite	$CuFeS_2$	<0.1
	Bornite	Cu_5FeS_4	<0.1
	Pyrite	FeS_2	<0.1
	Chalcocite	Cu_2S	0.2
	Covellite	CuS	<0.1
	Barite	$BaSO_4$	<0.1
	Dolomite	$CaMg\ (CO_3)_2$	27.4
	Calcite	$CaCO_3$	2.4
	Malachite	$Cu_2CO_3(OH)_2$	0.2
	Orthoclase	$KAlSi_3O_8$	3.6
	Kaolinite	$Al_2Si_2O_5(OH)_4$	2.1
	Rutile	TiO_2	0.2
	Hematite	Fe_2O_3	0.2
	Ilmenite	$FeTiO_3$	<0.1
	Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2$	12.4
	Titanite	$CaTiSiO_5$	0.5
	Quartz	SiO_2	28.4
	Biotite	$K(Fe,Mg)_3AlSi_3O_{10}(OH)_2$	9.5
	Muscovite	$KAl_2(AlSi_3O_{10})\ (OH)_2$	11.5
	Albite	$NaAlSi_3O_8$	0.1
	Ca Feldspar	$(Ca,Na)(Si,Al)_4O_8$	0.2
	Tenorite	CuO	<0.1
	Cuprite	Cu_2O	0.1
	Cu, Mn Oxide	CuO, MnO	0.1
	Chrysocolla	$(Cu,Al)_2H_2Si_2O_5(OH)4{\cdot}n\ (H_2O)$	<0.1
	Fe Oxide	Fe_2O_3	0.1

To identify the types of non-sulfide gangue (NSG) minerals and their interactions with sulfide minerals, polished sections were further analyzed using SEM coupled with a ZEISS microscope. This analysis assessed the degrees of the liberation of both sulfide and NSG minerals. The SEM results indicate that sulfide minerals are predominantly encapsulated. Figure 7a shows bornite encapsulated within quartz, while Figure 6b depicts covellite encased in dolomite. Figure 6c presents sphalerite embedded in chlorite. Figure 7d illustrates chalcocite embedded within a mixture of dolomite and quartz. A mixture of chalcocite and malachite embedded by dolomite is shown in Figure 7f. Additionally, iron oxides appear either as mixtures, as shown in Figure 7e, or as dispersed entities, as depicted in Figure 7d.



(a) (b)

(c) (d)

(e) (f)

Figure 6. Microscopic analysis of BMT by optical microscope for sulfide identification: (**a**) free and partially liberated pyrite; (**b**) partially liberated covellite; (**c**) partially liberated chalcopyrite; (**d**) encapsulated chalcopyrite; (**e**) partially liberated covellite; (**f**) free chalcopyrite.

Mineral liberation is typically quantified using automated quantitative mineralogy equipment. The degree of liberation refers to the extent of a mineral's exposure within a sample [57,85], defined by the percentage of minerals present as free particles relative to the total sample [86]. Figure 8 illustrates the different liberation states of minerals in the analyzed sample. All sulfide minerals, including pyrite, covellite, and bornite, are fully locked, except for chalcopyrite, which is 76.3% partially free. These grains have a surface free area of less than 30%, resulting in a very low degree of liberation. In contrast, gangue minerals exhibit higher degrees of liberation. Specifically, 59.11% of dolomite grains are completely free, 35.73% are partially free, and the remainder are encapsulated. For calcite, 30.61% of grains are completely free, 49.16% are partially free, and 20.23% are encapsulated (Figure 8a). Sulfide grains are predominantly found as inclusions within gangue minerals such as quartz, dolomite, biotite, muscovite, chlorite, calcite, and orthoclase (Figure 8b).

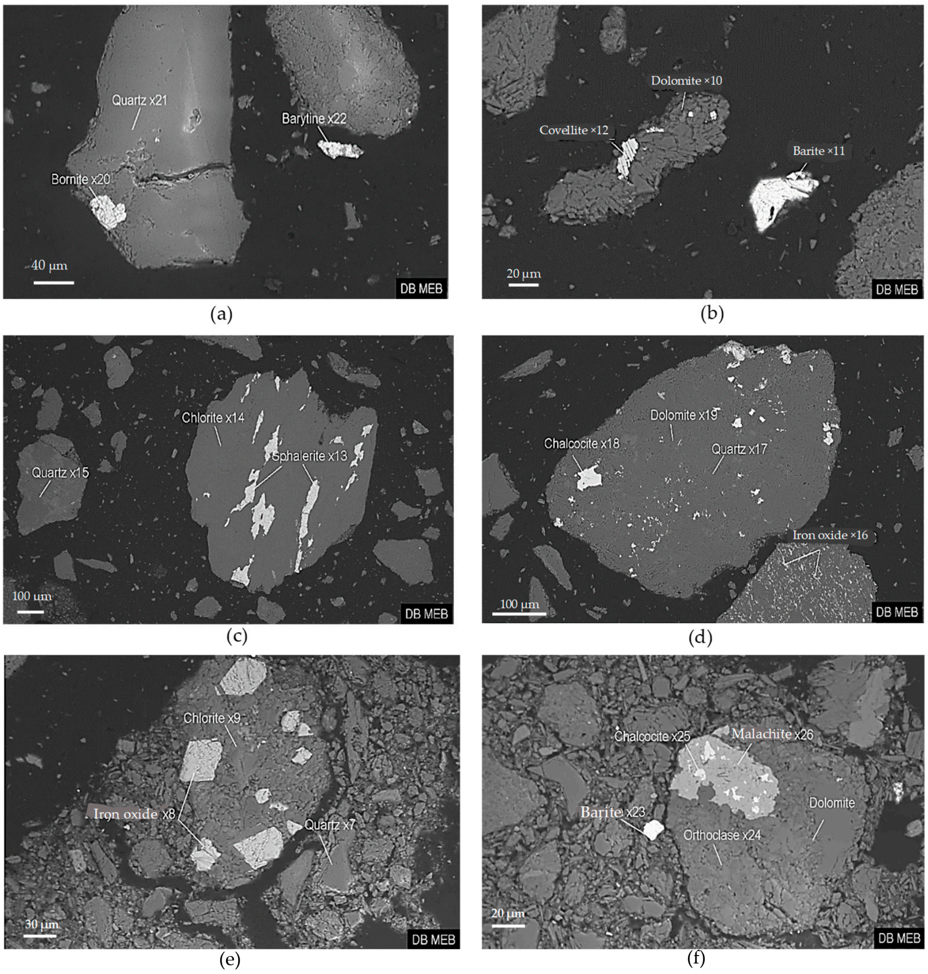


Figure 7. SEM images show sulfide minerals and non-sulfide gangue (NSG) minerals and their state of mixing with the sulfide minerals: (**a**) bornite encapsulated within quartz; (**b**) covellite encased in dolomite; (**c**) sphalerite embedded in chlorite; (**d**) chalcocite embedded within a mixture of dolomite; (**e**) iron oxides in mixture with chlorite; (**f**) Association of chalcocite and malachite.

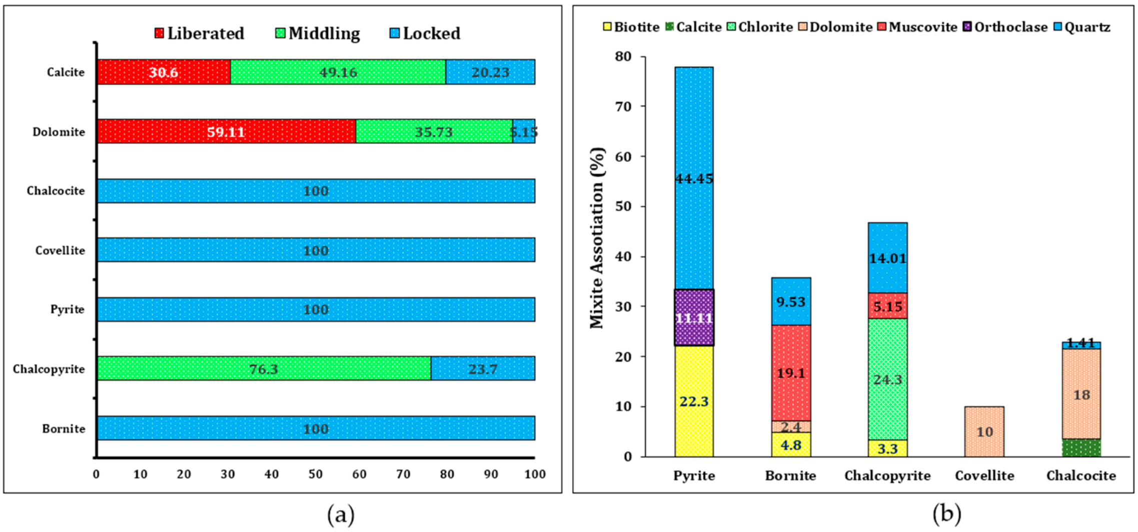


Figure 8. (**a**) Liberation degree of NSG and sulfides minerals. (**b**) Mixite association of the sulfide NSG minerals.

3.3. Geochemical Behavior of Tailings

3.3.1. Acid Generation Potential Assessment

The results of the pH paste test indicate that the pH values for all 73 samples range from 8.05 to 8.80 (Figure 9). This suggests that the tailings are likely non-acid-generating, which can be attributed to the presence of reactive carbonates.

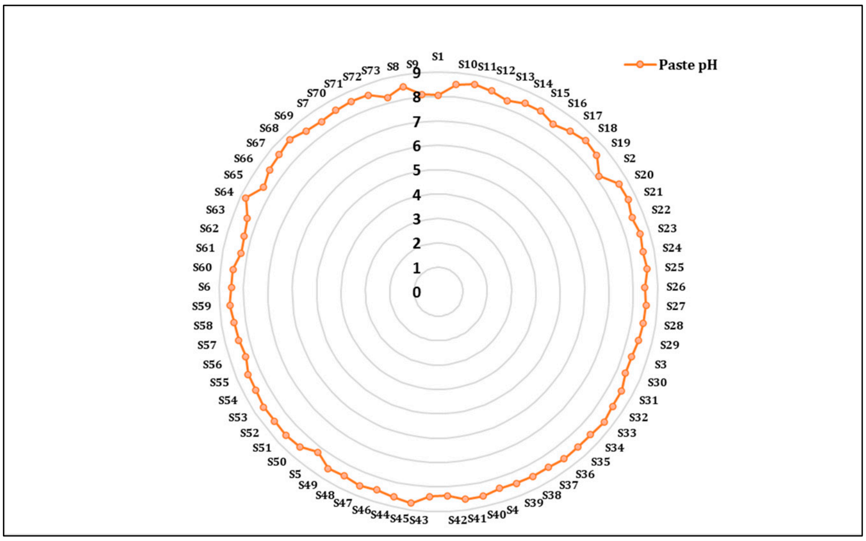


Figure 9. pH values of the BMT defined by static test paste pH.

The Acid–Base Accounting (ABA) results, summarized in Table 3, indicate that the BMT contain low levels of sulfide sulfur, ranging from 0.01% to 0.19%, and high levels of total carbon, ranging from 0.41 wt.% to 4.54 wt.%. The low sulfide sulfur content reflects the minimal presence of sulfide minerals in the tailings, while the high total carbon content indicates a substantial amount of carbonate minerals. This composition results in a low acid potential (AP), ranging from 0.31 to 5.94 kg $CaCO_3$/t, and a high neutralizing potential (NP), ranging from 34.15 to 378.18 kg $CaCO_3$/t. Consequently, the net neutralizing potential (NNP) ranges from 33.84 to 372.24 kg $CaCO_3$/t, surpassing the 20 kg $CaCO_3$/t threshold, which classifies all samples as non-acid-generating. Additionally, the NP/AP ratio (NPR) ranges from 63.69 to 109.26, well above the 2.5 kg $CaCO_3$/t standard for non-acid-generating materials. Based on the classification criteria proposed by [75], all 73 samples from BMT are confirmed as non-acid-generating (Figure 10).

Table 3. The Acid–Base Accounting (ABA) results.

Characterization	Parameter	Unit	Value $_{min}$	Value $_{max}$
ABA test results	S(total)	%	0.11	0.23
	S(Sulfates)		0.001	0.18
	S(sulfide)		0.1	0.19
	C(total)		0.41	4.54
	NP	$CaCO_3$/t	34.15	378.18
	AP		0.31	5.94
	NNP		33.84	372.24
	NPR		63.69	109.29

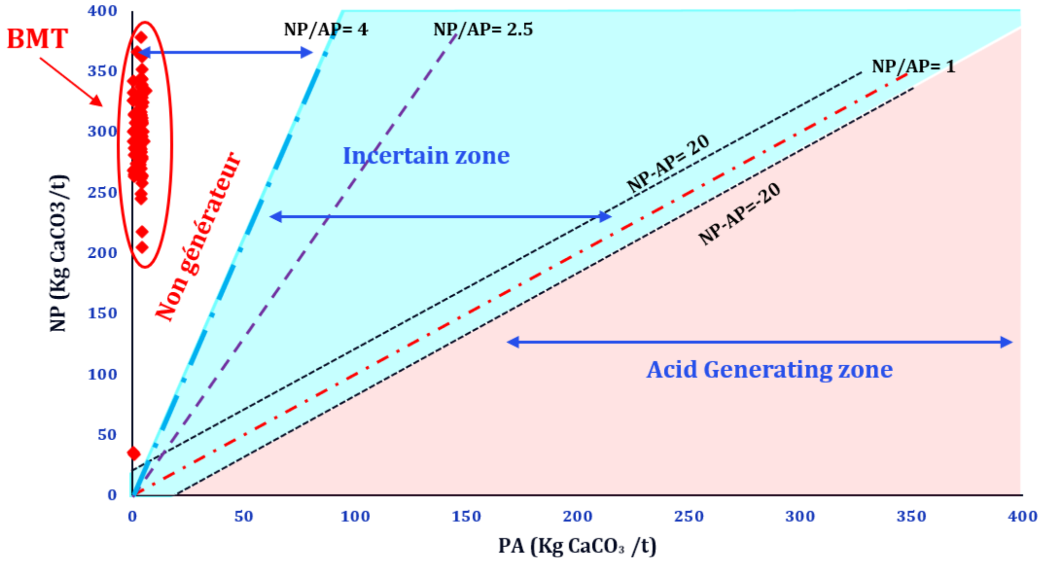


Figure 10. Acid Generation Potential of Bleïda Mine Tailings: Results of ABA Tests with Total NP and AP [75].

3.3.2. Weathering Cell Test Results

The geochemical behavior of the BMT was assessed using weathering test cells, monitoring the chemical composition of the leachate over 140 days, as illustrated in Figures 11 and 12. The leachate pH generally remained neutral, stabilizing between 6.5 and 7.8. Initially recorded at 6.8, the pH declined during the first 15 days, likely due to the oxidation of small quantities of free sulfides within the tailings. From day 33 onward, the pH stabilized between 7.1 and 7.8 (Figure 11a). This increase is attributed to the dissolution of gangue minerals with high acid-neutralizing potential, such as calcite and dolomite, combined with the depletion of reactive sulfide particles, mainly pyrite.

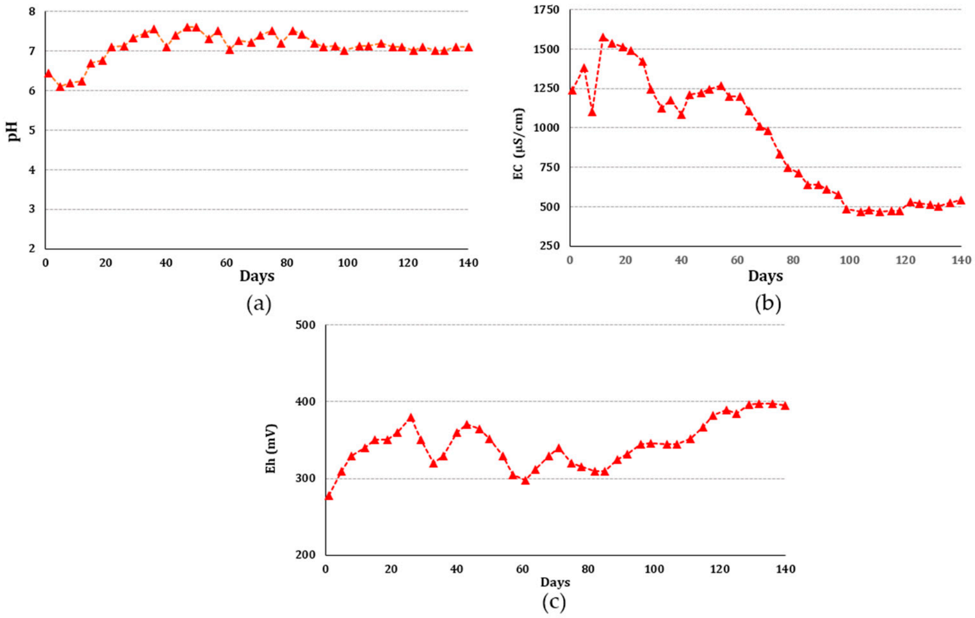


Figure 11. Evolution of pH (**a**), Electrical conductivity (**b**), and Eh (**c**) in leachates after 140 kinetic test day.

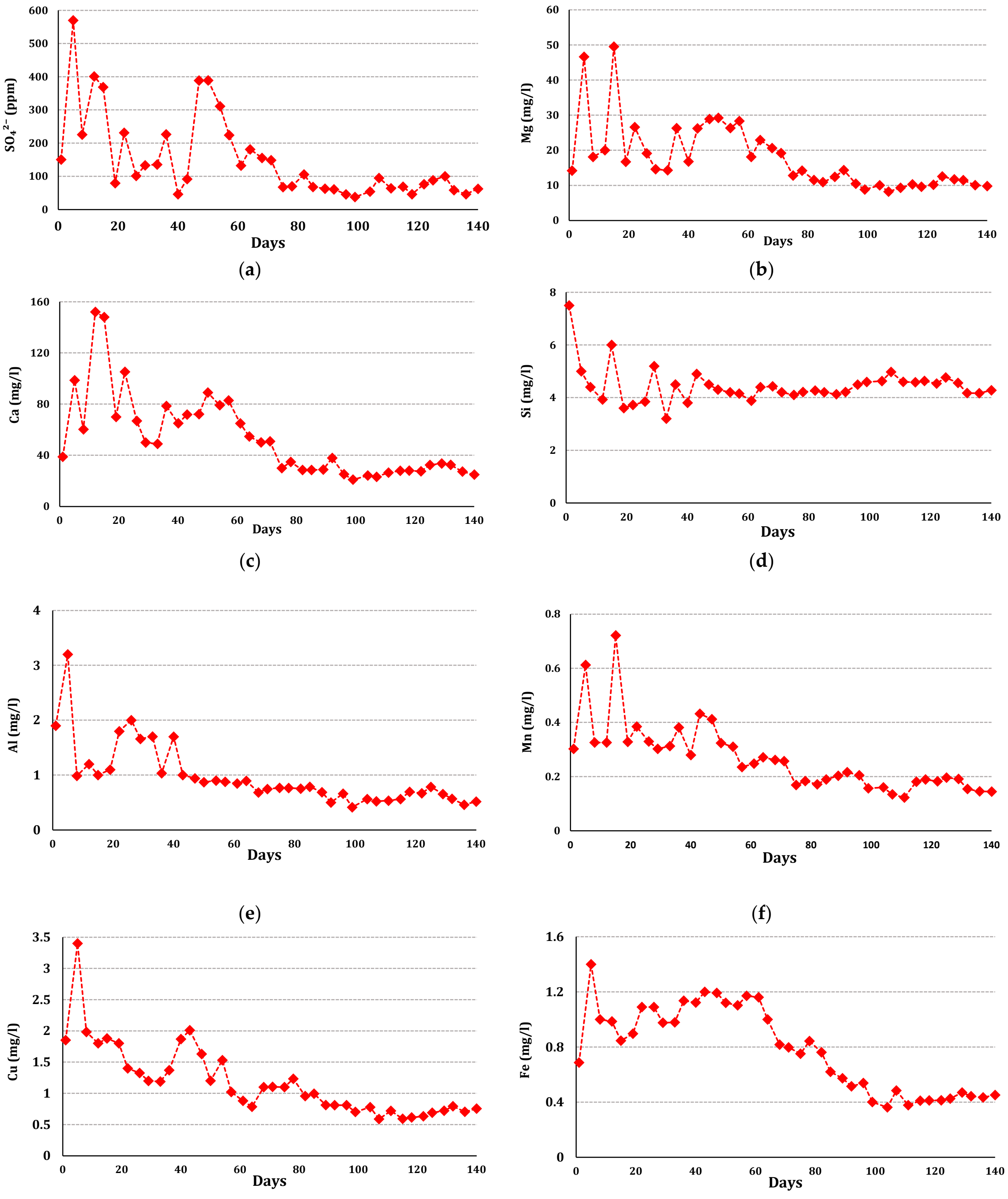


Figure 12. Concentrations of SO_4^{2-} (**a**), Mg (**b**), Ca (**c**), Si (**d**), Al (**e**), Mn (**f**), Cu (**g**), and Fe (**h**) of the studied leachates.

The electrical conductivity (EC) spiked between 1200 and 1500 µS/cm in the first 26 days of the test. Between days 26 and 64, EC values showed fluctuations, eventually stabilizing after day 100 and remaining steady until the end of the test (Figure 11b). The high conductivity indicates elevated ion concentrations in the leachate, likely resulting from the dissolution of primary minerals and possible redissolution of secondary minerals within the material.

The redox potential (Eh) exhibited a rising trend, increasing from 310 mV on the first day to 390 mV by the end of the test, indicating a shift towards a more oxidizing environment (Figure 11c).

Sulfate ($SO_4{}^{2-}$) concentrations in the leachates ranged from 570 mg/L to 37.69 mg/L. During the initial 50 days, sulfate levels fluctuated, but from day 71 onward, the concentration began to stabilize (Figure 12a). The presence of sulfates is attributed to the partial oxidation of sulfide minerals in the sample, primarily pyrite due to its high reactivity, followed by chalcopyrite, which has the highest degree of liberation, and other less liberated sulfides such as chalcocite, covellite, and bornite. The stabilization of sulfate levels is likely due to the depletion of sulfide and sulfate minerals in the tailings, along with the precipitation of sulfates as secondary minerals. Furthermore, the passivation of sulfide surfaces by the precipitated secondary minerals may also contribute to this observed stabilization.

Magnesium (Mg) concentrations in the leachates ranged from 49.5 mg/L to 8.25 mg/L (Figure 12b). Initially, Mg levels fluctuated during the first 47 days. Afterward, concentrations decreased and stabilized between 14 mg/L and 8.25 mg/L. Calcium (Ca) exhibited a similar trend, with concentrations ranging from 150 mg/L to 21 mg/L (Figure 12c). Following a decline starting on day 15, Ca concentrations stabilized between 21 mg/L and 29 mg/L from day 22 onward. The parallel trends in Mg and Ca concentrations, along with the relatively high Ca levels, suggest that both elements originate from the same mineral phases, specifically dolomite and calcite. These two minerals are known for their higher relative reactivity in acid-generating environments [87].

Manganese (Mn) concentrations remained below 0.8 mg/L throughout the test, despite the presence of small amounts of Mn-oxide minerals. Aluminum (Al) and silicon (Si) leaching rates varied between 2 and 0.5 mg/L for Al and 7.5 and 3.2 mg/L for Si, respectively (Figure 12d,e). The Al and Si concentrations are attributed to the dissolution of aluminosilicate minerals, primarily biotite and chlorite, which are relatively more reactive compared to other aluminosilicate minerals in the BMT, such as kaolinite, feldspar, and muscovite [87].

Copper (Cu) concentrations in the leachate primarily vary between 3 and 0.5 mg/L (Figure 12g). The primary source of dissolved Cu is the oxidation of copper sulfides, which have high oxidation rates [88], specifically covellite, chalcopyrite, and chalcocite.

Iron (Fe) concentrations range from 1.4 to 0.29 mg/L (Figure 12h). Mineralogical characterization indicates two main sources of Fe: the oxidation of iron sulfides, with pyrite being the most reactive, followed by chalcopyrite and covellite [88], and the dissolution of iron oxides. Both sources are present in limited quantities in the residues.

Arsenic (As) and zinc (Zn) concentrations remain below 0.5 mg/L. The low arsenic levels can be attributed to the absence of clearly arsenic-bearing minerals in the residues, often observed as impurities in other minerals, mainly in pyrite and Fe oxides. The trace amounts of Zn detected are likely due to minor amounts of sphalerite, as observed under SEM analysis (Figure 7c).

3.3.3. Toxicity Characteristic Leching Procedure (TCLP) Results

The TCLP test was conducted to assess the mobility of metal(loid)s in the tailings. The results, compared with regulatory limits established by the US EPA, indicate that the concentrations of leached inorganic contaminants (As, Ba, Cd, Cr, Pb, Se, and Be) are below these regulatory thresholds (Table 4).

Table 4. Results of TCLP test performed for BMT.

Metals	As	Ba	Cd	Cr	Pb	Se	Be
The concentrations of metals (mg/L)	0.008	1.7	0.002	0.1	0.027	0.04	0.00056
US EPA regulation limits (mg/L)	5	100	1	5	5	1	0.75

4. Discussion and Future Works

4.1. Environmental Statue and Geochemical Behavior of the Tailings

The geochemical behavior of the BMT, assessed through static tests including paste pH and Acid–Base Accounting (ABA), indicates that no acidity was produced during storage in the TSF and that a substantial amount of reactive carbonate is present. The acid potential (AP) and neutralization potential (NP), as determined by the ABA test, confirm that the material is classified as non-acid-generating, with NP exceeding AP. This classification is further supported by mineralogical characterization, which shows that acid-generating sulfide minerals are present in minor quantities with low degrees of liberation. This encapsulation limits their acid-generating capacity, minimizing environmental impact. These findings are in accordance with those of [89], who similarly discovered a high NP/AP ratio in tailings with comparable mineralogical compositions, thereby confirming their non-acid-generating potential. This behavior serves to underscore the importance of neutralizing minerals such as calcite and dolomite in mitigating acid generation risks.

Conversely, the tailings are rich in neutralizing minerals, such as dolomite, calcite, and biotite, with high degrees of liberation, which contributes significantly to the geochemical stability of the tailings. The long-term geochemical behavior, evaluated through weathering cell (WC) tests, demonstrates chemical stability, with the pH remaining neutral throughout the test period. Concentrations of potentially toxic elements stay below regulatory limits. Major elements like Al, Si, Mg, and Mn are released in small quantities relative to their initial concentrations in the tailings due to the limited dissolution of host minerals under test pH conditions. Additionally, metallic elements such as Cu, Zn, and Fe are also released in low quantities, attributed to the limited presence of carrier minerals and their low reactivity at the test pH. The low concentrations observed may also result from the precipitation of secondary minerals, as confirmed by geochemical modeling. The authors of [90] found similar results. They noted stable pH levels and a minimal leaching of metals in tailings containing neutralizing minerals. This helps to reduce risks to the environment.

Geochemical modeling results using Visual Minteq software indicate that the ion concentrations and chemical conditions (pH, Eh, and temperature) of the leachates recovered during weathering cell tests create favorable conditions for the precipitation of various compounds, as shown in Table 5. These precipitates include aluminum oxides, hydroxides, and oxyhydroxides, such as $Al(OH)_3$, Al_2O_3, $Al_4(OH)_{10}SO_4$, diaspore, and gibbsite, as well as copper hydroxides, including $Cu(OH)_2$, antlerite, and tenorite. Conditions also promote the formation of sulfate minerals, such as langite and brochantite, along with minerals like greenalite and hercynite.

Table 5. Geochemical modeling results using Visual Minteq.

Chemical Element	Compounds Probably Precipitate
Al	Al $(OH)_3$ Al_2O_3 $Al_4(OH)_{10}SO_4$ Diaspore Gibbsite
Cu	$Cu(OH)_2$ Antlerite Tenorite
$SO_4{}^{2-}$	Langite
	Brochantite
Others	Greenalite
	Hercynite

These secondary minerals form as a result of oxidation and neutralization processes, which help to lower and stabilize the concentrations of key chemical elements in the leachates from the weathering cells, particularly $SO_4{}^{2-}$, Al, Si, Mg, Fe, and Cu. These findings suggest that secondary mineral formation is a key mechanism for mitigating environmental risks, as noted in similar studies by [21], where such processes played a central role in maintaining geochemical stability.

The TCLP test confirms the non-hazardous nature of the tailings, demonstrating that heavy metals and metalloids, such as lead, cadmium, arsenic, and zinc, remain non-leachable and are present at concentrations well below regulatory limits for inert materials. Environmental test results indicate that the BMT are geochemically stable, supporting their classification as inert and safe for storage in the tailings facility. Consequently, these residues can be safely considered for potential applications, including reuse as a secondary product. This classification aligns with the findings of [91,92], who demonstrated that inert tailings could be effectively reused in construction applications such as ecological bricks and additives in cement.

4.2. Investigating Sustainable Tailings Management Options

In line with a sustainable management approach, it is essential to evaluate whether the tailings contain economically valuable elements that could be recovered before finalizing the tailings management plan. In this case, an assessment of residual copper resources in the tailings, conducted by [93], identified a potential of approximately 3000 tonnes of copper metal, with an average grade of 0.27%. Furthermore, reprocessing to recover residual copper proves more cost-effective than initial processing as it bypasses the need for mechanical preparation steps like crushing and grinding. This recovery potential should be integrated into future planning.

Regarding the reuse of mine waste, numerous studies have explored utilizing mine tailings as aggregates or additives in construction materials and sustainable building projects. Possible applications include mine backfill [94,95], ecological and green bricks [92,96], road construction material [97], additives in concrete and mortar [98,99], civil engineering projects [100], and house-building materials such as ceramics [101]. The suitability of a reuse application depends on the mineralogical and physicochemical characteristics of the material.

The high oxide content of SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, and Na_2O (Table 6) suggests that BMT may engage in secondary reactions, making it a valuable alternative for specific applications [102,103]. The substantial SiO_2 content and significant Al_2O_3 grade indicate the presence of aluminosilicate minerals (quartz, biotite, muscovite, and chlorite), which are critical for the geopolymerization process. This composition suggests that BMT could be used in the production of ecological bricks [104–106].

Table 6. Oxide content in BMT.

Elements	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	MnO	TiO_2	P_2O_5	Na_2O	SO_3
Concentration (%)	42.54	8.90	3.87	11.46	8.74	2.40	0.17	0.58	0.13	0.57	0.35

The potential for using BMT in the ceramics industry, especially in fired brick production, was evaluated based on its chemical composition using a ternary diagram [107]. This diagram, informed by a synthesis of the chemical compositions of natural clays typically used in fired brick manufacturing, is represented in Figure 13. The results indicate that the composition of BMT aligns well with the requirements for substituting natural clays in ceramic applications, particularly in the production of fired bricks.

The particle size distribution of Bleïda tailings classifies the material as silt loam, with particles smaller than sand and a relatively uniform size distribution (Cc = 0.75). Given these characteristics, BMT can be utilized as a fine aggregate (FA) in concrete [102] or as an additive in cement mortar [108,109]. Several studies [103,108,110] indicate that adding tailings as additives enhances the durability of concrete and mortar. These fine particles fill the voids between larger grains, reducing capillary spaces, which increases mechanical strength, water resistance, impermeability, and apparent density.

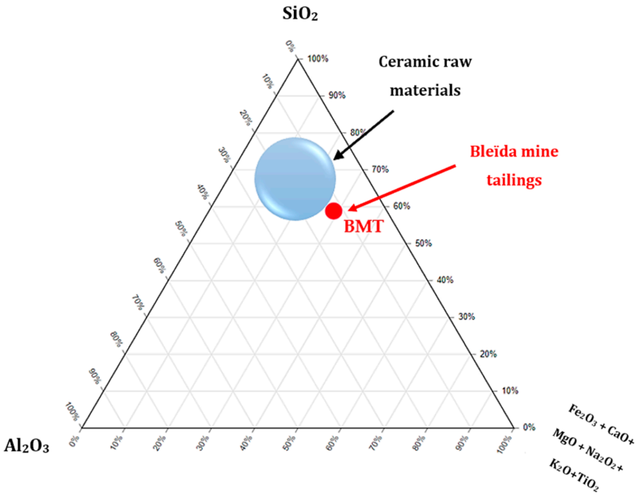


Figure 13. Comparison of Chemical Characteristics: Bleïda Tailings and Ceramic Raw Materials with Reference Data (adapted by [107,111]).

The study region, as well as the rest of Morocco, is undergoing substantial growth in urban development projects and road infrastructure, leading to a significant increase in demand for primary materials. This rising demand places considerable pressure on non-renewable natural resources, disrupts ecosystems, and threatens biodiversity. Reusing the studied tailings as a substitute for natural aggregates can help to mitigate the environmental impacts of mining operations, enabling the company to reduce its environmental footprint associated with tailings storage. Furthermore, this approach addresses the technical and economic challenges related to the surface storage of mine tailings.

5. Conclusions

This study provides a comprehensive characterization of Bleïda mine tailings, assessing their potential for contaminant drainage through static tests and examining their long-term geochemical behavior using weathering cell tests. Additionally, it evaluates the hazardousness of the tailings with the TCLP test. The results indicate that Bleïda mine tailings are geochemically stable and non-acid-generating, primarily due to a low content of acid-generating sulfides and a high proportion of neutralizing minerals, such as dolomite, calcite, and biotite. Weathering cell tests revealed stable chemical behavior with neutral pH levels throughout the testing period, and concentrations of potentially toxic elements remained below regulatory limits. Geochemical modeling with Visual Minteq confirmed the precipitation of secondary minerals, which helps to reduce the concentrations of chemical elements in the leachates. TCLP testing showed the tailings are non-hazardous, with heavy metals and metalloids well below regulatory limits for inert materials, supporting their classification as inert and suitable for safe storage in tailings facilities.

Furthermore, the mineralogical and physicochemical properties of the tailings demonstrate considerable potential for reuse in construction applications, including eco-friendly bricks and road construction materials, and as additives in concrete and mortar. The high content of oxides and aluminosilicate minerals makes them suitable for geopolymerization processes and other sustainable building applications. The granulometric characteristics of the residues also suggest their suitability as fine aggregates in concrete or as additives in mortar.

This study represents a substantial advancement in the understanding and management of mine tailings, offering a detailed characterization of Bleïda mine residues along with an in-depth evaluation of their geochemical stability and reuse potential. By confirming that these tailings are geochemically stable and non-hazardous, the study provides a solid foundation for safe management and reclamation practices. The geochemical testing and modeling results serve as valuable tools for developing strategies for tailings recovery and reuse. Additionally, by highlighting the potential of tailings for construction applications, this study showcases innovative ways to transform mine waste into valuable resources, contributing to more sustainable and environmentally responsible mining practices.

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Conflicts of Interest: Author Lahcen Mouhagir was employed by the Managem Group. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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