Rare Earth Elements in Bahia, Brazil: Potential for Global Production

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Rare earth elements (REE) are critical for modern technologies, especially in driving the global energy transition. Brazil, with substantial investments in the state of Bahia, has emerged as a key player in the global REE reserves. This study evaluates the presence of REE in sediments collected from Novo Horizonte, Bahia, to explore their potential for future exploitation. Sediment samples were processed using the USEPA3051A digestion method, followed by centrifugation and analysis via inductively coupled plasma optical emission spectrometry (ICP OES). The analysis revealed significant concentrations of REE, particularly cerium, neodymium, and yttrium. These results highlight Bahia's strategic importance in contributing to global REE production and supporting a sustainable, technology-driven economy.

Keywords: Rare Earth Elements (REE). Sustainability. Energy Transition.

Rare earth elements (REE) are vital components in many advanced technologies, particularly those driving the transition to renewable energy. According to the International Energy Agency, the demand for REE is projected to increase three to seven times by 2040 [1].

REEs are indispensable in applications such as catalysts, alloys, polishing compounds, phosphors, nuclear reactors, permanent magnets, key components of wind turbines, and electric vehicle motors. Growing demand for these technologies has elevated the importance of elements such as Praseodymium (Pr), Neodymium (Nd), Terbium (Tb), and Dysprosium (Dy) [2]. To meet the requirements of the 2016 Paris Agreement, REE demand would need to quadruple, emphasizing the urgency of exploring new ore deposits [3]. Despite their name, REEs are not exceptionally rare; some are more abundant in the earth's crust than copper (Cu) [4]. These elements occur in two main deposit types:

- Primary deposits are formed through magmatic-hydrothermal processes.
- Secondary deposits result from weathering and sedimentary processes.

Commonly exploited minerals include monazite and bastnaesite while emerging sources such as eudialyte and steenstrupine are investigated in regions like Greenland and Sweden [5].

REE can be obtained through three primary methods:

- Primary extraction: Mining directly from ore deposits.
- Recovery from secondary sources: Recycling from end-of-life electronics.
- Extraction from unconventional sources: Utilizing industrial waste, including coal ash and mine tailings [1].

Global Production and Supply Chain

China dominates global production, accounting for ~70% of rare earth oxide (REO) production, followed by the United States (14%) and Australia (4%) [6]. Beyond production, China leads in processing, handling approximately 85% of the global market, followed by Malaysia and

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Estonia. In 2020 China consumed 150,000 tons of REOs, leading global demand, followed by Japan, the United States, and the European Union [7].

In 2023, the United States imported $190 million worth of REE compounds and metals, a 7% decline from $208 million in 2022 [6]. As clean energy technologies and decarbonization initiatives expand, the demand for REE is expected to grow significantly [8]. This increase has driven the development of new exploration and processing projects worldwide to ensure a stable supply chain for these critical elements [9].

Brazil's Role in REE Reserves

Brazil holds approximately 15% of the world's REE reserves, ranking as the third-largest reserve globally with 21 million tons [6,10-12]. Notable reserves are distributed across regions such as:

- Araxá, Poços de Caldas, and Tapira (Minas Gerais).
- Jacupiranga (São Paulo).
- Catalão and Itapirapuã (Goiás).
- Pitinga Mine (Amazonas).
- Minaçu and Montividiu do Norte (Goiás) [12].

Other regions, including São Gonçalo do Sapucaí (Minas Gerais) and São Francisco de Itabapoana (Rio de Janeiro), also contain smaller REE deposits. Protected areas, such as Morro dos Seis Lagos (Amazonas) and Serra do Repartimento (Roraima), hold significant potential, but legal restrictions have hindered exploration [12].

Substantial investments have recently been directed towards Bahia, especially in the regions of Jequié [13-16] and Novo Horizonte, where promising REE deposits have been identified [17].

This study aims to analyze and characterize the presence of REE in sediment samples collected from Bahia, Brazil. Using inductively coupled plasma optical emission spectrometry (ICP OES), the research assesses their potential for economic exploitation and examines their geological distribution.

Materials and Methods

The research comprised three main stages: (i) soil sample collection, (ii) sample preparation, and (iii) sample characterization using ICP OES (Inductively Coupled Plasma Optical Emission Spectrometer). The iCAP PRO XP model from Thermo Fisher Scientific (Waltham, Massachusetts, USA) was utilized.

Soil Sample Collection

Soil samples were collected from the Novo Horizonte region in Bahia. Due to confidentiality constraints, the precise coordinates of the sampling locations are not disclosed. The sample collection followed the ABNT NBR 6457 standard [18], involving the removal of representative soil portions via scraping or excavation, which resulted in altered natural compactness and consistency.

Ten sediment samples, each weighing approximately 3 kg, were collected. These samples were packed in heavy-duty plastic bags and labeled with external and internal identifiers. The internal labels were enclosed in a protective plastic envelope and included details such as the collection location, date, and depth.

Sample Preparation

Sample digestion was performed using a microwave digestion system (Ethos A, Milestone, Italy) based on the USEPA3051A method [19]. Approximately 0.5 g of dried soil was weighed, and 9 mL of HNO_3 (69% v/v) and 3 mL of HCl (37% v/v) were added. The digestion protocol involved heating the mixture for 5.5 minutes to 175°C, maintaining this temperature for an additional 4.5 minutes. After cooling to room temperature, the digested sample was transferred to a 50 mL Falcon tube, diluted with ultra-pure water to a final volume of 40 mL, and centrifuged for 10 minutes at 4000 RPM. Blanks and a certified reference material (Buffalo River Sediment, NIST 8704) underwent identical procedures to ensure analytical accuracy.

Sample Characterization

Samples were analyzed using an ICP OES equipped with the following features:

- Concentric nebulizer connected to a cyclonic chamber.
- Vertical torch.
- Echelle polychromator.

Charge injection device (CID) matrix detector. The operating parameters for the ICP OES included:

- Radiofrequency power: 1.25 kW.
- Plasma gas flow: 12.5 L/min.
- Auxiliary gas flow: 0.50 L/min.
- Carrier gas flow: 0.50 L/min.
- Exposure duration: 20 seconds.
- Viewing orientation: Axial.

The following elements and their spectral lines (in nm) were analyzed:

- Atomic emission lines (I): As I (189.042), Si I (288.158).
- Ionic emission lines (II): Ba II (455.403), Cd II (214.438), Ce II (404.076), Co II (228.616), Cr II (283.563), Dy II (353.170), Er II (337.271), Eu II (412.970), Gd II (342.247), La II (412.323), Lu II (261.542), Mn II (257.610), Nd II (401.225), Ni II (231.604), Pb II (220.353), Pr II (422.535), Sc II (361.384), Sm II (360.949), Sr II (407.771), Tb II (350.917), Th II (283.231), Ti II (334.941), Tm II (342.508), V II (292.402), Y II (371.030), Yb II (369.419), Zr II (339.198).

The high-purity argon gas (99.999%) supplied by White Martins (São Paulo, SP, Brazil) was used during the analysis. Calibration curves for the ICP OES were constructed using 1000 mg/L CPA CHEM multi-element standards containing 17 rare earth elements from Aluretec®.

Detection Limits (LOD) and Quantification Limits (LOQ)

The background equivalent concentration (BEC) and signal-to-background ratio (SBR) were employed to calculate the limits of detection and quantification. The BEC was calculated using:

BEC=CstandardSBR,where SBR=Istandard−IblankIblank.\text{BEC} = \frac{\text{C}_{\text{standard}}}{\text{SBR}}, \quad \text{where} \, \text{SBR} = \frac{\text{I}_{\text{standard}} - \text{I}_{\text{blank}}}{\text{I}_{\text{blank}}}.
BEC=SBRCstandard,whereSBR=IblankIstandard−Iblank.

Here, Cstandard is the reference element concentration, and Istandard and Iblank are the emission intensities of the standard and blank solutions, respectively.

The LOD and LOQ were calculated as follows:

LOD=3×RSDblank×BEC100,LOQ=10×RSDblank×BEC100,\text{LOD} = \frac{3 \times \text{RSD}_{\text{blank}} \times \text{BEC}}{100}, \quad \text{LOQ} = \frac{10 \times \text{RSD}_{\text{blank}} \times \text{BEC}}{100},LOD=1003×RSDblank×BEC,LOQ=10010×RSDblank×BEC,
where RSDblank represents the relative standard deviation of blank solution emission intensity measurements.

Results and Discussion

The results of the characterization of soil samples from the Novo Horizonte-BA region are expressed in $\mu g\ g^{-1}$ and summarized in Table 1. The accuracy of the experimental data was assessed and confirmed by analysis of the certified reference material Buffalo River Sediment - NIST 8704. The results obtained were consistent with the certified values at a 95% confidence level, attesting to the reliability and suitability of the methodology for determining rare earth elements (REE).

Quantification and Comparison with Clarke Values

The study quantified 29 elements across 10 sediment samples. Each sample was analyzed in triplicate, with each element's mean and standard deviation calculated and presented. The concentrations of REEs found in the samples were compared with Clarke values, representing the average abundance of these elements in the earth's

Table 1. Quantification of 29 elements in 10 samples with mean and standard deviation.

Analyte	LOD ($\mu g\ g^{-1}$)	LOQ ($\mu g\ g^{-1}$)	Certified Value (NIST 8704) ($\mu g\ g^{-1}$)*	Value Found (NIST 8704) ($\mu g\ g^{-1}$)	Contents Found in the Samples ($\mu g\ g^{-1}$)	Abundance in Clarke's Table (ppm)
As	0.11	0.36	-	-	12.44±1.51	1.8
Cd	0.01	0.05	2.94±0.29	2.85±0.08	0.18±0.025	0.1
Ce	0.11	0.36	66.5±2.0	56.7±3.94	103.1±6.89	60
Co	0.34	1.14	13.57±0.43	16.8±1.26	87.11±5.96	25
Cr	0.31	1.02	121.9±3.8	114.7±7.79	13.3±1.48	100
Dy	0.05	0.15	-	-	6.53±0.39	3.5
Er	0.06	0.20	-	-	104.2±17.2	2.3
Eu	0.03	0.11	1.31±0.04	1.11±0.05	1.31±1.51	1.0
Gd	0.07	0.22	-	-	11.52±0.90	4.0
La	0.05	0.15	-	-	62.99±5.14	30
Lu	0.03	0.10	-	-	0.68±0.05	0.5
Mn	0.09	0.29	544±21	520±2.10	34.6±5.59	950
Nd	0.15	0.48	-	-	65.38±4.96	33
Ni	0.06	0.19	42.9±3.7	40.6±2.17	0.42±0.1	---
Pb	0.34	1.12	150±17	139±0.74	4.27±0.3	14
Pr	0.15	0.50	-	-	16.77±80.2	9.1
Si	0.11	0.35	-	-	108.1±13.2	---
Sm	0.15	0.51	-	-	6.73±0.5	6.0
Sr	0.04	0.13	-	-	4.95±2.84	375
Tb	0.17	0.55	-	-	1.6±0.13	0.9
Ti	0.08	0.25	-	-	145.7±25.8	---
Tm	0.09	0.29	-	-	1.20±0.19	0.3
V	0.04	0.12	94.6±4.0	96.9±3.76	4.13±0.28	70
Y	0.03	0.08	-	-	29.98±2.21	33
Yb	0.03	0.10	-	-	1.72±0.16	2.8
Zr	0.09	0.31	-	-	36.76±2.75	165

crust. Clarke values are important in economic geology to identify anomalous concentrations and guide resource exploitation strategies [20, 21].

Significant REE Findings

The analysis revealed substantial concentrations of key rare earth elements, including:

- Cerium (Ce): 70.95 µg/g
- Neodymium (Nd): 25.50 µg/g
- Erbium (Er): 104.2 µg/g

These concentrations suggest a slight enrichment in REEs, which aligns with the region's geological characteristics. The lithology, dominated by peralkaline rocks saturated in silica, is naturally enriched in REEs [22]. Additionally, the high concentrations may partially result from anthropogenic sources.

Applications and Industrial Relevance

The significant presence of cerium, neodymium, and yttrium is particularly notable due to their critical roles in modern industries, including:

- Permanent magnets for renewable energy technologies, such as wind turbines and electric vehicle motors.
- Catalysts used in industrial processes.
- Phosphors for energy-efficient lighting and displays.

These findings underscore the potential of the Novo Horizonte region as a strategic resource for rare earth elements, essential for advancing clean energy and high-tech applications.

Environmental and Economic Implications

REEs in sediment samples offer valuable insights for environmental monitoring and sustainable resource management. Future exploration and exploitation strategies must consider balancing economic development with environmental preservation.

Method Validation

The methodology employed, including microwave digestion and ICP OES analysis, demonstrated robustness and reliability. The alignment of results with the certified reference material (NIST 8704) further confirms the accuracy of the analytical approach. This validation ensures confidence in the findings and supports the method's applicability for future studies.

Conclusion

The analysis of sediment samples from the Novo Horizonte region in Bahia revealed significant concentrations of rare earth elements (REE), underscoring the importance of these deposits for future exploration in Brazil. The methodology employed, including microwave digestion and ICP OES analysis, proved effective and reliable for precisely determining these elements. The results contribute to a deeper understanding of the distribution of REE resources in the region, providing valuable insights for geological studies and resource management.

Given the growing global demand for clean technologies and renewable energy solutions, the data presented in this study point to a promising scenario for the sustainable development of REE reserves in Bahia. These resources are critical for various industrial applications, including electric vehicles, wind turbines, and other technologies driving the global energy transition. The findings highlight the potential of the Novo Horizonte region as a strategic source of REEs and contribute to efforts to ensure a balanced and sustainable approach to mineral extraction in the face of increasing environmental and economic challenges.

In conclusion, significant REE concentrations in Bahia present both an opportunity and a responsibility for sustainable exploitation, positioning Brazil as an important player in the global transition to clean energy and technological advancement.

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