Health Hazards Assessment and Geochemistry of ElSibai-Abu ElTiyur Granites, Central Eastern Desert, Egypt

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Abstract: In this paper, a thorough radio- and chem-ecological evaluation of ElSibai-Abu ElTiyur granites located within Egypt’s crystalline basement rocks was conducted for risk and dose assessments. Twenty granitic samples from the study area’s various lithological units were analyzed using high-resolution γ-ray spectrometry to determine the natural radioisotopes (U-238, Th-232, and K-40) concentrations. The average concentrations of U-238, Th-232, and K-40 were 38.72, 38.23, and 860.71 Bq/kg, respectively, exceeding the GAV (global average value) documented by UNSCEAR (Scientific Committee on the Effects of Atomic Radiation, Vienna, Austria). The radiological parameters and indices judging the usage of ElSibai-Abu ElTiyur granites in homes were computed. The obtained results showed that ElSibai-Abu ElTiyur granites are safe to be used by inhabitants as superficial building materials, as per the globally accepted values and the recommended safety limits approved by UNSEAR, WHO (World Health Organization, Geneva, Switzerland), ICRP (International Commission on Radiological Protection, Ottawa, ON, Canada), and EC (European Commission, Luxembourg). Further, the samples were subjected to ICP-MS (inductively coupled plasma mass spectrometry) analysis for quantifying radionuclide variations with chemical composition. Geochemically based on the ICP-MS results, the studied granites proved to be highly evolved A-type granites. They span the metaluminous to peralkaline fields. The REE patterns are characterized by the enrichment of the light rare earths (LREE) over the heavy ones (HREE) where \((\text{La/Yb})_n = 5.2\), \((\text{Gd/Yb})_n = 1.63\) with pronounced negative Eu-anomalies \((\text{Eu/Eu}^*)_n = 0.49\). The albite granite exhibits the highest concentrations of Ga, Nb, Ta, U, and Y, and REE (Gd, Dy, Ho, Yb) than the Na-metasomatic granites. Finally, the obtained data serve as a valuable future database for finding out the compatibility of the geochemical data with the natural radioactivity levels of granites.

Keywords: granites; chemical analysis; natural radioactivity; gamma rays; radiation risks

1. Introduction

Uranium and thorium are constant components of most minerals. The average content of these elements in the earth’s crust is 2 ppm for uranium and 12 ppm for thorium. A distinctive feature of the uranium ion is its ability to rapidly oxidize and convert to uranyl \((U^{VI})\). Hexavalent uranium can easily combine with oxygen and interact in complex compounds with carbonates, sulphates, and fluorides. In addition, it has the ability to precipitate in rocks containing reducing substances [1].

Many varieties of igneous rocks are particularly rich in uranium. The latter is concentrated in rocks containing SiO₂ and alkalis \((\text{Na}_2\text{O} \text{ and } \text{K}_2\text{O})\). The radionuclides, mentioned above, cause lung cancer by damaging the chromosome. In addition, uranium causes disorders in kidney functioning [2].
Environmentally, the natural radioactivity differs from one location to another, based on their geological setting. Due to the existence of abnormal amounts of radionuclides in rocks, various regions throughout the world have high levels of natural radiation [3].

From a geological point of view, the Egyptian deserts contain one of the best-preserved granites in the world. Since no systematic data on environmental radioactivity in Egypt were available, many studies commenced in 2002 with the objective to systematically measure the terrestrial gamma radiation, and determine its contribution to the annual effective dose equivalent to the population (e.g., [4–15]). It has been shown that many of these areas have high levels of radioactivity. No previous study has been conducted to investigate the distribution of natural radionuclides in ElSibai-Abu ElTiyur granites. There are three main points that make this study particularly important and interesting for radiometric studies. Firstly, it provides information on the geochemical composition associated with the environmental radioactivity of such granites. Secondly, the study of the enrichment/depletion processes, alteration, metasomatism, that affected the investigated rocks. Thirdly, we assess the possible radiological health hazards and compare the results with the recommended limits of UNSCEAR, EC, and WHO data.

2. Study Area

Gabal ElSibai-Abu ElTiyur (elevation 1477 m) is among the most prominent domes of the Eastern Desert of Egypt. It forms an elongated body, trending NW–SE. The study area (lat. 25°43′ N, long. 34°08′ E) represents the northern extension of the Nubian Shield. It is made up of Pan African migmatites, metasedimentary rocks, serpentinites, metavolcanic suites, volcanic arc sequences, gabbro–diorite–tonalite complexes, and late orogenic calc-alkaline granodiorite–granite complexes [16,17]. It cross-cuts the Pan-African host rocks including biotite–hornblende calc-alkaline granite, metasediments, and metavolcanics (Figure 1) [18]. Having the same trend of the Najd Fault System, these rocks were subjected to multiple phases of deformation resulting in the development of faults, quartz veins, and dykes.

ElSibai-Abu ElTiyur area is composed of hypersolvus alkaline granite, with albitized granite, intruding the Pan-African host hornblende–biotite calc-alkaline granitic rocks. The alkaline granites consist of perthite, quartz, arfvedsonite, biotite. Zircon, fluorite, apatite, and ilmenite are the accessories. Perthite is the first crystallized mineral, judging from the interstitial occurrence of quartz, arfvedsonite, and biotite. It forms medium to coarse, subhedral to euhedral grains. Quartz occurs as elongated grains, generally strained (undulatory extinction) showing no preferred orientation, advocating subjection to a deformation phase. Arfvedsonite forms anhedral to subhedral grains, commonly associated with zircon. The albite granite is characterized by the presence of high contents of secondary untwinned albite, biotite, arfvedsonite, with zircon and fluorite as accessories. Ilmenite occurs as anhedral grains in association with biotite and arfvedsonite. The granite host rocks consisted of variable contents of quartz (27–35 vol.%), K-feldspar (30–35 vol.%), plagioclase (20–30 vol.%), hornblende (1–12 vol.%), and biotite (1–5 vol.%), together with zircon, apatite, muscovite, and opaques as accessories [16].

3. Materials and Methods

3.1. Samples Collection

In this paper, the thorium, uranium, and potassium content in rock samples from a Neoproterozoic area located in the Central Eastern Desert (Figure 1) were determined. In order to obtain a representative coverage of most of the area, a total of 20 rock samples were collected (Figure 1).
The collected samples were crushed into a fine powder using a jaw crusher then sieved by a 200 μm mesh screen. All samples were dried at a temperature of 110 °C. Each sample had been weighted and transferred into an airtight cylindrical plastic container (47.6 mm radius, 82 mm height, and 0.5 mm thickness). Finally, the samples were saved for four weeks towards a secular equilibrium action between parents and their short-lived progenies in natural decay chains.

The gamma spectral analyses were performed using a coaxial Canberra HPGe detector (GR4020). The detector is characterized by a relative efficiency (40%) for 3” × 3” NaI(Tl) crystal and energy resolution (2 keV) for the 1332 keV Cobalt-60 γ-line. Moreover, it operates with a suitable lead shield (Model 747E, preventing more than 98% of the background noise). The radioisotopes concentration (terrestrial radioisotopes) for each sample were determined in Bq/kg using their counting spectrums, the latter were obtained and analyzed using Genie-2000 software.

Before starting the measurement, the system was calibrated for energy and efficiency. The energy calibration was carried out by acquiring spectra from standards sources of known energies such as $^{60}$Co (1.332 MeV and 1.172 MeV). For the efficiency calibration, ISOCS/Lab-SOCS Canberra’s Geometry Composer software (as a part of Genie-2000 software and based on the Monte Carlo Simulation) was used instead of the standard source. This was done individually for each sample to insert the geometry dimensions optimally and improve the efficiency of the HPGe detector.

The sample measuring time (counting spectrum) was approximately in the range between 8 to 24 h. The gamma-ray photopeaks corresponding to 1.4608 MeV ($^{40}$K) were taken into account to compute $^{40}$K activity in the samples. These gamma-ray photopeaks 0.6093, 0.1120, and 1.7645 MeV ($^{214}$Bi) and 0.2952 and 0.3519 MeV ($^{214}$Pb) were considered in reaching out the $^{238}$U activity in the samples. $^{232}$Th activity was reached through the gamma-ray photopeaks corresponding to 0.3383, 0.9112 and 0.9689 MeV ($^{228}$Ac) and 0.5832 and 2.6145 MeV ($^{208}$Tl) and 0.2386 MeV ($^{212}$Pb).
The activity concentration $A_{E_i}$ for the radioactive daughter of the radioisotope of interest ($^{40}$K, $^{238}$U, and $^{232}$Th) can be estimated from its corresponding energy peak $E_i$ via the following equation:

$$A_{E_i} = \frac{N_{E_i}}{\gamma_{E_i} \times \varepsilon_{E_i} \times t \times M_s}$$  \hspace{1cm} (1)

where $N_{E_i}$, $\gamma_{E_i}$, and $\varepsilon_{E_i}$ are the net peak count, the $\gamma$-decay transition probability, and the detector efficiency at energy $E_i$, respectively, $t$ is the sample measuring time and $M_s$ is the sample mass in kg. Hence the specific activity $A_{C_j}$ in Bq/kg of jth parent ($^{238}$U, $^{232}$Th, and $^{40}$K) having a number $n$ of detected daughters’ photopeaks, is obtained by:

$$A_{C_j} = \frac{1}{n} \sum_{i=1}^{n} A_{E_i}$$  \hspace{1cm} (2)

The $A_{C_U}$, $A_{C_{Th}}$, and $A_{C_K}$ were used to express the specific activity concentrations of $^{238}$U ($^{226}$Ra), $^{232}$Th, and $^{40}$K radioisotopes, respectively, $^{226}$Ra being the highest radiological significance in the disintegration chain of $^{238}$U is considered an alternative for $^{238}$U [19,20].

### 3.3. Geochemical Analysis

To confirm the gamma spectrometric analysis results and characterize the ElSibai-Abu ElTiyur granite from the chemical point of view, eight samples were analyzed for whole-rock major and trace elements composition at OMAC lab (Loughrea, Ireland). The concentrations of trace elements including Uranium (U), Thorium (Th), and rare-earth elements (REE), were detected using lithium borate fusion digestion and ICP-MS (ALS code ME-MS81). For the concentrations of the elements Ag, As, Cd, Co, Cu, Li, Mo, Ni, Pb, Sc, Ti, and Zn, the four-acid digestion method and ICP-AES (ALS code ME-4ACD81) were used. The concentrations of the major and minor oxides, including $K_2O$, were measured through lithium borate fusion digestion and ICP-AES (ALS code ME-ICP06). More detailed information on the analytical techniques and preparations at the OMAC lab are available at (www.alsglobal.com, accessed on 30 November 2021).

The U and Th elemental concentrations from the ICP-MS technique were given in ppm, whereas the K concentration obtained from $K_2O$ via the ICP-AES analysis, was in percent (%). Consequently, the specific activity concentrations in Bq/kg of $^{232}$Th, $^{238}$U, and $^{40}$K were computed as reported previously by El-Gamal et al. [9].

### 4. Results and Discussion

#### 4.1. Activity Concentrations of the Radioisotopes

The activity concentrations (Table 1) reported herein and used to assess the health hazards of the studied granites, are those obtained from the HPGe detector technique, while those from the ICP-MS analysis are used to confirm the results. Correlations between the concentrations of $^{238}$U, $^{232}$Th, and $^{40}$K obtained from the above-mentioned two techniques are shown in Figure 2. The radionuclides concentration values are highly consistent in both techniques with Pearson correlation coefficients of 0.929, 0.968, and 0.857 for $^{238}$U, $^{232}$Th, and $^{40}$K, respectively.

Table 1 and Figures 3 and 4 clearly show that the $^{238}$U activity concentrations of ElSibai-Abu ElTiyur granites varied from 16.89 ± 1.58 to 72 ± 6.48 Bq/kg with an average of 38.72 ± 3.38 Bq/kg, whereas the concentrations of $^{232}$Th in the samples, changed from 21.97 ± 2.31 to 70 ± 6.33 Bq/kg with a mean value of 38.23 ± 2.99 Bq/kg. On the other hand, the values of $^{40}$K activity concentrations were comparatively large (from 689.23 ± 49.77 to 1037.73 ± 55.91 Bq/kg with an average of 860.71 ± 18.59 Bq/kg).
Activity concentration values of radioisotopes (with ± uncertainties) for ElSibai-Abu ElTiyur granite samples.

| Sample ID | Activity Concentration [Bq/kg] |
|-----------|--------------------------------|
|           | **U-238** | **Th-232** | **K-40** |
| S1        | 53.40 ± 5.60 | 39.73 ± 4.10 | 911.76 ± 58.10 |
| S2        | 29.70 ± 3.05 | 34.75 ± 4.11 | 769.02 ± 50.65 |
| S3        | 28.59 ± 2.97 | 28.60 ± 2.97 | 852.35 ± 56.54 |
| S4        | 72.00 ± 6.48 | 52.91 ± 4.17 | 868.98 ± 10.71 |
| S5        | 34.96 ± 3.43 | 42.20 ± 4.29 | 790.19 ± 42.63 |
| S6        | 34.09 ± 3.12 | 26.29 ± 2.59 | 901.43 ± 47.87 |
| S7        | 22.94 ± 2.56 | 24.33 ± 2.66 | 827.67 ± 58.52 |
| S8        | 16.89 ± 1.58 | 23.24 ± 1.32 | 883.75 ± 42.42 |
| S9        | 19.07 ± 2.00 | 21.97 ± 2.31 | 805.07 ± 51.04 |
| S10       | 50.23 ± 4.84 | 57.99 ± 5.79 | 1037.73 ± 55.91 |
| S11       | 21.97 ± 2.31 | 689.23 ± 49.77 | 860.71 ± 18.59 |
| S12       | 16.89 ± 1.58 | 21.97 ± 2.31 | 400, 500 B/kg as documented by UNSCEAR [21] and UNSCEAR [22] in regular soil.

Activity concentration of 238U and 232Th, and 40K from previous studies was carried out by the values of the current work.

Furthermore, the mean values obtained for both 238U and 232Th concentrations are 50 and 50 Bq/kg for 238U and 232Th [22], Table 1 and Figure 3. While the mean concentration of 40K increases by a factor of 2.15 and 1.72 when compared to their GAVs.

**Table 1.**

| Sample ID | Activity Concentration [Bq/kg] |
|-----------|--------------------------------|
|           | **U-238** | **Th-232** | **K-40** |
| S1        | 53.40 ± 5.60 | 39.73 ± 4.10 | 911.76 ± 58.10 |
| S2        | 29.70 ± 3.05 | 34.75 ± 4.11 | 769.02 ± 50.65 |
| S3        | 28.59 ± 2.97 | 28.60 ± 2.97 | 852.35 ± 56.54 |
| S4        | 72.00 ± 6.48 | 52.91 ± 4.17 | 868.98 ± 10.71 |
| S5        | 34.96 ± 3.43 | 42.20 ± 4.29 | 790.19 ± 42.63 |
| S6        | 34.09 ± 3.12 | 26.29 ± 2.59 | 901.43 ± 47.87 |
| S7        | 22.94 ± 2.56 | 24.33 ± 2.66 | 827.67 ± 58.52 |
| S8        | 16.89 ± 1.58 | 23.24 ± 1.32 | 883.75 ± 42.42 |
| S9        | 19.07 ± 2.00 | 21.97 ± 2.31 | 805.07 ± 51.04 |
| S10       | 50.23 ± 4.84 | 57.99 ± 5.79 | 1037.73 ± 55.91 |
| S11       | 21.97 ± 2.31 | 689.23 ± 49.77 | 860.71 ± 18.59 |
| S12       | 16.89 ± 1.58 | 21.97 ± 2.31 | 50, 50 Bq/kg 

**Figure 2.** Correlation between 238U, 232Th, and 40K activity concentrations estimated using ICP-MS and HPGe.

**Figure 3.** Activity concentration of 238U and 232Th compared with their global average values (GAV) in regular soil and building materials.

**Figure 4.** Activity concentration of 40K compared with its GAV in regular soil and building materials.
Furthermore, the mean values obtained for both $^{238}$U and $^{232}$Th concentrations are slightly more than GAVs of these radionuclides in regular soil, namely 35 and 30 Bq/kg for $^{238}$U and $^{232}$Th, respectively [21], but they do not surpass their values in building materials, namely 50 and 50 Bq/kg for $^{238}$U and $^{232}$Th [22], Table 1 and Figure 3. While the mean concentration of $^{40}$K increases by a factor of 2.15 and 1.72 when compared to their GAVs (400 and 500 B/kg as documented by UNSCEAR [21] and UNSCEAR [22]) in regular soil and building materials, respectively (Table 1 and Figure 4). This result shows the suitability of the ElSibai-Abu ElTiyur granites for use as building materials in dwellings.

Table 1. The activity concentration values of radioisotopes (with ± uncertainties) for ElSibai-Abu ElTiyur granite samples.

| Sample ID | U-238          | Th-232         | K-40           |
|-----------|----------------|----------------|----------------|
| S1        | 53.40 ± 5.60   | 39.73 ± 4.10   | 911.76 ± 58.10 |
| S2        | 29.70 ± 3.05   | 37.45 ± 4.11   | 769.02 ± 50.65 |
| S3        | 28.59 ± 2.97   | 28.60 ± 2.97   | 852.35 ± 56.54 |
| S4        | 45.65 ± 5.04   | 42.55 ± 5.02   | 689.23 ± 49.77 |
| S5        | 19.07 ± 2.00   | 21.97 ± 2.31   | 805.07 ± 51.04 |
| S6        | 29.89 ± 3.25   | 32.13 ± 3.50   | 759.38 ± 54.16 |
| S7        | 22.94 ± 2.56   | 24.33 ± 2.66   | 827.67 ± 58.52 |
| S8        | 16.89 ± 1.58   | 23.24 ± 1.32   | 883.75 ± 42.42 |
| S9        | 31.31 ± 3.06   | 30.84 ± 1.73   | 828.44 ± 40.37 |
| S10       | 27.80 ± 2.74   | 39.06 ± 3.83   | 857.86 ± 45.29 |
| S11       | 34.96 ± 3.43   | 42.20 ± 4.29   | 790.19 ± 42.63 |
| S12       | 36.48 ± 3.15   | 33.32 ± 3.44   | 930.04 ± 50.00 |
| S13       | 56.23 ± 5.05   | 52.91 ± 5.08   | 871.26 ± 46.46 |
| S14       | 72.00 ± 6.48   | 52.91 ± 4.17   | 868.98 ± 10.71 |
| S15       | 65.00 ± 5.22   | 70.00 ± 6.33   | 950.00 ± 52.30 |
| S16       | 27.88 ± 2.19   | 22.78 ± 1.15   | 814.38 ± 39.00 |
| S17       | 34.09 ± 3.12   | 26.29 ± 2.59   | 901.43 ± 47.87 |
| S18       | 43.04 ± 4.27   | 35.44 ± 3.85   | 857.46 ± 47.57 |
| S19       | 50.23 ± 4.84   | 57.99 ± 5.79   | 1037.73 ± 55.91|
| S20       | 49.36 ± 4.14   | 53.47 ± 2.55   | 1008.23 ± 48.79|
| Min       | 16.89 ± 1.58   | 21.97 ± 2.31   | 689.23 ± 49.77 |
| Max       | 72.00 ± 6.48   | 70.31 ± 6.33   | 1037.73 ± 55.91|
| AV ± SE   | 38.72 ± 3.38   | 38.23 ± 2.99   | 860.71 ± 18.59 |
| GAV in regular soil [21] | 35 | 30 | 400 |
| GAV in building materials [22] | 50 | 50 | 500 |

Table 2 and Figure 5 show the results of the natural radioactivity levels of the investigated granites versus the previous studies on Egyptian granites as well as on those from other countries. The normalization for radionuclides concentrations values of $^{226}$Ra ($^{238}$U), $^{232}$Th, and $^{40}$K from previous studies was carried out by the values of the current work (Figure 5). It is found that the radioisotopes concentrations for $^{238}$U and $^{232}$Th for ElSibai-Abu ElTiyur granitic samples are smaller than those reported from most of the previous literature (Table 2 and Figure 5), reflecting their safe use as tiling materials in dwellings.
Table 2. The activity concentration (current work) compared with previous studies.

| Country Name                             | Activity Concentration (Bq/kg) | Reference | Literature ID |
|------------------------------------------|--------------------------------|-----------|---------------|
| **226Ra**                                | **232Th**                       | **40K**   |               |
| Egypt (ElSibai-Abu ElTiyur granite)      | (16.89–72)                      | (21.97–70) | (689.23–1037.73) | Current work | Current work |
| Egypt (Gebel Mueiha granites)            | 38.73                           | 38.23     | 860.71        | [9]           | L1           |
| Egypt (Gebel El-Missikat granites)       | (44.8–175.4)                    | (29.4–111.4) | (525.2–1045.2) | [7]           | L2           |
| Egypt (Gebel El-Qattar granites)         | 572.3                           | 114.5     | 764.1         | [8]           | L3           |
| Egypt (Saint Katherine granites)         | 104.4                           | 78.8      | 892.9         | [12]          | L4           |
| Egypt (commercial Egyptian granites)     | 138                             | 82        | 1081          | [23]          | L5           |
| Sudan (Nuba mountains granites)          | (12.8–28.7)                     | (21.1–39.8) | (111.6–443.3) | [24]          | L6           |
| Palestine (imported granite)             | 20.6                            | 30.5      | 295.2         | [25]          | L7           |
| KSA (local and imported granite)         | (1.53–77.16)                    | (0.51–89.82) | (19.47–1632.37) | [26]          | L8           |
| Jordan (local granite used as building materials) | 41.5                           | 58.4      | 897           | [27]          | L9           |
| Serbia (imported granite used in the construction industry) | (23–280) | (77–426) | (550–2240) | [28] | L10 |
| Greece (granites used as building materials) | (1–170)                        | (1–354)   | (49–1592)     | [29]          | L11          |
| India (granites used in Indian dwellings) | 82                             | 112       | 1908          | [30]          | L12          |
| Turkey (granite used as construction material) | (10–187)                     | (16–354)  | (104–1630)    | [31]          | L13          |
| Spain (Extremadura granite)              | 80                             | 101       | 974           | [32]          | L14          |
| Italy (commercial ornamental stones)      | 101                             | 48        | 1293          | [33]          | L15          |
| Cyprus (imported granites)               | 112                             | 107       | 1063          | [34]          | L16          |
| Brazil (commercial granites)             | 129                             | 131       | 882           | [37]          | L19          |
| USA (commercial granites)                | 31                              | 61        | 1210          | [36]          | L18          |
| SE part of Nigeria                       | (46–6120)                      | (92–3214) | (899–1927)    | [38]          | L20          |
| Pakistan (natural granite)               | 659                             | 598       | 1218          |               |              |

Figure 5. Normalization of radioisotope values (226Ra, 232Th, and 40K) from previous literature to their corresponding values in the current work for comparison purposes. The dashed line represents the present work normalized values.
4.2. Geochemical Characterization

The chemical composition of representative granitic samples from ElSibai-Abu ElTiyur area is given in Table S1 (Supplementary Material). They are highly evolved alkaline granites, judging from the elevated SiO$_2$ contents (71.6–76.6 wt.%). They exhibit a relative depletion in Al$_2$O$_3$ (11.75–14.8 wt.%), CaO (0.53–1.6 wt.%), and MgO (0.07 to 0.46 wt.%), with moderate enrichment in Na$_2$O (3.73–4.69 wt.%) and K$_2$O (3.44–5 wt.%). Most of the granites suffered from albitization, as indicated by the predominance of Na$_2$O over K$_2$O (Table S1). The Fe$_2$O$_3$tot/(Fe$_2$O$_3$tot + MgO) content varied from 0.78 to 0.99. The studied granites fall within the granite field on the discrimination diagram [39] (Figure 6a). The aluminum saturation index [ASI; molecular Al/(Ca–1 67P + Na + K)] [40] showed that the rocks of ElSibai-Abu ElTiyur have an aluminum saturation index (ASI) ranging from 0.88 to 1.04, indicating a chemical span from the metaluminous to the peralkaline character (Figure 6b). They show high K, calc-alkaline affinity on the K$_2$O versus SiO$_2$ diagram (Figure 6c).

![Figure 6](image_url)

Figure 6. (a) Classification of ElSibai-Abu ElTiyur granites (after Middlemost [39]); (b) A/CNK vs. A/NK diagram of Maniar et al. [41]; (c) Variation diagram of K$_2$O vs. SiO$_2$ (fields after Rickwood [42]); (d) chondrite-normalized REE patterns; (e) primitive mantle-normalized multi-element patterns (normalization values are taken from Sun et al. [43]); (f) plot of the studied granites on: *Ga/Al versus Na$_2$O + K$_2$O discrimination diagram [44]; (g) Nb-Y-Ga*3 ternary diagram [45]; (h) tectonic discrimination diagram, Rb versus (Nb + Y) diagram [46]. VAG—volcanic arc granitoids, ORG—oceanic ridge granitoids, WPG—within plate granitoids and Syn-COLG—syn-collision granitoids. (Symbols as in (a)).
In all studied rocks, thorium and uranium were found. The highest concentrations were found in samples S1, S13, S14, and S15 (Table S1). The main carriers of thorium and uranium in the rocks under investigation are the accessory minerals (zircon, apatite, and fluorite).

The granites of ElSibai-Abu ElTiyur are relatively enriched in the elements Rb (40–187 ppm) with an average of 90 ppm, Nb (6.8–130.5 ppm—avg. 33.6), Y (11.2–166 ppm—avg. 56.5), Zr (56–637 ppm—avg. 395.5) and Ga (20.1–33.4 ppm—avg. 25.5), compared to the crustal rocks average (19 ppm Nb; 24 ppm Y; 203 ppm Zr; 15 ppm Ga [47]. According to Štemprok [48], the F-rich melts are able to persist to the late stage of magmatic differentiation. Therefore, they are able to concentrate incompatible elements (Rb, Li, Ga, Sn, and Y) which can form stable complexes with F or H$_2$O at different magmatic temperatures [49]. The solubility relationships between zircon and apatite together with the high fluorine contents of the alkaline granitic melts are responsible for the enrichment of the high field strength elements (Zr, Hf, Nb, Ta, Ti, and occasionally Th), hosted in the accessory minerals [50]. The studied granites have Th/U ratios varying between 2.7 to 5.6 (average 3.8) which is within the range reported by many authors (3.5–4 [51]; 5.5 [52]; 3–4 [53]). They show an increase in the Gal/Al ratio with increasing alkalinity (Table S1). The albitized granite (sample S1) exhibits the highest concentration of Ga (33.4 ppm), Nb (130.5 ppm), Ta (6.8 ppm), U ( 6.66 ppm) and Y (166 ppm), and HREE (Gd, Dy, Ho, Yb) compared to the normal granites.

Chondrite-normalized REE patterns for the alkaline granites and the albited granite (sample S1) are presented in Figure 6d. The alkaline granites show enrichment in the REE (∑ REE average 285 ppm). They exhibit parallel to subparallel patterns. They are characterized by the enrichment of LREE over the HREE where the average (La/Sm)$_n$ is 2.33 and (Gd/Yb)$_n$ = 1.56. The ratio of (La/Yb)$_n$ is 4.77 (average) reflecting the fractionated nature of ElSibai-Abu ElTiyur alkaline granites. They manifest a moderate negative Eu anomaly where Eu/Eu* ranges from 0.16 to 0.63 (average 0.44). These REE patterns are consistent with the patterns of the alkaline A-type granites worldwide [54,55]. The REE pattern of the albited granite (La/Yb)$_n$ = 1.54) is the most enriched in HREE relative to the LREE, showing the least negative Eu-anomaly (Eu/Eu* = 0.16). This HREE enrichment parallels those of Na, Nb, Ga, U, Ta, and Y (sample S1 in Table S1), most likely related to the late-stage processes of albitionization and fluorine reaction [56].

The correlation coefficients for the major oxides and trace elements including U, Th, and REEs, were calculated for the ElSibai-Abu ElTiyur granites (Table S2 in Supplementary Material). As per Evans [57], the Pearson correlation coefficient is weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79), and very strong (0.80–1.00). According to the correlation matrix, all the interesting elements showed strong (>0.65) to very strong (>0.8) positive correlations with each other. LREEs and HREEs exhibit a good association with the incompatible elements. Uranium is strongly associated with SiO$_2$, Rb, and Th in rock-forming minerals, while thorium is highly linked to the elements Cs, Li, Pb, and Rb in the mineralogical phases.

All the samples of ElSibai-Abu ElTiyur granites plot in the A-type granite field [44], using the standard tectonic discrimination diagram (Figure 6f). They occupy the A2 field or OIB Ocean island setting (Figure 6g) on the Nb-Y-Ga*3 ternary diagram (Eb) [45]. They were emplaced in a within-plate setting (Figure 6h) [46], except for the two alkaline samples (S7 and S9) which experienced further fractionation, falling in the volcanic arc setting. We believe that they were emplaced with the opening of the Red Sea. The ratio Y/Nb varied between 0.75 and 2.26, i.e., they are derived from sources chemically similar to those of oceanic island basalts, while those with Y/Nb > 1.2 are derived from sources chemically similar to island arc or continental margin basalts. From all the above, we suggest that many processes including fractionation from mantle-derived basaltic magmas, during the phase of fracturing and crustal fading, following the termination of the Pan-African orogeny generated the granites of ElSibai-Abu ElTiyur.
4.3. Potential Health Hazards Assessment

All over the world, granites are used in dwellings and in construction works. To utilize safely these granites as a natural resource, the possible radiological risks that may have originated from the contained radioisotopes must be determined. Herein, several radiological indices and dosages were computed to estimate the radiological effects originated by ElSibai-Abu ElTiyur granites when used in dwellings compared with the global standards (Table 3).

Table 3. The globally radiological parameters with their approved safety limits.

| Radiological Parameters                             | Approved Values                                                                 | References                  |
|-----------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------|
| Concentrations of $^{238}$U, $^{232}$Th and $^{40}$K | $35, 50$ and $400$ Bq/kg (in regular soil)                                      | UNSCEAR [21]                |
|                                                     | $50, 50$ and $500$ Bq/kg (in building materials)                                | UNSCEAR [22]                |
| Radium equivalent activity ($Ra_{eq}$)              | $370$ Bq/kg                                                                     | NEA-OECD [58]               |
| Radon concentration (RC)                            | $200$ Bq $m^{-3}$                                                                | European Commission [59]    |
| Gamma index ($I_{\gamma}$) for superficial building materials | 2 (corresponds to a dose of $0.3$ mSv/y)                                       | European Commission [20]    |
| Alpha index ($I_{\alpha}$)                          | $0.5$ (corresponds indoor radon $\leq 200$ Bq $m^{-3}$)                        | European Commission [20]    |
| Absorbed gamma dose rate                            | $84$ mGy/h                                                                      | UNSCEAR [21]                |
| Average annual external effective dose              | $0.46$ mSv/y                                                                    | European Commission [20]    |
| Excess lifetime cancer risk (ELCR)                  | $0.29 \times 10^5$                                                              | UNSCEAR [21]                |
| Indoor radon concentration (IRC)                    | $40$ Bq $m^{-3}$                                                                 | UNSCEAR [21]                |
|                                                      | $100$ to $300$ Bq $m^{-3}$                                                      | WHO et al. [60]             |
|                                                      | $200$ Bq $m^{-3}$                                                                | European Commission [20]    |
| Indoor yearly effective dose owing to radon exposure (IYED$_{Rn}$) | $1.2$ mSv/y                                                                     | UNSCEAR [21]                |
|                                                     | $3$ to $10$ mSv/y                                                                | ICRP [61]                   |

4.3.1. Radium Equivalent Activity $Ra_{eq}$

Radium equivalent index in Bq/kg is a widely used radiological hazard index. It is a convenient index to compare the specific activities of rock samples containing different amounts of $^{238}$U, $^{232}$Th, and $^{40}$K. It is presented by Beretka et al. [62] as Equation (3) on the assumption that the same gamma dose rate was produced from $370$ Bq/kg of U-238 or $259$ Bq/kg of Th-232 or $4810$ Bq/kg of K-40.

$$Ra_{eq}[\text{Bq/kg}] = AC_{U} + 1.43AC_{Th} + 0.077AC_{K} \tag{3}$$

For safe use, $Ra_{eq}$ levels in granites should not outweigh the allowable limit (370 Bq/kg), equivalent to a 1.5 mSv effective dose per year [58].

The calculated $Ra_{eq}$ values of all studied samples were listed (Table 4) and plotted (Figure 7). It is clear that the samples of ElSibai-Abu ElTiyur granites have $Ra_{eq}$ values lying between $112.48$–$238.25$ Bq/kg (avg. value $159.66 \pm 8.15$ Bq/kg), i.e., not exceeding the adopted value (370 Bq/kg).
Table 4. The radiological parameters of ElSibai- Abu ElTiyur granites.

| Sample | $Ra_{eq}$ (Bq/kg) | $I_\alpha$ | $I_\gamma$ | AGDR (nGy/h) | IYEGD (mSv/y) | ELCR $\times 10^{-3}$ | RER (Bq/m² h) | IRC (Bq/m³) | IYAD$_{Rn}$ (mSv/y) |
|--------|-------------------|------------|-----------|--------------|---------------|----------------------|----------------|-------------|------------------|
| S1     | 180.42            | 0.27       | 0.68      | 20.72        | 0.10          | 0.34                 | 7.12           | 132.38      | 3.34             |
| S2     | 138.61            | 0.15       | 0.53      | 15.81        | 0.08          | 0.26                 | 3.96           | 73.63       | 1.86             |
| S3     | 135.13            | 0.14       | 0.52      | 15.62        | 0.08          | 0.25                 | 3.81           | 70.89       | 1.79             |
| S4     | 159.56            | 0.23       | 0.59      | 18.05        | 0.09          | 0.29                 | 6.09           | 113.16      | 2.86             |
| S5     | 112.48            | 0.10       | 0.44      | 13.09        | 0.06          | 0.21                 | 2.54           | 47.27       | 1.19             |
| S6     | 134.31            | 0.15       | 0.51      | 15.38        | 0.08          | 0.25                 | 3.99           | 74.12       | 1.87             |
| S7     | 121.47            | 0.11       | 0.47      | 14.11        | 0.07          | 0.23                 | 3.06           | 56.88       | 1.44             |
| S8     | 118.17            | 0.08       | 0.47      | 13.76        | 0.07          | 0.22                 | 2.25           | 41.88       | 1.06             |
| S9     | 139.19            | 0.16       | 0.53      | 16.03        | 0.08          | 0.26                 | 4.18           | 77.61       | 1.96             |
| S10    | 149.71            | 0.14       | 0.57      | 17.04        | 0.08          | 0.28                 | 3.71           | 68.91       | 1.74             |
| S11    | 156.15            | 0.17       | 0.59      | 17.69        | 0.09          | 0.29                 | 4.66           | 86.66       | 2.19             |
| S12    | 155.75            | 0.18       | 0.60      | 17.97        | 0.09          | 0.29                 | 4.87           | 90.44       | 2.28             |
| S13    | 198.97            | 0.28       | 0.74      | 22.52        | 0.11          | 0.36                 | 7.50           | 139.40      | 3.52             |
| S14    | 214.57            | 0.36       | 0.79      | 24.39        | 0.12          | 0.40                 | 9.60           | 178.50      | 4.51             |
| S15    | 238.25            | 0.33       | 0.88      | 26.72        | 0.13          | 0.43                 | 8.67           | 161.15      | 4.07             |
| S16    | 123.17            | 0.14       | 0.48      | 14.35        | 0.07          | 0.23                 | 3.72           | 69.13       | 1.75             |
| S17    | 141.10            | 0.17       | 0.55      | 16.43        | 0.08          | 0.27                 | 4.55           | 84.52       | 2.13             |
| S18    | 159.74            | 0.22       | 0.61      | 18.36        | 0.09          | 0.30                 | 5.74           | 106.70      | 2.69             |
| S19    | 213.06            | 0.25       | 0.80      | 24.11        | 0.12          | 0.39                 | 6.70           | 124.52      | 3.14             |
| S20    | 203.46            | 0.25       | 0.77      | 23.09        | 0.11          | 0.37                 | 6.58           | 122.37      | 3.09             |
| Min    | 112.48            | 0.08       | 0.44      | 13.09        | 0.06          | 0.21                 | 2.25           | 41.88       | 1.06             |
| Max    | 238.25            | 0.36       | 0.88      | 26.72        | 0.13          | 0.43                 | 9.60           | 178.50      | 4.51             |
| AV     | 159.66            | 0.19       | 0.61      | 18.26        | 0.09          | 0.30                 | 5.17           | 96.01       | 2.42             |
| SE     | 8.15             | 0.02       | 0.03      | 0.89         | 0.004         | 0.01                 | 0.45           | 8.38        | 0.21             |

Figure 7. $Ra_{eq}$ values variation of the investigated samples.

4.3.2. Gamma and Alpha Indices ($I_\gamma$ and $I_\alpha$)

Alpha and gamma indices ($I_\alpha$ and $I_\gamma$) as radiological parameters, can be applied to the population living in standard massive granitic walls rooms and workers in granite mines with good ventilation [63].
The gamma index (Iγ) for building materials resulting in external gamma irradiation [20] of a dose boundary of 1 mSv/y is computed as follows:

\[
I_\gamma = \frac{AC_{Ra}}{300} + \frac{AC_{Th}}{200} + \frac{AC_{K}}{3000}
\]  

(4)

As per the European Commission European Commission [20], the yearly effective gamma dose (YEGD) rates originate from building materials used in floors and surfaces (granites and other materials) of limited use (ornamental). If Iγ \(\leq 2\), it meets an increase in the YEGD dose \(\leq 0.3\) mSv/y (exemption level of building materials from all limitations about their radioactivity), when \(2 < I_\gamma \leq 6\) means it matches the YEGD \(\leq 1\) mSv/y (recommended action level).

Concerning the characterization of the excess alpha radiation exhaled from granite (as a building material in dwellings), the alpha index (Iα) has been calculated [63] using the following equation:

\[
I_\alpha = -\frac{AC_{Ra}}{200\ Bq\ kg^{-1}} \leq 1
\]  

(5)

The alpha index (Iα) reflects the concentration of \(^{226}\text{Ra}\) activity that should not be more than 200 Bq/kg, otherwise will lead to health risks. AC_{Ra} should be less than or equal to 200 Bq/kg, i.e., the suggested activity limit for \(^{226}\text{Ra}\) in the appropriate building material (Iα \(< 1\)) by ICRP and European Commission [9,58,60].

The mean value of the gamma index (Iγ) for the examined samples exceeds the alpha index (Iα) by a factor of three (Figure 8 and Table 4). The values of Iγ of all samples examined were less than 1. Similarly, the alpha index values did not outstrip 1, thus, these indices meet internal and external radiological recommendations (Table 3). Therefore, ElSibai-Abu ElTiyur granites could be used as surface building materials without any limitations.

![Figure 8](image-url)  

**Figure 8.** Variation of Iγ and Iα values for the investigated samples.

### 4.3.3. Absorbed Gamma Dose Rate (AGDR)

Estimation of the excess absorbed gamma dose rate indoors caused by building materials (increment to that of outdoors) relies essentially upon: (1) the concentrations of the radioisotopes (\(^{238}\text{U}, {232}\text{Th}, \text{and} {40}\text{K}\)), (2) the properties of these materials, and (3) design ways in dwellings [64]. As indicated by the European Commission [20], the extra AGDR
(in nGy h\(^{-1}\)) in the air within a room, owing to using the granite as superficial construction materials in its walls and floor, can be determined using the Equation (6) \([28,65]\):

\[
AGDR [\text{nGy h}^{-1}] = 0.12AC_{Ra} + 0.14AC_{Th} + 0.0096AC_{K}
\]  

Notably, the coefficients 0.12, 0.14, and 0.0096 in nGy h\(^{-1}\)/Bq/kg included in Equation (6) are estimated according to the model of the standard room dimension (4 m \(\times\) 5 m \(\times\) 2.8 m) designed by rectangular walls of concrete (20 cm in thickness and 2350 kg/m\(^3\) in density) and tiled with superficial material (3 cm thickness and 2600 kg/m\(^3\) density) in walls and floor.

The calculated values of the excess AGDR indoor originating from ElSibai-Abu ElTiyur granitic samples, when used as superficial building materials are given (Table 4) and compared to the recommended GAVs (Figure 9). They fluctuate between 13.09 to 26.72 nGy h\(^{-1}\) indoors UNSCEAR [21] and the European Commission European Commission [20], respectively (Table 4 and Figure 9).

**Figure 9. AGDR values variation in the investigated samples.**

### 4.3.4. Yearly Effective Gamma Dose (YEGD)

Based on the excess AGDR computed from Equation (7), the indoor yearly effective gamma dose increment (YEGD) in mSv y\(^{-1}\) to individuals in general society (the normal individuals invest 80% of their days indoors) has been estimated by Equation (9) as follows [20,21]:

\[
\text{YEGD [mSv y}^{-1}] = \text{IAGDR [nGy h}^{-1}] \times 8766 \times 0.8 \times 0.7 \text{ SvGy}^{-1} \times 10^{-6}
\]  

where 0.8, 0.7 Sv Gy\(^{-1}\), 8766 h, and 10\(^{-6}\) are the indoor occupancy factor, conversion coefficient from the absorbed dose in the air to the effective dose, yearly hours number, transformation number from nano to milli, respectively. The computed increments in the YEGD rates owing to the usage of ElSibae-Abu ElTiyur granitic samples as superficial materials indoors are illustrated in Table 4 and Figure 10. European Commission European Commission [20] reported that “building materials should be exempted from all restrictions concerning their radioactivity if the excess gamma radiation originating from them excel the annual effective dose of a member of the public by 0.3 mSv, at most. It is, therefore,
recommended that controls should be based on a dose range from 0.3–1 mSv y\(^{-1}\)”. In light of this approach, all current increments of the YEGD originating from the granites under investigation fluctuated in the exemption level (Figure 10), denoting that the granites under consideration can be safely used as superficial building materials.

4.3.4. Yearly Effective Gamma Dose (YEGD)

The values of ELCR originating from the studied granitic samples, when used as superficial material (Table 4) are plotted against their global average values originating outdoors and indoors (Figure 11). It is clear that the values of the indoor ELCR originating from ElSibai-Abu EItiyur granites are scattered near and around the line representing the ELCR global average values outdoors \(0.29 \times 10^{-3}\) (arising from gamma dose rate outdoor as background calculated according to UNSCEAR) [68], as well as having a mean value of \(0.3 \times 10^{-3}\) (approximately on the line). This mean value of ELCR (\(0.3 \times 10^{-3}\)) is smaller by a factor of 4 than its corresponding indoor global average of ELCR (\(1.16 \times 10^{-3}\) arising from gamma dose rate indoor due to only walls, floor, and ceiling Qureshi et al. [69]). The indoor global average value of ELCR (\(1.16 \times 10^{-3}\)) Qureshi et al. [69], is calculated for a typical room with concrete walls, floor, and ceiling having the following activity concentrations 50, 50, and 500 Bq/kg for \(^{226}\)Ra, \(^{232}\)Th, and \(^{40}\)K, respectively. According to the ELCR increment (being \(0.3 \times 10^{-3}\)) for the rock samples under investigation, in addition to what was reported by Mohammed et al. [68]: “equivalent values of ELCR equal to 1, 10, 100, and 1000 mSv/y will cause a mortal cancer of 0.004, 0.04, 0.4, and 4%, respectively”. Accordingly, cancer risk possibility, in a lifespan, due to the usage of ElSibai-Abu EItiyur granites as superficial material, is still insignificant to indoor ELCR.

The ELCR is an essential radiological risk assessment parameter because it predicts a person’s probability of acquiring cancer due to low-dose radiation exposures during his lifetime. Using Equation (8), the ELCR is attributable to the effective gamma dose excess incurred yearly indoors due to the use of granite as superficial materials is calculated [66].

\[
ELCR = \text{YEGD} \times \text{ALE} \times \text{RF}
\]  

(8)

where ALE and RF are the life average expectancy (66 years) [19] and risk fatal for stochastic impact (0.05 Sv\(^{-1}\) for the overall population), respectively [67].

The values of ELCR originating from the studied granitic samples, when used as superficial material (Table 4) are plotted against their global average values originating outdoors and indoors (Figure 11). It is clear that the values of the indoor ELCR originating from ElSibai-Abu EItiyur granites are scattered near and around the line representing the ELCR global average values outdoors \(0.29 \times 10^{-3}\) (arising from gamma dose rate outdoor as background calculated according to UNSCEAR) [68], as well as having a mean value of \(0.3 \times 10^{-3}\) (approximately on the line). This mean value of ELCR (\(0.3 \times 10^{-3}\)) is smaller by a factor of 4 than its corresponding indoor global average of ELCR (\(1.16 \times 10^{-3}\) arising from gamma dose rate indoor due to only walls, floor, and ceiling Qureshi et al. [69]). The indoor global average value of ELCR (\(1.16 \times 10^{-3}\)) Qureshi et al. [69], is calculated for a typical room with concrete walls, floor, and ceiling having the following activity concentrations 50, 50, and 500 Bq/kg for \(^{226}\)Ra, \(^{232}\)Th, and \(^{40}\)K, respectively. According to the ELCR increment (being \(0.3 \times 10^{-3}\)) for the rock samples under investigation, in addition to what was reported by Mohammed et al. [68]: “equivalent values of ELCR equal to 1, 10, 100, and 1000 mSv/y will cause a mortal cancer of 0.004, 0.04, 0.4, and 4%, respectively”. Accordingly, cancer risk possibility, in a lifespan, due to the usage of ElSibai-Abu EItiyur granites as superficial material, is still insignificant to indoor ELCR.

![Figure 10. YEGD values variation in the investigated samples.](chart)

4.3.5. Excess Lifetime Cancer Risk (ELCR)

The ELCR is an essential radiological risk assessment parameter because it predicts a person’s probability of acquiring cancer due to low-dose radiation exposures during his lifetime. Using Equation (8), the ELCR is attributable to the effective gamma dose excess incurred yearly indoors due to the use of granite as superficial materials is calculated [66].
4.3.6. Indoor Radon Exhalation and Concentration

As a result of radium (226Ra) disintegration of soils, rocks, and their products (construction materials), radon (222Rn) is generated and flows through their pores into the air [31]. The biggest annual radiation dose incurred by people arises from radon and its offspring in the air. Lung cancer probability can largely increase as a result of incurring this dose for the long term, especially in dwellings. Hence, it is important to estimate the activity concentration and the exhalation rate of indoor radon.

Evaluation of radon exhalation rate (RER), in building materials, and determining the resulting indoor radon concentration [70] is vital. As per the European Commission European Commission [20] for a model of a standard room of dimensions 4 m \times 5 m \times 2.8 m tiled with granitic slabs of 3 cm thickness (2600 kg/m\(^3\) density) in its walls and floor, and depending on the 226Ra concentration (AC\(_{Ra}\)), the following equation gives theoretically radon exhalation rate RER in Bq m\(^{-2}\) h\(^{-1}\) as described [28,71]:

\[
RER = (AC_{Ra} \cdot \lambda \cdot \rho \cdot \eta \cdot d) / 2
\]  

(9)

where \(\lambda\) (=0.0076/h) is the 226Ra decay constant and \(\rho\) (=2600 kg/m\(^3\)), \(\eta\) (=0.45) and \(d\) (=0.03 m) are the density, emanation coefficient, and thickness of granite slab used in tiling the room, respectively [28].

Table 4 shows the mean value (5.17 \pm 0.45 Bq m\(^{-2}\) h\(^{-1}\)) and range (2.25 to 9.6 Bq m\(^{-2}\) h\(^{-1}\)) of RER from ElSibai-Abu ElTiyur granites. They are consistent with previous studies (Chen et al. [72]) on building materials falling within the range 0.013 to 13 Bq m\(^{-2}\) h\(^{-1}\), and within the range (0.01 to 21 Bq m\(^{-2}\) h\(^{-1}\)) published by other authors [32,63,72] using different analytical methods.

According to the theoretical evaluation of radon exhalation rate in Equation (9), the indoor radon concentration (IRC) in Bq/m\(^3\) was calculated as follows [28,63]:

\[
IRC = \frac{RER \cdot S}{(\lambda + \lambda_o) \cdot V}
\]  

(10)

where \(S\) (in m\(^2\)), \(V\) (in m\(^3\)), and \(\lambda_o\) (in h\(^{-1}\)) are the surface area exhaled radon, room air volume, rate of air removal by ventilation, respectively. In this work, the worst cases were considered, where the removal rate by poor ventilation (\(\lambda_o = 0.1\) h\(^{-1}\)) and emanation coefficient value (\(\eta = 0.45\)) were taken [28,63,73]. Moreover, furniture occupancy has been
taken into consideration, consequently, the value of 2 m\(^{-1}\) for the proportion \(S/V\) in the above equation has been taken [28].

The computed radon exhalation rate values (RER) for the investigated granitic samples of ElSibai-Um ElTiyur (Table 4 and Figure 12) varied between 2.25 to 9.60 Bq m\(^{-2}\) h\(^{-1}\) with an average of 5.17 ± 0.45 Bq m\(^{-2}\) h\(^{-1}\). According to the RER values, the indoor radon concentration (IRC) was calculated. The IRC values range from 41.88–178.50 Bq m\(^{-3}\) with an average of 96.01 ± 8.38 Bq m\(^{-3}\) (Table 4 and Figure 12). This average is above the worldwide average (40 Bq m\(^{-3}\)) (UNSCEAR [21], but still below the permissible range (100 to 300 Bq m\(^{-3}\)) as recommended by the World Health Organization (WHO) [60] (Figure 12). This is quite clear, where 60% of the samples fulfills IRC < 100 Bq m\(^{-3}\) formula, while the remaining 40%, 100 < IRC < 300 Bq m\(^{-3}\) (Table 4). This mean value of indoor radon concentrations (IRC) is below the recommended limit of 200 Bq m\(^{-3}\) (European Commission European Commission [20] and ICRP [61]. Accordingly, the population exposure is unaffected significantly by radon emission from ElSibai-Abu ElTiyur granites if they are employed as tiles in residences.

\[
IRC = \frac{RER \cdot S \cdot (\lambda + \lambda_o)}{V} \quad (10)
\]

The computed radon exhalation rate values (RER) for the investigated granitic samples of ElSibai-Um ElTiyur (Table 4 and Figure 12) varied between 2.25 to 9.60 Bq m\(^{-2}\) h\(^{-1}\) with an average of 5.17 ± 0.45 Bq m\(^{-2}\) h\(^{-1}\). According to the RER values, the indoor radon concentration (IRC) was calculated. The IRC values range from 41.88–178.50 Bq m\(^{-3}\) with an average of 96.01 ± 8.38 Bq m\(^{-3}\) (Table 4 and Figure 12). This average is above the worldwide average (40 Bq m\(^{-3}\)) (UNSCEAR [21], but still below the permissible range (100 to 300 Bq m\(^{-3}\)) as recommended by the World Health Organization (WHO) [60] (Figure 12). This is quite clear, where 60% of the samples fulfills IRC < 100 Bq m\(^{-3}\) formula, while the remaining 40%, 100 < IRC < 300 Bq m\(^{-3}\) (Table 4). This mean value of indoor radon concentrations (IRC) is below the recommended limit of 200 Bq m\(^{-3}\) (European Commission European Commission [20] and ICRP [61]. Accordingly, the population exposure is unaffected significantly by radon emission from ElSibai-Abu ElTiyur granites if they are employed as tiles in residences.

![Figure 12. Variation of IRC in the investigated samples.](image)

4.3.7. Indoor Yearly Effective Dose Owing to Radon Exposure (IYED\(_{Rn}\))

The IYED\(_{Rn}\) in mSv y\(^{-1}\) incurred by the populations owing to the IRC is computed through the model presented in UNSCEAR [73] is as follows:

\[
\text{IYED}_{Rn}[\text{mSv y}^{-1}] = \text{IRC}[\text{Bq m}^{-3}] \times F_1 \times 8766[\text{h y}^{-1}] \times F_2 \times F_3 \quad (11)
\]

where \(F_1 (=0.4), F_2 (=0.8),\) and \(F_3 (=9 \times 10^{-6} \text{ mSv per Bq m}^{-3} \text{ h}^{-1})\) are the factors of equilibrium equivalent concentration, individuals’ indoor occupancy, and dose conversion, respectively [31,73].

The values of the IYED\(_{Rn}\) (Table 4 and Figure 13) of the measured samples fluctuated between 1.06 to 4.51 mSv/y with an average value of 2.42 ± 0.21 mSv/y, i.e., higher than the worldwide average (1.2 mSv/y) provided by UNSCEAR [21]. However, the IYED\(_{Rn}\) values for 30% of the considered samples lie within the (R.A.L.) recommended action level (3–10 mSv/y) stated in ICRP [61], while the remaining 70% are less than this level (Figure 13). As a result, ElSibai-Abu ElTiyur granites do not cause possible risks to the population.
The current data was statistically analyzed using both the Origin Pro 2019b and IBM SPSS statistics (version 23) software packages. The numerical and graphical outputs extracted from the statistical analysis were used for investigating the normality distribution of radioisotope concentrations and radiological parameters. Descriptive statistics for simplifying data by reducing it into a simple summary were performed. The descriptive statistics calculated include the minimum (Min), maximum (Max), mean, range, variance, standard deviation, kurtosis, and skewness (Table 5). The histogram together with the frequency distribution curve were determined and compared with the function of normal distribution using the Shapiro–Wilk and Anderson–Darling tests ($p$-value > 0.05). Additionally, the potential linear relationships among variables were also statistically introduced herein via Pearson correlations analysis.

Table 5. Basic descriptive statistics for concentrations of $^{238}$U, $^{232}$Th, and $^{40}$K, and radiological risk parameters.

| Variables | Range | Min | Max | Mean Value | Std. Deviation | Variance | Skewness | Kurtosis (Shapiro–Wilk) | Normality Test | GFT for Normal Distribution with A–D Test |
|-----------|-------|-----|-----|------------|----------------|----------|----------|------------------------|---------------|------------------------------------------|
| $^{238}$U | 55.110| 16.890| 72.000| 38.726 | 3.379 | 15.111 | 228.345 | 0.662 | $-0.256$ | 0.30063 | 0.25085 |
| $^{232}$Th | 48.000| 21.970| 70.000| 38.226 | 2.988 | 13.362 | 178.555 | 0.794 | 0.014 | 0.12877 | 0.19204 |
| $^{40}$K | 348.500| 689.230| 1037.730| 860.712 | 18.593 | 83.152 | 6914.183 | 0.251 | 0.441 | 0.9736 | 0.88759 |
| $^{238}$Ra | 125.770 | 112.480 | 238.250 | 159.664 | 8.152 | 36.457 | 1329.089 | 0.748 | $-0.484$ | 0.07763 | 0.0616 |
| $^{138}$I | 0.280 | 0.080 | 0.360 | 0.194 | 0.017 | 0.077 | 0.006 | 0.646 | $-0.301$ | 0.27676 | 0.20339 |
| $^{137}$Cs | 0.440 | 0.440 | 0.880 | 0.608 | 0.029 | 0.128 | 0.016 | 0.758 | $-0.512$ | 0.06745 | 0.05257 |
| $^{210}$Po | 13.630 | 13.090 | 26.720 | 18.262 | 0.891 | 3.986 | 15.891 | 0.741 | $-0.246$ | 0.29481 | 0.24563 |

For all variables (Table 5), standard deviations that are less than the means indicate a high degree of uniformity. However, the positive small values of the skewness of the radioisotopes ($^{238}$U, $^{232}$Th, and $^{40}$K) concentrations, as well as those for other parameters (Table 5), indicate that their distributions are not perfectly symmetric and deviated to the right (positive skewed). Moreover, kurtosis is a small negative of most of the variables...
reported herein as shown in Table 5. Therefore, a small flatter peak and small thinner tails distribution are assumed.

The normality of distribution for all variables was tested using the Shapiro-Wilk test. The p-values of the Shapiro–Wilk test for radioisotopes (U-238, Th-232, and K-40) concentrations and for radiological risk parameters are all greater than 0.05 (Table 5), confirming that the current data follows a normal distribution. To validate this, the Anderson–Darling test (A–D test) was used in conjunction with the goodness of fit test (GFT) for normal distribution. The findings show that the data set for the radioisotopes (U-238, Th-232, and K-40) concentrations and other radiological variables also follow the normal distribution where p-values greater than 0.05 for the normal test (Table 5).

The frequency distributions of radioisotopes concentrations as well as those of radiological variables (Figures S1–S9 in the Supplementary Material) were shown (Figures 14–16). The majority of the histograms show some degree of bimodality. The bimodal distributions of radioisotopes in ElSibai-Abu ElTyur granites reflect the different processes that the magma undergo during its ascending to the surface.

![Figure 14. Frequency distribution of $^{238}$U.](image)

![Figure 15. Frequency distribution of $^{232}$Th.](image)
Pearson correlations are provided to demonstrate the potential linear relationships between the concentrations of U-238, Th-232, and K-40 and the radiological parameters (Table 6). It is evident that all considered variables are positively correlated with each other. Regarding the radioisotopes concentrations, the correlation was very strong ($r > 0.8$) between $^{238}\text{U}$ and $^{232}\text{Th}$, while it was moderate ($r > 0.4$) between them and $^{40}\text{K}$. Moreover, $^{238}\text{U}$ and $^{232}\text{Th}$ concentrations displayed a very strong correlation with all radiological parameters where the correlation coefficients ($r$) oscillated between 1 to 0.928 and 0.967 to 0.865 for $^{238}\text{U}$ and $^{232}\text{Th}$, respectively (Table 6). On the other hand, $^{40}\text{K}$ has a weak correlation ($r = 0.397$) with $I_\alpha$, moderate correlations ($0.598 \geq r \geq 0.4$) with $\text{Ra}_{eq}$, $H_{ex}$, $H_{in}$, YEGD, RER, IRC, and $\text{IYED}_{\text{Rn}}$, and strong ones ($0.63 \geq r \geq 0.6$) with $I_\gamma$, ELCR, and AGDR. It should be noted that all radiological parameters were very strongly correlated ($1 \geq r \geq 0.927$) with one another. $^{238}\text{U}$ and $^{232}\text{Th}$ concentrations were considerably related and responsible for the slight radiological risks that might arise, while the $^{40}\text{K}$ concentrations were less relevant. The strong positive relationships demonstrate a common formation while the moderate positive relationships reveal that their formation varies somewhat in nature.

|       | U-238   | Th-232  | K-40    | $R_{\text{eq}}$ | $I_\alpha$ | $I_\gamma$ | AGDR   | YEGD     | ELCR     | RER      | IRC      | $\text{IYED}_{\text{Rn}}$ |
|-------|---------|---------|---------|-----------------|------------|------------|--------|----------|----------|----------|----------|---------------------|
| U-238 | 1.000   |         |         |                 |            |            |        |          |          |          |          |                     |
| Th-232| 0.865   | 1.000   |         |                 |            |            |        |          |          |          |          |                     |
| K-40  | 0.401   | 0.478   | 1.000   |                 |            |            |        |          |          |          |          |                     |
| $R_{\text{eq}}$ | 0.853   | 0.987   | 0.593   | 1.000           |            |            |        |          |          |          |          |                     |
| $I_\alpha$ | 0.999 | 0.865   | 0.397   | 0.937           | 1.000      |            |        |          |          |          |          |                     |
| $I_\gamma$ | 0.928 | 0.960   | 0.630   | 0.999           | 0.927      | 1.000      |        |          |          |          |          |                     |
| AGDR  | 0.942   | 0.959   | 0.607   | 1.000           | 0.940      | 0.999      | 1.000  |          |          |          |          |                     |
| YEGD  | 0.939   | 0.958   | 0.579   | 0.993           | 0.934      | 0.991      | 1.000  | 0.999    |          |          |          |                     |
| ELCR  | 0.946   | 0.955   | 0.603   | 0.998           | 0.944      | 0.997      | 0.999  | 0.992    | 1.000    |          |          |                     |
| RER   | 1.000   | 0.866   | 0.401   | 0.939           | 0.999      | 0.928      | 0.942  | 0.939    | 0.946    | 1.000    |          |                     |
| IRC   | 1.000   | 0.866   | 0.401   | 0.939           | 0.999      | 0.928      | 0.942  | 0.939    | 0.946    | 1.000    |          |                     |
| $\text{IYED}_{\text{Rn}}$ | 1.000 | 0.866   | 0.400   | 0.939           | 0.999      | 0.928      | 0.942  | 0.938    | 0.945    | 1.000    |          |                     |

6. Conclusions

The radioisotopes (U-238, Th-232, and K-40) concentrations and RER from ElSibai-Abu ElTyvir granitic samples, as well as the assessment of any potential health hazards when these rocks are used as decorative building materials, were investigated. Geochemically, uranium in the rocks of ElSibai-Abu ElTyvir is closely related to SiO2 (0.70), Rb (0.86),...
and Th (0.83) in rock-forming minerals. While thorium is strongly attached to Cs (0.89), Li (0.70), Pb (0.78), and Rb (0.96). Potassium, on the other hand, is highly correlated with SiO2 (0.69) and Pb (0.70). The mean values obtained for both 238U and 232Th concentrations in ElSibai-Abu ElTiyur granites are slightly more than GAVs of these radionuclides in regular soil, but they do not surpass their corresponding values in building materials. Meanwhile, the mean concentration of 40K herein is high compared to their GAVs in both regular soil and building materials. However, the radiation risk indices, the absorbed yearly effective excess gamma dose rates, the excess lifetime cancer risk, the radon exhalation rate, the radon concentration, and radon yearly effective dose rate indoors are within the safe recommended levels specified in the international standards for use these granites as construction materials. According to the statistical analysis applied herein, the data of the measured radioisotope concentrations (U-348, Th-232, and K-40)—besides all the estimated radiological parameters—follow normal distributions. Furthermore, it was found that the slight radioactivity level arising from the examined granite is ascribable mainly to 238U and 232Th concentrations, with only a slight contribution of 40K. The content of the radioactive elements and their hazardous parameters in the studied rocks complement the gap for the need for basic research to expand the raw material alternative for the production of building materials.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/app112412002/s1, Figures S1–S9 show the frequency distributions of Raeq, AGDR, Iα, Iγ, YEGD, ELCR, RER, IRC and IYEDDrn, respectively. Table S1: Major, trace and rare earth elements composition of ElSibai–Abu ElTiyur granites. Table S2: Pearson’s correlation coefficient between the major oxides, trace and rare elements.

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