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Content of Radionuclides in Soils of Hydraulic Development Areas in Brazil

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Abstract

This study aimed to quantify and assess the spatial distribution of ^{238}U, ^{232}Th, and ^{40}K in the soils of the Espora Hydroelectric Power Plant (Espora HPP) and Queixada Small Hydroelectric Power Plant (Queixada SHPP) watershed (model hydraulic development areas) and their relationship with the geological, chemical, physical, and biological aspects of the soil. The study areas are located in the Corrente River drainage basin, in the southwestern portion of the state of Goiás, Brazil. Radionuclides were quantified using a PGIS-2 portable gamma spectrometer, with measurements taken at 21 sampling points. Soil samples were collected from the surface layer (0–20 cm) for particle-size and chemical analyses. The results indicated that the average radionuclide contents in the soils were 64.49 Bq/kg for ^{40}K, 45.44 Bq/kg for ^{238}U, and 4.53 Bq/kg for ^{232}Th. When comparing these values with the global average established by UNSCEAR, it was observed that ^{232}Th and ^{40}K concentrations were below the global reference, whereas ^{238}U concentration exceeded the world average of 33 Bq/kg. Particle-size characterization revealed significant variability in soil texture, with sand content ranging from 51.46 to 90.91%, clay content from 7.45 to 30.64%, and silt content from 1.64 to 17.90%. Organic matter content had an average of 10.09 g/kg, while soil pH ranged from 4.67 to 6.54. The results of this study have demonstrated the relevance of integrating radiometric and geochemical data for assessing environmental safety in hydroelectric development areas. The approach adopted can support monitoring programs and decision-making processes related to soil management and land-use planning in regions influenced by hydraulic infrastructures.

Keywords: gamma spectrometry; radionuclide; soil; environmental impact; hydraulic development

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1. Introduction

The Cerrado Biome in Brazil occupies almost 25% of the Brazilian territory, being responsible for approximately 60% of national grain production. Soils in these areas are chemically poor, but with favorable relief for exploitation. For agricultural activities to

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be possible, the only way to make up for the deficiency of nutrients such as phosphorus and potassium is through fertilizers. Phosphate fertilizers and one of their by-products, agricultural gypsum, may contain radioactive elements, depending on the rock used to manufacture these fertilizers [1]. Monitoring radionuclides in soils is essential to assess environmental risks and possible anthropogenic impacts, especially in areas with intense agricultural activity with the use of phosphate fertilizers and correctives with high concentrations of radioactive elements [2,3]. Studies indicate that the absorption of radionuclides by plants constitutes one of the main routes of transfer of these elements to humans through the food chain [4,5]. In addition, research has shown that any dose of radiation can increase the risk of developing chronic diseases, such as cancer, kidney failure, and lung diseases, resulting from prolonged exposure to ionizing radiation by humans and animals [6–9].

Gamma spectrometry has been widely used in the quantification of radionuclides in environmental studies, allowing accurate evaluation of the radiation emitted by geological materials and surface soils [10,11]. This technique is based on the natural decay of radionuclides and is an effective geophysical method for measuring radiation sources on the Earth's surface. Radionuclide levels can be determined by means of portable gamma spectrometers, such as PGIS-2, whose data are evaluated according to the reference values established elsewhere [12–14]. Several studies have applied gamma spectrometry, apparent resistivity and magnetic susceptibility as useful strategies for the analysis and distribution of radionuclides in the environment [15]. For example, the natural radioactivity of the soil in the state of Haryana, northern India, was measured with the aim of determining the risks associated with gamma radiation [16]. Moreover, in Tamil Nadu, also in India, measurements of the radiation dose rate at 540 sites concluded that the highest concentrations of gamma radiation were associated with the presence of radionuclides in mountainous rocks and coastal soils [17]. Similar studies were conducted in the area of influence of the Emas National Park [18], and in soils and sediments around a uranium tailings reservoir in southern China [19].

The current work is innovative because it combines radiometric, geochemical, and geomorphological analyses to assess the spatial distribution of the natural radionuclides ^{238}U, ^{232}Th, and ^{40}K in soils located within hydroelectric development areas, with direct influence of crops such as soybean, maize, sugarcane and cotton. Unlike previous works that focus solely on radiometric quantification, this research integrates geological, physical, and biological variables to interpret the environmental processes controlling radionuclide distribution. The results provide a novel framework for understanding the interactions between soil characteristics and radiological parameters, contributing to environmental monitoring and management in regions influenced by hydraulic infrastructures.

In this context, this study aimed to contribute by quantifying the concentrations and distributions of the radionuclides ^{238}U, ^{232}Th and ^{40}K in the soils of the watershed of the Espora HPP and Queixada SHPP, GO, Brazil, and determining whether they are related to geological characteristics as well as anthropogenic activities using fertilizers, mainly phosphate fertilizers and agricultural gypsum that may contain radioactive elements. The choice of the area of this study is due to the intense agricultural use, particularly with soybean and maize cultivation, and the frequent use of fertilizers and agricultural correctives such as gypsum, which can influence the dynamics of radionuclides in the environment.

2. Materials and Methods

2.1. Study Area

Located in the southwest of Goiás, Brazil, the research area has a territorial extension of 1019.71 km^2, situated in the region of influence of the reservoir of the Espora HPP, and the Queixada SHPP (Figure 1), covering the municipalities of Serranópolis, Itarumã, and

Aporé. The area is located in the middle third of the Corrente River, formed by the junction of the Formoso and Jacuba rivers, a tributary of the right bank of the Paranaíba River, which delimits the border between the states of Goiás and Minas Gerais and is part of the Paraná Basin.

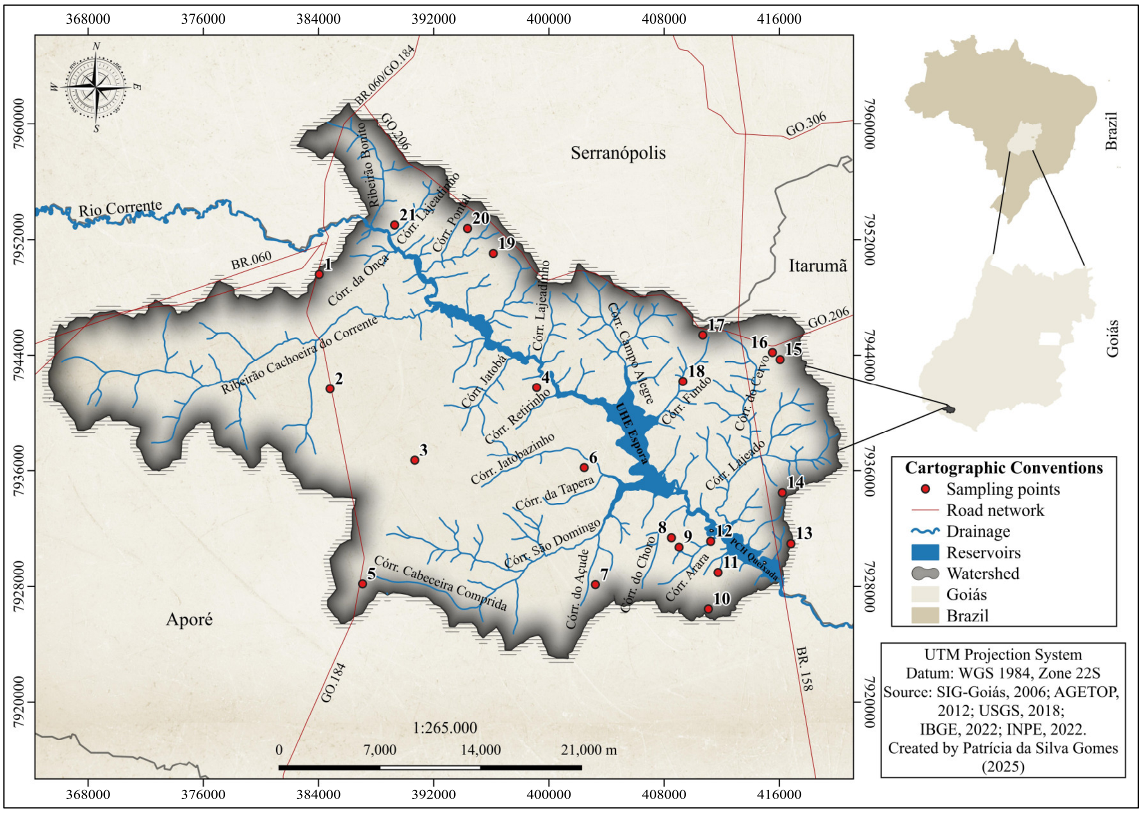

Figure 1. Location of the soil sampling points in the study area.

According to Köppen's climate classification, the Midwest region of Brazil has an Aw climate, characterized by a rainy season between October and April (summer) and a less rainy season from May to September (winter) [20,21]. Climate dynamics play a fundamental role in understanding the environmental conditions of the region, being influenced by relief, vegetation and air masses. This affects the availability of rainfall, temperature, humidity level and other factors that directly impact land use and occupation, local economy, agricultural activities and the weathering processes responsible for disintegration and transformation. The watershed under study is occupied by agricultural activity, with emphasis on the cultivation of maize, soybean, and sugarcane [22]. Physical, geological, pedological and spatialization maps of radionuclides were created using QGIS 3.22 software. The watersheds were delimited based on a shuttle radar topography mission (SRTM) image available on the website presented elsewhere [23]. Cartographic bases from the database of the state geoinformation system of Goiás-Brazil [23], available on the website www.sieg.go.gov.br, accessed on 5 February 2025, with scales of 1:250,000 and 1:500,000, were also used.

2.2. Sample Collection

Twenty-one sampling points strategically distributed, based on geological and land use criteria, were chosen. Samples were collected on the soil surface (at 0–20 cm depth using a Dutch auger manufactured by SoloTest, São Paulo, SP, Brazil) in a 20 m × 20 m sampling grid to minimize abrupt local variations, with images of each sampling point georeferenced using the Google Earth 2020 and MAPConvert software version 5.5.5.4 (NUVIA Dynamics, Mississauga, ON, Canada). This sampling depth (topsoil) was chosen because it is where most of the root systems of annual crops such as soybean and maize are located in the search for nutrients, mainly phosphorus and potassium. According to the UNSCEAR guidelines, radionuclide concentrations in the uppermost soil layer (0–20 cm) are the most representative of present environmental conditions and anthropogenic influences [24,25]. Therefore, the sampling strategy adopted in this study focused on surface horizons, which are directly affected by agricultural management, fertilizer application, and atmospheric deposition. This approach allows the identification of current enrichment patterns associated with human activities, while deeper soil horizons remain predominantly influenced by geogenic processes.

2.3. Sample Preparation Method

The collected soil samples were dried in an oven at 40 °C and subjected to laboratory analyses to determine the physical-chemical properties: soil texture (sand, silt and clay fractions), pH value and organic matter (OM) content. Particle-size analyses were performed by the pipette method, according to Stokes' law, pH was determined by the potentiometric method in soil-water suspension in the proportion 1:2.5, and organic matter content was quantified by the method of chemical oxidation with potassium dichromate [26]. To determine the pH of the soil in water, the following protocol was employed: an aliquot of 10 cm^3 of the soil sample was added to a plastic cylinder with a lid of 4 × 4 cm, followed by the addition of 25 mL of distilled water. The mixture was mechanically stirred for 15 min and, after a minimum resting period of 30 min, the pH reading was performed.

2.4. Acquisition of Gamma-Spectrometric Data

Radionuclides in the soils were quantified using a PGIS-2 gamma spectrometer, manufactured by NUVIA Dynamics Inc. (Mississauga, ON, Canada) and equipped with a 3″ × 3″ NaI(Tl) scintillation detector, with an energy range from 20 keV to 3 MeV and an energy resolution of 7.5% at 662 keV. This instrument performs automatic energy and efficiency calibration through a built-in reference source and an internal software algorithm, ensuring stable and reproducible readings under field conditions. The calibration procedure follows the manufacturer's standard protocol for in situ gamma spectrometry measurements. The minimum detectable activity (MDA) for the radionuclides ^{40}K, ^{238}U and ^{232}Th were 12, 5, and 4 Bq/kg, respectively, under field measurement conditions. The uncertainty associated with the spectrometric measurements was evaluated considering the counting statistics of each acquisition. The uncertainties of the specific activities ranged from ±5% for ^{40}K, ±7% for ^{238}U, and ±8% for ^{232}Th, values consistent with those expected for portable gamma spectrometry measurements performed under field conditions. The average concentrations of radionuclides in the soil were analyzed in relation to the limits recommended elsewhere [13,14]. In addition, the values obtained were compared with data from previous studies, including those conducted in different works [27–29].

2.5. Variable Analysis

The collected data were statistically processed using R software, version 4.4.2, and QGIS 3.22.7 software for spatial analysis. Descriptive statistics were applied to characterize the variability of radionuclides and soil properties, including calculation of means, standard deviation and coefficient of variation. The relationship between the variables was investigated using principal component analysis (PCA), a multivariate statistical technique that reduces the dimensionality of the data without significant loss of information. PCA allowed the identification of radionuclide distribution patterns and their correlation with the physical-chemical attributes of the soil. The data regarding the concentrations of U, Th and K were organized in electronic spreadsheets and spatialized using the inverse distance weighted (IDW) mathematical model in QGIS 3.22.7 software. This interpolation method is widely used in the spatial analysis of irregularly distributed data, weighting the values based on the distance between the sampling points, where closer values exert greater influence on the final estimate [30]. Radionuclide concentrations were spatialized using the units of measurement provided by the PGIS-2 gamma spectrometer: potassium (%), uranium (ppm) and thorium (ppm). These values were converted to Becquerel (Bq/kg), in order to enable comparison with data from international studies. The conversion of radionuclide concentrations from either ppm or % to Bq/kg followed the recommendations described elsewhere [13,14] and presented in Equation (1):

$$A = C \times \rho \times f \tag{1}$$

in which, A is the radionuclide activity (Bq/kg), C is the radionuclide concentration (ppm or %), ρ is the density of the soil sample (kg/m^3), and f is the radionuclide-specific conversion factor (12.35 for ^{238}U, 4.06 for ^{232}Th, and 313 for ^{40}K).

Inferential statistics were applied to evaluate the significance of the differences observed between radionuclide concentrations and soil types. For this, Pearson's correlation tests were used to verify linear associations between variables, as well as Analysis of Variance (ANOVA) to test significant differences between soil groups. The level of significance was set at 5% ($p < 0.05$).

3. Results and Discussion

3.1. Geology of the Study Area

The geology of the study area in Figure 2 is part of the Paraná sedimentary basin, being composed of five main geological units: Undifferentiated Detrital Covers (Qdi), Alluvial Deposits (Q2a), Cachoeirinha Formation (ENch), Vale do Rio do Peixe Formation (K2vp) and Serra Geral Formation (K1δsg).

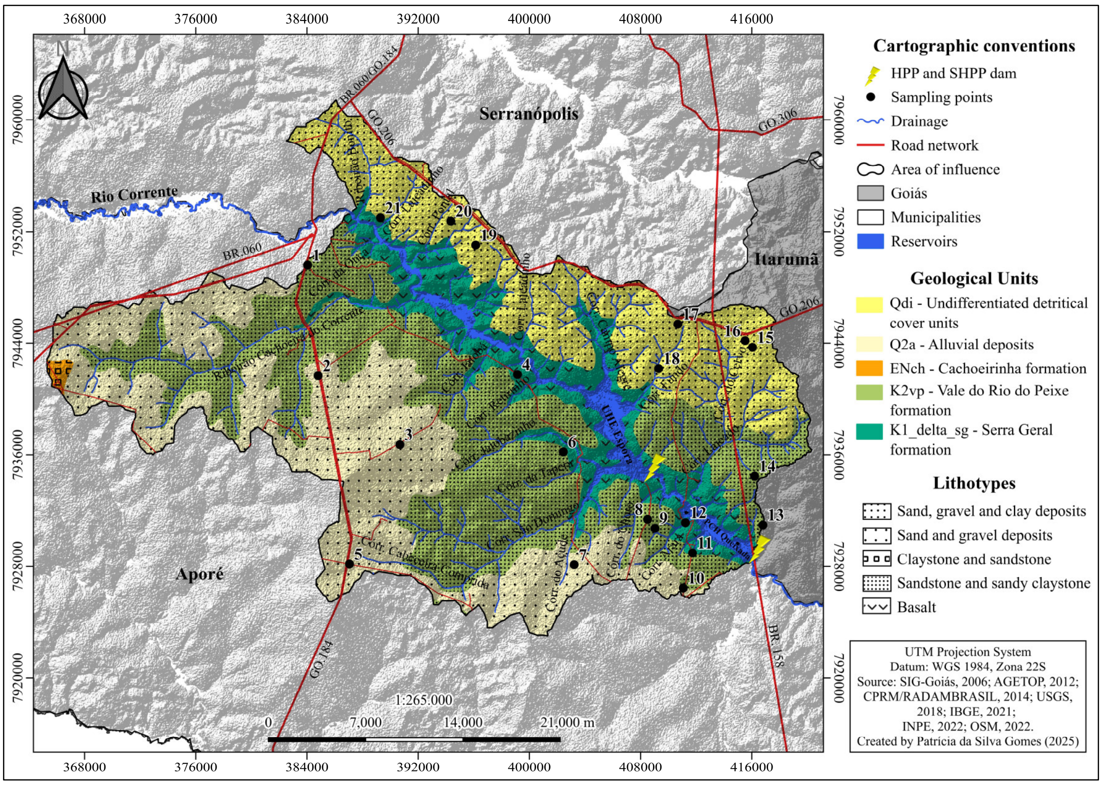

Figure 2. Geology of the study area. Adapted from CPRM/RADAMBRASIL (2014).

The Undifferentiated Detrital Covers (Qdi) unit is located on the left bank of the study area and is composed of sand, gravel and clay deposits. This unit occupies approximately 20.56% of the total area as shown in Table 1, and its deposition occurred in the Pleistocene [31]. It is characterized by allochthonous materials with a depth of less than 3 m, associated with the Botucatu, Bauru and Cachoeirinha Formations. These deposits are composed of fine to coarse, silty-clayey, occasionally conglomeratic sands, and gravel deposits cemented by iron oxides and hydroxides, without the development of lateritic profiles [32,33].

Table 1. Stratigraphic composition of the geological formations of the study area.

Era	Period	Epoch	Geological Units	Lithotypes	Code	Area km^2	%
Cenozoic	Neogene	Pleistocene	Undifferentiated detrital cover units	Sands and gravel deposits	Qdi	209.69	20.56
		Holocene	Alluvial deposits	Sand deposits	Q2a	283.6	27.81
	Paleogene	Paleocene	Cachoeirinha formation	Claystone and Sandstone	ENch	2.81	0.28
Mesozoic	Cretaceous	Upper	Vale do Rio do Peixe formation	Sandstone	K2vp	357.86	35.09
		Lower	Serra Geral formation	Basalt	K1_delta_sg	165.74	16.25
			Total:			1019.7	100

Source: CPRM/RADAMBRASIL (2014). Adapted by the authors (2023).

The Alluvial Deposits (Q2a), of Holocene origin, are the second largest geological unit in the study area, occupying 283.6 km^2 (27.81%) of the region. This unit extends along the right bank of the reservoir and comprises trough and floodplain sediments, composed of fine to coarse sands, gravel and lenses of silty-clay material and peat [34]. In addition to its geological importance, this formation contains economically relevant minerals, such as diamonds, gold and cassiterite, which are exploited in mining activities in Brazil [34].

The Cachoeirinha Formation (ENch), dated to the Paleocene, is the unit of smallest extension within the study watershed, covering 2.81 km^2 (0.28%). This formation corresponds to lateritic clay-sandy lenses interspersed with levels of conglomerates [35]. Its genesis is associated with the deposition of gravity-driven mass flows and the reworking of ancient river deposits, evidenced by the presence of rounded pebbles [34].

The Vale do Rio do Peixe Formation (K2vp), of the Upper Cretaceous, is the geological unit with the largest extension in the study area, covering 357.86 km^2. This formation consists of strata of light gray, beige or pinkish, massive, fine to very fine, occasionally medium, usually poorly selected sandstones with subordinate plane-parallel and cross-stratification [34]. The Vale do Rio do Peixe Formation is widely distributed in the state of Goiás, occurring in locations such as the Emas National Park and in the municipalities of Rio Verde, Itarumã, Cachoeira Alta, Serranópolis, Caçu and Quirinópolis [34].

The Serra Geral Formation (K1δsg), belonging to the São Bento Group and of lower Cretaceous origin, occupies 165.74 km^2 and is mainly found along the Corrente River valley. This unit is predominantly composed of basaltic flows, with intertrap sandstones, dikes, and diabase sills [35]. In the watershed of the Espora HPP and Queixada SHPP, six soil classes were identified as shown in Figure 3: *Neossolo Quartzarênico Álico* (RQ) (Arenosols), *Neossolo Quartzarênico Distrófico* (RQd) (Arenosols), *Latossolo Vermelho Álico* (LV) (Ferralsols), *Latossolo Vermelho Distrófico* (LVd) (Ferralsols), *Argissolo Vermelho-Amarelo Distrófico* (PVAd) (Acrisols) and *Neossolo Litólico Distrófico* (RLd) (Leptosols) [23].

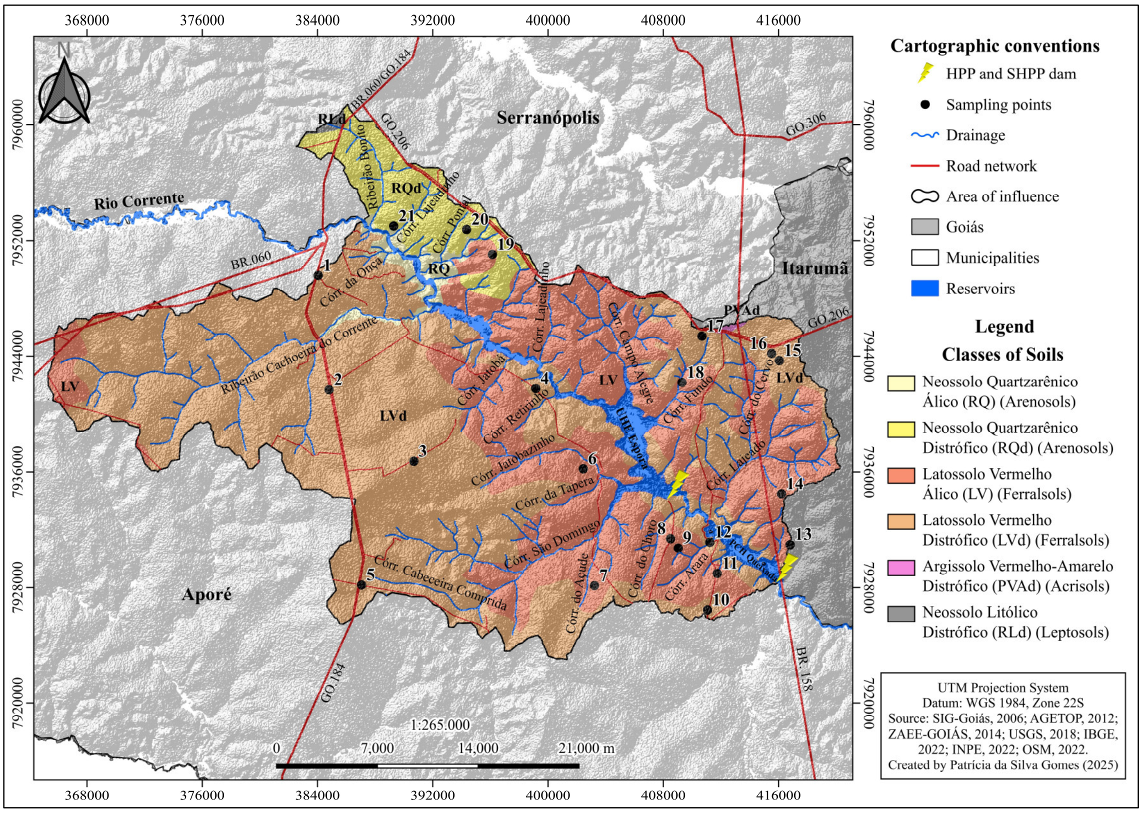

Figure 3. Map of soils of the study area. Adapted from ZAEE-Goiás (2014).

The soil classification adopted in this study follows the Brazilian Soil Classification System (SiBCS) proposed by Embrapa, which represents the official national framework and provides a more detailed description of tropical soils compared to international systems [36]. This approach was preferred because it reflects the pedogenetic processes typical of the Cerrado biome, allowing a more accurate environmental interpretation. To facilitate international comparison, approximate correspondences can be established between SiBCS and WRB [37]. For instance, *Latossolo Vermelho* corresponds to *Ferralsols*, *Argissolo Vermelho-Amarelo* corresponds to *Acrisols*, and *Neossolo Quartzarênico* corresponds to *Arenosols*. According to WRB [37], the Neossolo Litólico Distrófico (RLd), which has shallow profiles over rock, is categorized as Leptosol, while the Neossolos Quartzarênicos (RQ and RQd), which are distinguished by sandy texture and quartz dominance, correspond to Arenosols. This clarification has been added in the text to improve the global understanding of the local pedological context.

According to Embrapa, *Neossolos Quartzarênicos* (Arenosols) are composed of mineral material with a sequence of horizons A-C. Their predominant texture is sandy or loamy sand, with a minimum depth of 150 cm from ground level. They are quartz-rich soils, containing 95% or more quartz in the coarse sand and fine sand fractions [36]. The *Neossolo Quartzarênico Álico* (RQ) (Arenosols) occupies 2.17% of the study area, located upstream of the watershed, while the *Neossolo Quartzarênico Distrófico* (RQd) (Arenosols) comprises 6.51% of the area, located upstream of the left bank. The sandy texture of these soils, combined with the low content of available water, can limit root development in subsurface [38].

Latossolos (Ferralsols) are characterized as acidic, dystrophic and eutrophic soils, common in equatorial, tropical and subtropical zones. They are typical of river sediments or terraces and have a predominantly flat to gently undulating relief, originating from different types of rocks and sediments [36]. The *Latossolo Vermelho Álico* (LV) (Ferralsols) occupies approximately 34.5% of the study area, extending along the banks of the Espora HPP and Queixada SHPP reservoirs. The *Latossolo Vermelho Distrófico* (LVd) (Ferralsols), in turn, is the most representative soil class, covering 56.5% of the area, predominating on the right bank. This type of soil, especially when clayey or very clayey, can show greater compaction, especially if the fine sand content is high [38].

The *Argissolo Vermelho-Amarelo Distrófico* (PVAd) (Acrisols) is the smallest soil class in the study area, occupying 1.01 km^2 as shown in Table 2. It is located on the left bank of the watershed, near point 17. This soil usually occurs in undulating to strongly undulating reliefs, with a yellowish or yellowish-red color in the B horizon and a higher clay content compared to the A horizon [38].

Table 2. Soil classes in the area of influence of the Espora HPP and Queixada SHPP.

Soil Class	Code	Area km^2	%
Neossolo Quartzarênico Álico (Arenosols)	RQ	22.08	2.17
Neossolo Quartzarênico Distrófico (Arenosols)	RQd	66.43	6.51
Latossolo Vermelho Álico (Ferralsols)	LV	351.92	34.51
Latossolo Vermelho Distrófico (Ferralsols)	LVd	576.69	56.55
Argissolo Vermelho-Amarelo Distrófico (Acrisols)	PVAd	1.01	0.10
Neossolo Litólico Distrófico (Leptosols)	RLd	1.58	0.16
Total:		1019.7	100

Source: ZAEE-Goiás (2014). Adapted by the authors (2023).

The *Neossolo Litólico Distrófico* (RLd) (Leptosols) occupies 1.58 km^2 and is located upstream of the watershed, on the left bank. This soil class is characteristic of undulating to very rugged reliefs, showing a shallow profile, where the thickness of the A-Cr-R horizons or the A horizon on the rock does not exceed 50 cm [38].

Overall, the soils in the Espora HPP and Queixada SHPP watersheds are typical of the Cerrado biome, developed under intense weathering and leaching processes that lead to advanced soil evolution. According to the SiBCS, these soils are predominantly Ferralsols (*Latossolos*), Acrisols (*Argissolos*), and Arenosols (*Neossolos*), characterized by low natural fertility, acidic pH (4.5–6.0), and low cation exchange capacity [36]. The mineralogical composition is dominated by kaolinite, gibbsite, hematite, and goethite, with high contents of Fe and Al oxides. Such features promote the strong adsorption of uranium and thorium isotopes and influence the mobility of potassium. These characteristics are consistent with regional studies conducted in Cerrado soils, which describe them as deep, well-drained, and highly weathered profiles formed from basaltic and sandstone parent materials [36,39].

3.2. Radionuclide Concentrations in Soils

The values obtained for ^{40}K shown in Table 3 and Figure 4 at points 2, 5, 6, 15 and 20 were higher than 70 Bq/kg, representing the highest concentrations. Although this study focused primarily on the natural radionuclides ^{238}U, ^{232}Th, and ^{40}K, which are the main contributors to terrestrial gamma radiation, it is acknowledged that other radionuclides, both natural and anthropogenic (e.g., ^{210}Pb, ^{90}Sr, and ^{137}Cs), may also occur in the environment and contribute to the total radioactivity of soils [40]. Future investigations should consider the inclusion of these radionuclides to provide a more comprehensive radiological assessment of hydraulic development areas.

At points 2 and 5, there is the geological formation of alluvial deposits, while point 6 is located in the Vale do Rio do Peixe Formation. Samples 15 and 20 are associated with the Undifferentiated Detrital Cover Units, with predominant lithotypes of sand, sandstone

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and gravel. The predominant soil class is *Latossolo Vermelho* (Ferralsols), whose land use is aimed at agriculture and forestry. In the case of ^{238}U, points 1, 5, 10, 17 and 19 stand out, located under Alluvial Deposits, Vale do Rio do Peixe Formation and Undifferentiated Detrital Cover Units. The predominant soil class at these points is *Latossolo Vermelho* (Ferralsols), with use predominantly focused on vegetation and pasture. As for ^{232}Th, the highest concentrations were observed at points 11, 12, 13, 17 and 20. Points 11 and 12 are located over the Serra Geral Formation, while point 13 is located in the Vale do Rio do Peixe Formation, both under *Latossolo Vermelho* (Ferralsols). Samples 17 and 20 are associated with the Undifferentiated Detrital Cover Units and have, respectively, *Latossolos Vermelhos* (Ferralsols) and *Neossolos Quartzarênicos* (Arenosols).

Table 3. Concentrations (Bq/kg) of ^{40}K, ^{238}U and ^{232}Th radionuclides at the sampling points.

Points	Geological Units	Soil Classes	Land Use and Occupation	^{40}K	^{238}U	^{232}Th
				------ Bq/Kg ------		
1	K2vp	LVd	Vegetation	53.940	48.253	4.908
2	Q2a	LVd	Agriculture	72.540	45.313	5.108
3	Q2a	LVd	Agriculture	68.200	47.995	3.704
4	K1_delta_sg	LVd	Agriculture	65.720	44.870	3.195
5	Q2a	LVd	Pasture	70.990	48.056	3.496
6	K2vp	LV	Silviculture	77.500	45.928	2.149
7	Q2a	LV	Silviculture	66.030	47.896	2.141
8	K2vp	LV	Agriculture	64.480	44.182	4.644
9	K2vp	LV	Uncovered area	59.210	44.870	4.733
10	Q2a	LV	Vegetation	63.860	49.495	4.652
11	K1_delta_sg	LV	Pasture	56.420	46.174	6.321
12	K1_delta_sg	LV	Pasture	64.480	40.516	6.109
13	K2vp	LV	Silviculture	58.900	40.836	7.021
14	K2vp	LV	Pasture	67.890	46.076	3.362
15	Qdi	LVd	Silviculture	72.540	41.316	2.792
16	Qdi	LVd	Silviculture	60.760	42.349	5.836
17	Qdi	LVd	Pasture	58.590	48.942	6.011
18	Qdi	LV	Pasture	63.550	46.150	4.172
19	Qdi	LV	Vegetation	58.590	48.880	5.767
20	Qdi	RQd	Agriculture	70.990	44.698	6.931
21	K1_delta_sg	RQd	Agriculture	59.210	41.426	2.182

Source: CPRM/RADAMBRASIL (2014). Adapted by the authors (2023).

Table 4 shows the mean concentrations of Th, U, and K radionuclides in the study area and comparative values from other studies found in the literature.

Table 4. Average concentrations in terms of natural activities (Bq/kg) of the elements Th, U and K in soils according to some authors.

Sample Site	Soil			Reference
	^{40}K	^{238}U	^{232}Th	
	------ Bq/kg ------			
(Study area)	64.5	45.4	4.5	Present Study
Paraná basin (Paraná)	59.0	28.2	47.6	[29]
Rio de Janeiro	113.1	32.1	73.8	[41]
Minas Gerais	297.2	53.5	66.1	[42]
Enugu-Abakaliki (Nigeria)	126.2	18.7	7.8	[43]
Ojota (Nigeria)	458.6	30.3	54.47	[44]
Italy	970.3	50.1	71.9	[45]
Tanzania	652.4	42.59	35.48	[46]
Kenia	732.6	93.4	150.5	[47]
MH, Lao Cai (Vietnam)	551	93.0	198	[48]
World average	420	33	45	[26]

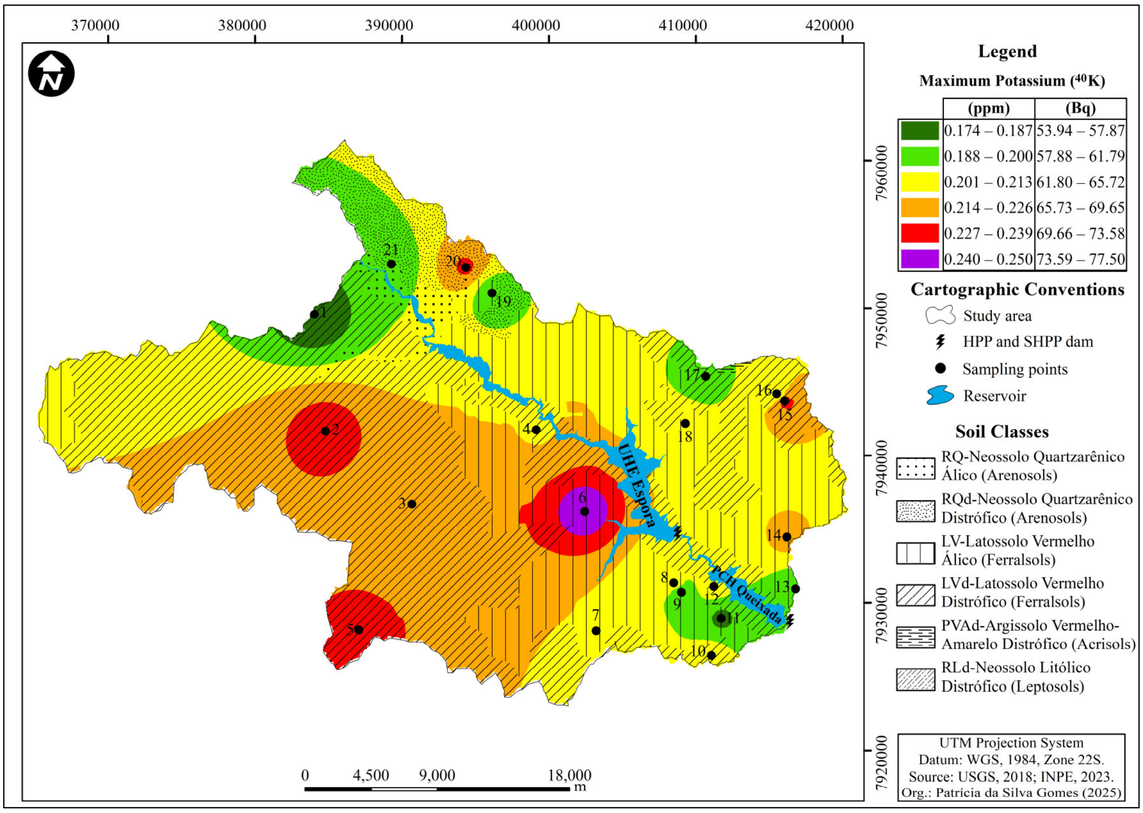

Figure 4. Potassium concentration in the soil of the study area.

The concentrations of the ^{40}K radionuclide are not evenly distributed in the soils of the study area. The results indicate that the activity levels were relatively higher in the areas with agriculture and reforestation compared to the areas of pasture and natural Cerrado vegetation. Several studies indicate that the application of fertilizers in plants can result in a significant increase in the concentrations of ^{40}K, due to its use for replacing essential nutrients and improving productivity indices. Therefore, the variations in radionuclide concentrations in agricultural soils can directly be related to the use of fertilizers and other agrochemical inputs. However, the presence of radionuclides in reforestation areas can be associated with geological variability, resulting of the different mineralogical compositions [43,49]. The Espora and Queixada watersheds are dominated by Ferralsols with naturally low potassium content, requiring nutrient supplementation through mineral fertilizers. Therefore, the spatial correlation between agricultural land use and elevated ^{40}K values observed in this study indicates that the increase in ^{40}K activity is mainly related to anthropogenic enrichment from fertilizer inputs. Similar findings were also reported elsewhere after analyzing agricultural soils and observing that the concentrations of ^{238}U, ^{232}Th, and ^{40}K are closely related to fertilizer application and soil management practices, reinforcing the relationship between agricultural activities and the redistribution of natural radionuclides in the environment [50]. Topsoils are the most sensitive to environmental changes and land use, being therefore widely used in assessments of radionuclide distribution [24,25]. Some researchers emphasize the importance of analyzing vertical soil profiles to more accurately differentiate the geogenic inheritance from possible surface enrichment, since variations with depth reflect the influence of parent material, weathering intensity, and long-term pedogenetic processes [6,19,45]. Although these approaches provide an additional line of evidence to confirm geogenic sources, they are complementary techniques that do not diminish the importance of investigations in surface layers. Therefore, even if vertical characterization can improve future interpretations, the dataset presented is robust enough to analyze spatial patterns and identify possible environmental factors in the 0–20 cm range.

^{238}U concentrations in the soils of the study area showed higher average values when compared to the averages of Paraná, Rio de Janeiro, Nigeria and the world average, although in Kenya and Vietnam the average values are even higher. Uranium uptake by plants is influenced by several factors, including plant species and climatic conditions [51,52]. Among the species studied, tobacco (*Nicotiana tabacum* L.) stands out as a hyperaccumulator of radionuclides, with a greater capacity for absorption and retention of these elements compared to other agricultural crops, such as cereals and vegetables [52,53].

^{232}Th levels were below the average compared to Brazilian soils and international levels. Overall, the results indicate that radionuclides were detected in all analyzed samples at measurable levels. However, a non-uniform distribution of these radionuclides was observed in the study area, with considerable variations between the different landscapes. These variations may be associated with the geological characteristics of the regions studied, as well as the geochemical processes involved in soil formation and its mineralogical content [1,49].

Potassium concentrations in the soils of the study area are below the average established for Brazilian and international soils, according to the available literature. The minimum concentration recorded was 53.94 Bq/kg at point 1, while the maximum was 77.50 Bq/kg at point 6. These values are close to those found for soils in the Paraná basin [29]. In general, the lowest concentrations were detected in the north and southeast of the reservoir, while the highest concentrations occurred on the right bank, in the western and southwestern portions as shown in Figure 4.

It can be observed that the highest concentrations of ^{40}K are located in Alluvial Deposits, Undifferentiated Detrital Cover Units and in the Vale do Rio do Peixe Formation, corresponding to points 2, 5, 6, 15 and 20. The soils are predominantly *Latossolos Vermelhos* (Ferralsols) with sandy texture, used for agriculture and reforestation. The ^{40}K levels are similar to those found in the Paraná Basin [29], while the other states and countries compared had higher averages, as well as the world average of 420 Bq/kg. The highest concentrations were observed on the right bank of the study area, which may be associated with the use of phosphate fertilizers. Soils such as *Latossolos Álicos* and *Latossolos Distróficos* (Ferralsols) have low nutritional potential, which leads to the use of fertilizers for soil correction, mainly for agricultural purposes [22]. Potassium is found naturally in the Earth's crust, especially in the mineral potassium feldspar, which contains potassium aluminum silicate [54,55].

Uranium concentration ranged from 40.52 Bq/kg at point 12 to 49.50 Bq/kg at point 10 as shown in Figure 5.

The average concentrations of Uranium found were similar to those observed in the states of Rio de Janeiro and Minas Gerais. When compared internationally, the mean concentrations are closer to the values recorded in Italy and Tanzania. The lowest concentrations of Uranium were observed upstream of the Espora reservoir, as well as on the left bank, between the southeast and east regions. The highest concentrations were found in the northeast, northwest and southwest regions. The points with the highest U concentrations (1, 5, 10, 17 and 19) are located in the Vale do Rio do Peixe Formation, Alluvial deposits and Undifferentiated Detrital Cover Units, where there is a predominance of *Latossolos Vermelhos Álicos* and *Latossolos Vermelhos Distróficos* (Ferralsols), whose texture is linked to the sand and sandstone deposits. Sandy soils are composed of eroded sand particles, and Uranium may be present due to geological processes, such as the decomposition of uraniferous minerals in adjacent rocks. Despite the sediments composed predominantly of

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quartz, which would normally have lower values, the highest concentrations were detected in the northeast, northwest and southwest.

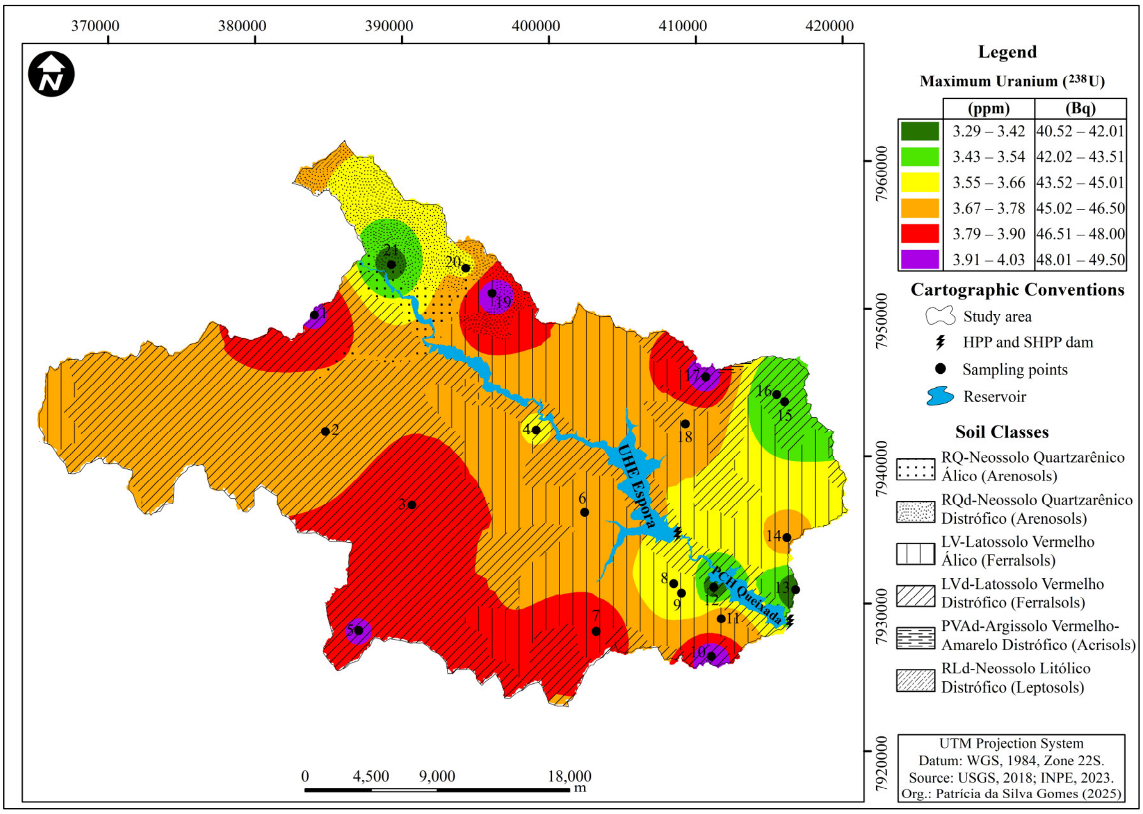

Figure 5. Uranium concentration in the soil of the study area.

Thorium concentrations ranged from 2.14 to 7.02 Bq/kg as shown in Figure 6, and the values are below average when compared with the average values of Brazilian and international soils as previously shown in Table 4, with a world average of 45 Bq/kg.

In general, the lowest concentrations of Thorium were found upstream of the Espora reservoir and on the right bank, in the southwestern portion. The highest concentrations were observed in the northeast, on the left bank of the reservoir, and in the southeast region, near the Queixada SHPP dam. Although there are low concentrations, it is noticeable that the area has points with higher concentrations, such as points 11, 12 and 13 around the Queixada SHPP and points 17, 19 and 20 on the left bank of the watershed. Despite having low concentrations, some points such as 11, 12 and 13 in the Queixada SHPP region, and 17, 19 and 20 on the left bank of the watershed exhibit higher concentrations. Points 11, 12 and 13 are associated with *Latossolos* (Ferralsols), whose predominance is due to the Serra Geral Formation; on the other hand, points 17, 19 and 20 are associated with soils of the Vale do Rio do Peixe Formation.

In general, higher radiation levels have been associated with igneous rocks, while sedimentary rocks have relatively lower radiation levels [56]. Another possible explanation is associated with erosive processes, in which Th-rich minerals were eroded and transported to the most downstream parts of the study watershed, where they were concentrated [57]. Located on the left bank of the watershed, points 17, 19 and 20 are situated on *Latossolo Vermelho* (Ferralsols) and *Neossolo Quartzarênico* (Arenosols). The geology along the entire left bank of the reservoir is characterized by the predominance of the Undifferentiated Detrital Cover Unit, consisting of sand and gravel deposits. Therefore, mineral quartz predominates at these points. Thorium is found in quartz and feldspar minerals in rocks or forming Th minerals such as thorianite, monazite, cheralite, huttonite, and thorite [57].

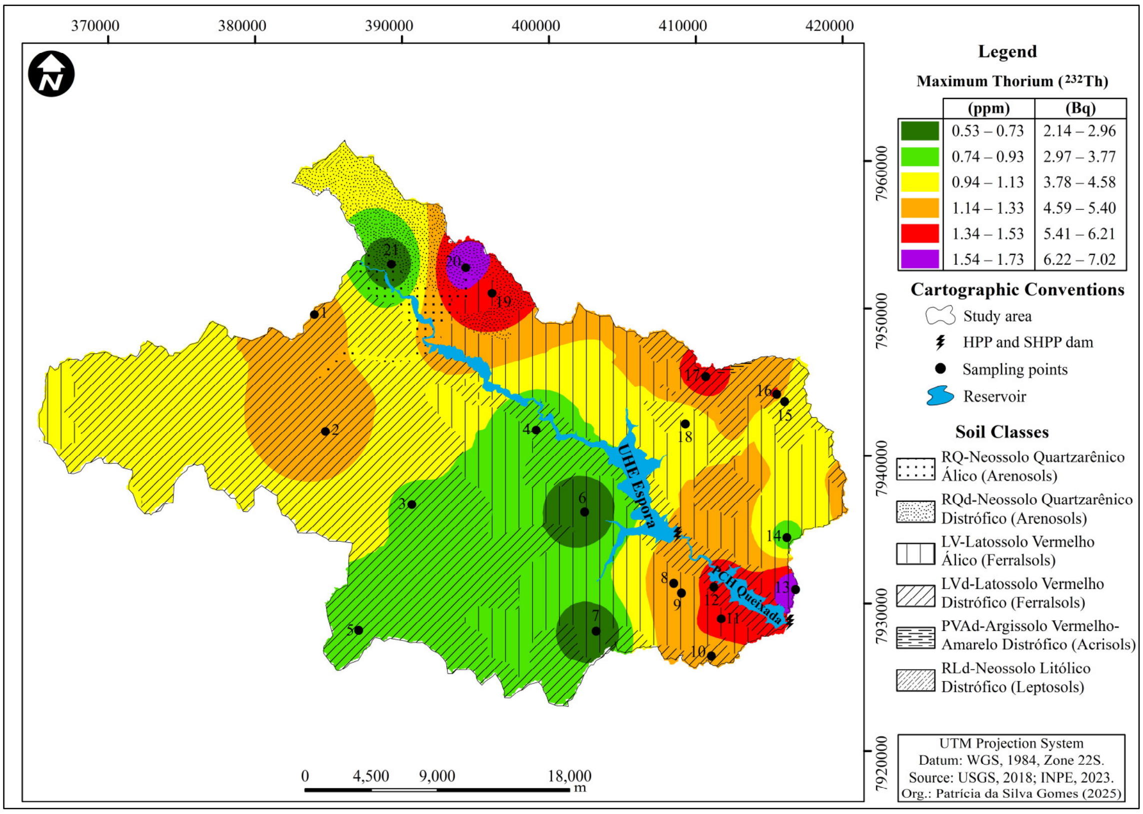

Figure 6. Thorium concentration in the soil of the study area.

At point 20, in addition to the characteristics mentioned, the predominant land use is agriculture. Th concentration in sedimentary soils depends on the type of parent rock, but the concentration of Th in the soil in agricultural area may be higher due to the use of either phosphate fertilizers or phosphate rock processed with sulfuric acid [58,59]. An increase in ^{232}Th concentrations was observed in soils with sugarcane cultivation in the municipality of Barretos, possibly due to the intensive use of fertilizers [60].

3.3. Principal Component Analysis (PCA)

The concentrations of the natural radionuclides ^{40}K, ^{238}U, and ^{232}Th and the results of the analyzed parameters (pH, organic matter, sand, clay and silt) in the soils collected at 0–20 cm depth are shown in Table 5.

Table 5. Statistical results of radionuclide concentrations, chemical data and particle-size data of soils collected at 0–20 cm depth.

	^{40}K	^{238}U	^{232}Th	pH (H_2O)	OM	Sand	Clay	Silt
	------ Bq/kg ------				g/kg	---------- % ----------		
Minimum	53.94	40.52	2.14	4.67	0.49	51.46	7.45	1.64
Maximum	77.50	49.50	7.02	6.54	24.64	90.91	30.64	17.90
Mean	64.49	45.44	4.53	5.52	10.09	85.11	10.43	4.47
Stand. Deviation	6.17	2.83	1.56	0.54	4.85	7.98	4.86	3.22
Coeff. of Variation	9.56	6.23	34.37	9.82	48.07	9.38	46.56	72.09

It can be observed that the soil texture has sand contents within the range of 51.46 to 90.91%, clay contents between 7.45 and 30.64% and silt contents between 1.64 and 17.90%. Organic matter has a minimum concentration of 0.49 g/kg and a maximum of 24.64 g/kg. The pH ranged from 4.67 to 6.54. Potassium concentration ranged from 53.94 to 77.50 Bq/kg, uranium ranged from 40.52 to 49.50 Bq/kg, and thorium concentration ranged from 2.14 to 7.02 Bq/kg.

PCA was used to identify the multivariate patterns governing the distribution of radionuclides (^{40}K, ^{238}U, ^{232}Th) in the study area, simultaneously considering soil physicochemical attributes (texture, organic matter, and pH). This technique is widely recognized for its robustness in interpreting complex and collinear environmental datasets and is particularly suitable for heterogeneous pedological systems such as those investigated in the current study. Thus, PCA enables the understanding of structural relationships among variables that would not be identified by univariate tests, meeting the aims of the study and the multivariate approach required for this type of analysis. The first two principal components shown in Figure 7 explained most of the total variance in the dataset, revealing distinct patterns between radionuclides and soil characteristics. PC1 highlighted a positive association between the elements ^{238}U and ^{232}Th and silt, clay, and organic matter contents, indicating that these radionuclides tend to concentrate in finer fractions with greater adsorption capacity. PC2 revealed a positive correlation between ^{40}K and sandy soils, particularly in agricultural and forestry areas, suggesting combined influence from both textural characteristics and anthropogenic input associated with potassium-based fertilizers.

Figure 7 shows the Principal Component Analysis (PCA) results for the 21 sampling points considering different environmental variables.

These trends are consistent with observations from recent studies. When analyzing lateritic soils in Mamuju, Indonesia, demonstrated that U and Th show strong affinity for finer particles and high organic matter contents, reinforcing the interpretation for PC1 [61]. Similarly, the continuous application of NPK-based fertilizers contributes to the enrichment of ^{40}K and increases in ^{238}U and ^{232}Th in agricultural soils, corroborating the pattern observed in PC2 [62]. Soil attributes, such as texture, mineralogy, and pH exert significant control over radionuclide mobility and availability, supporting the multivariate approach adopted in this study [63].

Eight variables were used, synthesizing in the two main axes the chemical and physical characteristics and the occurrences of radionuclides ^{40}K, ^{238}U and ^{232}Th in the soil. It can be observed that the closer the points are positioned in the PCA, the greater their similarity. The analyzed data are qualitatively related to the concentrations of ^{40}K, ^{238}U and ^{232}Th and the variables sand, clay, silt, pH and OM of the soil. A positive correlation is observed between the concentrations of ^{40}K at points 2, 5, 6 and 15 and the sand content. These points are located in areas with deposits of sand, gravel, clay, sandstone and sandy claystone. For the ^{238}U variable, a positive correlation was observed at points 10, 17, 18 and 19, also associated with sand content, with sand, gravel and clay deposits at these sites. As for ^{232}Th, the concentrations at sampling points 11, 13, 16 and 19 showed a higher correlation with deposits of basalts, sand, gravel, clay, sandstone and sandy claystone, and were also more associated with sand content. According to PCA, pH and organic matter showed a positive correlation with points 4, 12 and 21, which are related to the clay and silt variables. Point 12 had the highest concentration of organic matter (24.64 g/kg). The variables pH, OM, clay and silt were more correlated with uranium concentrations.

Thorium (Th) and uranium (U) can be adsorbed on clay minerals and organic matter [57], corroborating the experimental results presented in this work. At point 12, where the land use is pasture, the higher concentration of organic matter can be justified by the action of the root system of the plants, as roots distribute organic matter in the superficial layer of the soil [64]. The more acidic pH found in the study area, characteristic of *Latossolos Vermelhos* (Ferralsols), is consistent with the description of soils aged, acidic or strongly acidic, with a virtual absence of illuviation [65]. Similar results were found associating acidic soils with the slow mineralization of organic matter, releasing organic acids both in surface and in subsurface [66].

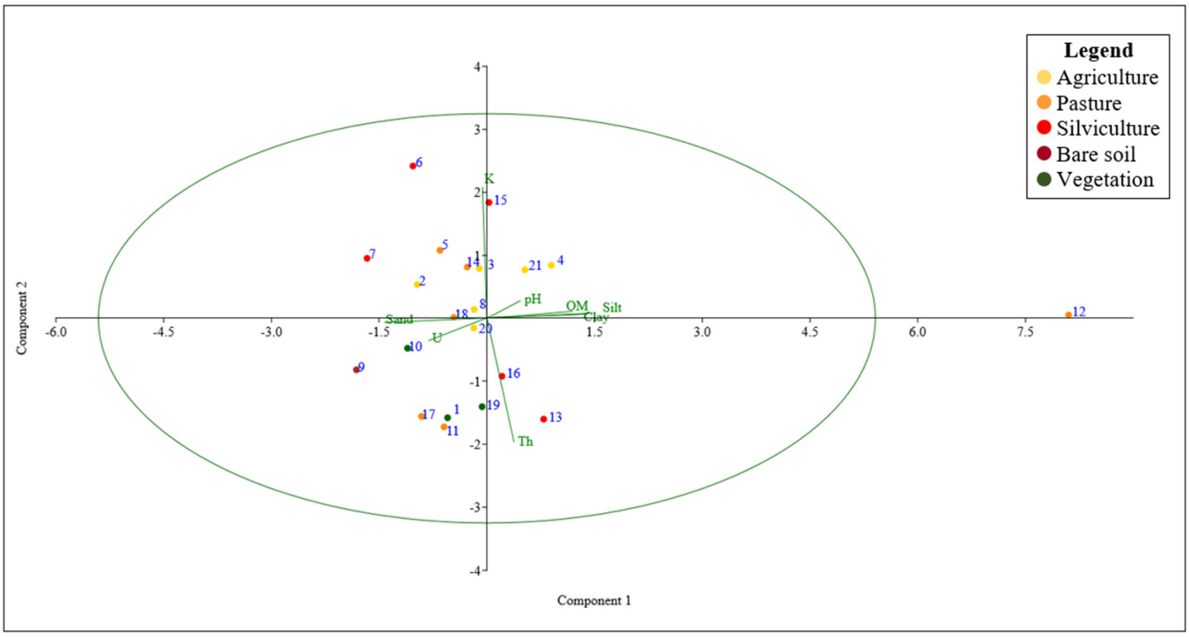

Figure 7. Principal component analysis (PCA) results for the 21 sampling points considering different environmental variables.

The use of PCA is also supported by studies applying the technique to interpret the natural distribution of radionuclides in volcanic ash-derived soils in the Argentine Patagonia [67]. Their findings demonstrated that PCA can separate distinct environmental processes and identify the variables that most influence radionuclide geochemistry. As in the current work, those authors emphasize that multivariate analysis provides an integrated understanding of the system, overcoming the limitations of univariate techniques. Thus, PCA proved fully adequate for the objectives of this study, allowing the identification of two main environmental patterns: (i) the enrichment of U and Th in clayey and silty soils, which are more weathered and richer in organic matter; (ii) the enrichment of ^{40}K in sandy soils, where there is a combined influence of texture and agricultural practices.

4. Conclusions

The soil texture has sand contents ranging from 51.46 to 90.91%, clay contents from 7.45 to 30.64% and silt contents from 1.64 to 17.90%. The organic matter contents ranged from 0.49 to 24.64 g/kg, whereas the pH values ranged from 4.67 to 6.54. Potassium concentrations ranged from 53.94 to 77.50 Bq/kg, uranium concentrations ranged from 40.52 to 49.50 Bq/kg, and thorium concentrations ranged from 2.14 to 7.02 Bq/kg. The average radionuclide contents were 64.49, 45.44 and 4.53 Bq/kg for ^{40}K, ^{238}U and ^{232}Th, respectively. These results confirmed that the ^{40}K concentrations were below the averages established for Brazilian and international regulations, ^{238}U concentrations were similar to those reported in Tanzania and Italy soils, and ^{232}Th concentrations were lower than the averages found in soils from other Brazilian states. Higher concentrations of ^{40}K, ^{238}U and ^{232}Th were determined in the Alluvial Deposits, Undifferentiated Detrital Cover Units, and the Vale do Rio do Peixe Formation, which consist predominantly of sand

and sandstone deposits. *Latossolos* (Ferralsols), which usually have low fertility and are corrected by the use of fertilizers, may have influenced the concentrations of K and Th, as indicated in the PCA results. A positive correlation between sand content and ^{40}K, ^{238}U and ^{232}Th concentrations, as well as stronger correlations involving clay, silt, pH and organic matter, suggests interactions between radionuclides and soil constituents. The highest average ^{40}K concentration (64.49 Bq/kg) may be an indicative of environmental pollution by fertilizers, since part of the study area has intense agricultural activity. Overall, the distribution of radionuclides in the soils of the Espora HPP and Queixada SHPP watersheds may be related to geological, pedological, and anthropogenic factors. Finally, it is important to investigate the weathering and leaching processes on porous and permeable soil surfaces, as radionuclides may be transported to the subsoil, increasing the risk of groundwater contamination.

Author Contributions: P.d.S.G.: Data curation and formal analysis. A.A.d.B.: Data curation and formal analysis. J.B.P.C.: Conceptualization, funding acquisition, project administration, and writing—original draft. F.L.R.: Data curation and formal analysis. H.M.R.: Data curation and formal analysis. V.A.B.: Writing—original draft. A.T.P.: Data curation, funding acquisition, resources, supervision, and writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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References

1. Rocha, H.M.; Cabral, J.B.P.; Ramalho, F.L.; Barcelos, A.A.; Gomes, P.S.; Becegato, V.A.; Paulino, A.T. Distribution of Radionuclides in Soils of Drainage Basin/Cerrado Biome and Their Relationship with the Land Occupation and Use Model. *Appl. Geochem.* **2025**, *179*, 106253. [CrossRef]
2. Zgorelec, Ž.; Šoštarić, M.; Babić, D.; Šestak, I.; Mesić, M.; Perčin, A.; Petrinec, B. Effects of Fertilisation on Radionuclide Uptake by Maize from an Acidic Soil in Northwestern Croatia. *Soil. Tillage Res.* **2021**, *212*, 105030. [CrossRef]
3. Jakhu, R.; Ignatov, A.; Chaligava, O.; Grozdov, D.; Zinicovscaia, I. Radionuclide Content in Soil from Agricultural Lands in the Russian Federation. *Eur. Phys. J. Spec. Top.* 2025, 1–7, *in press*. [CrossRef]
4. Avwiri, G.O.; Ononugbo, C.P.; Olasoji, J.M. Radionuclide Transfer Factors of Staple Foods and Its Health Risks in Niger Delta Region of Nigeria. *Int. J. Innov. Environ. Stud. Res.* **2021**, *9*, 21–32.
5. Salam, M.B.; Hussein, H.H.; Abojassim, A.A. Assessment of Transfer Factor of Radionuclide from Agriculture Soil to Rice Samples in Al-Abbasiyah City, Al-Najaf Governorate. *Eur. Phys. J. Plus* **2025**, *140*, 315. [CrossRef]
6. Jeelani, G.; Hassan, W.; Saleem, M.; Sahu, S.K.; Pandit, G.G.; Lone, A. Trace Metal and Radionuclide Geochemistry of Soils in Western Himalaya: Implication to Ecological and Radiological Hazards. *Environ. Earth Sci.* **2022**, *81*, 205. [CrossRef]

7. Jibiri, N.N.; Eke, B.C. Radionuclide Contents in Soil, Sediments and Food Samples, and Incidences of Cancer in Oil Producing Localities in Imo State South-East Nigeria. *J. Radiat. Res. Appl. Sci.* **2022**, *15*, 90–97. [CrossRef]
8. Noguera, A.; Azcune, G.; Bentos Pereira, H.; Fornaro, L. Radionuclide Distribution in the Barra de Valizas—Aguas Dulces Region, Uruguay. *Environ. Earth Sci.* **2022**, *81*, 195. [CrossRef]
9. Kaintura, S.S.; Tiwari, K.; Devi, S.; Thakur, S.; Prasad, M.; Meena, D.; Singh, P.P. Mapping of Radionuclides for Radiological Impact Assessment in Cultivated Soils of Punjab, India. *Appl. Radiat. Isot.* **2025**, *223*, 111881. [CrossRef]
10. Prihatiningsih, W.R.; Makmur, M. Radioactivity Monitoring and Radiological Assessment of Radionuclides at Western Coastal of South Sulawesi. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *860*, 012012. [CrossRef]
11. Aureliano, T.; Ghilardi, A.M. Mapeamento Da Borda Sul-Sudeste Da Bacia Do Araripe Com Auxílio de Gamaespectrometria e Magnetometria. *Geol. USP Série Científica* **2024**, *24*, 73–85. [CrossRef]
12. Naeem, N.; Sohail, M.; Ahmed, R.; Masood, S. Application of Gamma Spectrum Analysis Techniques for Natural Radioactivity Measurements Using NaI(Tl) Detector. *Environ. Monit. Assess.* **2025**, *197*, 418. [CrossRef] [PubMed]
13. Minty, B.R.S. *A Review of Airborne Gamma-Ray Spectrometric Data Processing Techniques*; Bureau of Mineral Resources, Geology and Geophysics, Canberra (Australia): Canberra, Australia, 1988.
14. Dickson, B.L.; Scott, K.M. Interpretation of Aerial Gamma-Ray Surveys—Adding the Geochemical Factors. *AGSO J. Aust. Geol. Geophys.* **1997**, *17*, 187–200.
15. Becegato, V.A. Aplicação de Técnicas Geofísicas e Geoquímicas em Duas Glebas Agrícolas do Noroeste do Estado do Paraná e Suas Relações Com Fertilizantes Fosfatados. Ph.D. Thesis, Universidade Federal do Paraná, Curitiba, Brazil, 2005.
16. Singh, B.; Kant, K.; Garg, M. Monitoring of Natural Radionuclides by Alpha Scintillometry and Gamma Spectrometry Techniques in Soil of District Palwal, Southern Haryana, India. *Int. J. Environ. Anal. Chem.* **2024**, *104*, 73–86. [CrossRef]
17. Raja, V.; Neelakantan, M.A. Spatial Interpretation, Radiological Mapping of Background Gamma Radiation and Risk Evaluation for Southern Regions of Tamil Nadu, India. *Environ. Forensics* **2024**, *25*, 59–67. [CrossRef]
18. Ramalho, F.L.; Cabral, J.B.P.; Becegato, V.A. Radionuclídeos naturais: Área de influência do parque nacional das emas. In *Análise Integrada e Estudos Geográficos Comparados em Bacias Hidrográficas de São Paulo, Goiás e Rio Grande do Sul*; Universidade Franciscana: Santa Maria, Brazil, 2020; pp. 296–321.
19. Liu, Y.; Zhou, W.; Liu, H.; Wei, Q.; Gao, B.; Chen, G. Spatial Variability and Radiation Assessment of the Radionuclides in Soils and Sediments around a Uranium Tailings Reservoir, South of China. *J. Radioanal. Nucl. Chem.* **2020**, *324*, 33–42. [CrossRef]
20. Cardoso, M.R.D.; Marcuzzo, F.F.N. Classificação Climática de Köppen-Geiger Para o Estado de Goiás e o Distrito Federal. *ACTA Geográfica* **2014**, *8*, 40–55. [CrossRef]
21. Gomes, J.G.; Matos, R.M.P. Análise de Tendencias Multitemporal Nos Municípios de Alto Paraíso, Cavalcante e Colinas Do Sul–GO. *Rev. Tocantinense Geogr.* **2018**, *7*, 117–127.
22. de Barcelos, A.A. Avaliação Das Condições Limnológicas e Sedimentológicas do Reservatório da Usina Hidrelétrica de Espora-GO. Ph.D. Thesis, Universidade Federal de Jataí, Jataí, Brazil, 2021.
23. SIEG. Sistema Estadual de Geoinformação de Goiás. Available online: http://www.sieg.go.gov.br/siegdownloads/ (accessed on 5 February 2025).
24. UNSCEAR. *Sources and Effects of Ionizing Radiation*; United Nations: New York, NY, USA, 2000; Volume 1, ISBN 92-1-142238-8.
25. UNSCEAR. *Sources, Effects and Risks of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation*; United Nations: New York, NY, USA, 2020.
26. Camargo, O.A.; Moniz, A.C.; Jorge, J.A.; Valadares, J.M.A.S. *Métodos de Análise Química, Mineralógica e Física de Solos do Instituto Agronômico de Campinas*; Instituto Agronômico: Campinas, Brazil, 2009.
27. dos Santos, A.C.L.; de Tarso Luiz Menezes, P.; do Nascimento, C.T.C. Gamaespectrometria Aplicada Em Solo Agrícola No Noroeste Do Estado Do Rio de Janeiro. *Rev. Bras. Geofísica* **2008**, *26*, 181–194. [CrossRef]
28. Becegato, V.A.; Becegato, V.R.; Baum, C.A.; Lavnitcki, L.; Paulino, A.T. Multivariate Statistical Analysis Correlating 238U, 232Th, and 40K Equivalent Activities in Soil to Geochemical Data from an Agricultural Area. *J. Soils Sediments* **2019**, *19*, 1901–1910. [CrossRef]
29. Bocardi, J.M.B. Valores de Referência de Qualidade de Metais, Macroelementos e Radionuclídeos em Solos do Oeste do Paraná. Ph.D. Thesis, Universidade Estadual do Centro-Oeste, Guarapuava, Brazil, 2019.
30. de Vargas, T.; Gomes, M.G.; Belladona, R.; Adami, M.V.D. Aplicação do Interpolador IDW Para Elaboração de Mapas Hidrogeológicos Paramétricos Na Região Da Serra Gaúcha. *Sci. Cum Ind.* **2018**, *6*, 38–43. [CrossRef]
31. CPRM/RADAMBRASIL SIEG Downloads—IMB. Available online: http://www.sieg.go.gov.br/maps/datasieg/geologia.zip (accessed on 5 February 2025).
32. Marconato, A.; Turra, B.B.; Salvador, E.D.; Chieregati, L.A.; D'Agostino, L.Z.; Perrotta, M.M.; Lopes, R.d.C. *Programa Geologia do Brasil Mapa Geológico do Estado de São Paulo. Escala 1:750.000*; CPRM: São Paulo, Brazil, 2005.
33. Moreira, M.L.O.; Moreton, L.C.; de Araújo, V.A.; de Lacerda Filho, J.V.; da Costa, H.F.d. *Geologia do Estado de Goiás e Distrito Federal*; CPRM/SIC—FUNMINERAL: Goiânia, Brazil, 2008.

34. Bizzi, L.A.; Schobbenhaus, C.; Vidotti, R.M.; Gonçalves, J.H. *Geologia, Tectônica e Recursos Minerais Do Brasil: Texto, Mapas & SIG*; CPRM—Serviço Geológico do Brasil: Brasília, Brazil, 2003.
35. de Lacerda Filho, J.V.; Gollmann, K.; dos Santos, D.R.V.; Martins, F.R.; Souza, J.O.; Carneiro, J.d.S.M.; Meneghini, P.F.V.-B.; Hattingh, K.; da Silva, É.R.; Eberhardt, D.B. *Projeto Geologia e Metalogenia da Porção Oeste de Goiás*; CPRM: Goiânia, Brazil, 2021.
36. dos Santos, H.G.; Jacomine, P.K.T.; dos Anjos, L.H.C.; de Oliveira, V.Á.; Lumbreras, J.F.; Coelho, M.R.; de Almeida, J.A.; de Araújo Filho, J.C.; de Oliveira, J.B.; Cunha, T.J.F.; et al. *Sistema Brasileiro de Classificação de Solos*, 5th ed.; Embrapa: Brasília, Brazil, 2018; ISBN 978-85-7035-800-4.
37. WRB. *World Reference Base for Soil Resources*, 4th ed.; International Union of Soil Sciences (IUSS): Vienna, Austria, 2022.
38. do Prado, H. *Arquivo do Agrônomo-No 1 (2ª Edição-Ampliada e Totalmente Modificada) A Pedologia Simplificada*; POTAFOS: São Paulo, Brazil, 1995.
39. Silva, C.A.D.O.; da Assunção, H.F.; da Costa, C.H.M. Environmental Management and Its Influence on the Quality of Cerrado Soils. *Rev. Ciência Geográfica* **2024**, *28*, 258–273. [CrossRef]
40. Șenilă, M.; Neag, E.; Tănăselia, C.; Șenilă, L. Removal of Cesium and Strontium Ions from Aqueous Solutions by Thermally Treated Natural Zeolite. *Materials* **2023**, *16*, 2965. [CrossRef] [PubMed]
41. Ribeiro, F.C.A.; Lauria, D.d.C.; Silva, J.I.R.; Lima, E.S.A.; do Amaral Sobrinho, N.M.B.; Pérez, D.V. Baseline and Quality Reference Values for Natural Radionuclides in Soils of Rio de Janeiro State, Brazil. *Rev. Bras. Cienc. Solo* **2018**, *42*, e0170146. [CrossRef]
42. Peixoto, C.M.; Balaine, F.; Taddei, M.H.T.; Jacomino, V.M.F. Determination of soil screening levels for U and Th in Minas Gerais State, Brazil. In *Naturally Occurring Radioactive Material (NORM VII), Proceedings of an International Symposium, Beijing, China, 22–26 April 2013*; International Atomic Energy Agency (IAEA): Beijing, China, 2013; pp. 13–21.
43. Ugbede, F.O.; Osahon, O.D.; Akpolile, A.F. Natural Radioactivity Levels of ^{238}U, ^{232}Th and ^{40}K and Radiological Risk Assessment in Paddy Soil of Ezillo Rice Fields in Ebonyi State, Nigeria. *Environ. Forensics* **2022**, *23*, 32–46. [CrossRef]
44. Usikalu, M.R.; Morakinyo, R.O.; Orosun, M.M.; Achuka, J.A. Assessment of Background Radiation in Ojota Chemical Market, Lagos, Nigeria. *J. Hazard. Toxic. Radioact. Waste* **2023**, *27*, 04022041. [CrossRef]
45. Tositti, L.; Cinelli, G.; Brattich, E.; Galgaro, A.; Mostacci, D.; Mazzoli, C.; Massironi, M.; Sassi, R. Assessment of Lithogenic Radioactivity in the Euganean Hills Magmatic District (NE Italy). *J. Environ. Radioact.* **2017**, *166*, 259–269. [CrossRef]
46. Focus, E.; Rwiza, M.J.; Mohammed, N.K.; Banzi, F.P. The Influence of Gold Mining on Radioactivity of Mining Sites Soil in Tanzania. *EQA—Int. J. Environ. Qual.* **2021**, *46*, 46–59.
47. Kinyua, R.; Atambo, V.O.; Ongeri, R.M. Activity Concentrations of ^{40}K, ^{232}Th, ^{226}Ra and Radiation Exposure Levels in the Tabaka Soapstone Quarries of the Kisii Region, Kenya. *Afr. J. Environ. Sci. Technol.* **2011**, *5*, 682–688.
48. Duong, N.T.; Van Hao, D.; Bui, V.L.; Duong, D.T.; Phan, T.T.; Le Xuan, H. Natural Radionuclides and Assessment of Radiological Hazards in MuongHum, Lao Cai, Vietnam. *Chemosphere* **2021**, *270*, 128671. [CrossRef]
49. Oladele, B.B.; Ugbede, F.O.; Arogunjo, A.M. Study of Activity Concentrations of ^{40}K, ^{238}U and ^{232}Th for Assessment of Radiation Dose in Agricultural Soils of Southwestern Nigeria. *Int. J. Environ. Health Res.* **2023**, *33*, 1640–1651. [CrossRef]
50. Rahman, K.A.; Khan, R.; Rashid, M.d.B.; Aldawood, S.; Islam, M.d.S.; Islam, M.d.T.; Uddin, M.d.M.; Idris, A.M.; Khan, M.d.H.R.; Habib, M.d.A.; et al. Monitoring and Health Risks Assessment of Primordial Radionuclides in Vegetables and Agricultural Soils in Some Hilly Regions of Southeastern Bangladesh. *Arch. Environ. Contam. Toxicol.* **2025**, *89*, 95–124. [CrossRef]
51. Tagami, K.; Uchida, S. Soil-to-Crop Transfer Factor: Consideration on Excess Uranium from Phosphate Fertilizer. In *Uranium in Plants and the Environment*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 163–180.
52. Mwalongo, D.A.; Haneklaus, N.H.; Carvalho, F.P.; Lisuma, J.B.; Kivevele, T.T.; Mtei, K.M. Influence of Phosphate Fertilizers on the Radioactivity of Agricultural Soils and Tobacco Plants in Kenya, Tanzania, and Uganda. *Environ. Sci. Pollut. Res.* **2023**, *30*, 83004–83023. [CrossRef]
53. John, W.A.; Lückel, B.; Matschiavelli, N.; Hübner, R.; Matschi, S.; Hoehenwarter, W.; Sachs, S. Endocytosis is a Significant Contributor to Uranium(VI) Uptake in Tobacco (Nicotiana Tabacum) BY-2 Cells in Phosphate-Deficient Culture. *Sci. Total Environ.* **2022**, *823*, 153700. [CrossRef]
54. Schumann, W. *Gemas Do Mundo*, 9th ed.; Ao Livro Técnico: Rio de Janeiro, Brazil, 2002.
55. Luz, A.B.; Lins, F.A.F. *Rochas & Minerais Industriais: Usos e Especificações*; CETEM/MCT: Rio de Janeiro, Brazil, 2005; ISBN 85-7227-217-8.
56. Bajoga, A.D.; Al-Dabbous, A.N.; Abdullahi, A.S.; Alazemi, N.A.; Bachama, Y.D.; Alaswad, S.O. Evaluation of Elemental Concentrations of Uranium, Thorium and Potassium in Top Soils from Kuwait. *Nucl. Eng. Technol.* **2019**, *51*, 1638–1649. [CrossRef]
57. Mello, D.C.; Demattê, J.A.M.; Mello, F.A.O.; Poppiel, R.R.; Silvero, N.E.Q.; Safanelli, J.L.; Souza, A.B.; Di Raimo, L.A.D.L.; Rizzo, R.; Resende, M.E.B.; et al. Applied Gamma-Ray Spectrometry for Evaluating Tropical Soil Processes and Attributes. *Geoderma* **2021**, *381*, 114736. [CrossRef]
58. Wetterlind, J.; Forges, A.C.R.; Nicoullaud, B.; Arrouays, D. Changes in Uranium and Thorium Contents in Topsoil after Long-Term Phosphorus Fertilizer Application. *Soil. Use Manag.* **2012**, *28*, 101–107. [CrossRef]

59. Fesenko, S.V.; Emlutina, E.S. Thorium Concentrations in the Environment: A Review of the Global Data. *Biol. Bull.* **2021**, *48*, 2086–2097. [CrossRef]
60. Gonçalves, I.L.; Geraldo, L.P.; Semmler, R. Medidas de Radioatividade Natural Em Amostras de Solos de Cultivo Da Cana-de-Açúcar Na Região de Barretos, SP. *Cienc. Cult.* **2012**, *8*, 65–73.
61. Abdullah, A.R.A.; Permana, S.; Srigutomo, W.; Maulana, A.; Irwanto, D.; Seno, H.; Purnama, D.S.; Wafda, H.; Wulandari, C.; Wahyudi, W.; et al. Investigating the Soil Surface Properties behind Elevated Natural Radiation in Mamuju, Indonesia. *Sci. Rep.* **2025**, *15*, 38287. [CrossRef] [PubMed]
62. Mankala, J.B.; Sawe, S.F.; Moirana, R.L. Assessing the impact of phosphate fertilizer application on radionuclide accumulation in soil and Spinacia oleracea. *J. Ecol. Eng.* **2025**, *26*, 38–48. [CrossRef] [PubMed]
63. Dirican, A.; Dikmen, H.; Şahin, M.; Gülay, Y.; Özkök, Y.Ö.; Kaya, N.; Vural, M. Transfer Factors of ^{238}U, ^{232}Th, ^{40}K, ^{210}Pb to Crops and Radiation Impact Assessment in Semi-Arid Environment. *J. Radioanal. Nucl. Chem.* **2024**, *333*, 5597–5606. [CrossRef]
64. Figueiredo, C.C.; Ramos, M.L.G.; Tostes, R. Propriedades Físicas e Matéria Orgânica de Um Latossolo Vermelho Sob Sistemas de Manejo e Cerrado Nativo. *Biosci. J.* **2008**, *24*, 24–30.
65. Jordão, C.P.; Alves, N.M.; Pereira, J.L.; Bellato, C.R.; Alvarez, V.V.H. Adsorção de Íons Cu^{2+} Em Latossolo Vermelho-Amarelo Húmico. *Quim. Nova* **2000**, *23*, 5–11. [CrossRef]
66. Lima, J.S.S.; Silva, S.A.; Silva, J.M. Variabilidade Espacial de Atributos Químicos de um Latossolo Vermelho-Amarelo Cultivado em Plantio Direto. *Rev. Ciência Agron.* **2013**, *44*, 16–23. [CrossRef]
67. La Manna, L.; Gaspar, L.; González Comunian, D.; Navas, A. Assessment of Environmental Radionuclides and Controlling Factors in Volcanic Soils of Andean Patagonia. *Geoscience* **2025**, *15*, 348. [CrossRef]