



# Radiological hazard assessments of natural radionuclides in surface soil in Chau Binh, Vietnam

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## ABSTRACT

An assessment of primordial concentrations in soil samples from Chau Binh, Nghe province, Vietnam, was conducted to evaluate potential radiological hazards to local inhabitants. The average activity concentration of the radionuclides determined using HPGe  $\gamma$ -ray spectrometry, were found to be ( $96.8 \text{ kg}^{-1}$ ) for  $^{238}\text{U}$ , ( $249.7 \text{ kg}^{-1}$ ) for  $^{232}\text{Th}$ , and ( $473.5 \text{ kg}^{-1}$ ) for  $^{40}\text{K}$ , being higher than the world average concentration values. The risk indices computed, subsequently, indicate the absorbed dose ( $42.6 - 362.5 \text{ nGy}^{-1}$ ) and annual effective dose equivalents ( $1.3 \text{ mSv}$ ) received by individuals to be higher than the permissible limits recommended by UNSCEAR. Such high radiation levels in Chau Binh attributes to the geological characteristics of the soil which is deposited with rich placers of monazite mineral. The composition including orthophosphate, Silimanite, Garnet, Biotite-amphibolite quartzite and marble lenses further adds to the elevated levels of radioactivity in this region. In addition to this, higher concentration of  $^{232}\text{Th}$  than  $^{238}\text{U}$ , indicates the environment to be oxidizing in nature.

## 1. Introduction

The presence of natural radionuclides, specifically  $^{226}\text{Ra}$ ,  $^{40}\text{K}$ ,  $^{238}\text{U}$ , and  $^{232}\text{Th}$ , has been observed on Earth since its inception, and as such, they are commonly referred to as primordial radionuclides [1]. The natural radionuclides distribution is influenced by a variety of factors, including geological processes, weathering, human activities, including mining activities, nuclear power plants, and atmospheric deposition. According to [2], soil and sediments have generally been recognized as possible repositories for radionuclides and other forms of pollutants. Soils that contain radionuclides act as an interface between the air and water and other elements of the physical environment [3].

The significance of soil in radiation exposure is twofold: it functions both as a continuous source of radiation exposure and as a medium for

radionuclide transfer to living organisms [4]. The top layer of the soil is where most radiation exposure from soil occurs [5,6]. Here, radioactivity is mostly induced by  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ , or their decay products. This mandates effective radiation monitoring in several locations of the earth by assessing the radioactivity concentrations in surface soil samples. Since the life forms are being constantly exposed to the background radiation in the environment, understanding the patterns and drivers of radionuclides distribution becomes crucial for developing effective strategies to mitigate the risks associated with exposure to natural radionuclides [7,8].

The distribution of radionuclides in soil exhibits geographical variability [9], primarily attributed to differences in environmental matrices such as rocks, soil, sand, sediments, and silt [10,11]. They have been recognized as a possible factor in contributing to the

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environment's unequal distribution and enrichment of radioactive concentrations. Such non-uniform distribution of radiation has led to the identification of certain regions as natural high background radiation areas, where elevated levels of radiation are observed [12–14]. Some of the natural high background radiation areas of the world and the annual effective dose rate to the inhabitants residing in these areas are as follows: Yangjiang, China (4.3 mSv/y); Erasma coast, Orissa, India (2.4 mSv/y); Kerala, India (0.5 – 15 mSv/y); Pocos de Caldas, Araxa, Tapira and Guarapari in Brazil (3.5 – 10 mSv/y) and Ramsar, Iran (0.6 – 131 mSv/y) [15,16]. In these areas of high background radiations, the exorbitant presence of these natural radionuclides is due to the placer deposits present (where in most of the cases, it is monazite) accompanied with the process of disintegration of rocks and other materials [17–21]. Along with it, radionuclides bearing accessory minerals, for eg: sphene, zircon, apatite, allanite, mica and feldspars are the primary reason for high radioactivity [22]. Hence the natural radioactivity present in the soil depends mainly on the activity of the parent rocks and the type of formation and transfer processes of the radionuclides.

Exposure to Naturally Occurring Radioactive Materials (NORM) has been linked to many physiological issues, such as kidney malfunction, lung cancer, renal failure, and bone abnormalities [23,24]. Since naturally occurring primordial radioactive nuclides may have detrimental impacts on human health through ionizing radiation, their presence in the surrounding environment is a cause for great concern. While the exact mechanisms by which NORM exposure leads to these health problems are not yet fully understood, there is growing evidence to suggest a causal relationship. As such, efforts to mitigate NORM exposure and its associated health risks are of critical importance [23]. Ninety-six percent of the radiation dose that people worldwide receive comes from natural sources, and 4 % from artificial according to estimates [3,25,26]. The investigation of radionuclides' behaviour has revealed that they can cause both internal and external radiation exposures.

In the present investigation, an attempt was made to evaluate the characterization of the natural radionuclides present in Binh Chau village, located on the southeastern coast of Vietnam. There are few or no studies on the characteristics of natural radionuclide and the radiation hazard assessment to resident living in the study area. The current area of investigation is significant because it contains monazite placers, which might contribute to high radioactivity in these regions. Monazite, an orthophosphate of rare earth elements containing primarily uranium and thorium, contaminates the soil necessitating to monitor the radioactivity levels in such regions and the resulting toxicity to the environment and human health. Previous investigations carried out in the mineral deposits/ placers in geographical areas of Vietnam [27–31], had inferred the activity concentration of investigated radionuclides to be above the world average values. They further added the radionuclides dynamics in soil to be potentially dependent on the underlying geology of the region. For instance, in the southern region of the Vietnam country, the  $^{238}\text{U}$  and  $^{232}\text{Th}$  are present in minimal amounts in soil as they are derived from basalt and ancient alluvial sediments with low nutrient content. In contrast high radiation levels as observed in soils of North Vietnam region are due to diverse range of rock types such as granite, tonalite, mafic rocks, granodiorite, and migmatite, which altogether increases the radiological risk to the population. Hence, considering the significant influence of geographical characteristics on radioactivity levels of a region, in the present study, we attempt to ascertain the activity concentrations of radionuclides  $^{226}\text{Ra}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$  upon studying the geological composition, metamorphic history, alteration, weathering of the rocks, radionuclides' enrichment / depletion process at Binh Chau Village. This ultimately paves a way for understanding the radiological risks and potential impact on the public health and safety of Binh Chau village inhabitants. The data also serves to protect public health, development planning and orientation of sustainable resource exploitation in the selected area.

## 2. Materials and methods

### 2.1. Study area details

Chau Binh area in Quỳ Châu district, Nghệ An province, Vietnam has the characteristics of mountainous to high mountains with an altitude of 100 - 800 m, the terrain gradually rises to the northwest with a slope of 15 - 40°. The study region spans a total area of about 140 km<sup>2</sup>, a population of about 10,000 people, a dense river and stream system with the main river being the Hieu River, where the vegetation is quite rich mainly with regenerated forests [32,33]. In terms of climate, the region has 2 distinct dry seasons from November to April month of the year with rainfall of about 100–300 mm. The rainy season commences from May to October with rainfall from 1200 - 1500 mm, with the highest rainfalls in August. The study area has a rather complex geological structure, with the presence of Proterozoic age metamorphic sedimentary formations to Quaternary deposits and magmatic rocks of the Yen Sun complex. The primary mineral is monazite sandstone distributed in sedimentary formations by the Quaternary. The geological formations are distributed in the northwest-southeast direction.

The distribution from left to right of the geological map (Fig. 1) includes the below mentioned as follows:

- **Quaternary (Q) sediments:** This formation is mainly distributed in the survey and assessment areas including the regions of Quỳ Châu district, Quỳ Hop district of Nghệ An province. Main components of it includes pebbles, gravel, sand, clay and lateritized debris.
- **The Big River Formation (O3-S1sc2):** This region lies between the Quaternary Formation, as shown in (Fig. 1). It consists of powdered sand interspersed with quartzite-sericite shales, quartzites, and acid eruptive sediments [33].
- **The Compensation Formation (PR3-bk 1-2):** This region consists of two strata subsystems. The main composition is two-plexiglass quartzite-plagioclase-silimanite, granite-containing biotite, plagioclase-silimanite shale, biotitic quartzite - amphibole and marble glasses (Fig. 1).
- **Geological objects of the Y Yen Sun Complex (γ1ysk-p):** It is distributed to the southwest as represented in (Fig. 1). Main ingredients include plagiogranite, two-mica granite, amphibole granite and pegmatite.

Features of monazite ore: The mine has two ore bodies, the first ore body is distributed in the clay sand layer containing gravel, the ore body surrounds the banks of Co Ba stream, extending almost continuously for more than 2000 m, in the direction of northwest and southeast, with widths ranging from 50 to 300 m [34,35]. The radiation intensity ranged from 0.22 to 0.97 μSv/h. The second ore body is distributed in the sediment Aluvi, a strip-like ore body extending 2700 m in a northwest-southeast direction, the width ranges from 30 to 150 m. The radiation intensity ranged from 0.13 to 0.74 μSv/h.

### 2.2. Sampling procedure

Surface soil samples were collected from Chau Binh, an area with dense population in Vietnam (Fig. 1) for radionuclides assessment by following the standard sampling guidelines of IAEA [36]. Twenty-one soil samples were taken from residential areas that were near and surrounding the Monazite placer deposits. At each of the sampling sites, around five topsoil samples were collected upto a depth of 30 cm. The soils were mixed up, removed stone and roots and then the selected 1–2 kg, were packaged, and sent to the laboratory. The collected samples were dried for 24 to 48 h in oven at 110°C. The soil was milled and sieved into 0.2 mm-diameter samples. The study and IAEA reference samples were weighed and packed in containers to avoid radon release and lead an equilibrium between  $^{226}\text{Ra}$  and her progenies for four weeks before measurement. The  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ),  $^{238}\text{U}$  and  $^{40}\text{K}$

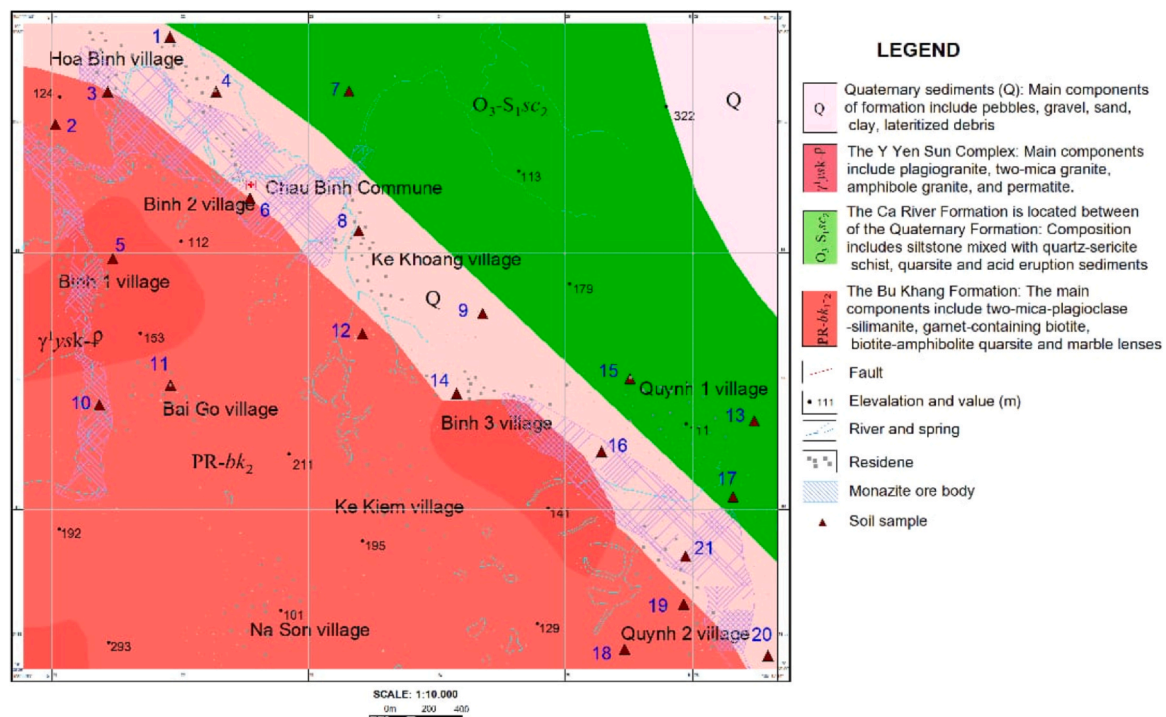


Fig. 1. Geo coordinates of the study area. Alt-text: Figure showing the sampling sites along with the co-ordinates.

were measured by the low background, with shielded lead chamber model 747, with high-resolution HPGe semiconductor detector. The gamma detector was used with the model BE6530 of Canberra™. The detector has a relative efficiency of 65 %, and energy resolution of 1.9 keV at the peak of  $^{60}\text{Co}$  1332 keV. The Genie 2000 software was used for analysed spectrum.

Based on the corresponding gamma lines in each sample, the activity concentration was calculated. The activity concentration of  $^{226}\text{Ra}$  was determined using the gamma lines of 1120.3 keV, 609.3 keV, and 1764.5 keV,  $^{40}\text{K}$  was determined using the gamma line of 1460 keV,  $^{238}\text{U}$  was determined using the line of 1001 keV (which was confirmed by  $^{235}\text{U}$  measurement with the 186 keV line). Both results based on 1001 keV line of  $^{234\text{m}}\text{Pa}$  and verified by  $^{235}\text{U}$  are similar, the difference of activity concentration is less than 5 %.  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ) was determined using the lines of 911.2 keV, (there is equilibrium between  $^{228}\text{Ra}$  and  $^{208}\text{Tl}$ , and the equilibrium between  $^{232}\text{Th}$  and  $^{228}\text{Ra}$  as the assumption and the really measured radionuclide is  $^{228}\text{Ra}$ ).  $^{232}\text{Th}$  was detected in soil samples under the assumption that  $^{232}\text{Th}$  and  $^{228}\text{Ra}$  ( $^{228}\text{Th}$ ) were in equilibrium [18,37–40].

The solid samples' different densities caused the self-gamma absorption, and standard samples were introduced using the technique outlined by [41]. The following formula is used to determine the activity concentrations of  $^{226}\text{Ra}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ), and  $^{40}\text{K}$  [42].

$$A_{sp} = \frac{N_{sp} M_{st} A_{st} C_i}{N_{st} M_{sp}} \quad (1)$$

Where:  $A_{sp}$  – Activity concentration of sample under study,  $A_{st}$  Activity concentration of standard sample,  $N_{sp}$ – Net intensity measured,  $M_{sp}$ – sample mass,  $M_{st}$  – standard mass,  $C_i$  - the correction factor for variation in sample and standard density.

The following equation was used for determining the Minimum Detection Limit (MDA) [43,44], which will be of concern for the lowest activity concentration sample, as mentioned below:

$$\text{MDA}(\text{Bq/kg}) = \frac{2, 71 + 4, 65\sqrt{N_B}}{t \times \varepsilon \times I_\gamma \times M} \quad (2)$$

Where:  $N_B$  – Counts of background;  $t$  - measurement time (s);  $\varepsilon$  – Detector's absolute efficiency (%);  $I_\gamma$  - probability of gamma emission;  $M$  - sample mass(kg).

The equation for uncertainty calculations, as employed for the present investigation was calculated using the formula as mentioned below:

$$\sigma_{A_{sp}} = A_{sp} \sqrt{\left(\frac{\sqrt{N_i}}{n_i}\right)^2 + \left(\frac{\sqrt{N_{st}}}{n_{st}}\right)^2 + \left(\frac{\sqrt{N_B}}{n_B}\right)^2} \quad (3)$$

Where:  $\sigma_{A_{sp}}$  – Activity uncertainty of measured isotope in sample,  $N_i$ ,  $N_{st}$ ,  $N_B$  are number of counts at measured peak i, peak i of standard sample, and background sample.

### 2.3. Radiological hazard risk parameters

#### 2.3.1. Absorbed dose rate

The gamma dose rate ( $D$ ) calculates the quantity of energy that ionising radiation deposits in a material and is used in determining the stochastic and deterministic effects of ionizing radiation to the general population [40,45]. The  $D$  has been evaluated using the conversion factors (Nano Gray per hour)  $\text{nGy h}^{-1}$  per  $\text{Bq kg}^{-1}$ .  $0.62 \text{ nGy.h}^{-1}/\text{Bq kg}^{-1}$  for  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ), it equals to  $0.46 \text{ nGy.h}^{-1}/\text{Bq kg}^{-1}$  for  $^{226}\text{Ra}$ , and  $0.042 \text{ nGy.h}^{-1}/\text{Bq kg}^{-1}$  for  $^{40}\text{K}$ . It was computed as follows [46].

$$D(\text{nGy.h}^{-1}) = 0.46A_{Ra} + 0.62A_{Th} + 0.042A_K$$

where,  $A_{Ra}$ ,  $A_{Th}$ , and  $A_K$  are activity concentration ( $\text{Bq/kg}$ ) of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ( $^{228}\text{Ra}$ ), and  $^{40}\text{K}$  respectively.

#### 2.3.2. Radium equivalent activity

Utilizing  $Ra_{eq}$ , it is possible to sum up the radiation risks and gamma output associated with different ratios of the elements  $^{232}\text{Th}$ ,  $^{238}\text{U}$ , and  $^{40}\text{K}$  in samples. It was calculated using a recognised relationship defined by [47,48]. Also,  $Ra_{eq}$  quantifies homogeneity in terms of radiation exposures in the unevenly distributed natural radionuclides in the samples [45]. This expression is given as [49]:

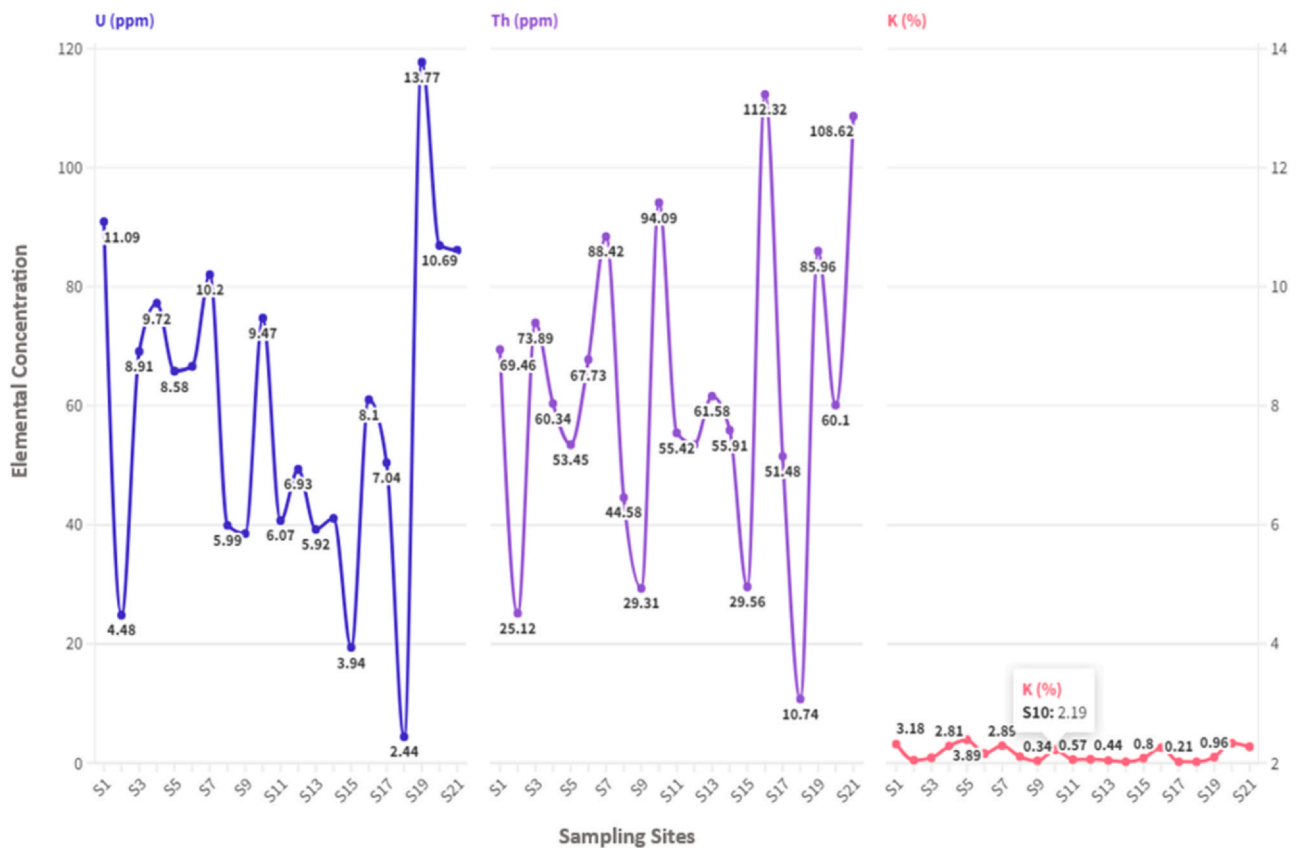


**Fig. 2.** Elemental concentration of U (ppm), Th (ppm), K (%). **Alt-text** – Graph showing elemental concentration of U (ppm), Th (ppm) and K(%) along the 21 sampling sites.

$$Ra_{eq} = A_{Ra} + 0.077 A_K + 1.43 A_{Th}$$

presented the maximum safe limit of  $Ra_{eq}$  to be  $370 \text{ kg}^{-1}$ .

### 2.3.3. External hazard index ( $H_{ex}$ )

$H_{ex}$  gives the yield of gamma from various combinations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  in the sample, is typically used to reflect external exposure. It is defined by [48] as:

$$H_{ex} = A_{Ra}/370 + A_K/4810 + A_{Th}/259$$

### 2.3.4. Internal hazard index ( $H_{in}$ )

$H_{in}$  is used to describe the radiological risk posed by radon and its daughters to the respiratory system [50]. It is stated as:

$$H_{in} = A_{Ra}/185 + A_K/4810 + A_{Th}/259$$

The  $H_{in}$  and  $H_{ex}$  values must be low than 1 for negligible radiation hazard.

### 2.3.5. Radioactivity level index ( $I_\gamma$ )

This index ( $I_\gamma$ ) is used to estimate the amount of radiation exposure, particularly the risk from gamma rays brought on by naturally occurring radionuclides in specific materials [50].

$$I_\gamma = A_{Ra}/150 + A_{Th}/100 + A_K/1500 \leq 1 \text{ nGy h}^{-1}$$

The safe limit for this index is  $\leq 1$ .

### 2.3.6. Annual effective dose equivalent (AEDE)

AEDE, which estimates the effective dose to an individual throughout the year can be determined using the following equation [40].

$$\text{For Outdoor, AEDE (mSv/y)} = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6}$$

$$\text{For indoor, AEDE (mSv/y)} = D \times 8760 \times 0.8 \times 0.7 \times 10^{-6}$$

Where D is absorbed gamma dose rate in nGy/h, a conversion factor ( $0.7 \text{ Sv/Gy}$ ), occupancy factors of 0.2 for outdoor exposure and 0.8 for interior exposure, and a time conversion factor ( $8760 \text{ h.y}^{-1}$ ).

### 2.3.7. Excess lifetime cancer risk (ELCR)

The ELCR represents a reasonable upper bound estimate of the likelihood that an individual will have cancer at some point in their lives because of radiation exposure. It can be estimated using the following formula [50].

$$\text{ELCR} = \text{AEDE} \times \text{RF} \times \text{DL}$$

where AEDE - annual effective dose equivalent, DL is the life duration of 70 years and RF is risk factor given as  $0.05 \text{ Sv}^{-1}$ .

## 2.4. Radio-elemental ratios

Ratio of elemental concentration of Thorium and Uranium can be employed to detect the oxygenation status of the investigated deposits.  $e\text{Th}/e\text{U}$  ratio is critical in detecting the geochemical face [51]. In reducing conditions uranium remains stable, immobile and in tetravalent state, or it can also become soluble and transportable hexavalent phase. On the other hand, there is geo chemical relationship between uranium and thorium, and thorium occurs only in its tetravalent state which is insoluble [52]. In the present study, the elemental concentrations were found by employing the conversion factors as follows:  $1 \text{ U} = 12.35 \text{ Bqkg}^{-1}$  of  $^{238}\text{U}$ ;  $1 \text{ ppm Th} = 4.06 \text{ Bqkg}^{-1}$  of  $^{232}\text{Th}$ ; and  $1 \% \text{ K} = 313 \text{ Bqkg}^{-1}$  of  $^{40}\text{K}$  [51]. From these concentrations, the ratios were obtained, where a ratio of  $e\text{Th}/e\text{U}$  less than 2 indicates reducing

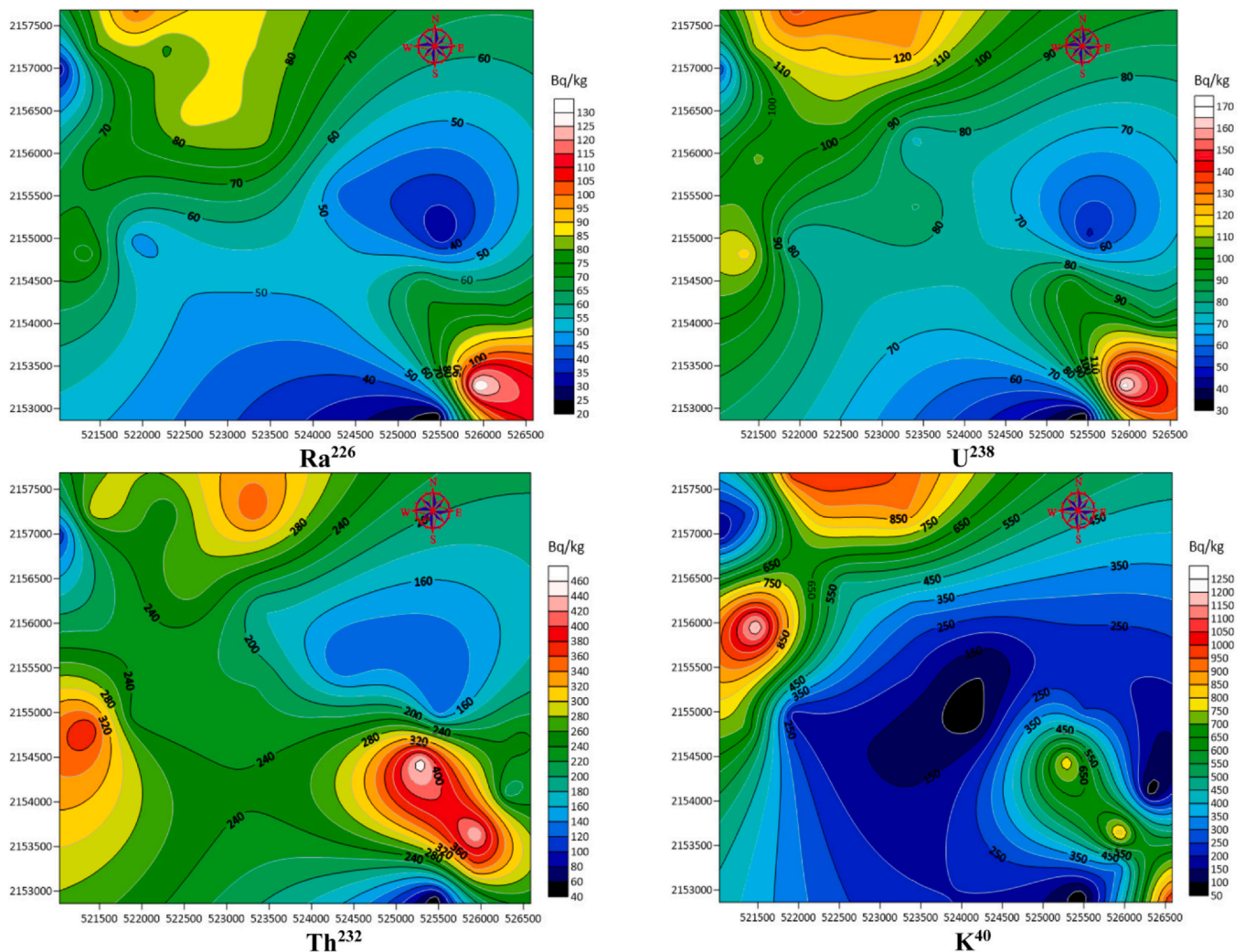


**Fig. 3.** Spatial distribution map for radionuclides activity concentration across the study area. **Alt-text:** Figure showing spatial variation of  $^{226}\text{Ra}$ ,  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  across the sampling sites.

environment and promotes uranium enrichment. The intermediate values (2 to 7) are believed to indicate quick deposition of igneous rock debris, and poor weathering, whereas  $e\text{Th}/e\text{U} > 7$ , signifies the loss of favourable enrichment, perhaps due to leaching [53]. By utilising conversion factors provided by [54], the measured activity concentrations of  $^{232}\text{Th}$ ,  $^{226}\text{Ra}$ , and  $^{40}\text{K}$  in  $\text{Bq.kg}^{-1}$  can be translated to  $e\text{U}$ ,  $e\text{Th}$  elemental concentrations in ppm, and potassium in percentage. 1 % K equals  $313 \text{ kg}^{-1}$  of  $^{40}\text{K}$ , one ppm Th equals  $4.06 \text{ kg}^{-1}$  of  $^{232}\text{Th}$ , and one ppm U equals  $12.35 \text{ kg}^{-1}$  of  $^{238}\text{U}$ .

### 3. Results and discussion

#### 3.1. Activity concentration of primordial radionuclides in the studied sites

The Activity concentration of primordials in the well-known province of Chau Binh, which is characterized by the presence of high mountains as its unique feature has been presented in (Tab-1). The mean radionuclide's activity concentration fell in ascending order as follows:  $^{226}\text{Ra} < ^{238}\text{U} < ^{232}\text{Th} < ^{40}\text{K}$ . Looking at the concentration of these individual radionuclides, the  $^{226}\text{Ra}$  activity ranged from 20.7 to  $131 \text{ Bq.kg}^{-1}$ , with the highest value being recorded at S19. The activity of  $^{238}\text{U}$  ranged from 30.1 to  $170 \text{ Bq.kg}^{-1}$ , being higher in location S19. The activity of  $^{232}\text{Th}$  was comparatively very high than the concentration of the other primordial radionuclides, the values ranging from 43 to  $456 \text{ Bq.kg}^{-1}$  and the activity being highest in location S16.

While the activity of  $^{40}\text{K}$  present, ranged from 57 to  $1218 \text{ Bq.kg}^{-1}$ , the highest values of it was obtained in location S5. Overall, the average concentration of were observed to be 71, 96.8, 249.7, 473.5 all of which are greater than the world average concentrations ( $^{238}\text{U}$  - 30  $\text{Bq/kg}$ ;  $^{232}\text{Th}$  - 35  $\text{Bq/kg}$  and  $^{40}\text{K}$  - 400  $\text{Bq/kg}$ ) [55]. The distribution of these radionuclides analyzed tends to be influenced by a variety of factors, including geological processes, weathering or due to the interference of human activities [56–58]. Comparing these values of the present study, the activity concentration of radionuclides are higher in Chau Binh than other places in Vietnam and certain high background radiation areas of the world, as shown in (Tab-2) (Fig. 3).

#### 3.2. Mineral composition and factors governing the background radiation of the studied sites

In general, the presence of radionuclides in the environment can be attributed to various natural and anthropogenic sources, including mining activities, nuclear power plants, and atmospheric deposition [59,60]. The variability in the enrichment of the radionuclides depends on these factors and on the interference of human activities in the area [61]. In the present study, higher radioactivity level, as observed in the selected sites were natural, due to the presence of monazite ore body. The radionuclides concentration and the consequent radiological risks were thus higher than the world average concentrations ( $^{238}\text{U}$  - 30  $\text{Bq/kg}$ ,  $^{232}\text{Th}$  - 35  $\text{Bq/kg}$  and  $^{40}\text{K}$  - 400  $\text{Bq/kg}$ ) and the permissible limits

**Table 1**  
Activity concentration of radionuclides, elemental concentration ratios and radiological risk parameters.

| Sample  | <sup>226</sup> Ra (Bq/kg) | <sup>232</sup> Th (Bq/kg) | <sup>40</sup> K (Bq/kg) | eTh/eU       | eK/eU | eK/eTh | Req    | ADR    | AEDE | ELCR | H <sub>ex</sub> | H <sub>in</sub> | GRLI |
|---------|---------------------------|---------------------------|-------------------------|--------------|-------|--------|--------|--------|------|------|-----------------|-----------------|------|
| S1      | 101 ± 9.2                 | 137 ± 12.8                | 282 ± 31.3              | 996 ± 113.4  | 6.26  | 0.29   | 580.95 | 275.45 | 0.34 | 1.18 | 1.57            | 1.84            | 2.08 |
| S2      | 30.4 ± 3.8                | 55.3 ± 6.2                | 102 ± 11.4              | 145 ± 12.6   | 5.61  | 0.10   | 187.43 | 93.25  | 0.11 | 0.4  | 0.51            | 0.59            | 0.66 |
| S3      | 78.3 ± 8.2                | 110 ± 12.3                | 300 ± 33.5              | 272 ± 28.6   | 8.29  | 0.10   | 528.24 | 243.44 | 0.3  | 1.04 | 1.43            | 1.64            | 1.85 |
| S4      | 79.2 ± 6.7                | 120 ± 13.2                | 245 ± 22.9              | 878 ± 99.7   | 6.21  | 0.29   | 497.16 | 240.3  | 0.29 | 1.03 | 1.34            | 1.56            | 1.78 |
| S5      | 74.2 ± 8.1                | 106 ± 9.8                 | 217 ± 24.5              | 1218 ± 143.4 | 6.23  | 0.45   | 478.3  | 231.2  | 0.28 | 0.99 | 1.29            | 1.49            | 1.74 |
| S6      | 86.7 ± 8.8                | 107 ± 11.3                | 275 ± 30.7              | 488 ± 52.4   | 7.82  | 0.18   | 517.53 | 236.03 | 0.29 | 1.01 | 1.4             | 1.63            | 1.83 |
| S7      | 85.1 ± 9.1                | 126 ± 14.6                | 359 ± 39.8              | 905 ± 86.3   | 8.67  | 0.28   | 668.16 | 313.06 | 0.38 | 1.34 | 1.8             | 2.03            | 2.38 |
| S8      | 82.5 ± 7.8                | 181 ± 6.2                 | 181 ± 16.4              | 325 ± 29.5   | 7.44  | 0.17   | 366.36 | 157.16 | 0.19 | 0.67 | 0.99            | 1.21            | 1.29 |
| S9      | 42.6 ± 4.7                | 72.3 ± 8.1                | 119 ± 12.6              | 105 ± 11.4   | 5.01  | 0.06   | 220.86 | 109.69 | 0.13 | 0.47 | 0.6             | 0.71            | 0.77 |
| S10     | 77.1 ± 8.2                | 117 ± 12.8                | 382 ± 40.3              | 685 ± 72.8   | 9.94  | 0.23   | 676.11 | 313.55 | 0.38 | 1.35 | 1.83            | 2.03            | 2.4  |
| S11     | 47.1 ± 5.1                | 75.0 ± 5.9                | 225 ± 24.4              | 178 ± 19.4   | 9.13  | 0.09   | 382.56 | 178.03 | 0.22 | 0.76 | 1.03            | 1.16            | 1.34 |
| S12     | 61.6 ± 5.4                | 85.6 ± 9.1                | 217 ± 22.3              | 192 ± 21.3   | 7.71  | 0.09   | 386.69 | 178.68 | 0.22 | 0.77 | 1.04            | 1.21            | 1.35 |
| S13     | 60.3 ± 6.8                | 73.1 ± 6.9                | 250 ± 27.7              | 139 ± 16.2   | 10.40 | 0.07   | 428.5  | 190.61 | 0.23 | 0.82 | 1.16            | 1.32            | 1.5  |
| S14     | 52.9 ± 4.9                | 75.5 ± 8.3                | 227 ± 20.9              | 65.3 ± 7.2   | 9.15  | 0.03   | 382.54 | 174.73 | 0.21 | 0.75 | 1.03            | 1.18            | 1.33 |
| S15     | 30.4 ± 2.8                | 48.6 ± 5.2                | 120 ± 14.1              | 250 ± 21.7   | 7.50  | 0.20   | 221.25 | 105.43 | 0.13 | 0.45 | 0.6             | 0.68            | 0.78 |
| S16     | 69.8 ± 7.2                | 100 ± 8.9                 | 456 ± 50.2              | 795 ± 83.8   | 13.87 | 0.31   | 783.1  | 355.01 | 0.44 | 1.52 | 2.11            | 2.3             | 2.78 |
| S17     | 73.2 ± 8.1                | 86.9 ± 7.8                | 209 ± 16.6              | 65.4 ± 6.1   | 7.31  | 0.03   | 377.11 | 169.13 | 0.21 | 0.73 | 1.02            | 1.22            | 1.31 |
| S18     | 20.7 ± 2.4                | 30.1 ± 4.2                | 43.6 ± 3.9              | 57 ± 4.8     | 4.40  | 0.07   | 87.44  | 42.63  | 0.05 | 0.18 | 0.24            | 0.29            | 0.31 |
| S19     | 131 ± 14.5                | 170 ± 18.3                | 349 ± 36.8              | 302 ± 26.5   | 6.24  | 0.07   | 653.32 | 302.02 | 0.37 | 1.3  | 1.76            | 2.12            | 2.28 |
| S20     | 111 ± 9.8                 | 132 ± 14.5                | 244 ± 26.5              | 1033 ± 115.3 | 5.62  | 0.31   | 539.46 | 251.75 | 0.31 | 1.08 | 1.46            | 1.76            | 1.93 |
| S21     | 96.6 ± 8.9                | 131 ± 12.1                | 441 ± 48.7              | 849 ± 96.7   | 10.24 | 0.26   | 792.6  | 362.54 | 0.44 | 1.56 | 2.14            | 2.4             | 2.81 |
| Maximum | 131                       | 170                       | 456                     | 1218         | 13.87 | 0.45   | 792.6  | 362.5  | 0.4  | 1.6  | 2.1             | 2.4             | 2.8  |
| Minimum | 20.7                      | 30.1                      | 43.6                    | 57           | 4.40  | 0.03   | 87.4   | 42.6   | 0.1  | 0.2  | 0.2             | 0.3             | 0.3  |
| Average | 71                        | 96.8                      | 249.7                   | 473.5        | 7.76  | 0.18   | 464.6  | 215.4  | 0.3  | 0.9  | 1.3             | 1.4             | 1.6  |

(ADR – 59 nGy/h, AEDE – 1 mSv/y, Hex and Hin – 1, ELCR –  $0.29 \times 10^{-3}$ ) prescribed by UNSCEAR [40], respectively. Highest level of radioactivity was observed in sites which were situated within the monazite ore body such as (S21, S16 and S10), as shown in (Fig. 3). As evidenced from the spatial distribution map, the regions farther away from the ore body has lower activity concentrations when compared to those situated closer to or within the monazite ore body. The monazite placers in general are an orthophosphate of thorium and rare earths that comprises of phosphorous pentoxide, silicon dioxide, cerium oxide, iron oxide, titanium oxide, thorium and several other elements in traces [62]. It is highly radioactive due to the higher contents of thorium present in it and less commonly uranium, which subsequently reflected in the activity concentration of radionuclides in these regions studied. In addition to this, the presence of quaternary sediments, being rich in sand, clay, lateritized debris etc, were also responsible for contributing to the net radioactivity, as suggested in the study of [45]. The geological composition of the site S10 reveals to be rich in minerals such as Silimanite, Garnet, Biotite-amphibolite quarsite and marble lenses. Following these sites, those that were located distantly from the monazite placers such as S7, exhibited high radioactivity as well. Though these sites are located away from monazite placers unlike S21 and S16, a scenario in which the concentration of radionuclides tends to decrease, high radioactivity in this region attributes to composition of rocks, reflecting the significant influence of geological composition on radioactivity levels. Our findings thereby support and corroborate with the research findings of [27–31]. Examining the site S7, which falls in the region of Ca river and between the quaternary formations, the radionuclides activity here could be correlated to the composition of sediments which were acid erupted and bestowed with minerals [29], that is siltstone mixed with quartz – sericite schist and quarsite (Fig. 1). Based on the foregoing, it becomes apparent that monazite ore mine might act as a crucial factor in contributing to the radioactivity of the study region, along with the role of minerals such as sillimanite, biotite – amphibolite, quarsite, marble lenses and combination of quaternary sediments with mica-plagioclase which exhibited an equivalent role in affecting the radionuclides activity [34].

### 3.3. Radio-elemental concentrations

The elemental concentration ratios, that is between eTh/eU, eK/eU and eK/eTh acts as an effective indicator in estimating the relative depletion or radioisotopes enrichment that has occurred in an environment [37]. Estimating the ratios will help us understand the variations that had occurred in the complex metamorphic history of the environment following degradation or embellishment history, alterations or weathering in the affected rocks that has been investigated, which all in turn affects the elemental abundance of original eU, eTh and eK concentration in the rocks and soil [63]. The calculated elemental concentration of eU and Th in ppm and eK in weight %, have been presented in (Fig. 2).

As evidenced from the results, the concentration of eU ranged from 2.4 to 13.7 ppm, while the concentration of Th had a range of 10.7 to 112.3 ppm. The concentration of K varied from 0.18 to 3.9 %. The results of the elemental concentrations of eU and Th in soil were much higher than the average UCC value of (2.7, 10.5 ppm respectively) [64]. On the other hand, the potassium percentage was comparable to the UCC (2.8). Higher values obtained in the analysed samples could be due to higher values obtained from the activity concentrations of the radioactive mineral studied. The ratio of eK/eTh ranged between 0.01 to 0.07, eK/eU ranged 0.03 to 0.45 whereas the ratios of eTh/eU, in the present study were very large (Tab-1), having a range of (4.41 to 13.87) with an average of 7.77, and exceeding the average UCC value (3.8) [51]. The observed higher concentration of Thorium when compared to that of Uranium, indicates that the nature of the environment is an oxidising one [65]. It is because under such oxidizing conditions, Th remains as Th4+ and is immobile, whereas U4+ gets

**Table 2**Comparison studies for Activity concentration of radionuclides,  $Ra_{eq}$ , ADR,  $AEDE_{outdoor}$  across the world.

| Study area                       | $^{238}U$ (Bq/Kg) | $^{232}Th$ (Bq/Kg) | $^{40}K$ (Bq/Kg) | ADR (nGy/h) | AEDE (mSv/y) | $H_{ex}$ | $H_{in}$ | ELCR                   | References    |
|----------------------------------|-------------------|--------------------|------------------|-------------|--------------|----------|----------|------------------------|---------------|
| Chau Binh, Vietnam               | 96.8              | 249.7              | 473.6            | 215.4       | 1.32         | 1.3      | 1.4      | 0.9                    | Present study |
| Northeastern desert, Egypt       | 4735              | 4017               | 1619             | 3381        | 4.1          | 24.1     | 34       | 16865                  | [39]          |
| Kanyakumari, India               | 158               | 794                | 251              | 1022        | 1.25         | 1.06     | 1.2      | -                      | [29]          |
| Johor, Malaysia                  | 968               | 1210               | 2450             | 1281        | 1.17         | -        | -        | -                      | [54]          |
| Mazandaran, Iran                 | 7838              | 162                | 139              | 612         | 0.75         | -        | -        | $0.26 \times 10^{-3}$  | [57]          |
| Northwest Nigeria                | 72                | 362                | 1052             | 276         | 1.35         | 1.35     | 1.53     | $0.95 \times 10^{-3}$  | [42]          |
| Variscan crystal massif, georgia | 25.8              | 39.6               | 690.6            | 68.3        | 0.42         | 0.49     | -        | -                      | [18]          |
| Guangdong, China                 | 246               | 376                | 1747             | 381.5       | 0.49         | 0.7      | -        | -                      | [58]          |
| Southwestern Uganda mines        | 147               | 120                | 1658             | 191.6       | 0.39         | -        | -        | -                      | [59]          |
| Kirklareli, Turkey               | 73                | 151                | 2084             | 283         | 0.17         | -        | -        | -                      | [60]          |
| Ho Chi Minh, Vietnam             | 33                | 25                 | 215              | 64          | 0.07         | -        | -        | -                      | [17]          |
| Chennai coast, India             | 47                | 26.6               | 372              | 220.9       | 1.08         | 1.35     | 1.72     | -                      | [61]          |
| Democratic Republic of Congo     | 378               | 170                | 240              | 121.1       | 0.2          | 0.5      | 0.7      | 0.6                    | [62]          |
| Calabria, Italy                  | 21.3              | 30.3               | 849              | 63          | 0.11         | 0.35     | 0.41     | -                      | [63]          |
| Canakkale, Turkey                | 2392              | 6978               | 2176             | 205         | 1.2          | -        | -        | -                      | [64]          |
| Varkala, India                   | 554               | 3397               | 1597             | 2420        | 2.96         | -        | -        | $10.37 \times 10^{-3}$ | [65]          |
| World average/ Permissible limit | 30                | 35                 | 400              | 59          | 1            | -        | -        | -                      | [32]          |

converted to the U6 + state, in which it becomes soluble and mobile, which facilitates leaching from the sediment matrix [43,66]. Sedimentary processes such as weathering, erosion, transportation, and sorting play a role in the distribution and concentration of Th-bearing minerals, leading to their accumulation in placer deposits of the studied region, where Monazite ore contributed chiefly to the heavy minerals through fluvial processes. Their deposition and accumulation were further facilitated by the transportation of river systems such as Hieu river and Co Ba stream, flowing across these regions followed by re-working of currents and waves, concentrating the identified heavy minerals including Silimanite, Garnet, Biotite-amphibolite and quarsite.

### 3.4. Gamma absorbed dose rates to humans near the study site

Generally speaking, the amount of rock that makes up each lithologically separated area and the amount of soil that developed there influence the amount of terrestrial environmental radiation dosage that individuals are exposed to [67]. The gamma beta radiation field produced as a result of radionuclides disintegration, thus has the potent to cross the soil-air interface upon which the humans get exposed to it [68]. Hence, estimating the gamma and absorbed dose rate will pave a way for analysing the health effects that an individual may suffer from, due to radiation exposure in the particular area. In the present study, the terrestrial outdoor gamma dose rates of Chau Binh, as presented in (Tab - 1) had an average dose rate of 215.4 nGy/h with the values ranging from 42.6 – 362.5 nGy/h. Higher values were obtained for the absorbed dose rate, being greater than the world average (59 nGy/h) as prescribed by [48]. The highest ADR was observed in S21 and such higher values obtained can be related to the 'high activity concentrations of  $^{238}U$ ,  $^{232}Th$ ,  $^{40}K$ , and  $^{226}Ra$  in the current research area, which were likewise greater than the global average. The absorbed dose rate of the current study is further comparable with some of the NHBRA's such as Iran, Nigeria, China, India, Turkey, as present in (Table 2).

### 3.5. Computation of radiological risk parameters due to radionuclides exposure

The maximum value of  $Ra_{eq}$  in any geological material or those which are to be used for construction purposes must be less than 370 Bq/kg [69]. However, the  $Ra_{eq}$  of the present study ranged from 87.4 to 792.6 Bq/kg, with an average of 464.5 Bq/kg, which is higher than the above set limits of 370 Bq/kg (Tab-1). Out of 21 samples, most of the samples, that is almost the  $Ra_{eq}$  of 17 samples were higher than

the world average. Similarly, the values computed for  $AEDE_{outdoors}$  ranged from 0.05 to 0.44 with an average of 0.26, which is 4 times higher than the world average [44]. The hazard index  $H_{ex}$  and  $H_{in}$  values ranged between 0.24 to 2.14 and between 0.29 to 2.40, respectively (Tab-1). In general, the average values of  $H_{ex}$  and  $H_{in}$  were much higher than the recommended value of 1, which suggests the presence of radon and its short-lived daughter products. They were also comparable and lower than the values of other similar studies performed, as shown in (Tab-2). This therefore eventually declares that the soil from these areas is not suitable for construction purposes as it would potentially increase the radiological hazard to the residents, following the ELCR values which ranged from  $0.18 \times 10^{-3}$  to  $1.56 \times 10^{-3}$ , with an average value of  $0.92 \times 10^{-3}$  for all sampling sites (Tab-1). Since the values were four orders of magnitude higher than the world mean level of 0.00029, the study suggests possible carcinogenic risk to humans if at all the geological materials from these areas are to be used as building materials for the dwellings. The values of ELCR of the present study were also found to be higher than the findings of [70,71] and lower than [46,50,72], as shown in (Tab-2). Further the study highlights to consider the consistent elevation in the values of  $Ra_{eq}$ , ADR, AEDE, ELCR,  $H_{in}$ , and  $H_{ex}$  to be the greatest at sampling sites S21 and S16. Hence the people of the province or government must ensure that the rock or geological materials from these sites, with special consideration are not used for any sort of purposes as indicates a very high exposure to ionising radiation as proven by the current research.

### 3.6. Statistical analysis

The descriptive statistical analysis results for the radionuclides activity concentration and associated radiological risks are given in (Tab - 3). The basic statistical parameters calculated include the mean, standard deviation (SD), range, kurtosis and skewness coefficient. The high mean and SD values, particularly for  $^{40}K$ , indicate significant spatial variability in radionuclide distributions across the study area. With respect to skewness and kurtosis, relatively low skewness values ( $-0.23$  to  $0.55$ ) were obtained for all parameters, suggesting near-symmetric distributions (Tab- 3). The negative kurtosis values observed for all parameters ( $-1.27$  to  $-0.04$ ) indicate platykurtic distributions, characterized by fewer and less extreme outliers than would be expected in a normal distribution [44]. This pattern suggests that the radiological parameters are relatively uniformly distributed across the study area, albeit at elevated levels. It further supports and validates the

**Table 3**

Descriptive statistics of the studied radiological parameters.

|                | <sup>226</sup> Ra | <sup>238</sup> U | <sup>232</sup> Th | <sup>40</sup> K | R <sub>eq</sub> | ADR    | AEDE  | ELCR  | H <sub>ex</sub> | H <sub>in</sub> | GRLI  |
|----------------|-------------------|------------------|-------------------|-----------------|-----------------|--------|-------|-------|-----------------|-----------------|-------|
| Mean           | 71.03             | 96.78            | 249.70            | 473.46          | 464.56          | 215.41 | 0.26  | 0.92  | 1.25            | 1.45            | 1.64  |
| Std. Deviation | 27.61             | 33.83            | 107.37            | 384.07          | 191.56          | 87.58  | 0.11  | 0.38  | 0.52            | 0.58            | 0.68  |
| Skewness       | 0.07              | 0.07             | 0.16              | 0.55            | −0.10           | −0.10  | −0.11 | −0.10 | −0.09           | −0.23           | −0.09 |
| Kurtosis       | −0.04             | −0.15            | −0.16             | −1.27           | −0.47           | −0.62  | −0.62 | −0.62 | −0.48           | −0.56           | −0.52 |
| Minimum        | 20.70             | 30.10            | 43.60             | 57.00           | 87.44           | 42.63  | 0.05  | 0.18  | 0.24            | 0.29            | 0.31  |
| Maximum        | 131.00            | 170.00           | 456.00            | 1218.00         | 792.60          | 362.54 | 0.44  | 1.56  | 2.14            | 2.40            | 2.81  |

reliability of radionuclides activity concentration measurement and suggest that the radiation levels in the study area are influenced by consistent geological factors rather than isolated anomalies.

### 3.7. Policy recommendations and actionable measures

Based on the elevated radiation levels identified through the present study, immediate policy interventions are essential, as listed below:

- Land-use restrictions - People are likely to prohibit construction activities within 500 m of monazite ore bodies, particularly at sites S16 and S21 where dose rates exceed 300 nGy/h.
- Building material regulations must also restrict the use of local soil for the construction purposes, given the R<sub>eq</sub> values exceeding 370 Bq/Kg
- Radon mitigation systems should be mandatory for existing structures within the ore zone, while agricultural restrictions are necessary for soils exceeding 2 × world average concentrations to prevent food chain contamination and ensure long-term public safety.
- Continuous radiation monitoring networks are to be established with quarterly assessments to track temporal variations.
- Community health surveillance programs focusing on respiratory and renal health are recommended for residents in these high-exposure zones.

## 4. Conclusion

Activity concentration of primordials <sup>226</sup>Ra, <sup>232</sup>Th, <sup>238</sup>U, <sup>40</sup>K were investigated in the soil samples of Chau Binh, Vietnam using HPGe γ-ray spectrometry. Results revealed the average concentration of radionuclides to range from 71 Bq/kg, 96.8 Bq/kg, 249.7 Bq/kg and 473.5 Bq/kg respectively, where they were higher than the world average concentrations [55] and other places of the world. Based on the values obtained, the radionuclides were classified in the following order as: <sup>40</sup>K > <sup>232</sup>Th > <sup>238</sup>U > <sup>226</sup>Ra. High radioactivity in the environment stemmed primarily from monazite placers, with some contribution from minerals like mica-plagioclase, sillimanite, biotite-amphibolite, quartzite, and marble lenses. Areas within monazite ore bodies showed elevated radioactivity due to significantly higher <sup>232</sup>Th content compared to other radionuclides. Furthermore, all the radiological risks computed exceeded UNSCEAR's recommended safety levels, recommending the need to implement radiation safety policies for the protection of local population.

### Ethical approval

This article does not contain any studies with human participants, or animals by any of the authors.

### Consent to participate

All authors contributed to the study conception and design. All authors read and approved the final manuscript.

### Consent for publication

All authors gave their consent for research publication.

### CRediT authorship contribution statement

**Mohamed Saiyad Musthafa:** Visualization, Validation, Conceptualization. **Linh Tin Khac Nguyen:** Methodology, Data curation. **Van-Dung Nguyen:** Writing – review & editing, Validation. **Tien-Manh Nguyen:** Resources, Methodology, Data curation. **Thi Thuy Huong Ngo:** Formal analysis, Data curation. **Tien Chu Trung:** Formal analysis, Data curation. **Kumara Perumal Pradhoshini:** Writing – original draft, Methodology, Conceptualization. **Bharathi Santhanabharathi:** Visualization, Supervision, Formal analysis, Data curation, Conceptualization. **Van-Hao Duong:** Visualization, Validation, Supervision, Investigation, Formal analysis, Conceptualization.

### Data availability statement

The data and methods related to this study are available upon request to the authors.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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