International Journal of Environmental Monitoring and Analysis
2025, Vol. 13, No. 6, pp. 290-302
https://doi.org/10.11648/j.ijema.20251306.11

Research Article

Acid-generating Potential of Mine Wastes from the Perkoa Polymetallic Zinc Deposit in Central-western Burkina Faso

Isso Felix Bado[1, *], Adama Yameogo[1, 2], Abdoul Aziz Tarpaga[1], Nicolas Kagambega[1, 2]

[1]Geosciences and Environment Laboratory, Joseph Ki-Zerbo University, Ouagadougou, Burkina Faso

[2]Mining Engineering Department, Yembila Abdoulaye Toguyeni University, Fada N'Gourma, Burkina Faso

Abstract

Perkoa polymetallic zinc deposit, formed in a context of massive volcanogenic sulphides, generated large volumes of potentially reactive wastes during its exploitation due to the predominance of sulphide minerals. The aim of this study is to assess the acid-generating potential, i.e. the potential to generate acid mine drainage (AMD), of these wastes. To this end, four representative samples of these wastes were collected in a targeted manner at the Perkoa mine site, including waste rock, mine tailings and crusher waste. The analyses focused on determining the mineralogy by X-ray diffraction, the physico-chemical parameters (pH, electrical conductivity), the sulphur and carbon contents, and the acidity and neutralization potentials. The results reveal, with the exception of waste rock, acidic pH values (< 5), high electrical conductivity (> 500 µS/cm) and high sulphide content, mainly pyrite, sphalerite and pyrrhotite. The acid potential (AP) shows high values between 5 and 1000 kg CaCO3/t. On the other hand, the neutralization potential (NP) is low, with NPR (NP/AP) ratios below 1 and negative NNP (NP-AP) values in the range of -1300 to -5 kg CaCO3/t. These results show that these wastes would not be able to neutralise any acid that might be generated as a result of their oxidation. The most reactive acidogenic minerals are pyrite and pyrrhotite. Acid-producing mineral species are represented by silicates such as actinolite, microcline and chlorite. In summary, these results confirm a high risk of AMD development from mine wastes.

Keywords

Mine Wastes, Acid Mine Drainage, Perkoa, Burkina Faso

1. Introduction

In 2023, the mining industry contributed 539.391 billion CFA francs to Burkina Faso's national revenue, accounting for 14.8% of gross domestic product (GDP), with local purchases of mining goods and services accounting for 37.83%, or 450,177,545,361 CFA francs [1]. While the mining industry is a source of economic benefits and job creation, it also has harmful effects on the environment. These harmful effects are felt in terms of human health, water resources, flora, fauna, landscape, soil and air [2, 3]. In addition, mining and mineral processing generate various types of wastes, which must be managed rationally and safely in order to protect the environment [4-6]. To this end, the structures used to store these

*Corresponding author: isso_bado@ujkz.bf (Isso Felix Bado)

Received: 6 September 2025; **Accepted:** 22 September 2025; **Published:** 12 November 2025

mine wastes products are among the largest human constructions, reaching heights of over 100 metres and lengths of more than ten kilometres [7]. In addition, the complex geochemistry of metal deposits and the use of chemicals for ore processing tend to amplify the effects of pollution resulting from mining [3]. According to [8], mining sites also face multiple environmental impacts, particularly those associated with acid mine drainage (AMD), which involves metal leaching and the use of chemicals. For example, mine wastes from a deposit with geochemical characteristics that include sulphide minerals can lead to the development of acid mine drainage (AMD) due to the oxidation of sulphides [9-14]. In Burkina Faso specifically, the risk of AMD has been highlighted at mining sites through studies by [15] on the former Poura mine and [16] on the Youga mine. The phenomenon of acid mine drainage cannot therefore be ruled out at mining sites in Burkina Faso, despite the low rainfall. With regard to the Perkoa mining site, previous studies have revealed a predominance of sulphide minerals in the geological formations [17-22]. The studies of [20] have particularly demonstrated that mineralisation is mainly associated with sulphide minerals, including iron-rich sphalerite (30%), pyrite (25%), barite (10%) and hexagonal pyrrhotite (5%). To this end, the mineralogy of the Perkoa deposit is problematic from an environmental point of view as it constitutes a factor likely to trigger AMD.

Based on the above, the objective of this study is to assess the acidogenic characteristics of the materials constituting the mine wastes from the exploitation of the polymetallic deposit at the Perkoa zinc mine.

2. Material and Method

2.1. Study Area

The area covered by this study is the Perkoa zinc mine, operated between 2013 and 2022 by Nantou Mining SA, located northwest of the municipality of Réo, Sanguié province, in the Centre-West region of Burkina Faso (Figure 1). Mining was mainly underground, but an open pit was used to extract shallow ore during the first years of mining operations.

The study area has a North Sudanese climate [23], characterised by a long dry season (October to May) and a short rainy season (June to September). Two wind regimes occur annually: the harmattan and the monsoon. The harmattan, a dry wind blowing from October to April, predominates during the dry season, with cool (October to February) and hot (March-April) variants. The monsoon, characterised by humid winds, occurs between May and September, with a peak in August. According to data from the National Meteorological Agency (ANAM), average annual rainfall ranges from 0 to 234 mm, with more than 80% occurring between July and September and a peak in August. Temperatures are generally moderate, although the months of March to May see peaks of 40 to 41°C. The Centre-West has a hydrographic network dominated by the Mouhoun and Nazinon rivers and their tributaries, as well as several shallow areas [23, 24]. The region has 190 dams and reservoirs, 34% of which are located in the province of Sanguié.

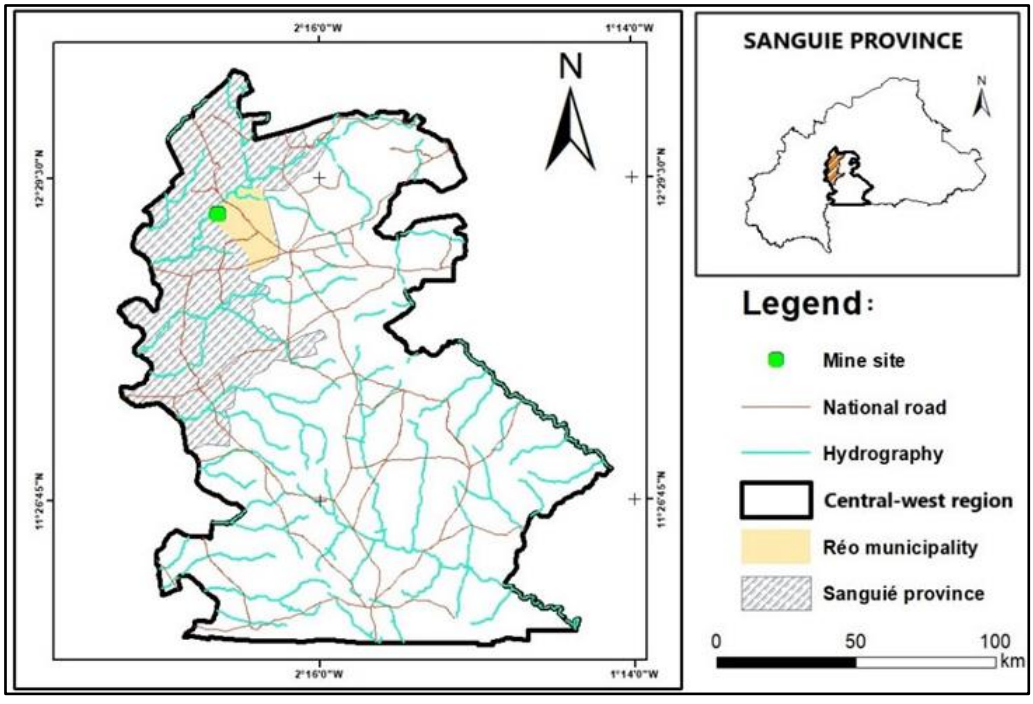

Figure 1. *Study area location [25].*

2.2. Methodology

2.2.1. Sampling

Targeted sampling was carried out on four types of mine wastes (Figure 2): waste rock (RS), crusher waste (RB) and mining tailings taken from cells 1 (Rcel1) and 3 (Rcel3) of the tailing's storage facility. The RS comes from excavation waste rock (open pit and underground) exposed between 2013 and 2022. The RB is the result of the trommel (8 mm mesh) reject at the crusher. Finally, Rcel1 and Rcel3 correspond respectively to the oldest and most recent tailings, stored in the first and last cells of the tailings storage facility (TSF).

Each sample, weighing between 0.5 and 5 kg, is a composite sample of three to five sub-samples taken at intervals of 10 to 20 m. The samples are then crushed and ground to 75 µm. A representative fraction of 500 g is prepared for analysis.

Figure 2. *Overview of the studied mine wastes: (a) Waste rock (RS); (b) Crusher waste (RB); (c) Mine tailings from cell 1 (Rcel1), (d) Mine tailings from cell 3 (Rcel3).*

2.2.2. Analysis

(i). Mineralogical Composition

The mineralogical composition was determined by X-ray diffraction (XRD). This method has the advantage of ensuring good compaction and uniform distribution of the sample in order to improve the diffraction results. The XRD method of mineralogical analysis is based on the principle that each mineral has one or more characteristic crystallographic planes that cause X-ray diffraction. For each mineral, one or more characteristic peaks are observed on the diffractogram, the height of which is proportional to the intensity of the diffraction [26-29].

(ii). Chemical Composition

The quantification of metallic and non-metallic elements, grouped under the name of potentially harmful elements (PHEs), was carried out by inductively coupled plasma optical emission spectroscopy (ICP-OES). To this end, 1 g of each solid material sample, previously ground and homogenised, was subjected to complete digestion with aqua regia, yielding analysable solutions. ICP-OES was used to target the following elements: As, Cd, Co, Cr, Cu, Fe, Pb, Ni and Zn. In addition, the Mg, Mn, Ca and S contents were also determined in order to complete the geochemical characterisation of the samples.

(iii). Sulphate Content

As for sulphate content, approximately 2 g of each pulverised sample is leached with ultrapure water and the resulting solution is filtered before being analysed by ion chromatography, with separation on an ion exchange column and conductometric detection.

(iv). Static tests for Acid Mine Drainage prediction

1). pH and Electrical Conductivity (EC) in Saturated Paste

The pH and conductivity test in saturated paste was used to assess the acidogenic characteristics of Perkoa mine wastes. In practice, samples of mine wastes are moistened with distilled water at a liquid-to-solid ratio of 2:1, then left to stand for 24 hours. The pH and electrical conductivity of the resulting solutions are then measured, and a pH value below 4 indicates potential acid generation [30]. This test was also used to quickly estimate the behaviour of materials with regard to acid mine drainage according to the classification of [31], which distinguishes four classes (Table 1).

Table 1. Acid mine drainage level classification [31].

AMD class	Characteristic
Class I: confirmed acid mine drainage	Confirmed acid mine drainage for waste with a pH of less than or equal to 4 and electrical conductivity (EC) greater than 1000 µS/cm
Class II: Confirmed Developing Acid Mine Drainage	confirmed developing acid mine drainage Confirmed developing acid mine drainage for mine wastes with a pH between 4 and 5 and an EC greater than 750 µS/cm
Class III: Potential Developing acid mine drainage	Potential developing acid mine drainage for mine wastes with a pH between 5 and 6 and an EC greater than 500 µS/cm
Class IV: No risk of acid mine drainage	No risk of acid mine drainage for waste with a pH greater than 6 and an EC less than or equal to 500 µS/cm

2). Sulfur Content and Miller et al. (1991) Criteria

The sulphur content, determined from LECO analyses, enabled the acidogenic characteristics of mine wastes to be assessed. [32] propose a threshold content of 0.3% to distinguish between samples that are not acidogenic and those that are potentially acid-generating.

3). Static Acid-Base Accounting (ABA) Test

The static acid-base Accounting (ABA) test was used to predict the acidogenic nature of mine wastes. This test considers sulphides that are likely to produce acidity and alkaline minerals that are likely to reduce or neutralise acidity. For the ABA test, sulphur and carbonate contents were determined using a device called LECO, which performs infrared analysis in an induction furnace [33].

The Acid Potential (AP) is calculated using the formula: AP =% total sulphur x 31.25 [34].

The Neutralization Potential (NP) was calculated by multiplying the carbon content by a factor of 83.3 (NP =% inorganic carbon x 83.3) [9, 35, 36].

The diagnosis of mine wastes is then established using the NPR, which is the ratio of NP to AP, and the Net Neutralization Potential (NNP), which is the difference between NP and AP. The calculated NNP and NPR ratio are used to classify different mine wastes according to the following limits [9] (Table 2).

Table 2. Diagnostic Criteria for Acid Generation Potential of Mine Wastes [9].

Parameter	Acid generating	Uncertain potential	Non-acid generating
NNP (NP-AP) (kg $CaCO_3$/t)	NNP < -20	-20 < NNP < 20	NNP > 20
NPR (NP/AP)	NPR < 1	1 < NPR < 2	NPR > 2

N. B.: AP (Acid Potential), NP (Neutralization Potential), NNP (Net Neutralization Potential), NPR (Neutralization Potential Ratio)

Furthermore, Plante et al. (2015) suggest that for cases with low sulphur content (<1%) or high sulphur content (>5%), the results should be interpreted using the NNP rather than the NPR.

3. Results and Discussions

3.1. Mineralogical Composition

Mineralogical analysis of the samples studied reveals that the mineral species can be divided into three groups. This classification considers the contribution of each mineral to the development or neutralization of acid mine drainage: acidogenic, neutralising and inert [37-39] (Table 3).

According to [40], understanding the mineralogy and chemical reactivity of materials is a prerequisite for controlling AMD in mining contexts, thereby reinforcing sustainable site management practices.

Minerals such as pyrite (FeS_2), pyrrhotite ($Fe_{1-x}S$) and sphalerite (ZnS) are known to play a major role in acid production through their oxidation upon contact with meteoric water and oxygen in the air [3, 39, 41].

Pyrite is particularly abundant in samples Rcel1 (> 41%) and Rcel3 (> 23%), reflecting their high acid-generating potential (Table 3, Figure 4). Pyrrhotite, although less abun-

dant in these mine wastes, is known for its faster oxidation and greater impact on acidity generation [43, 44]. Sphalerite, observed mainly in Rcel1 mine tailings (6.1%) and in small quantities in other mine wastes, is one of the sulphide minerals that produce little or no acid [44, 45].

Furthermore, the minerals that can be considered neutralising in the mine wastes studied are mainly silicates such as chlorite, epidote, actinolite, plagioclase and microcline, which contribute to buffering the acidity generated [37, 44]. These minerals contain basic cations such as Ca^{2+}, Mg^{2+} and Al3+, which can neutralize acidity through dissolution [46]. However, although these minerals are present, their concentrations remain insufficient to balance the high acidity that could potentially be generated by the more abundant acidogenic minerals, especially in the Rcel1 and Rcel3 tailings. In addition, all mine wastes are characterized by an absence of carbonate minerals such as dolomite and calcite, which are more effective AMD neutralizers than the observed silicates [37, 47, 48].

Minerals that can be considered inert or having little involvement in the AMD process for Perkoa mine wastes are quartz, micas (muscovite and paragonite), zircon and rutile (Table 3). These minerals contribute very little or nothing to the generation or production of acidity [37].

The presence of gypsum in trace amounts in the Perkoa mine wastes is a characteristic indicator of geochemical conditions dominated by acid mine drainage. Gypsum is generally observed in acid mining environments as a reaction product between sulphate generated by the dissolution of metal sulphides such as pyrite and calcium released by altered silicates or carbonates [3, 49, 50]. The same applies to barite.

Table 3. *Mineralogical composition of mine wastes.*

Mineral	Group	Mineral content of the samples (%)			
		RS	RB	Rcel1	Rcel3
Acid-generating minerals					
Pyrite	Sulphur	0.3	3.5	42.1	27.3
Pyrrhotite	Sulphur	0.1	0.0	0.1	5.7
Sphalerite	Sulphur	0.0	0.2	6.1	1.5
Neutralizing minerals					
Chlorite	Silicate	1.0	4.7	0.8	3.5
Epidote	Silicate	2.7	8.8	1.8	0.7
Actinolite	Silicate	2.1	11.4	8.7	3.8
Microcline	Silicate	0.1	1.2	1.2	0.0
Plagioclase	Silicate	3.3	11.1	4.4	6.6
Almandine	Silicate	0.0	0.0	0.4	0.0
Inert minerals					
Quartz	Silicate	57.3	43.2	18.8	33.5
Zircon	Silicate	0.0	0.6	0.9	0.4
Paragonite	Silicate	9.8	0.0	0.0	0.0
Muscovite	Silicate	23.0	15.3	1.4	13.7
Rutile	Oxyde	0.1	0.0	0.0	0.0
Secondary or inert minerals					
Gypsum	Sulfate	0.1	0.0	0.5	0.2
Barite	Sulfate	0.0	0.0	12.7	3.0

3.2. Chemical Composition

The results of the analysis reveal a high proportion of sulphur (Table 4) with 2,200 mg/kg for RS, 23,000 mg/kg for RB, and high levels in old mine tailings Rcel1 (220,000 mg/kg) and 140,000 mg/kg in recent tailings (Rcel3). These high sulphur levels reflect much the same trend as the notable presence of sulphide minerals (Table 3). Indeed, the presence of sulphur in these mine wastes is closely linked to pyrite, pyrrhotite and galena, whose oxidation when exposed to water and air can generate acid mine drainage [39].

Sulphate concentrations in mine wastes range from 160 mg/kg (RS) to 3,700 mg/kg (Rcel1), with relatively high levels in Rcel3 (1,200 mg/kg) and RB (530 mg/kg). These sulphates mainly come from the oxidation of sulphides (pyrite, pyrrhotite, sphalerite), promoting the acidification of wastes [42, 51]. In mine wastes such as those at Perkoa, sulphates can be an important indicator of the degree of oxidation of sulphide minerals. High sulphate concentrations generally indicate advanced alteration, leading to the formation of secondary sulphate minerals characteristic of environments marked by acid mine drainage [52].

At the same time, iron also shows the highest proportions, ranging from values above 50,000 mg/kg for waste rock and mill wastes to over 190,000 mg/kg in recent tailings (Rcel3) and over 210,000 mg/kg in old tailings (Rcel1). These relatively high iron contents in these tailings are undoubtedly associated with sulphide minerals such as pyrite and pyrrhotite, as well as ferromagnesian silicates such as chlorite, epidote and actinolite, present in the mine wastes (Table 3). It should be noted that iron in its two forms (Fe^{2+} and Fe^{3+}) in the environment plays an important role in the expansion of acid mine drainage. Ferrous iron (Fe^{2+}) initially intervenes in the process as a product of the oxidation of pyrite, which releases Fe^{2+}, SO_4^{2-} and H^+. This Fe^{2+} is in turn oxidised to Fe^{3+} by oxygen or by bacteria such as Acidithiobacillus ferrooxidans, which accelerate the reaction. The Fe^{3+} thus regenerated acts as a powerful oxidant of pyrite, thereby maintaining a highly acidifying cycle [44, 52, 53].

Calcium levels reach up to 12,268 mg/kg in RB and 7,876 mg/kg in Rcel3. Magnesium follows a similar pattern for RB with 10,495 mg/kg. Manganese is predominant in RS (5,216 mg/kg) and RB (2,043 mg/kg)), but remains low in the other samples such as Rcel1 and Rcel3 (< 700 mg/kg). These elements (Ca, Mg and Mn), although present, come mainly from silicates in low proportions (Table 3) and are less reactive with limited buffering capacity [37, 39]. Under acidic conditions, the hydrolysis of manganese is particularly unfavourable to buffering capacity due to the release of H^+ protons, thus contributing to increased acidification of the environment [44]. The same is also observed for aluminium, which has high concentrations in all mine wastes (3,794 to 26,528 mg/kg) and is also susceptible to acidifying hydrolysis.

In terms of potentially harmful elements, high levels were observed in all mine wastes, including arsenic (1,149 mg/kg), cadmium (150 mg/kg), chromium (310 mg/kg), cobalt (27 mg/kg), copper (174 mg/kg), lead (4,739 mg/kg), nickel (59 mg/kg) and zinc (50,664 mg/kg). With the oxidation of the minerals that make up the various mine wastes streams, potentially harmful elements (PEHs) become increasingly bioavailable and likely to migrate to soil and water, where they can constitute major contaminants [51].

Table 4. *Chemical composition of mine wastes.*

Parameter	Unit	LD	Sample			
			RS	RB	Rcel1	Rcel3
Aluminium	mg/kg	2	11703	26528	5989	11235
Arsenic	mg/kg	1	915	504	491	537
Cadmium	mg/kg	0,1	14	35	150	<0,1
Calcium	mg/kg	50	1448	12268	4088	7876
Chromium	mg/kg	0,2	69	310	270	120
Cobalt	mg/kg	0,5	<0,5	19	<0,5	27
Copper	mg/kg	2	35	69	74	174
Iron	mg/kg	5	56421	55351	210169	196623
Lead	mg/kg	1	4240	2322	1335	583
Magnesium	mg/kg	1	1699	10495	1766	4234
Manganese	mg/kg	1	5216	2043	673	625

Parameter	Unit	LD	Sample			
			RS	RB	Rcel1	Rcel3
Nickel	mg/kg	0,5	20	59	50	51
Sulphur	mg/kg	1	2200	23000	220000	170000
Zinc	mg/kg	1	1306	6071	50664	14689
Sulphate	mg/kg	5	160	530	3700	1200

3.3. Tests for Acid Mine Drainage Prediction

3.3.1. pH and Electrical Conductivity (EC) in Saturated Paste

The different types of mine wastes were classified according to their potential to generate AMD, based on pH/electrical conductivity pairs (Table 5). Cross-analysis of pH and electrical conductivity values provides an initial assessment of AMD generation potential, in accordance with the classes defined by [31]. This approach makes it possible to associate the degree of acidity with the dissolved ionic load, as well as the associated level of environmental risk. It also reflects the intensity of sulphide oxidation processes and the mobility of Potentially Harmful Elements (PHEs).

Table 5. *Characterisation of mine wastes according to AMD classification based on pH and electrical conductivity (EC) [31].*

AMD class	pH	EC (µS/cm)	Diagnostic	Studied mine wastes		
				Sample	pH	EC (µS/cm)
I	pH ≤ 4	> 1000	confirmed acid mine drainage	Rcel1	4.1	1101
II	4 < pH ≤ 5	> 750	Confirmed Developing Acid Mine	Rcel3	4.66	745
III	5 < pH ≤ 6	> 500	Potential Developing acid mine drainage	RB	5.88	682
/	pH < 6	≤ 500	Acidic sample	RS	4.81	396

N. B.: Waste rock (RS), Crusher waste (RB), Mine tailings from cell 1 (Rcel1) and Mine tailings from cell 3 (Rcel3)

Rcel1 tailings have a pH of around 4 and an EC greater than 1000 µS/cm, which places them in Class I, characterised by proven acid mine drainage. This reflects advanced oxidation of sulphides, involving a high release of dissolved ions into the interstitial solution. These mine wastes must be considered highly acidogenic and require appropriate neutralization or isolation measures [49, 54].

The mine wastes represented by Rcel3, with a pH of 4.66 and an electrical conductivity of 745 µS/cm, belong to class II, reflecting developing acid mine drainage. This intermediate level reveals a progression towards acidification, possibly associated with the initiation of oxidation reactions of sulphide minerals or the persistence of an even less active or ineffective buffering effect [55].

The mill wastes have a pH of 5.88 and electrical conductivity of 682 µS/cm. These wastes correspond to class III, indicating developing AMD potential. They thus constitute a moderately acidic environment revealing a residual presence of sulphides in a weakly neutralising mineralogical matrix.

Overall, this classification reveals marked heterogeneity in the geochemical behaviour of the different wastes. The most acidic residues are often associated with a fine fraction rich in sulphides, while those with low acidogenic potential are likely to originate from sulphide-poor lithologies or lithologies that have undergone prior alteration. These results highlight the need to consider mineralogy, grain size and geochemical history in the development of AMD [42, 56].

3.3.2. Sulphur Threshold According to Miller

According to [32], a total sulphur threshold greater than 0.3% indicates a material that is potentially capable of generating AMD. Sulphur content varies depending on the type of mine

wastes (Figure 3, Table 6).

The Rcel1 and Rcel3 mine tailings have very high sulphur contents, ranging from 19 to 44%, which is well above the 0.3% threshold. These levels reflect a high presence of sulphide minerals, confirming the high risk of AMS generation associated with these materials, which is also corroborated by low pH values and high conductivity.

RB waste has sulphide contents of 3.1%, which is also above the critical threshold of 0.3%. This therefore indicates a significant potential for acidity generation through the oxidation of sulphides in the presence. These materials are considered to be at risk, although their geochemical behaviour may depend on their mineralogical nature with the neutralising minerals present [44] (Bussière and Guittonny, 2021).

On the other hand, RS wastes have very low sulphur contents, with values of 0.25%, below the threshold of 0.3%. This indicates a low presence of reactive sulphides, which considerably limits their acid-generating potential. These materials could therefore be considered as no-generating of AMD.

In summary, this assessment of the acidogenic nature of mine wastes using the threshold set by [32] is consistent with the classification criteria of [31] used above. These results confirm the value of sulphur analysis as a preliminary indicator of AMD generation potential, particularly when integrated into a more comprehensive geochemical assessment [57, 58].

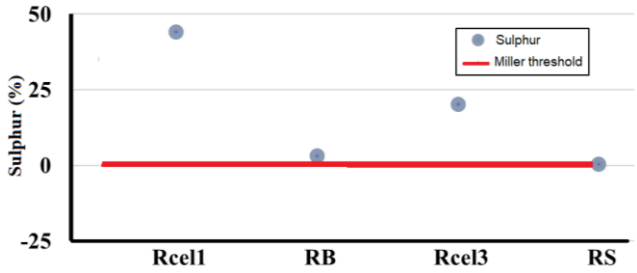

Figure 3. *Sulfur content compared to Miller threshold.*

3.3.3. Net Acidity Production Test

The results show that for all mine wastes, the acid potential (AP) is significantly higher than the neutralization potential (NP) (Table 6).

Rcel1 mining tailings has very high total sulphur content (44%) and very high acid potential of 1375 kg $CaCO_3$/t. On the other hand, the neutralization potential is extremely low (approximately 1.7 kg $CaCO_3$/t), resulting in a very negative net neutralization potential (NNP = NP - AP) (<−1373 kg $CaCO_3$/t) and an NPR ratio (NP/AP) of almost zero (NPR ≈ 0.001). These different values place these mine wastes in the acidogenic zone (Figure 4) with a high acid potential and therefore a high risk of acid mine drainage generation [46, 51].

The Rcel3 mine tailings have relatively high sulphur contents of 19% with a relatively high acid potential of around 600 kg $CaCO_3$/t, compared to a neutralising potential of 8,330 kg $CaCO_3$/t. The NNP is negative but less pronounced (−589,586) compared to the old tailings (Rcel1) with a low NPR (0.007). This implies a potential for acidity generation, and therefore for actual AMD, but this is likely to be mitigated due to the recent nature of the Rcel3 tailings, in addition to the probable presence of neutralising minerals capable of partially inhibiting the acidity generated [51, 59]. This observation highlights the importance of incorporating mineralogical parameters into the assessment of AMD risks.

RB wastes are characterized by a significantly lower sulphur content of around 3.1% with an acid potential also reduced to 97 kg $CaCO_3$/t and a neutralising power of around 3 kg $CaCO_3$/t. The NNP is also negative (−93) with an NPR of around 0.03. This configuration indicates a moderate potential for AMD generation, confirming that these materials pose a lower environmental risk compared to Rcel1 and Rcel3 mine tailings, which would contain a significant proportion of sulphide minerals [40]. However, RB wastes are not completely free of AMD risk.

Finally, RS wastes, with the lowest sulphur content (0.19%) and an acid-generating potential of around 7 kg $CaCO_3$/t, also have a relatively low neutralising power (0.8 kg $CaCO_3$/t). The NNP (−5) and NPR (0.14) classify these wastes as presenting a lower or uncertain risk of acid rock drainage [46, 51].

In summary, these results show that samples Rcel1, RB, and Rcel3 are potentially acid-generating, with very negative NNP and NPR well below 1, according to [9]. This indicates a high risk of acid generation and therefore acid mine drainage. These results corroborate a mineralogy dominated by sulphides and poor in neutralising minerals [42]. As for the RS wastes samples, they are located in the uncertainty zone according to the NP and slightly at the limit of the acidogenic zone (Figure 4), thus requiring kinetic tests to confirm their geochemical behavior [60-62].

Table 6. *Acid and neutralization potentials of mine wastes.*

Parameter	Sulphur	Carbon	AP	NP	NNP (NP-AP)	NPR (NP/AP)
LOD	0.01	0.01	/	/	/	/
Unit	%	%	Kg $CaCO_3$/t	Kg $CaCO_3$/t	Kg $CaCO_3$/t	/

Parameter	Sulphur	Carbon	AP	NP	NNP (NP-AP)	NPR (NP/AP)
RS	0.25	0.02	7.8125	1.666	-6.147	0.213
RB	3.1	0.04	96.875	3.332	-93.543	0.034
Rcel1	44	0.02	1375	1.666	-1373.334	0.001
Rcel3	20	0.1	625	8.330	-616.670	0.013

N. B.: AP (Acid Potential), NP (Neutralization Potential), NNP (Net Neutralization Potential), NPR (Neutralization Potential Ratio), LOD (Limit of Detection)

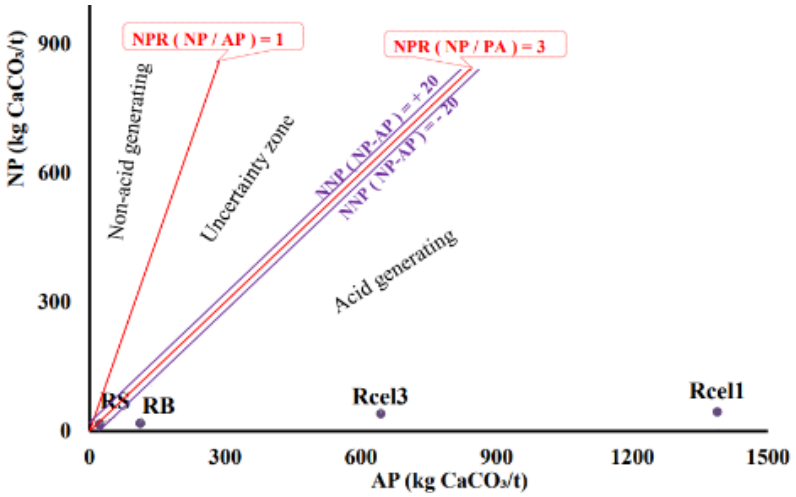

Figure 4. Position of mine wastes samples according to static test criteria [42].

4. Conclusion

The assessment of the acid generation potential of mine wastes from the Perkoa zinc mine shows that the majority of the samples studied have a high potential for acid generation, or even confirmed acid generation. The Rcel1 and Rcel3 mine tailings samples have pH values between 3.49 and 4.66 and electrical conductivities (EC) greater than 1000 µS/cm. This corresponds to the classes of confirmed or developing acid mine drainage. This situation is confirmed by the very high total sulphur values reaching 44% for Rcel1 and a very low NPR ratio of around 0.001. This implies a very insignificant neutralisation potential (< 2 kg $CaCO_3$/t) and negatively marked NNP values of around -1300 kg $CaCO_3$/t. Mineralogically, these same samples are very rich in acidogenic sulphide minerals, particularly pyrite (up to 42.1%), sphalerite (7.9%) and pyrrhotite (5.7%), while potentially neutralising minerals are present in low proportions in the form of silicates such as chlorite, actinolite and plagioclases. These low proportions of silicates are insufficient to balance the acidity contribution of acidogenic mineral species. On the other hand, RS waste rock samples, although their pH remains below 6, have an electrical conductivity of less than 500 µS/cm and low sulphur content (< 0.3%). These waste rock samples have an NPR less than 1 and an NNP around -5, indicating a very limited or uncertain acid generation potential. Finally, RB crusher waste samples, containing approximately 3% sulphur, with a pH between 5 and 6, and an EC greater than 500 µS/cm, present a moderate risk of Class III acid mine drainage (AMD).

Abbreviations

ABA	Acid-base Accounting
AMD	Acid Mine Drainage
ANAM	National Meteorological Agency
AP	Acid Potential
EC	Electrical Conductivity
ICP-OES	Inductively Coupled Plasma - Optical Emission Spectroscopy
LOD	Limit of Detection
NNP	Net Neutralization Potential
NPR	Neutralization Potential Ratio
pH	Hydrogen Potential
PHEs	Potentially Harmful Elements
PN	Neutralization Potential
RB	Crusher Waste
Rcel1	Mine Tailings From Cell 1

Rcel3	Mine Tailings from Cell 3
RS	Waste Rock (RS)
XRD	X-ray Diffraction

Acknowledgments

The authors would like to thank the managers of the former NANTOU MINING company, who facilitated the fieldwork, and the Higher Education Support Programme (PAES) for the study grant awarded.

Author Contributions

Isso Felix Bado: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software and writing - Original draft

Adama Yameogo: Formal Analysis, Supervision, Validation, Visualization

Abdoul Aziz Tarpaga: Formal Analysis, Supervision, Validation, Visualization

Nicolas Kagambega: Conceptualization, Formal Analysis, Methodology, Project administration, Supervision, Validation, Visualization, Writing-review & editing

Funding

The study was supported by the Higher Education Support Programme (PAES) for the study grant awarded.

Data Availability Statement

The data is available from the corresponding author upon reasonable request. These data supporting the outcome of this research work have been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] MEMC, (2023). Annuaire statistique 2022 du Ministère de l'Energie, des Mines et des Carrières. Annuaire statistique 2022 du Ministère de l'Energie, des Mines et des Carrières.

[2] Chopard, A. (2017). *Évaluation environnementale de minerais sulfurés polymétalliques basée sur une approche minéralogique pluridisciplinaire* (Thèse de doctorat, Université du Québec en Abitibi-Témiscamingue). Université du Québec en Abitibi-Témiscamingue. 424p. https://depositum.uqat.ca/id/eprint/705/

[3] Kagambega, N. (2017). Solutions techniques pour l'atténuation des impacts environnementaux liés à l'activité minière et étude de facteurs aggravants. Thèse de doctorat en génie de l'environnement de l'Université de Laval (Québec, Canada), 282 p.

[4] Aubertin, M., Bussière, B., Bernier, L., Chapuis, R., Julien, M., Belem, T., Simon, R., Mbonimpa, M., Benzaazoua, M. (2002). La gestion des rejets miniers dans un contexte de développement durable et de protection de l'environement. Congrès annuel de la Société canadienne de génie civil. Article No. GE-045. Montréal, Québec, Canada.

[5] ELAW (Environmental Law Alliance Worldwide), (2010). Guide pour l'évaluation des EIE des projets miniers (2010). USA, 130 p. Environmental Law Alliance Worldwide. (2010). *Guide pour l'évaluation des études d'impact environnemental (EIE) des projets miniers* (130 p.). https://elaw.org/wp-content/uploads/archive/attachments/publicresource/guidebook_evaluating_mining_eia_french.pdf

[6] Poulard, F., Daupley, X., Didier, C., Pokryszka, Z., d'Hugues, P., Charles, N., Dupuy, J.-J., & Save, M. (2017). *Exploitation minière et traitement des minerais* (Tome 6, Collection « La mine en France », 79 p.). Bureau de Recherches Géologiques et Minières (BRGM). https://www.mineralinfo.fr/sites/default/files/documents/2021-01/tome_06_exploitation_miniere_traitement_minerais_final24032017.pdf

[7] Aubertin, M., Bussière, B., James, M., Mbonimpa, M., & Chapuis, R. P. (2013). Revue de divers aspects liés à la stabilité géotechnique des ouvrages de retenue de résidus miniers. Partie II: Analyse et conception. *Déchets Sciences et Techniques, 64*(18), 38-50. https://doi.org/10.4267/dechets-sciences-techniques.2314

[8] Erazola, M., (2013). L'encapsulation des résidus miniers acides dans le pergélisol québécois : est-ce une pratique durable ? (Essai). Université de Sherbrooke. 96 p. https://usherbrooke.scholaris.ca/items/ec930c94-4b2c-4d75-bf0b-f2f07a04e9a

[9] MEND, (2009). Prediction manual for drainage chemistry from sulphidic geologic materials (No. Report 1.20.1).

[10] Ethier, M. P., (2018). Évaluation de la performance d'un système de recouvrement monocouche avec nappe surélevée pour la restauration d'un parc à résidus miniers abandonnés.

[11] Toubri, Y., (2022). Integrating multidisciplinary modeling tools to support upstream mine waste management. Thèse de doctorat. Polytechnique Montréal. 322 p.

[12] Forcier, K., (2023). Sélection d'isolats fongiques en association avec quelques plantes pionnières du site Aldermac à drainage minier acide dans la région de Rouyn-Noranda en Abitibi-Témiscamingue (Maîtrise). Université Laval, Québec, Canada. 159 p.

[13] L'Hermite, P., (2023). Modélisation des écoulements dans des sites de stockage de résidus miniers (These de doctorat). Sorbonne université. 288 p.

[14] Mouafo, V. T., (2023). Contrôle du DMA des stériles du projet

Lac Guéret de Mason Graphite à l'aide d'amendements alcalins. Mémoire de maîtrise. Polytechnique Montréal.

[15] Kagambèga, N., Sawadogo, S., Bamba, O., Zombré, P., Galvez, R., (2014). Acid mine drainage and heavy metals contamination of surface water and soil in south west Burkina Faso-West Africa 2, 9-19.

[16] Ouedraogo, B., Kagambèga, N., Ouédraogo, M., (2018). Méthodes prédictives géochimiques statiques et plan de fermeture de mine. Cas de la mine d'or de Youga—Burkina Faso. Journal des sciences 18, 13_23.

[17] Marcoux, E., Ouedraogo, M. F., Feybesse, J. L., Milesi, J. P., Prost, A. E., (1988). Géochimie et géochronologie isotopiques: âge Pb/Pb à 2120±41 M. a. des corps sulfurés massifs à Zn-Ag de Perkoa (Burkina Faso). Comptes Rendus de l'Académie des Sciences, Série II, Mécanique, Physique, Chimie, Sciences de l'Univers, Sciences de la Terre, 306, 589-594.

[18] Napon, S., (1988). Le Gisement d'amas sulfuré (ZN-AG) de Perkoa dans la province du Sangyé (Burkina Faso-Afrique de l'Ouest) : cartographie, étude pétrographique, géochimique et métallogénique. Thèse de doctorat. Université Franche Comte Besançon. 307 p.

[19] Ratomaharo, V. S., (1990). Utilisation des données minéralogiques et géochimiques pour la reconstitution lithostratigraphique de l'encaissant volcano-sédimentaire du gîte d'amas sulfuré (Zn) protérozoïque inférieur de Perkoa (Burkina Faso). Thèse de doctorat. Université Pierre et Marie Curie, Paris 6.

[20] Schwartz, M. O., Melcher, F., (2003). The Perkoa Zinc Deposit, Burkina Faso. Economic Geology 98(7), 1463-1485. https://doi.org/10.2113/gsecongeo.98.7.1463

[21] Smuts, W., 2010. Perkoa Zinc on the comeback trail: due diligence in progress: project development. Inside Mining 3, 6-9. https://doi.org/10.10520/EJC104030

[22] Bado, F. I., Kagambèga, N., & Yameogo, A. (2024). Kinetics of neutralization of polymetallic mining discharges from the Perkoa zinc deposit in central-western Burkina Faso. *Journal of Environmental Science and Engineering, 8*(3), 1-13. https://doi.org/10.33799/jesse.v8i3.673

[23] Thiombiano, Y. (2020). *Optimisation de la séquence d'extraction à la mine de Perkoa, cas de la zone 310-400* (Mémoire de maîtrise, Université Laval). Université Laval. 132 p. https://corpus.ulaval.ca/jspui/handle/20.500.11794/44262

[24] Guira, Y., (2020). Gestion des résidus miniers : cas de la mine d'amas sulfures de Perkoa - Burkina Faso (Master). Université Joseph KI-ZERBO. 79 p.

[25] Bado, I. F., Kagambega, N. et Yameogo, A., (2024). Geochemistry of Mining Discharges from the polymetallic Deposit of the Perkoa Underground Zinc Mine in Central western Burkina Faso - West Africa. Orient. J. Chem., Vol. 40(6), 1809-1817. ISSN: 0970 - 020X, ONLINE ISSN: 2231-5039. http://dx.doi.org/10.13005/ojc/400633

[26] Klein, C., Hurlbut, C. S., Jr. (1993). Manual of mineralogy (21e éd.). John Wiley & Sons, Inc. 681p. ISBN 978-0-471-59955-7.

[27] Taylor, J. C., & Hinczak, I. (2001). *A practical guide to the understanding of the method and successful phase quantifications* (Rietveld made easy). The Authors. 201 p. ISBN 0975079808.

[28] Guinebretière, R. (2002). *Diffraction des rayons X sur échantillons polycristallins* Lavoisier. 287 p. ISBN 978-2-7462-0557-4.

[29] Villeneuve, M., (2004). Évaluation du comportement géochimique à long terme de rejets miniers à faible potentiel de génération d'acide à l'aide d'essais cinétique (Maîtrise). Université de Montréal. 323 p.

[30] Collon, P., (2003). The evolution of the quality of water in the abandoned mines of the lorrain iron basin: from laboratory experiments to in situ modelling. Thèse de doctorat, Institut National Polytechnique de Lorraine, 247 p.

[31] Brunet, J. F., Coste, B. (2000). Bibliographie préliminaire à la gestion des DMA de Rosia Poieni (Roumanie). Bureau de Recherches Géologiques et Minières (BRGM) rp50626-fr. 116 p. https://infoterre.brgm.fr/rapports/RP-50626-FR.pdf

[32] Miller, S. D., Jeffery, J. J., Wong, J. W. C., (1991). Use and Misuse of the Acid Base Account for "AMD" Prediction. Presented at the Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage, Montreal, Canada, pp. 489-506.

[33] Gordio, A., Kagambèga, N., Bamba, O., Sako, A., & Miningou, M. Y. W. (2014). Prediction of acid mine drainage occurrence at the Inata gold mine - Burkina Faso, West Africa. *Academia Journal of Environmental Sciences, 2*(3), 043-051. https://doi.org/10.15413/ajes.2014.020303

[34] Sobek, A. A., Schuller, W. A., Freeman, J. R., and Smith, R. M. (1978). Field and laboratory methods applicable to overburden and minesoils. US EPA 600/2-78/054, Industrial Environmental Research Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, Ohio. 218 p.

[35] Lawrence, R. W., Scheske, M., (1997). A method to calculate the neutralization potential of mining wastes. Environmental Geology 32, 100-106. https://doi.org/10.1007/s002540050198

[36] Chtaini, A., (1999). Contrôle du drainage minier acide à l'aide de boues alcalines d'usines de pâtes à papiers. Thèse de doctorat, Université de Sherbrooke 316 p. http://savoirs.usherbrooke.ca/handle/11143/1699

[37] Jambor, J. L., Dutrizac, J. E., Raudsepp, M., (2007). Measured and computed neutralization potentials from static tests of diverse rock types. Environ Geol 52, 1019-1031. https://doi.org/10.1007/s00254-006-0542-4

[38] Nordstrom, D. K. (2011). Mine waters: Acidic to circumneutral. *Elements, 7*(6), 393-398. https://doi.org/10.2113/gselements.7.6.393

[39] Blowes, D. W., Ptacek, C. J., Jambor, J. L., Weisener, C. G.,

Paktunc, D., Gould, W. D., & Johnson, D. B. (2014). The geochemistry of acid mine drainage. In *Treatise on Geochemistry* (Vol. 9, pp. 131-190). Elsevier. https://doi.org/10.1016/B978-0-08-095975-7.00905-0

[40] Younger, P. L., Banwart, S. A., & Hedin, R. S. (2002). *Mine Water: Hydrology, Pollution, Remediation*. Springer Science & Business Media. 442 p. ISBN 978-1-4020-0138-3

[41] Verburg, R., Bezuidenhout, N., Chatwin, T., Ferguson, K., (2009). The global acid rock drainage guide (GARD Guide). Mine Water and the Environment 28, 305-310. https://doi.org/10.1007/s10230-009-0078-4

[42] International Network for Acid Prevention (INAP). (2018). *The Global Acid Rock Drainage Guide (GARD Guide)*. https://www.gardguide.com/images/5/5f/TheGlobalAcidRockDrainageGuide.pdf

[43] Nordstrom, D. K., & Alpers, C. N. (1999). Geochemistry of acid mine waters. In G. S. Plumlee & M. J. Logsdon (Éds.), *The environmental geochemistry of mineral deposits: Part A: Processes, methods and health issues* (pp. 133-160). Society of Economic Geologists.

[44] Bussière, B., Guittonny, M. (Eds.), (2021). Hard rock mine reclamation: from prediction to management of acid mine drainage, 1st ed. CRC Press, Boca Raton. 409 p. https://doi.org/10.1201/9781315166698

[45] Rimstidt, J. D., & Vaughan, D. J. (2003). Pyrite oxidation: A state-of-the-art assessment of the reaction mechanism. *Geochimica et Cosmochimica Acta, 67*(5), 873-880. https://doi.org/10.1016/S0016-7037(02)01165-1

[46] Akcil, A., Koldas, S., (2006). Acid Mine Drainage (AMD): causes, treatment and case studies. Journal of Cleaner Production, 14, 1139-1145. https://doi.org/10.1016/j.jclepro.2004.09.006

[47] Sverdrup, H. U., (1990). The Kinetics of Base Cation Release Due to Chemical Weathering. Lund University Press.

[48] Kwong, Y. J. (1993). Prediction and prevention of acid rock drainage from a geological and mineralogical perspective. Canada Centre for Mineral and Energy Technology, Ottawa, Ont. Technical Report MIC-96-03209/XAB, 72 p.

[49] Jambor, J. L., Dutrizac, J. E., Raudsepp, M., Groat, L. A., (2003). Effect of Peroxide on Neutralization-Potential Values of Siderite and Other Carbonate Minerals. J of Env Quality 32, 2373-2378. https://doi.org/10.2134/jeq2003.2373

[50] Parbhakar-Fox, A., & Lottermoser, B. G. (2015). A critical review of acid rock drainage prediction methods and practices. *Minerals Engineering, 82*, 107-124. https://doi.org/10.1016/j.mineng.2015.03.015

[51] Lottermoser, B. G. (2007). Mine wastes: Characterization, treatment and environmental impacts (3rd ed., 304 p.). Springer Science & Business Media. https://doi.org/10.1007/978-3-540-48630-5

[52] Nordstrom, D. K. (2015). Hydrogeochemistry and microbiology of mine drainage. *Treatise on Geochemistry, 9*, 1-40. https://doi.org/10.1016/B978-0-08-095975-7.00901-6

[53] Lindsay, M. B. J., Moncur, M. C., Bain, J. G., Jambor, J. L., Ptacek, C. J., & Blowes, D. W. (2015). Geochemical and mineralogical aspects of sulfide mine tailings. *Applied Geochemistry, 57*, 157-177. https://doi.org/10.1016/j.apgeochem.2015.01.009

[54] Blowes, D. W., Al, T., Lortie, L., Gould, W. D., Jambor, J. L. (1995). Microbiological, chemical, and mineralogical characterization of the kidd creek mine tailings impoundment, Timmins area, Ontario. Geomicrobiology Journal, 13. 13-31 https://doi.org/10.1080/01490459509378001

[55] Morin, K., & Hutt, N. (1997). *Environmental geochemistry of minesite drainage: Practical theory and case studies* (1st ed.). MDAG Publishing. ISBN 0-9682039-0-6.

[56] Lapakko, K. A., (1994). Evaluation of Neutralization Potential Determinations for Metal Mine Waste and a Proposed Alternative. ASMR 1994, 129-137. https://doi.org/10.21000/JASMR94010129

[57] Diaby, N., Dold, B., Pfeifer, H.-R., Holliger, C., Johnson, D. B., Hallberg, K. B., (2007). Microbial communities in a porphyry copper tailings impoundment and their impact on the geochemical dynamics of the mine waste. Environ. Microbiol. 9, 298-307.

[58] Whitworth, A. J., Forbes, E., Verster, I., Jokovic, V., Awatey, B., & Parbhakar-Fox, A. (2022). Review on advances in mineral processing technologies suitable for critical metal recovery from mining and processing wastes. *Cleaner Engineering and Technology, 7*, 100451. https://doi.org/10.1016/j.clet.2022.100451

[59] Mendez, M. O., & Maier, R. M. (2008). Phytostabilization of mine tailings in arid and semiarid environments—An emerging remediation technology. *Environmental Health Perspectives, 116*(3), 278-283. https://doi.org/10.1289/ehp.10608

[60] Bouzahzah, H., Benzaazoua, M., Bussière, B., Plante, B., (2014). Revue de littérature détaillée sur les tests statiques et les essais cinétiques comme outils de prédiction du drainage minier acide. Environnement, Ingénierie & Développement 66, 14-31. https://doi.org/10.4267/dechets-sciences-techniques.340

[61] Bouzahzah, H, Benzaazoua, M., Bussière, B., Plante, B., (2014). Recommandations sur l'utilisation des outils de prédiction du drainage minier acide. Environnement, Ingénierie & Développement, 68, 1-12. https://doi.org/10.4267/dechets-sciences-techniques.111

[62] Plante, B., Bussiere, B., Bouzahzah, H., Benzaazoua, M., Demers, I., Kandji, E.-H. B., (2015). Revue de littérature en vue de la mise à jour du guide de caractérisation des résidus miniers et du minerai (Recherche No. Rapport PU-2013-05-806). Université du Québec en Abitibi-Témiscamingue (UQAT)/Unité de recherche et de service en technologie minérale (URSTM), Rouyn-Noranda, Québec, Canada. 61 p.