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CHEMICAL CHARACTERIZATION AND DETERMINATION OF CONTAMINANT ELEMENTS IN LOW-GRADE CASSITERITE FROM THE BOM FUTURO MINE (RO), WESTERN AMAZON

CARACTERIZAÇÃO QUÍMICA E DETERMINAÇÃO DE ELEMENTOS CONTAMINANTES EM CASSITERITA DE BAIXO TEOR PROVENIENTE DO GARIMPO BOM FUTURO (RO), AMAZÔNIA OCIDENTAL

CARACTERIZACIÓN QUÍMICA Y DETERMINACIÓN DE ELEMENTOS CONTAMINANTES EN CASITERITA DE BAJO TENOR PROVENIENTE DEL GARIMPO BOM FUTURO (RO), AMAZONÍA OCCIDENTAL

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Jessé Castro dos Santos[1], Sylviane Beck Ribeiro[2]

ABSTRACT
The present study aimed to perform the chemical characterization and determination of contaminant elements in low-grade cassiterite samples from the Bom Futuro Mine, located in the Western Amazon (RO), Brazil. The research sought to assess the elemental composition of the ore, identify potentially toxic metals, and provide technical support for discussions on mineral utilization and environmental risks associated with its exploitation. Representative samples were collected from different mining fronts and tailings piles, following geological and mineral exploration criteria. The samples were prepared according to standardized protocols for drying, grinding, and homogenization, and subsequently analyzed using X-Ray Fluorescence (XRF) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The results revealed that tin (Sn) is the main element in the samples, with average contents ranging from 45% to 46%, characteristic values of secondary alluvial deposits in the region. Moderate concentrations of iron (Fe) and tungsten (WO_3) were observed, as well as low levels of potentially toxic metals such as lead (Pb), arsenic (As), cadmium (Cd), and zinc (Zn), all below environmental reference limits. The compositional homogeneity and low moisture contents (0.17–0.23%) reinforce the representativeness of the samples and the analytical reliability of the results. Thus, it was verified that the low-grade cassiterite from the Bom Futuro Mine presents a composition favorable to mineral recovery and low geoenvironmental risk, demonstrating economic potential and sustainability for regional mining.

Keywords: Cassiterite. XRF. ICP-OES. Heavy Metals. Western Amazon.

RESUMO
O presente estudo teve como objetivo realizar a caracterização química e a determinação de elementos contaminantes em amostras de cassiterita de baixo teor provenientes do Garimpo Bom Futuro, localizado na Amazônia Ocidental (RO). A pesquisa buscou avaliar a composição elementar do minério, identificar metais potencialmente tóxicos e subsidiar

[1] Master's student in Environmental Sciences. Universidade Federal de Rondônia (UNIR).
E-mail: jessecastrosantos@hotmail.com Orcid: https://orcid.org/0009-0007-1420-6607
[2] Dr. in Forest Engineering. Universidade Federal de Rondônia (UNIR).
E-mail: sylvianebeck@unir.br Orcid: https://orcid.org/0000-0003-4882-8213

discussões sobre o aproveitamento mineral e os riscos ambientais associados à sua exploração. Para isso, foram coletadas amostras representativas em diferentes frentes de lavra e pilhas de rejeitos, seguindo critérios geológicos e de exploração mineral. As amostras foram preparadas segundo protocolos padronizados de secagem, moagem e homogeneização, e posteriormente analisadas pelas técnicas de Fluorescência de Raios X (FRX) e Espectrometria de Emissão Óptica com Plasma Indutivamente Acoplado (ICP-OES). Os resultados obtidos revelaram que o estanho (Sn) constitui o principal elemento nas amostras, com teores médios entre 45% e 46%, valores característicos de depósitos secundários aluvionares da região. Foram observados teores moderados de ferro (Fe) e tungstênio (WO_3), além de baixas concentrações de metais potencialmente tóxicos, como chumbo (Pb), arsênio (As), cádmio (Cd) e zinco (Zn), todos abaixo dos limites de referência ambientais. A homogeneidade composicional e os baixos teores de umidade (0,17–0,23%) reforçam a representatividade das amostras e a qualidade analítica dos resultados. Dessa forma verificou-se que a cassiterita de baixo teor do Garimpo Bom Futuro apresenta composição favorável ao reaproveitamento mineral e reduzido risco geoambiental, evidenciando potencial econômico e sustentabilidade para a mineração regional.

Palavras-chave: Cassiterita. FRX. ICP-OES. Metais Pesados. Amazônia Ocidental.

RESUMEN

El presente estudio tuvo como objetivo realizar la caracterización química y la determinación de elementos contaminantes en muestras de casiterita de bajo tenor provenientes del Garimpo Bom Futuro, ubicado en la Amazonia Occidental (RO), Brasil. La investigación buscó evaluar la composición elemental del mineral, identificar metales potencialmente tóxicos y ofrecer fundamentos técnicos para las discusiones sobre el aprovechamiento mineral y los riesgos ambientales asociados con su explotación. Se recolectaron muestras representativas en diferentes frentes de extracción y pilas de relaves, siguiendo criterios geológicos y de exploración minera. Las muestras fueron preparadas según protocolos estandarizados de secado, molienda y homogeneización, y posteriormente analizadas mediante las técnicas de Fluorescencia de Rayos X (FRX) y Espectrometría de Emisión Óptica con Plasma Acoplado Inductivamente (ICP-OES). Los resultados obtenidos revelaron que el estaño (Sn) constituye el elemento principal de las muestras, con contenidos medios entre 45% y 46%, valores característicos de depósitos secundarios aluviales de la región. Se observaron concentraciones moderadas de hierro (Fe) y tungsteno (WO_3), además de bajos niveles de metales potencialmente tóxicos, como plomo (Pb), arsénico (As), cadmio (Cd) y zinc (Zn), todos por debajo de los límites de referencia ambiental. La homogeneidad composicional y los bajos niveles de humedad (0,17–0,23%) refuerzan la representatividad de las muestras y la calidad analítica de los resultados. De esta manera, se verificó que la casiterita de bajo tenor del Garimpo Bom Futuro presenta una composición favorable para el reaprovechamiento mineral y un riesgo geoambiental reducido, evidenciando potencial económico y sostenibilidad para la minería regional.

Palabras clave: Cassiterita. FRX. ICP-OES. Metales Pesados. Amazonia Occidental.

1 INTRODUCTION

Cassiterite (SnO_2) is the main tin ore mined worldwide, being a strategic resource for several production chains, especially the electronics, metallurgical and chemical industries (Mitchell *et al.,* 2019). In Brazil, tin production is prominent in the North Region, with historical relevance in the state of Rondônia, where the Bom Futuro Mine, one of the largest cassiterite deposits in South America, is located (Silva; Oliveira, 2020). In recent years, interest in low-grade deposits has grown due to the progressive depletion of high-purity ores, requiring the improvement of analytical and processing techniques capable of identifying and quantifying impurities and contaminants at trace concentrations (De la Roche *et al.,* 2018).

Chemical characterization of low-grade ores is essential to understand their mineralogical composition and the geochemical behavior of trace elements that can act as environmental contaminants (Costa *et al.,* 2021). Elements such as lead (Pb), arsenic (As), cadmium (Cd), chromium (Cr) and manganese (Mn) may be present in small proportions in the crystalline structure or in associated phases, and, when released into the environment during mining and processing processes, represent significant risks to biota and human health (Guimarães; Rezende, 2022). Thus, the detailed analysis of the elemental composition of low-grade cassiterite allows not only to assess the economic potential of the ore, but also to identify possible sources of contamination associated with artisanal and semi-industrial mining in the Western Amazon.

In the Amazonian context, mineral exploration has a relevant socioeconomic role, but it is also associated with environmental impacts resulting from the inadequate disposal of tailings and the contamination of water bodies (Santos; Almeida; Souza, 2020). The absence of strict technical control in mining operations favors the accumulation of heavy metals in the soil and water, requiring regional geochemical investigations to help diagnose and mitigate these impacts (Ferreira *et al*., 2023). In this way, the characterization of samples from the Bom Futuro mine contributes to the knowledge of local geoenvironmental conditions and to the sustainable management of Amazonian mineral resources.

The application of analytical techniques such as X-ray Fluorescence (XRF) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) has been shown to be effective in the identification and quantification of principal and trace elements in complex mineral matrices (Mendes; Rodrigues; Soares, 2021). These methodologies allow the chemical composition to be determined with high precision and provide subsidies for geochemical correlations that indicate the origin of the contaminants and the degree of alteration of the samples (Brito *et al.,* 2022). Such information is fundamental for the development of mineral reuse strategies and for the reduction of environmental liabilities in the Amazon region.

In view of this scenario, the present study aimed to carry out the chemical characterization and determination of the contaminant elements present in samples of low-grade cassiterite from the Bom Futuro Mine (RO), in order to evaluate its elemental composition, identify potentially toxic metals and subsidize research on mineral use and environmental risks related to its exploitation. The results obtained can contribute to the advancement of technical-scientific knowledge about tin ores from the Western Amazon, as well as to the development of more sustainable practices in regional mining.

2 THEORETICAL FRAMEWORK

2.1 THE ECONOMIC AND GEOLOGICAL IMPORTANCE OF CASSITERITE IN WESTERN AMAZONIA

Cassiterite (SnO_2) is the main tin mineral mined on a global scale, representing the main source of this metal for the metallurgical and electronics industries. In the Brazilian context, its extraction has significant economic relevance, especially in the Western Amazon, where the state of Rondônia stands out as one of the largest national producers. In this region, the Bom Futuro mining emerges as one of the most important secondary occurrences of cassiterite, the result of weathering processes that favored the residual concentration of the ore in alluvial and eluvial deposits (Souza *et al.,* 2019).

The exploration of cassiterite in the Bom Futuro Mine not only boosted local economic development, but also consolidated Rondônia as a strategic hub for tin production in Brazil. This activity generates direct and indirect jobs, fosters associated production chains, and contributes to the collection of taxes and regional investments (Mitchell *et al*., 2018). However, the intensive mining dynamics and the advance of the exploration of low-grade ores require a more judicious technical approach, based on responsible mining practices and the control of environmental impacts.

In this context, it is essential to develop studies aimed at the chemical and geochemical characterization of low-grade cassiterite samples, since such analyses provide subsidies to evaluate the economic potential of the ore and identify possible environmental risks associated with the presence of contaminating elements. The integration between geological knowledge, instrumental analysis and sustainable environmental management is essential to ensure the rational use of the mineral resources of the Western Amazon, reconciling productivity, socio-environmental responsibility and preservation of local ecosystems.

2.2 SECONDARY DEPOSITS AND MINERALOGICAL CHARACTERISTICS OF LOW-GRADE CASSITERITE

The low-grade cassiterite deposits present in the Western Amazon are characterized by their predominantly secondary nature, resulting from intense chemical weathering processes and residual concentration of heavy minerals from tin-enriched granitic rocks (De la Roche *et al*., 2020). These processes act over long geological periods, promoting the disaggregation of primary rocks and the selective accumulation of resistant minerals, including cassiterite (SnO_2), the main source of economically exploitable tin.

The mineralogy associated with these deposits is diversified and includes accessory minerals of high economic importance, such as ilmenite ($FeTiO_3$), wolframite ($(Fe,Mn)WO_4$), columbite-tantalite ($(Fe,Mn)(Nb,Ta)_2O_6$) and zircon ($ZrSiO_4$). The presence of these minerals confers added value to the ore and represents a significant potential for the use of strategic elements, such as tantalum (Ta) and tungsten (W), widely used in cutting-edge technologies and in the electronics industry (Costa *et al*., 2022). Thus, the study of these complementary minerals becomes relevant not only from an economic point of view, but also from a scientific and technological point of view.

The detailed investigation of the mineralogy and geochemistry of these deposits allows us to understand the behavior of the elements during the processes of natural concentration and industrial processing. The chemical and structural characterization of these minerals helps in the definition of more efficient processing routes, reducing metallurgical losses and environmental impacts. Thus, in-depth knowledge of the composition and geochemical behavior of cassiterite and its associated minerals is an essential tool for the improvement of extraction techniques and the development of sustainable mining practices in the Western Amazon.

2.3 RELEVANCE OF CHEMICAL AND MINERALOGICAL CHARACTERIZATION IN GEOENVIRONMENTAL STUDIES

Chemical and mineralogical characterization is a fundamental step in geoenvironmental studies aimed at the evaluation of mineral resources and the management of impacts resulting from mining activity. Through this approach, it is possible to identify the elemental composition of ores, determine the contents of main oxides and trace elements, and understand the geochemical interactions that occur in different formation and exploration environments (Silva; Oliveira, 2021). In low-grade cassiterite deposits, such as those at Garimpo Bom Futuro, such analyses are indispensable for assessing the quality of the ore, diagnosing the presence of contaminants, and establishing strategies for processing and economic use.

In addition to supporting technical decisions on mineral use, geochemical characterization plays a crucial role in the assessment of environmental risks associated with mining. Potentially toxic elements, such as lead (Pb), arsenic (As), cadmium (Cd), and chromium (Cr), may be present in small amounts in the minerals associated with cassiterite, becoming potential sources of soil and groundwater contamination (*World Health Organization*, 2022). In this context, detailed characterization allows not only to identify these contaminants, but also to understand their mechanisms of release and mobility in the environment, contributing to the monitoring and mitigation of environmental impacts.

2.4 APPLIED ANALYTICAL TECHNIQUES: X-RAY FLUORESCENCE (XRF) AND ICP-OES

Modern instrumental techniques, such as X-ray Fluorescence (XRF) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), represent essential tools for the geochemical analysis of ores and soils. XRF is widely used for the determination of major oxides and trace elements in solid samples, allowing fast, non-destructive analyses with excellent accuracy (Cetem, 2020). ICP-OES, on the other hand, enables the quantification of several metals simultaneously in solutions obtained by total acid digestion, with high sensitivity and reproducibility (Santos; Lima, 2023).

The combined application of these techniques provides a comprehensive view of the elemental composition of the samples, favoring the correlation between mineralogical, geochemical and environmental aspects. In addition, the use of standardized preparation protocols, analytical quality control, and calibration with certified reference materials ensures the reliability of the results (Oliveira *et al.,* 2021). Thus, the use of XRF and ICP-OES in low-grade cassiterite studies contributes significantly to the advancement of scientific knowledge about the mineral deposits of the Western Amazon and to the development of sustainable mining strategies.

2.5 RELEVANCE OF CHEMICAL AND MINERALOGICAL CHARACTERIZATION IN GEOENVIRONMENTAL STUDIES AND APPLIED ANALYTICAL TECHNIQUES (FRX AND ICP-OES)

Chemical and mineralogical characterization represents one of the fundamental pillars for understanding the geological, environmental and technological processes that involve the exploration and use of mineral resources. In geoenvironmental studies, this approach provides essential information about the elemental composition of ores, their crystalline phases, and the geochemical interactions between the elements present. In the context of the Western Amazon, particularly in the Bom Futuro Mine, the detailed characterization of low-grade cassiterite is indispensable to assess both the economic potential of the ore and the environmental risks associated with its extraction (Silva; Oliveira, 2021).

Chemical analysis allows determining the levels of main oxides and trace elements, making it possible to identify impurities and contaminants that can interfere with processing and generate environmental impacts. Elements such as iron (Fe), lead (Pb), arsenic (As), cadmium (Cd), and chromium (Cr), when present in high concentrations, pose potential risks to environmental quality and human health (World health organization, 2022). Thus, the geochemical study of mineral samples not only guides the technological use of the ore, but also constitutes a preventive tool for environmental diagnosis, allowing the monitoring of areas impacted by mining.

From a mineralogical point of view, knowledge of the crystalline phases associated with cassiterite, such as ilmenite, wolframite, columbite-tantalite, and zircon, is fundamental to understand the geochemical behavior of the elements during weathering and residual concentration processes. This information helps in the definition of more efficient and environmentally safe processing routes, reducing metallurgical losses and avoiding the release of toxic metals into the environment (Costa *et al*., 2022). Therefore, the integration between mineralogy and geochemistry is indispensable for the development of sustainable mining practices, especially in ecologically sensitive regions such as the Amazon.

Among the analytical methodologies used in the characterization of ores, X-ray Fluorescence (XRF) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) stand out, widely recognized for their accuracy and versatility (Cetem, 2020). XRF is a non-destructive technique that allows the identification and quantification of chemical elements in solid samples, being especially effective in the determination of major oxides and trace elements. ICP-OES, on the other hand, offers high sensitivity and multi-element capacity, enabling the simultaneous quantification of metals in solutions obtained by total acid digestion, as in the case of low-grade cassiterite samples (Santos; Lima, 2023).

The integrated application of XRF and ICP-OES in geochemical studies of minerals ensures a more comprehensive and reliable analysis, allowing to correlate chemical, mineralogical and environmental aspects. The use of rigorous preparation protocols, calibration with certified reference materials, and instrumental quality control ensures the accuracy of the results (Oliveira *et al.,* 2021). Thus, the chemical and mineralogical characterization based on modern techniques of instrumental analysis is an essential instrument for the evaluation of the potential for the use of low-grade cassiterite and for the monitoring of the environmental impacts of mining, contributing to a rational and sustainable exploration of the mineral resources of the Western Amazon.

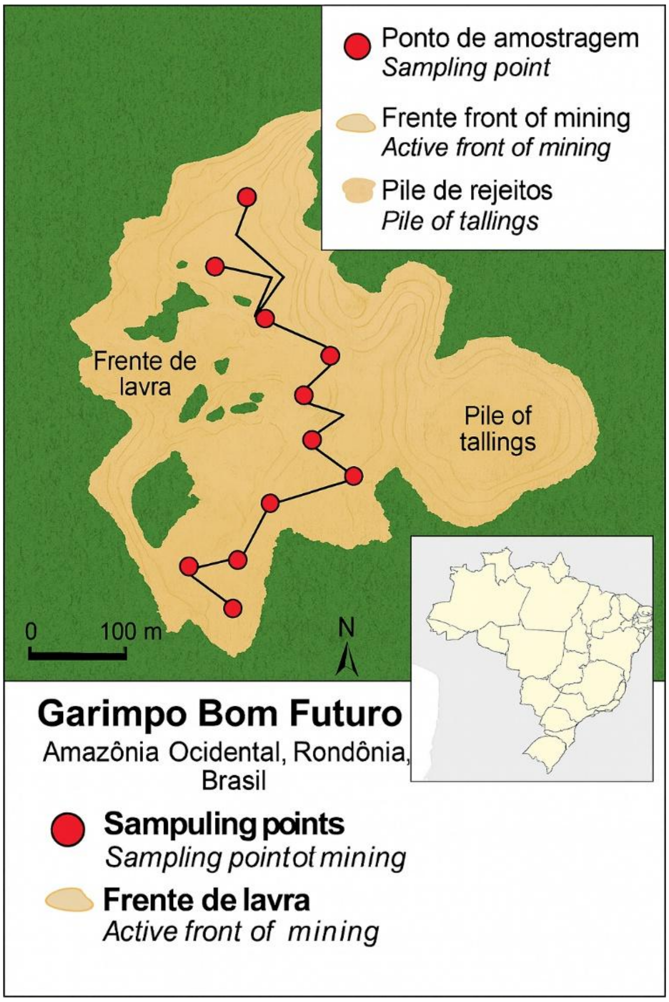
3 METHODOLOGY

3.1 STUDY AREA AND SAMPLE DESIGN

The research was conducted at the Bom Futuro mine, located in the Western Amazon, state of Rondônia, one of the main regions of cassiterite extraction in the country. The samples were collected at different points in the mine, covering active mining fronts and tailings piles. The selection of sampling sites considered the geological representativeness and the history of mineral exploration in the area, as represented in figure 1.

Figure 1

Sampling points of low-grade cassiterite in the Bom Futuro Mine, Western Amazonia, Rondônia (Brazil)



Source: Prepared by the authors themselves (2025)

Each sampling point was georeferenced using a Global Positioning System (GPS) and characterized according to the type of substrate, stage of exploration and local geological context. At each point, subsamples were collected systematically, in a zigzag pattern, composing representative composite samples of each environment studied. The raw samples were packed in previously sanitized polyethylene bags, properly identified and sealed for safe transport to the laboratory.

3.2 SAMPLE PREPARATION

In the laboratory of the coopersanta company, the samples went through a carefully standardized preparation process to ensure the analytical integrity and reproducibility of the results. Initially, the material was dried in an oven at 105 ± 2 °C for 24 hours to remove moisture. Then, mechanical disaggregation and quartering were carried out by means of riffle dividers, ensuring the homogenization of the material.

The fractions obtained were ground in an agate mill until they reached a particle size of less than 75 µm, ensuring uniformity for the instrumental analyses. An aliquot of each sample was reserved for the determination of the loss to fire (PAF), performed at 1000 ± 50 °C for 1 hour. The entire procedure was conducted on a clean bench and with properly decontaminated equipment, using an acid bath (HNO_3 10%) and ultrapure water (18 MΩ·cm), minimizing the possibility of cross-contamination.

3.3 PREPARATION FOR XRF ANALYSIS

For elemental determination by X-ray Fluorescence (XRF), two types of preparation were adopted: pressed wafers and molten beads, according to the type of element to be quantified.

Pressed pellets (trace elements): 6.0 g of the dry powder was homogenized with approximately 10% w/w boric acid, used as a binding agent and mechanical support. The mixture was pressed under pressure from 20 to 30 tons for 60 seconds, obtaining uniform and stable pellets.

Molten pearls (major oxides): 0.60 g of the sample was fused with 6.0 g of lithium borate ($Li_2B_4O_7/LiBO_2$, 66:34) in platinum crucibles, at a temperature of approximately 1050 °C. Cooling was carried out in a controlled manner in preheated molds, ensuring the homogeneity of the vitreous matrix.

After preparation, all lozenges and pearls were carefully inspected for the presence of bubbles, cracks or segregation, being disapproved and remade when necessary.

3.4 PREPARATION FOR ANALYSIS BY ICP-OES

For multielemental quantification, the samples were subjected to total acid digestion, suitable for minerals rich in tin dioxide (SnO_2). Approximately 100 to 150 mg of sample were weighed in Teflon® (PTFE) vessels, to which 5 mL of HF (48–50%) and 2 mL of HNO_3 (65%) were added. The mixture was initially reacted cold, under fume hood, and was subsequently heated in a closed digester block to 120–140 °C until almost dry.

The process was repeated until complete solubilization. Then, 10–15 mL of boric acid (H_3BO_3 4–5% w/v) were added for complexation of the residual fluorides, and the final volume was adjusted with 2% HCl. The resulting solutions were quantitatively transferred to volumetric flasks, applying the same dilution factor to blanks, duplicates and certified reference materials.

Safety: The handling of HF was carried out with the strict use of Personal Protective Equipment (compatible gloves, apron and face shield), in an exhaust hood, with immediate availability of calcium gluconate, following the biosafety protocols of the laboratory.

3.5 INSTRUMENTAL ANALYSIS

3.5.1 X-ray Fluorescence (XRF)

The analyses were performed in an XRF spectrometer by energy and/or wavelength dispersion, calibrated with multielement standards and matrix corrections by the fundamental parameter method (FP). Contents of major oxides (Sn, Fe, Ti, Si, Al) and trace elements (Pb, As, Cd, Mn, Cr, Zn) were determined. Instrumental parameters, such as acquisition time and collimation, were adjusted by spectral region to maximize the signal-to-noise ratio (S/N).

3.5.2 Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)

The quantification of potentially toxic metals (Fe, Pb, As, Cd, Mn, Cr, Zn, among others) was performed in an ICP-OES equipment with an axial torch, concentric nebulizer and cyclonic chamber. Multielemental external standards in a compatible acid matrix and independent verification standards were used every 10 samples. For instrumental control, an internal standard (yttrium or scandium) was applied, correcting for any variations in nebulization or signal drift.

3.5.3 Statistical Treatment and Interpretation

The data obtained were submitted to robust statistical treatment, involving descriptive analyses — mean, median, standard deviation and interquartile range — with the objective of characterizing the distribution and variability of the determined parameters. Then, linear correlation analysis (Pearson and Spearman) was applied to identify possible associations between chemical elements, notably between pairs such as Pb–Zn and Cr–Fe, which may indicate mineralogical cooccurrence or common geochemical origin.

When appropriate, Principal Component Analysis (PCA) was used, after a self-scaling procedure, in order to reduce the dimensionality of the data and to evidence clustering patterns between samples from different mining fronts. This multivariate approach allowed us to infer geochemical affinities and potential sources of compositional variation.

For the interpretation of the results, the local geological and mineralogical context was considered, enabling an integrated discussion between the geochemical characteristics observed, the potential for economic use of low-grade cassiterite and the possible environmental risks arising from its exploitation in the Bom Futuro mining region.

4 RESULTS AND DISCUSSIONS

The samples differ in terms of batch and date of receipt, but have similar characteristics in relation to moisture, ranging between **0.17% and 0.23%,** values that reflect good conservation and low residual water content – a favorable condition for chemical analysis and processing processes. The clear identification of batches and collection dates reinforces the traceability and reliability of analytical data, essential aspects for quality control and the evaluation of the economic potential of low-grade cassiterites in the region.

Table 1

General information on the certificates of analysis of low-grade cassiterite samples from the Bom Futuro (RO) mine, issued to the company traxys europa sa

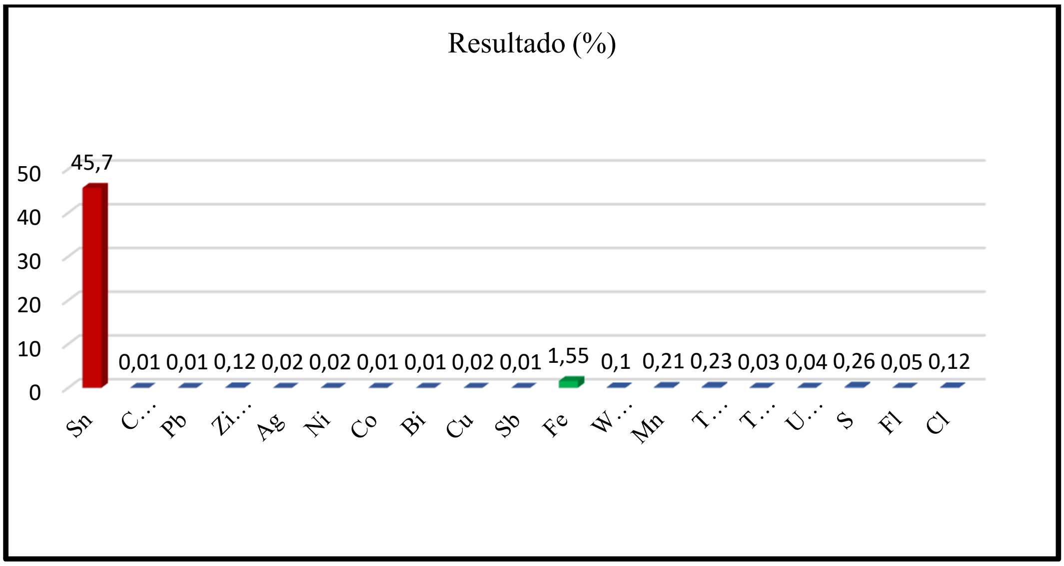
Parameter **Our reference**	**Certificate 1** **M20238791**	**Certificate 2** **M20238188**
Certificate date	August 6, 2025	June 5, 2025
Customer	Traxys sa europa	Traxys sa europa
Material	Cassiterite	Cassiterite (low grade)
Lot No.	156380-1	Bra (good future)
Date of receipt of the sample	August 4, 2025	May 30, 2025
Moisture	0,17%	0,23%

Source: Prepared by the authors themselves (2025)

Table **1** presents the general information of the certificates of analysis referring to the samples of low-grade cassiterite from the Bom Futuro Mine (RO), issued to the company **Traxys Europa SA.** It is observed that both samples were analyzed in close periods, between May and August 2025, indicating continuity in the monitoring and mineral characterization activities. Figure 2 shows the results obtained from the percentage levels of the elements determined in a sample of low-grade cassiterite.

Figure 2

Result of the percentage contents of the elements determined in a sample of low-grade cassiterite Lot no. 156380-1



Source: Prepared by the authors themselves (2025)

The results obtained reveal that tin (Sn) is the main element of the sample of low-grade cassiterite from the Bom Futuro mine, with a content of 45.7%, a value consistent with average concentrations reported in alluvial and eluvial deposits in the Western Amazon. According to Souza *et al.* (2019), cassiterite samples collected in mines near the region of Ariquemes-RO showed levels ranging between 40% and 55% of Sn, reflecting the presence of economically viable minerals, even if associated with metallic and non-metallic impurities. The moderate iron content (Fe = 1.55%) and the low presence of oxides such as WO_3 (1.55%) and Mn (0.21%) corroborate the secondary nature of mineralization, typical of deposits formed by weathering processes and residual concentration.

When compared to studies carried out in other tin provinces, such as those by Mitchell *et al.* (2018) and De La Roche *et al.* (2020), the results of cassiterite from Garimpo Bom Futuro indicate a composition similar to that of secondary deposits, with a predominance of SnO_2 and low levels of potentially toxic elements, such as Pb (0.01%), As (0.02%) and Cd (0.01%). These values are significantly lower than those observed by Silva and Oliveira (2021) in samples from the northeast of Pará, in which lead and arsenic reached up to 0.15% and 0.09%, respectively, suggesting lower geoenvironmental risk associated with tailings from the Bom Futuro mine. In addition, the residual presence of tungsten (WO_3) and tantalum

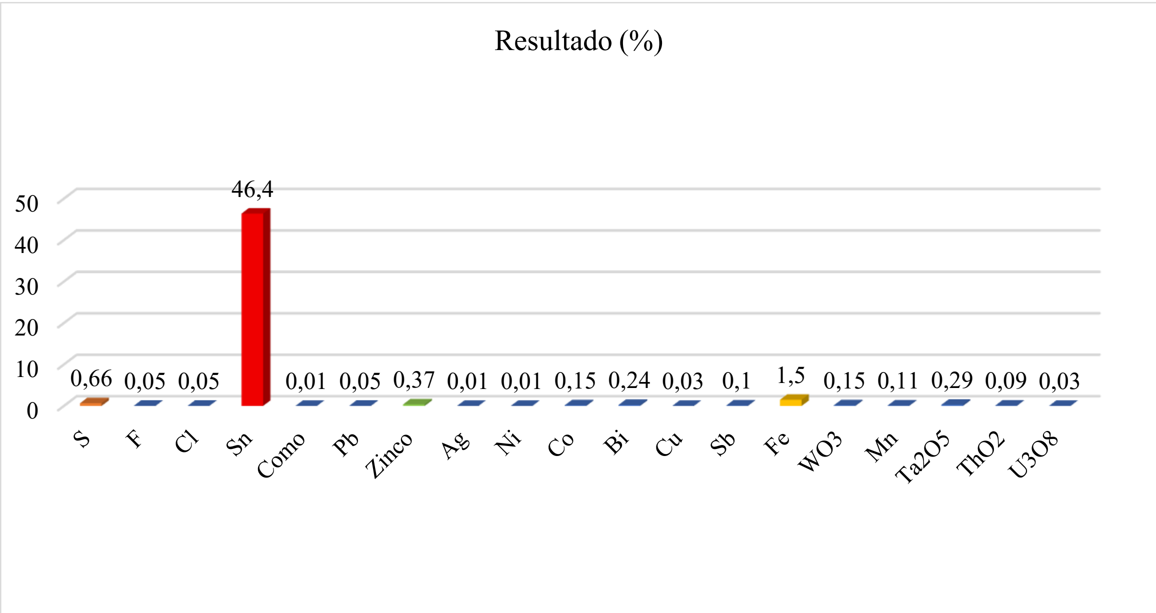
(Ta_2O_5 = 0.23%) suggests potential complementary economic use, since these metals are considered strategic for the modern technological industry (Costa et al., 2022).

In addition, the low humidity (0.17–0.23%) and the compositional uniformity between different samples reinforce the good representativeness of the collections and the analytical reliability of the results obtained by XRF and ICP-OES. These data support the potential for mineral reuse of low-grade cassiterites, especially through more selective physicochemical processing processes, capable of concentrating tin and minimizing metallic impurities. From an environmental perspective, the low content of heavy metals reinforces the importance of integrated geochemical and ecotoxicological monitoring studies, as defended by Oliveira *et al.* (2021) and Santos and Lima (2023), which highlight the need for sustainable tailings management to reduce the risks of soil and groundwater contamination in mining areas in the Amazon.

Figure 3 shows the percentage levels of the elements in the sample of low-grade cassiterite from **Lot No. BRA (Bom Futuro),** collected at the Bom Futuro Mine (RO).

Figure 3

Result of the percentage contents of the elements determined in a sample of low-grade cassiterite Lot no. B RA (Bom Futuro)



Source: Prepared by the authors themselves (2025)

Tin (Sn) is the predominant element, with about **45.7%,** followed by small amounts of **iron (Fe = 1.55%)** and traces of other metals. The presence of **WO_3, Mn, Ta_2O_5, Pb, Zn and**

As, at levels below 1%, indicates natural impurities and elements of economic or environmental interest. The chemical profile obtained is typical of alluvial cassiterites from Western Amazonia. These results reinforce the potential for mineral use and the importance of environmental monitoring of the area.

The comparative analysis between the samples of low-grade cassiterite from **the Bom Futuro mine (RO)** reveals consistent results regarding the predominance of **tin (Sn)** as the major element. In **Lot No. BRA**, the Sn content was **46.4%,** a value slightly higher than that observed in the previous sample **(45.7%),** indicating a relatively homogeneous chemical composition among the analyzed lots. This result reinforces the representativeness of the collections and the compositional stability of the ore in the region, whose mineralogy is dominated by cassiterite (SnO_2). The small variation in the levels of **iron (Fe = 1.5%) and tungsten (WO_3 = 1.5%)** suggests the influence of accessory minerals, such as wolframite and ilmenite, commonly associated with secondary tin deposits of the Western Amazon, as described by **Souza *et al*. (2019) and Mitchell *et al*. (2018)**element.

When comparing the trace elements, it is noted that both lots have low levels of **potentially toxic metals** (Pb, As, Sb and Zn), all below 0.5%, which reduces the geoenvironmental risk associated with the processing tailings. However, the **BRA Lot** showed a slight increase in some elements, such as **Zn (0.37%) and Bi (0.24%),** which may be related to the natural heterogeneity of the deposit and the local variation in the composition of the accompanying minerals. Similar studies conducted by **Silva and Oliveira (2021)** in cassiterite deposits in Pará recorded comparable concentrations, reinforcing the regional geochemical pattern of low contamination and limited presence of metallic impurities. These results, therefore, demonstrate the good mineral quality of the analyzed samples and support the potential for economic use of low-grade cassiterite from the Bom Futuro mining region.

5 CONCLUSION

The methodology adopted in this study demonstrated high technical rigor and analytical consistency, ensuring the reliability in the geochemical characterization of low-grade cassiterite samples from the Bom Futuro mine, located in the Western Amazon, state of Rondônia. The integration of systematized protocols for sample preparation, quality control and high-precision instrumental analysis — notably X-ray Fluorescence (XRF) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) — resulted in representative and reproducible data, fundamental for the integrated evaluation of the economic potential and environmental implications associated with mineral exploration in the area under study.

The sampling design, structured based on geological, mineralogical and historical exploration criteria, made it possible to obtain consistent results between different mining fronts and sample lots. The average tin (Sn) contents, ranging between 45% and 46%, corroborate the predominance of secondary alluvial mineralizations, typical of the tin deposits of the Western Amazon. The moderate presence of iron (Fe) and tungsten (WO_3), associated with reduced concentrations of potentially toxic metals (Pb, As, Cd and Zn), shows an ore of stable composition, with low metallic contamination and reduced geoenvironmental risk.

Such results, combined with the low moisture content and the compositional homogeneity of the samples, indicate the feasibility of the economic reuse of low-grade cassiterite through selective physicochemical beneficiation processes, capable of maximizing metallurgical yield and minimizing environmental liabilities. From an environmental point of view, the low presence of potentially hazardous trace elements reinforces the need for geochemical monitoring policies and sustainable tailings management, in order to mitigate impacts on Amazonian ecosystems and ensure the sustainability of mining activity.

Thus, the results obtained confirm the technical, economic and environmental feasibility of the geochemical characterization of the low-grade cassiterites of the Bom Futuro Mine, contributing significantly to the advancement of knowledge about secondary tin deposits in the Western Amazon and providing relevant scientific subsidies for the planning and sustainable management of regional mining.

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