

Geochemical analysis of U-nat, ^{210}Pb , and the isotopes ^{226}Ra and ^{228}Ra in soils of the Lagoa Real Uranium Province (Bahia, NE Brazil)

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Abstract. The Lagoa Real Uraniferous Province, located between Caetité, Lagoa Real, and Livramento de Nossa Senhora (BA), constitutes the largest uranium reserve in Brazil, with approximately 112,000 tons of U_3O_8 , and an average annual production of 300 tons. Its Archean and Paleoproterozoic rocks, rich in mineralized albitites, constitute an important natural source of radiation, generating geochemical anomalies that are potentially harmful to the environment and human health. This study aimed to correlate the geochemical behavior of uranium (U), lead-210 (^{210}Pb), and radium ($^{226}\text{Ra}/^{228}\text{Ra}$) in soils in the region, aiming to understand their distribution, interrelationships, and geoenvironmental implications. Twenty samples were collected and analyzed at the Environmental Control Laboratory of INB/URA, using Liquid Scintillation Spectrometry and ICP-MS. The results were analyzed using linear regression (R^2) and spatial interpolation (IDW). A strong correlation was observed between U-nat, ^{210}Pb , and ^{226}Ra ($R^2 > 0.68$), indicating that their mobility depends on the mineralogical composition and soil pH. The highest concentrations occurred in clayey soils rich in iron oxides, particularly in the western portion of the study area. The

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radiogenic behavior of the isotopes suggests the influence of weathering and adsorption processes on the dispersion of radioelements. It is concluded that the Lagoa Real Complex presents significant geochemical anomalies, requiring continuous monitoring and public policies aimed at mitigating radiological and chemical risks in the region.

Keywords: Uranium; Radium; Lead; Soils; Lagoa Real Complex.

Resumo. Análise geoquímica do U-nat, ^{210}Pb e dos isótopos ^{226}Ra e ^{228}Ra nos solos da Província Uranífera de Lagoa Real (Bahia, NE Brasil). A Província Uranífera de Lagoa Real, localizada entre Caetité, Lagoa Real e Livramento de Nossa Senhora (BA), constitui a maior reserva de urânio do Brasil, com cerca de 112 mil toneladas de U_3O_8 e produção média anual de 300 t. Suas rochas arqueanas e paleoproterozóicas, ricas em albititos mineralizados, configuram uma importante fonte natural de radiação, gerando anomalias geoquímicas potencialmente danosas ao meio ambiente e à saúde humana. Este estudo teve como objetivo analisar correlacionalmente o comportamento geoquímico do urânio (U), chumbo-210 (^{210}Pb) e rádio ($^{226}\text{Ra}/^{228}\text{Ra}$) em solos da região, visando a compreender sua distribuição, interrelações e implicações geoambientais. Foram coletadas 20 amostras e analisadas no Laboratório de Controle Ambiental da INB/URA, utilizando Espectrometria de Cintilação em Meio Líquido e ICP-MS. Os resultados foram tratados por regressão linear (R^2) e interpolação espacial (IDW). Observou-se forte correlação entre U-nat, ^{210}Pb e ^{226}Ra ($R^2 > 0,68$), indicando que sua mobilidade depende da composição mineralógica e do pH do solo. As maiores concentrações ocorreram em solos argilosos e ricos em óxidos de ferro, na porção oeste da área analisada. O comportamento radiogênico dos isótopos sugere influência dos processos de intemperismo e adsorção na dispersão dos radioelementos. Conclui-se que a Província Uranífera de Lagoa Real apresenta anomalias geoquímicas significativas, exigindo monitoramento contínuo e políticas públicas voltadas à mitigação dos riscos radiológicos e químicos na região.

Palavras-chave: Urânio; Chumbo; Rádio; Solos; Província Uranífera de Lagoa Real.

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Introduction

This study refers to the Uranium Province of Lagoa Real, in the South-Central Region of the State of Bahia, Brazil (Caetité, Lagoa Real, and Livramento de Nossa Senhora) (Costa et al., 1985; IBGE, 2019), and investigates natural radioactivity and rock/soil interactions associated with uranium mining and other radionuclides. Uranium in soils originates from rocks, which, through weathering processes, transfer their minerals and chemical elements via the disaggregation and alteration of the parent rock. U concentrations in soil show strong spatial variability, controlled by lithology (e.g.,

granites, black shales, and phosphorites) and by supergene processes (Drever, 1997; Bonotto and Silveira, 2006; Kabata-Pendias and Pendias, 2011; IAEA, 2014).

The geological characterization of the region is associated with elongated albitites and geological shear zones of Archean and Paleoproterozoic rocks, including granites, gneisses, and metavolcanic rocks (Marinho and Oliveira, 1990; Cruz et al., 2007; Chaves, 2013).

In this context, uranium-enriched rocks emit ionizing radiation through both direct and indirect exposure pathways, with soils acting as an indirect pathway for dispersion (Martín et al., 2025). Geological and environmental indicators associated with the uranium series suggest that in the Lagoa Real Uranium Province there is characteristic mineralization, where uraninite and U-silicate minerals occur in albitites (albite > 70%) along shear zones, frequently associated with sodic metasomatism; alteration halos and fine disseminations are common (Marques et al., 2021; Mishra et al., 2024). Uranium-series disequilibria are also observed, as activity ratios of $^{234}\text{U}/^{238}\text{U}$, $^{230}\text{Th}/^{234}\text{U}$, and $^{231}\text{Pa}/^{235}\text{U}$ deviate from secular equilibrium, indicating recent uranium migration in groundwater, and are useful for tracing flow, recharge, and leaching in aquifers of uranium-bearing areas.

Mineralogical analysis of ore bodies shows that approximately 65%-70% of the rock consists of albite-plagioclase, 10%-20% pyroxene, 2.5% garnet, 2.5% epidote, 1.5% biotite, and 1%-2% carbonates (Scislewski et al., 2005). The ore paragenesis is characterized by uraninite + titanite + carbonate $\pm$ zircon, with uraninite filling voids between crystals and grains of titanite and albite. The presence of this mineralization is considered of significant national economic potential (Cruz et al., 2007). Uranium mineralization as uraninite (UO_2), which upon oxidation forms U_3O_8 , occurs through various geological processes that concentrate and transform the element under specific physical and chemical conditions.

Through weathering processes acting on uraninite, uranium and its decay products are gradually released into soil and groundwater (Drever, 1997; Choppin et al., 2002; Fuzikawa et al., 2011).

Exposure to natural radiation associated with radionuclides in the Earth's crust is mainly linked to elements of the uranium (^{238}U) and thorium (^{232}Th) series. Major exposure pathways include ingestion of radionuclides present in soil, water, and food, as well as inhalation of dust particles (Melo, 2009). According to Vasconcelos (2010), soils are one of the main sources of natural radiation, and their radioactivity depends on the geological conditions of each region.

The geochemical behavior of uranium in soils under oxidizing conditions is characterized by hexavalent uranium (UO_2^{2+} , uranyl ion), which is highly mobile and forms complexes with carbonates, phosphates, sulfates, and organic matter, increasing solubility. Under reducing conditions (water-saturated soils), uranium is reduced to tetravalent uranium (U^{4+}), precipitating as UO_2 (uraninite), which is chemically immobile. Retention and adsorption of UO_2^{2+} occur in clays, iron, aluminum, and manganese oxides, as well as organic matter (McBride, 1994; IAEA, 1996; Kabata-Pendias and Pendias, 2011).

Radium (Ra) tends to be adsorbed in clay-rich soils, especially under neutral to slightly acidic pH conditions. In highly acidic soils, however, adsorption is significantly reduced, favoring mobility (Greeman et al., 1999; Kabata-Pendias and Pendias, 2011; Carvalho et al., 2023). Although radium does not change oxidation state (always Ra^{2+}), redox conditions can influence the minerals to which it is adsorbed. For example, anoxic (oxygen-poor) soils may release metals bound to oxides, including radium (IAEA, 1996; Greeman et al., 1999; UNSCEAR, 2000; Dai et al., 2007; Kabata-Pendias and Pendias, 2011). The transport of radium (^{226}Ra and ^{228}Ra) in soil is influenced by several physical and chemical factors, including adsorption, leaching, ion exchange, and precipitation processes (IAEA, 2014).

Lead (Pb) exhibits low mobility in soils and is strongly adsorbed onto kaolinite clays, organic matter, and iron, aluminum, and manganese oxides. It may become more mobile in acidic soils (low pH) and in soils saturated with other cations (Ca^{2+} , Zn^{2+}). Although poorly mobile, it accumulates in the A horizon and in plants growing in contaminated soils with low calcium content, increasing the risk of bioaccumulation in organisms (McBride, 1994; Kabata-Pendias and Pendias, 2001; Alloway, 2013).

The soils of the study area are products of the local bedrock exposed in the region. Weathering processes mechanically and chemically disintegrate rocks, facilitating erosion and dispersion of material away from its source (Choudhuri, 1997). This process produces sediments in two ways: (i) resistant minerals derived from mechanical disintegration of the parent rock, and (ii) newly formed minerals resulting from chemical decomposition. Primary minerals transform into secondary minerals through weathering rather than converting directly into one another (Mason, 1971). Soils also include water and air. During soil formation, there is a decrease in Ca, Mg, Na, and K, and to a lesser extent Al and Fe, while Si may increase; thus, organic matter and clay minerals represent the most active soil fractions (Mason, 1971).

The mobility of uranium (U) and its radionuclides in environmental systems is a relevant topic for environmental and geoscientific sciences, particularly due to the potential contamination of soils and waters resulting from mining activities, ore processing, and waste disposal. Uranium geochemical behavior is controlled by physical, chemical, and biogeochemical processes that influence its speciation, solubility, and transport. Uranium generally occurs in oxidation states IV and VI, and their distribution is strongly controlled by Eh and pH conditions (Langmuir, 1997; Zänker et al., 2000).

Therefore, understanding the factors controlling uranium mobility in natural environments is essential for environmental risk assessment, monitoring impacted areas, and developing mitigation and remediation strategies for radioactive contaminants in soils.

The objective of this study is to analyze and geochemically correlate U, ^{210}Pb , and the isotopes ^{226}Ra and ^{228}Ra in the Uranium Province of Lagoa Real, in order to understand their distribution, interrelationships, and geoenvironmental implications.

The specific objectives are (a) to determine the concentrations of $^{\text{nat}}\text{U}$, ^{210}Pb , ^{226}Ra , and ^{228}Ra at 20 sampling points; (b) to evaluate their spatial distribution in soils using interpolation methods; (c) to analyze statistical correlations among radionuclides considering their mobility and interaction with the soil matrix; and (d) to discuss the environmental implications of their presence and geochemical behavior, especially regarding potential soil anomaly risks.

Studies on natural radioactivity in soils are of significant scientific importance, as this methodology allows quantification of one of the main pathways of dispersion and supports the development of control strategies and preventive measures to minimize environmental problems.

Materials and methods

This research was conducted in the Uranium Province of Lagoa Real, where 20 soil samples were collected (Figure 1). The sampling area selection followed the studies of Nogueira (2018), and sampling procedures followed IAEA Standard Operating Procedures (SOPs) (IAEA, 2020), at a depth of 20 cm. Samples were homogenized, quartered, and stored in properly labeled plastic bags (IAEA, 2020). The 20 samples (Figure 2), collected on April 14, 2022, were analyzed at the Environmental Control Laboratory of INB/URA. ^{226}Ra , ^{228}Ra , and ^{210}Pb were determined by co-precipitation with barium sulfate, with radiometric readings performed by Liquid Scintillation Spectrometry, while uranium determinations were performed by ICP-MS (Cruz et al., 2007b; Carvalho et al., 2022).



Figure 1. Uranium Province of Lagoa Real.

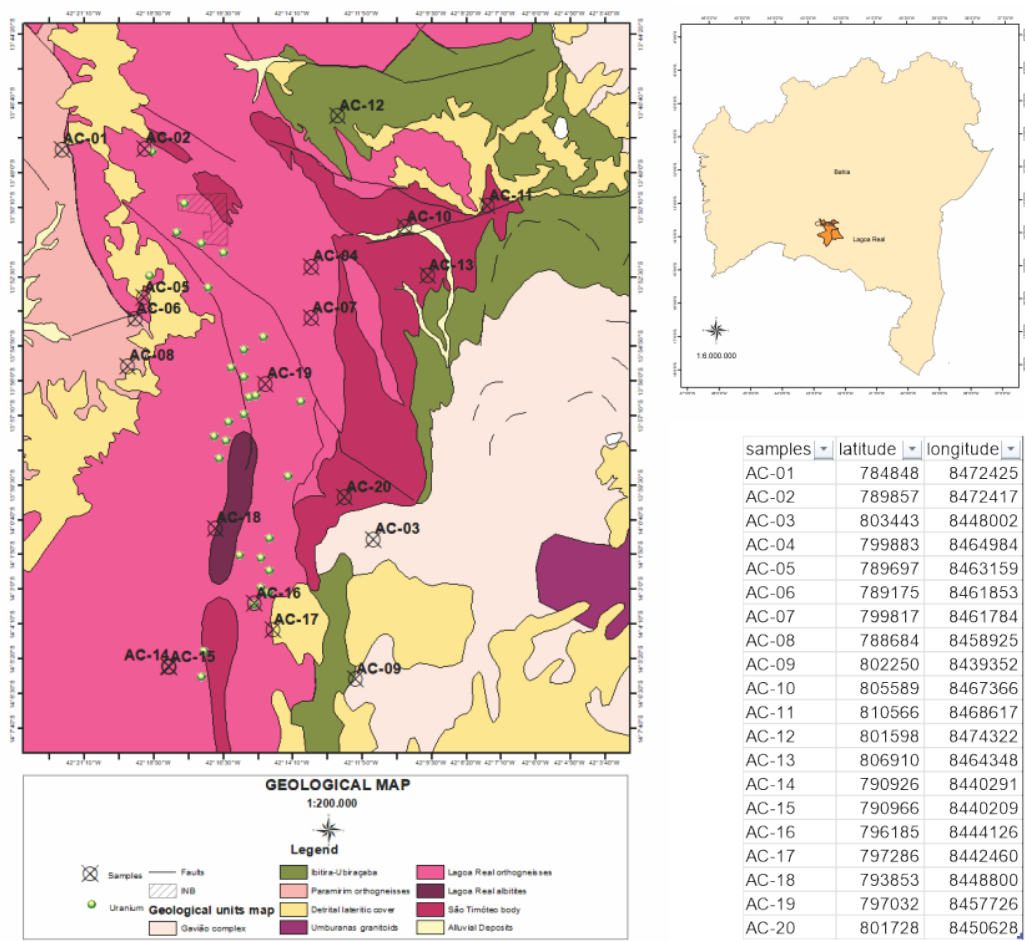


Figure 2. Geological map of the Uranium Province of Lagoa Real, modified from the Bahia Mineral Exploration Company (CBPM, 2006).

After sampling, ^{235}U samples underwent physicochemical preparation and instrumental analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), according to Porto et al. (2026). Samples were dried for 12 h in an oven (130 °C and 200 °C), cooled, weighed, and sieved (60 mesh), followed by microwave-assisted digestion using a MARS 6® system in two stages with temperature ramps up to 200 °C, without the need for H_3BO_3 due to reduced gelatinous residue formation. A Perkin Elmer NexION® 300X ICP-MS equipped with a collision cell was used. Analyses were conducted in no-gas and helium modes depending on the control of polyatomic interferences required for each matrix. Quantification was based on ^{238}U isotopes, converted to natural uranium (U-nat) according to isotopic abundances.

For ^{226}Ra , ^{228}Ra , and ^{210}Pb samples, preparation and analysis followed Medrado et al. (2026), including digestion, radiochemical separation, determination of chemical yield, preparation of extracts, and counting procedures. After decontamination and 24 h immersion in 10% (v/v) HNO_3 , followed by sequential rinsing with ultrapure water ($> 18.2 \text{ M}\Omega\cdot\text{cm}$), samples were digested using a mixture of HF (40%), HNO_3 (65%), and solid H_3BO_3 , adjusted to contain 2% (v/v) nitric acid. Carrier solutions of Ba^{2+} and Pb^{2+} (15 $\text{mg}\cdot\text{mL}^{-1}$) were added. Sequential separation of ^{226}Ra and ^{228}Ra was performed by controlled redissolution in 0.25 $\text{mol}\cdot\text{L}^{-1}$ EDTA at $\sim 90^\circ\text{C}$, followed by pH adjustment (4.0-4.5) to induce selective reprecipitation. The supernatant enriched in ^{210}Pb was collected for further processing. Measurements were performed using a Quantulus GCT 6200 liquid scintillation counter equipped with pulse shape analysis (PSA) and a BGO guard detector (Medrado et al., 2026).

Data were compared and interpreted using Excel-based linear correlation (R^2) graphs and spatial interpolation using the Inverse Distance Weighted (IDW) method, applied to estimate spatial distribution (Lu and Wong, 2008), through the ArcGIS 10.8 Geostatistical Analyst toolbox. ^{228}Ra could not be interpolated due to all results being $< 6.2 \times 10^{-9}$.

Results and discussion

The data were organized in Microsoft Excel (2020) with geographic coordinates in UTM, DATUM 23S (Table 1). Comparisons were performed using graphs and spatial interpolation to evaluate U, ^{210}Pb , and $^{226}\text{Ra}/^{228}\text{Ra}$ concentrations in each sample. Figure 3 presents the interpolation results, and the graphs are shown in Figure 4.

Table 1. Soil sample results for U, ^{210}Pb , and $^{226}\text{Ra}/^{228}\text{Ra}$.

Point	U-nat (Bq/kg)	U-nat (mg/kg)	Uncertainty U-nat (Bq/kg)	Uncertainty U-nat (mg/kg)	Ra-226 (Bq/kg)	Ra-226 (mg/kg)	Uncertainty Ra-226 (Bq/kg)	Uncertainty Ra-226 (mg/kg)	Pb-210 (Bq/kg)	Pb-210 (mg/kg)	Uncertainty Pb-210 (Bq/kg)	Uncertainty Pb-210 (mg/kg)	Ra-228 (Bq/kg)	Ra-228 (mg/kg)	Uncertainty Ra-228 (Bq/kg)	Uncertainty Ra-228 (mg/kg)
AC-01	250.2	9.9	23.8	0.9	172.83	4.7E-06	19.88	5.4E-07	99.52	6.0E-10	15.88	9.5E-11	169.92	1.7E-09	21.8	2.2E-09
AC-02	121.8	4.8	11.3	0.4	79.61	2.2E-06	11.46	3.1E-07	65.61	4.0E-10	11.51	6.9E-11	< 61.54	< 6.2E-09	-	-
AC-03	103.0	4.1	4.8	0.2	83.33	2.3E-06	11.33	3.1E-07	75.5	4.5E-10	13.6	8.2E-11	86.68	8.7E-09	10.51	1.1E-09
AC-04	00.3	3.6	4.2	0.2	68.26	1.8E-06	10.44	2.8E-07	55.45	3.3E-10	12.22	7.4E-11	< 61.54	< 6.2E-09	-	-
AC-05	100.1	3.9	4.0	0.2	20.5	5.5E-07	4.86	1.3E-07	70.9	4.3E-10	15.7	9.5E-11	< 61.54	< 6.2E-09	-	-
AC-06	153.2	6.0	12.9	0.5	35.11	9.5E-07	6.85	1.9E-07	80.78	4.9E-10	17.27	1.0E-10	< 61.54	< 6.2E-09	-	-
AC-07	91.9	3.6	1.6	0.1	85.51	2.3E-06	11.12	3.0E-07	51.1	3.1E-10	12.52	7.5E-11	< 61.54	< 6.2E-09	-	-
AC-08	518.8	20.4	5.0	0.2	259.93	7.0E-06	13.78	3.7E-07	212.51	1.3E-09	22.31	1.3E-10	265.78	2.7E-08	23.34	2.3E-09
AC-09	39.4	1.6	1.4	0.1	42.27	1.1E-06	8.33	2.3E-07	22.57	1.4E-10	5.29	3.2E-11	< 61.54	< 6.2E-09	-	-
AC-10	69.0	2.7	2.4	0.1	34.26	9.3E-07	7.09	1.9E-07	32.78	2.0E-10	7.58	4.5E-11	< 61.54	< 6.2E-09	-	-
AC-11	45.7	1.8	0.8	0.0	36.99	1.0E-06	6.95	1.9E-07	38.22	2.3E-10	8.29	5.0E-11	< 61.54	< 6.2E-09	-	-
AC-12	80.6	3.2	2.1	0.1	13.01	3.5E-07	3.76	1.0E-07	29.77	1.8E-10	6.95	4.2E-11	< 61.54	< 6.2E-09	-	-
AC-13	73.4	2.9	2.7	0.1	77.3	2.1E-06	10.36	2.8E-07	63.7	3.8E-10	13.72	8.3E-11	< 61.54	< 6.2E-09	-	-
AC-14	81.0	3.2	1.7	0.1	92.39	2.5E-06	11.82	3.2E-07	62.07	3.7E-10	12.71	7.7E-11	85.6	8.6E-09	10.38	1.0E-09
AC-15	85.7	3.4	3.9	0.2	42.83	1.2E-06	7.45	2.0E-07	39.31	2.4E-10	9.24	5.0E-11	< 61.54	< 6.2E-09	-	-
AC-16	88.6	3.5	7.8	0.3	83.75	2.3E-06	11.72	3.2E-07	49.02	3.0E-10	9.37	5.5E-11	< 61.54	< 6.2E-09	-	-
AC-17	71.6	2.8	3.4	0.1	25.97	7.0E-07	5.64	1.5E-07	54.55	3.3E-10	12.12	7.3E-11	< 61.54	< 6.2E-09	-	-
AC-18	143.8	5.7	1.5	0.1	14.97	4.0E-07	3.89	1.1E-07	38.71	2.3E-10	8.92	5.4E-11	< 61.54	< 6.2E-09	-	-
AC-19	89.7	3.5	5.0	0.2	39.3	1.1E-06	7.35	2.0E-07	37.58	2.3E-10	9.25	5.6E-11	< 61.54	< 6.2E-09	-	-
AC-20	174.4	6.9	4.7	0.2	40.33	1.1E-06	7.46	2.0E-07	58.69	3.5E-10	13.32	8.0E-11	< 61.54	< 6.2E-09	-	-

The spatial interpolation analysis reveals a heterogeneous distribution due to variations in the concentrations of U, ^{210}Pb , and ^{226}Ra across the studied area. It is further observed that sample AC-08 constitutes the main anomalous core, presenting values of

518.8 Bq/kg for U, 259.93 Bq/kg for ^{226}Ra , and 212.51 Bq/kg for ^{210}Pb . This indicates that the Ultisol (Argissolo) acts as an adsorbent for ^{226}Ra due to its clay-rich nature and its cation exchange capacity (CEC), which refers to the soil's ability to adsorb and exchange cations between the solid phase of the soil. This property contributes to cation retention due to the negatively charged structure of clay minerals, which attract and retain cations such as calcium, magnesium, potassium, and ammonium (Ker et al., 2012). Soils with high CEC contribute to greater element retention, reducing affinity for iron oxides.

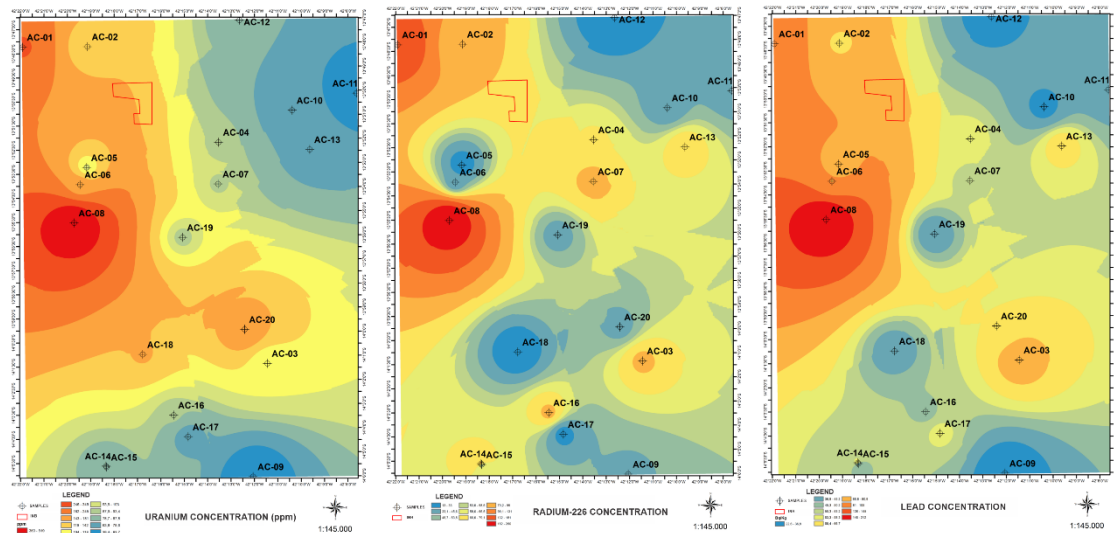


Figure 3. Spatial interpolation of ^{210}Pb , ^{226}Ra , and U samples.

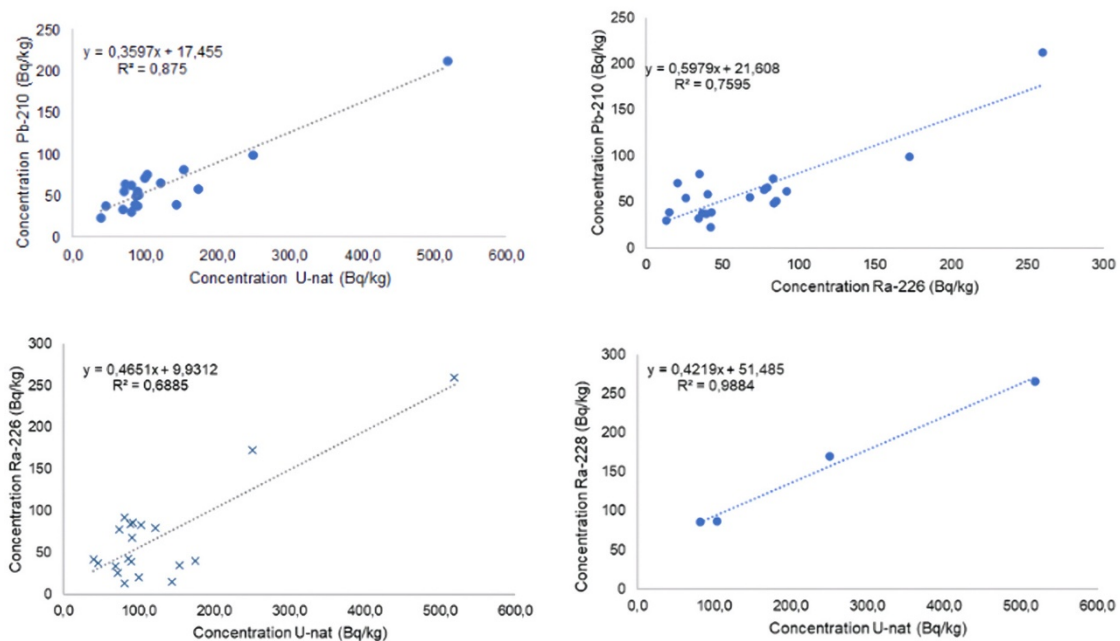


Figure 4. Linear correlation R^2 .

Ultisols (Argissolos) present a mixture of 1:1 and 2:1 clay minerals, with variable predominance depending on the parent material, degree of weathering, and climatic

conditions. The most common clays in these soils are kaolinite, smectite (montmorillonite), illite, and, to a lesser extent, vermiculite, as well as iron and aluminum oxides such as goethite and hematite (Kämpf and Curi, 2012). The pH of these soils ranges from slightly acidic to neutral; according to Carvalho et al. (2022), it varies between 6.09 and 7.05. Under these conditions, ^{226}Ra adsorption onto clay minerals tends to be favored, which is consistent with the retention pattern observed at the AC-08 anomalous core (Greeman, 1999; Kabata-Pendias and Pendias, 2011; Carvalho et al., 2023).

Samples AC-01 and AC-02 showed intermediate to high concentrations of U (121.8-250.2 Bq/kg), ^{226}Ra (79.61-172.83 Bq/kg), and ^{210}Pb (65.61-99.52 Bq/kg), forming a transitional range that suggests radionuclide dispersion from the critical nucleus, represented by sample AC-08.

On the other hand, sampling points such as AC-09, AC-12, AC-18, and AC-19 are located in low-concentration zones (39.4-143.8 Bq/kg for U, 13.01-42.27 Bq/kg for ^{226}Ra , and 22.6-45.2 Bq/kg for ^{210}Pb), representing Inceptisols (Cambissolos), which exhibit low to moderate development, weak to moderate structure, and generally significant contents of 2:1 clay minerals, including illite, vermiculite, and, in some cases, smectite, depending on the parent material (IUSS Working Group WRB, 2022). These clay minerals are secondary stable products formed by the decomposition of other aluminosilicate minerals (Mason, 1971). The studied Inceptisols are considered less acidic, less clayey, and more sandy than the Ultisols in the study area. Their occurrence reflects the activity of these radionuclides in the parent material, mainly in the clay fraction (Wasserman et al., 2002).

These results reveal a spatial gradient consistent with the low availability of ^{210}Pb in the soils of the region, in accordance with studies indicating that ^{210}Pb exhibits low to moderate mobility, while ^{226}Ra and U are mobile under specific conditions (oxidizing environments and slightly acidic to neutral pH), being responsible for the migration of natural radioactivity in soils and groundwater (IAEA, 1996; UNSCEAR, 2000; Kabata-Pendias and Pendias, 2011; Carvalho et al., 2023).

The mobility of ^{210}Pb in soils is low, and it tends to be strongly adsorbed onto soils by kaolinite clays, organic matter, and iron, aluminum, and manganese oxides. It may exhibit mobility in acidic soils (low pH) and in soils saturated with other cations (Ca^{2+} , Zn^{2+}). Although poorly mobile, it accumulates in the A horizon of soils and in contaminated soils with low calcium content, increasing the risk of bioaccumulation in organisms (McBride, 1994; Kabata-Pendias and Pendias, 2011; Alloway, 2013).

The linear regression (R^2 , used to aid visualization between two variables) between concentrations of natural uranium (U-natural) and ^{210}Pb shows a strong positive correlation ($R^2 = 0.875$), suggesting that the increase in uranium concentration is directly associated with an increase in ^{210}Pb activity in the analyzed soils (Figure 4).

The regression equation ($y = 0.3597x + 17.455$) indicates that for each unit increase in uranium concentration, there is an average increase of approximately 0.36 Bq/kg in ^{210}Pb concentration, in addition to an intercept value of 17.45 Bq/kg.

This result is consistent with geochemical and radioactive decay processes, since ^{210}Pb is part of the ^{238}U decay chain via ^{226}Ra and ^{222}Rn , accumulating in the environment due to the differing mobility of its intermediate radionuclides (IAEA, 1996; Choppin et al., 2002; Silva, 2015; Carvalho et al., 2023).

The high correlation obtained reinforces the hypothesis that the ^{210}Pb anomaly in the region does not occur independently but is strongly conditioned by the presence of uranium and the radiogenic behavior of the rock-soil system. Both U-natural and ^{210}Pb present cumulative toxicological and radiological effects. While uranium is associated with both chemical and radiological toxicity (ATSDR, 2013), ^{210}Pb is related to risks of internalization in living organisms and may contribute to significant effective doses when inhaled or ingested (Santos, 2011).

The comparative analysis of linear regressions between natural uranium (U-natural) and its associated radionuclides (^{226}Ra and ^{228}Ra) reveals distinct but complementary patterns that enhance the understanding of soil anomalies in the studied region.

The regression between U-natural and ^{226}Ra shows a moderate to strong correlation ($R^2 = 0.6885$), lower than that observed for ^{210}Pb . This suggests that, although ^{226}Ra is directly linked to ^{238}U decay, its geochemical mobility is more strongly influenced by specific environmental conditions such as soil pH, grain size, carbonate content, and water circulation. Radium (Ra) tends to be strongly adsorbed onto soil particles, especially clays, hydrated oxides (Fe, Mn), and organic matter (Smith and Amonette, 2006; Urso et al., 2019). In addition, ^{226}Ra plays a key role as a precursor of radon (^{222}Rn), whose high mobility increases dispersion risks beyond the soil (Kim et al., 2001; Alene Assefa, 2025).

Thus, while ^{210}Pb reflects the local and persistent accumulation of the anomaly, ^{226}Ra represents a dynamic link of radiological mobility capable of intensifying risks through radon generation (Alene Assefa, 2025). Together, the two regressions demonstrate that natural contamination is not limited to the presence of uranium but encompasses the full spectrum of its radioactive progeny, confirming the need for integrated monitoring that considers both chemical risks (U) and radiological risks (^{226}Ra and ^{210}Pb).

Conclusions

The geochemical analysis carried out in the Uranium Province of Lagoa Real (Bahia, Brazil) allowed a simplified characterization of the behavior of uranium (U), lead-210 (^{210}Pb), and radium isotopes ($^{226}\text{Ra}/^{228}\text{Ra}$) in the soils of the studied region. These results represent local trends and not a definitive regional characterization, confirming the presence of significant anomalies in surface soils that reflect the complex interaction between lithology and supergene processes of uraninite mineralization in the rocks. The results obtained by ICP-MS and liquid scintillation spectrometry showed a strong correlation between U-natural, ^{210}Pb , and ^{226}Ra ($R^2 > 0.68$), indicating that the mobility of these radioelements is strongly controlled by soil mineralogical composition, pH, and iron oxide content, in agreement with previous studies conducted in the area.

In samples AC-01 and AC-02, intermediate to high concentrations of U, ^{210}Pb , and ^{226}Ra were observed, ranging from 121.8 to 250.2 Bq/kg for U, from 79.61 to 172.83 Bq/kg for ^{226}Ra , and from 65.61 to 99.52 Bq/kg for ^{210}Pb , forming a transitional range that suggests radionuclide dispersion from the critical core, the point represented by sample AC-08.

Areas dominated by sample AC-08 exhibited the highest concentration values, characterizing it as a critical nucleus of retention and possible radiogenic redistribution. Sampling points AC-09, AC-12, AC-18, and AC-19 are located in low-concentration zones (between 39.4 and 143.8 Bq/kg for U, 13.01 and 42.27 Bq/kg for ^{226}Ra , and 22.6 and 45.2 Bq/kg for ^{210}Pb).

U-natural and ^{210}Pb show a strong positive correlation ($R^2 = 0.875$), suggesting that the increase in uranium concentration is directly associated with an increase in ^{210}Pb activity in the analyzed soils.

The radiogenic behavior of ^{210}Pb , a member of the ^{238}U decay chain via ^{226}Ra and ^{222}Rn , demonstrated significant accumulation due to the low mobility of its intermediates, reinforcing the importance of correlation analysis to understand the geochemical cycle of uranium and its decay products.

From an environmental and public health perspective, the results indicate the need for integrated and continuous radiation protection policies, since uranium, ^{210}Pb , and ^{226}Ra all present cumulative chemical and radiological toxicity.

The study also demonstrated that, even in areas without mining activity, there were relevant concentrations of uranium (U), lead-210 (^{210}Pb), and radium ($^{226}\text{Ra}/^{228}\text{Ra}$) in the soils of the region, indicating that there is no direct relationship between mineral extraction and soil anomalies in this area.

However, the temporal and spatial limitations of the investigation prevented analyses from being carried out at the mining site itself. In addition, the lack of Brazilian legislation establishing detection limits for the analyzed parameters in soils did not allow the definition of concentration levels as low, medium, or high.

It is concluded that the geochemical characterization performed constitutes an important contribution to the environmental monitoring of the studied region, highlighting the urgency of mitigation and control strategies based on scientific data and in accordance with the standards of the International Atomic Energy Agency (IAEA) and the Brazilian National Nuclear Energy Commission (CNEN). For future studies, the expansion of the number of samples and the incorporation of temporal series and epidemiological indicators are recommended, in order to establish quantitative relationships between environmental anomalies and health outcomes.

Conflicts of interest

The authors declare that there are no known competing interests or personal relationships that could have influenced the inferences reported in this article.

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