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Measurement of NORM in Building Materials to Assess Radiological Hazards to Human Health and Develop the Standard Guidelines for Residents in Thailand: Case Study in Sand Samples Collected from Seven Northeastern Thailand Provinces

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Abstract: A total of 223 sand samples collected from seven provinces in Northeastern Thailand were analyzed for their gamma radioactivity from naturally occurring radioactive materials (NORMs), and the data were used to calculate the concentrations of Ra-226, Th-232, and K-40. Radiological safety indicators such as the indoor external dose rates (D_{in}), the annual indoor effective dose (E_{in}), the activity concentration index (I), the radium equivalent activity (Ra_{eq}), the external hazard index (H_{ex}), the internal haphazard index (H_{in}), and the excess lifetime cancer risk ($ELCR$) were calculated. The activity concentrations were found to be 36 ± 10 Bq/kg for Ra-226, 2.64 ± 0.58 Bq/kg for Th-232, and 323 ± 168 Bq/kg for K-40. D_{in} is 62 ± 23 nGy/h. The E_{in} is 0.30 ± 0.11 mSv/y. The activity concentrations and other indicators were reported by each province and compared with the safety standards and are found to be within the safe limits in this study. The results can be used to develop the standard guideline levels for choosing building materials in Thailand.

Keywords: building materials; radiological hazard; sand; standard guidelines; Northeastern Thailand

1. Introduction

Building materials such as rock, soil and sand are formed from the earth's crust, enriched with naturally occurring radioactive materials (NORMs). The main radionuclides in NORMs are long-lived radionuclides such as uranium-238 (U-238), thorium-232 (Th-232), radium-226 (Ra-226), and potassium-40 (K-40), etc. These radioisotopes are the main external source of irradiation that enters the human body [1]. Klepeis et al. (2001) investigated how humans might be impacted by pollutants in our various indoor and outdoor environments by assessing the time humans spend in various locations. This study found that normally human beings spend nearly 90% of their time indoors [2]. Therefore, their exposure to radiation in the residence is strongly related to the radioactivity from building materials [3]. The health risk concern when they are exposed to NORMs is regarded as the potential for developing cancer, because the emitted ionizing radiation is a known carcinogen [3]. Thus, an increase in exposure to ionizing radiation results in an increased risk of developing cancer. So far, several reported activity concentrations are relatively low compared with NORMs from the mineral industry; even though the ICRP 1990 reported that the chronic exposure of low doses from ionizing radiation can increase the risk of health damage to individuals, which may occur decades after exposure [4]. The annual effective dose of public exposure does not exceed the dose limit (1 mSv/y) recommended from ICRP publication 103 [5]. Building materials have been recommended by several organizations to have their radioactivity measured before being put on the market, especially by the EU Basic Safety Standards (EU-BSS), Standard GB 6566-2001 (limits of radionuclides in building materials) and other national standards. The EU-BSS requires the determination of activity concentration (Ra-226, Th-232 and K-40) in building materials and the index (I) value to be less than one [6,7]. The index value of one can be used as a conservative screening tool for identifying materials that during their use would cause doses exceeding the reference level (1 mSv/y excess in addition to outdoor exposure) in the case of a bulk amount inbuilt [7]. Furthermore, the IAEA Specific Safety Guide No. SSG-32 proposes the use of an activity concentration index as a screening tool for identifying building materials that may need to be subject to restrictions. The limit values of the index (I) depend on the dose criterion adopted and the use of the material (Table 1).

Table 1. Limit values for the index (I) [8].

Does Criterion	0.3 **mSv/y**	1 **mSv/y**
Materials used in bulk amounts, e.g., concrete	$I \leq 0.5$	$I \leq 1$
Superficial and other materials with restricted use: tiles, boards, etc.	$I \leq 2$	$I \leq 6$

The building materials on sale in Thailand consist of raw materials from both local production and abroad. The radionuclide concentrations in building materials in Thailand were reported to be within a wide range. There are currently no standard or safety limits of radionuclides in building materials to control production or the importing of building materials into the country. Sand is a component of many building materials in Thailand such as cement, concrete, block bricks, brick, sandstone tiles, land reclamation, etc. Many researchers worldwide reported the different levels of NORMs in the sand samples of their country. Xinwei and Xiaolan (2006) [9] reported levels of the natural radioactivity from the Baoji Weihe Sand Park, China; the radioactivity concentration of the sand ranges from 10 to 38 Bq/kg for Ra-226, 27 to 48 Bq/kg for Th-232 and 635 to 1127 Bq/kg for K-40. Vasconcelos et al. (2011) [10] reported that the activity concentrations of Ra-226, Th-232 and K-40 in beach sand ranged from 8 to 8300 Bq/kg, from 21 to 18,450 Bq/kg, and from 3 to 3110 Bq/kg, respectively. Malain et al. (2010) [11] reported that the levels of the activity concentrations of Ra-226, Th-232, and K-40 in beach sand samples along the Andaman coast of Thailand were found to lie in the range of 3 ± 0.1 to 24 ± 0.1, 3 ± 0.1 to 35 ± 1, 11 ± 1 to 654 ± 22 Bq/kg, respectively. Most studies reported the levels of radionuclides in beach sand, whereas only a small number of papers reported the radionuclides in sand from building materials. Although the database of activity concentrations of radionuclides in sand for construction and the estimations of the haphazard index are more beneficial in terms of human health, because several reports indicated that the building materials are the main external and internal source of indoor irradiation.

The aim of this research is to determine the natural radionuclides levels in sand samples which are used in Thailand. These samples were collected from seven Northeastern Thailand provinces to analyze the activity concentration of major NORM isotopes, Ra-226, Th-232, and K-40, and to use these values to calculate the indoor external dose rates (D_{in}), the annual indoor effective dose (E_{in}), the activity concentration index (I) and the radium equivalent activity (Ra_{eq}) for the gamma radiation emitted by the building materials and to assess the health hazard indices such as the external hazard index (H_{ex}), the internal haphazard index (H_{in}), and the excess lifetime cancer risk (ELRCA). The determination of Ra-226, Th-232, and K-40 values and other indicators of each province were estimated. These results can be used to develop the standard guideline levels for choosing building materials in Thailand.

2. Materials and Methods

2.1. Study Area

This study is part of a research project which aims to measure the radioactivity of building materials used in Thailand. The database can be used to develop the standard guideline levels in Thailand. In this study, all sand samples were collected from Loei, Nong Bua Lam Phu, Khon Kaen, Nakhon Ratchasima, Nong Khai, Bueng Kan, and Sakhon Nakhon provinces in Northeastern Thailand. The studied area can be divided into four zones: the upper northeast province group 1 (Loei, Nong Bua Lam Phu, Nong Khai, Bueng Kan), the upper northeast province group 2 (Sakon Nakhon), the central northeast province (Khon Kaen), and the lower northeast province group 1 (Nakhon Ratchasima). The fifth zone, lower northeast province group 2, was planned but due to the COVID-19 situation, we were not able to obtain samples from this zone. Khon Kaen, Nakhon Ratchasima and Sakhon Nakhon are large cities and trade centers including the building material center of the northeast. The sand samples were collected by random sampling to determine the natural radionuclide levels in sand samples from each zone in Northeastern Thailand. The study areas are shown in Figure 1.

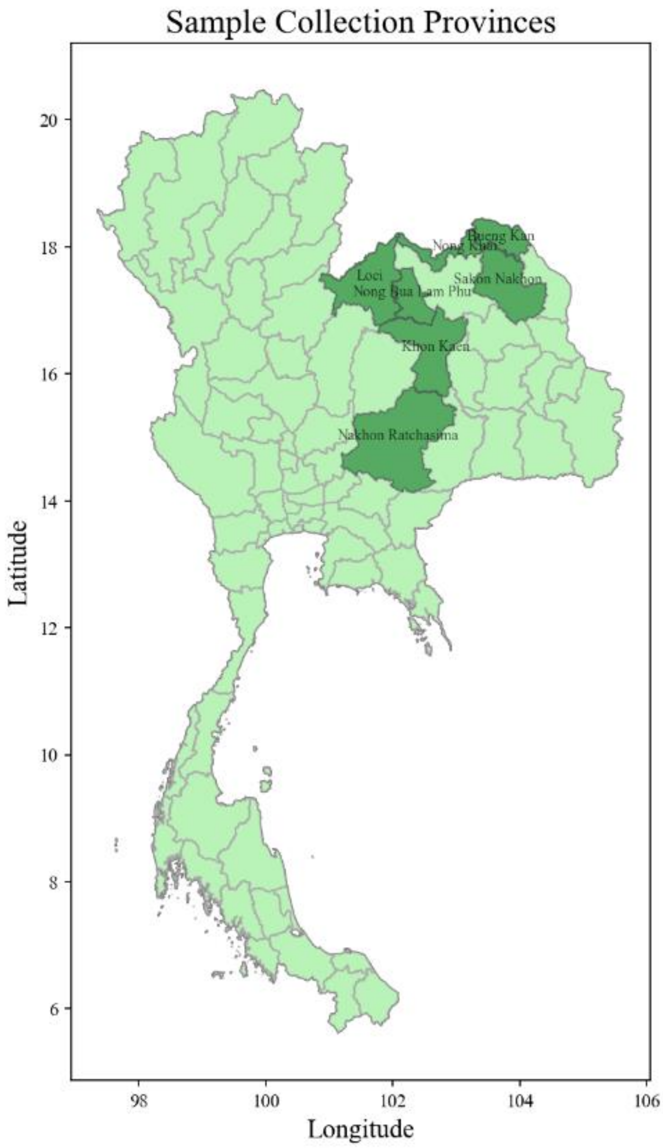


Figure 1. Study areas include Loei, Nong Bua Lam Phu, Khon Kaen, Nakhon Ratchasima, Nong Khai, Bueng Kan, and Sakon Nakhon provinces of Thailand. The unit for latitude and longitude is degree (°).

2.2. Sample Collection and Preparation

The sand samples were obtained from local residents of each province, weighing about 2 kg per sample. The samples were bought from local building material stores. Sand samples were kept in plastic bags and labelled by the sample code and province along with the geographical coordinate of each sampling point by global positioning system (GPSmap 78 s, Garmin). Sand samples (shown in Figure 2) were sifted out from the rubble and dried in an oven at 105 °C for 24 h, then the dried samples were packed in fully cylindrical plastic containers which were sealed with silicone glue and PVC tape, dry weighed and kept for one month.

(**a**) (**b**)

Figure 2. Sand samples (**a**) and the gamma-ray detector (**b**).

2.3. Gamma-Ray Detector and Calibration

Natural radioactivity was measured using a high-purity germanium (HPGe) gamma-ray detector (Oxford, USA) with a relative efficiency of 30%. The energy resolution (FWHM) of the detector is 2 keV at 1332 keV of a Co-60 source. The energy and efficiency calibration of the detector were carried out using certified reference materials IAEA-RGU-1 and IAEA-RGTh-1. The detector was shielded with 10 cm of lead to reduce gamma radiation from the environment and interferences with the radiation metering system.

2.4. Radioactivity Measurement, Dose and Hazard Index Calculation

Samples in Marinelli containers were counted for their gamma radioactivity for 80,000 s per sample. Background radiation counts were obtained with a blank Marinelli container under the same conditions before the measurement of samples. The average of the background counts was subtracted from the sample spectrum. The gamma-ray photo peaks corresponding to 186 keV, 911 keV, 1460 keV corresponded to the emitted gamma from Ra-226, Th-232, K-40, respectively. The activity concentration (C) in the sand samples was calculated using the following equation [12]:

$$\mathrm{C(Bq/kg)} = \frac{C_a}{\varepsilon \times I_{eff} \times M_s} \tag{1}$$

where C_a is the net gamma count rate (count per second), ε is the detector efficiency of a specific gamma ray, I_{eff} is the intensity of the gamma line in radionuclides, and M_s is the mass of the sand sample in kilograms. We assumed that in this case these sand samples will be used as a component of building materials. Thus, the indoor external dose and the annual indoor effective dose were used to calculate the other indicators in this study. The indoor external dose rates (D_{in}) in (nGy/h) could be obtained from the following equation (UNSCEAR, 2000) [3]:

$$D_{in} = 0.92 \times A_{Ra} + 1.1 \times A_{Th} + 0.080 \times A_K \tag{2}$$

where A_{Ra}, A_{Th}, and A_K are the activity concentration of Ra-226, Th-232 and K-40 in (Bq/kg), respectively. The annual indoor effective dose (E_{in}) in (mSv/y) is determined as follows (UNSCEAR, 2000) [3]:

$$E_{in} = D_{in} \times 8760 \times 0.7 \times 0.8 \times 10^{-6} \tag{3}$$

where D_{in} is the indoor external dose rate in (nGy/h), 8760 is the number of hours in a year, 0.7 (Sv/Gy) is the conversion factor, which convert the absorbed dose rate in the air to the human effective dose, and 0.8 is the indoor occupancy factor. The E_{in} value should be <1 mSv/y. The European Commission (EC) proposed an index called the gamma index (I) to verify whether the guidelines of the EC for building materials usage are met. I is calculated using the following formula (EC, 1999) [13]:

$$I = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \tag{4}$$

The radium equivalent activity (Ra_{eq}) is an evaluation index of the radiation hazard associated with the building materials used. Assuming that all of the decay products of Ra-226 and Th-232 are in radioactive equilibrium with their precursors, Ra_{eq} is calculated from the formula below [14]. The Ra_{eq} value should be $\leq$370 Bq/kg.

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.07A_K \tag{5}$$

The external hazard index (H_{ex}), is an assessment of the excess gamma radiation from the building materials. H_{ex} was calculated using the following Equation [14]:

$$H_{ex} = \frac{A_{Ra}}{370\ \text{Bq/kg}} + \frac{A_{Th}}{259\text{Bq/kg}} + \frac{A_K}{4810\text{Bq/kg}} \tag{6}$$

The value of H_{in} should be below 1 to ensure the safe use of building materials, which corresponds to the upper limit of Ra_{eq} (370 Bq/kg).

The internal haphazard index (H_{in}) is an assessment of the excess radiation due to radon from the building materials. H_{in} can be used for considering the excess internal radiation due to the inhalation of Rn-222 and its short-lived decay products from building materials, which is determined as [15]:

$$H_{in} = \frac{A_{Ra}}{185\ \text{Bq/kg}} + \frac{A_{Th}}{259\ \text{Bq/kg}} + \frac{A_K}{4810\ \text{Bq/kg}} \tag{7}$$

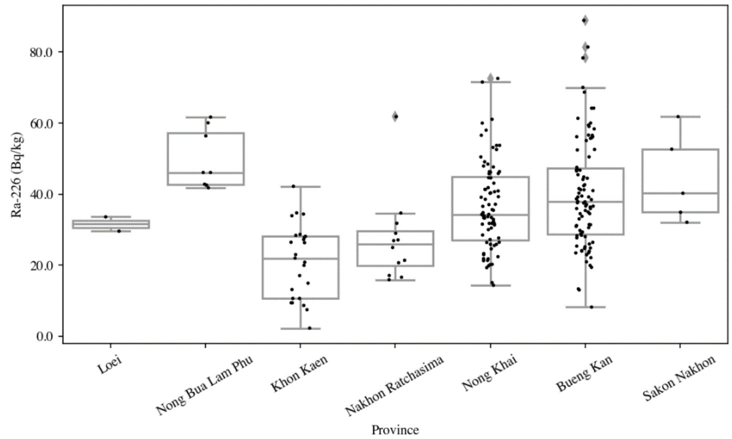
where A_{Ra}, A_{Th}, and A_K in Equations (2) and (4)–(7) are the activity concentration of Ra-226, Th-232 and K-40 in (Bq/kg), respectively. The value of H_{in} should be $\leq$1. The excess lifetime cancer risk ($ELCR$) due to radioactive exposure form spending a lifetime in residences with these sand mixtures was calculated using the following equation [16,17]: The $ELCR$ values do not indicate a level that safe or acceptable.

$$ELCR = AEDE \times DL \times RF \tag{8}$$

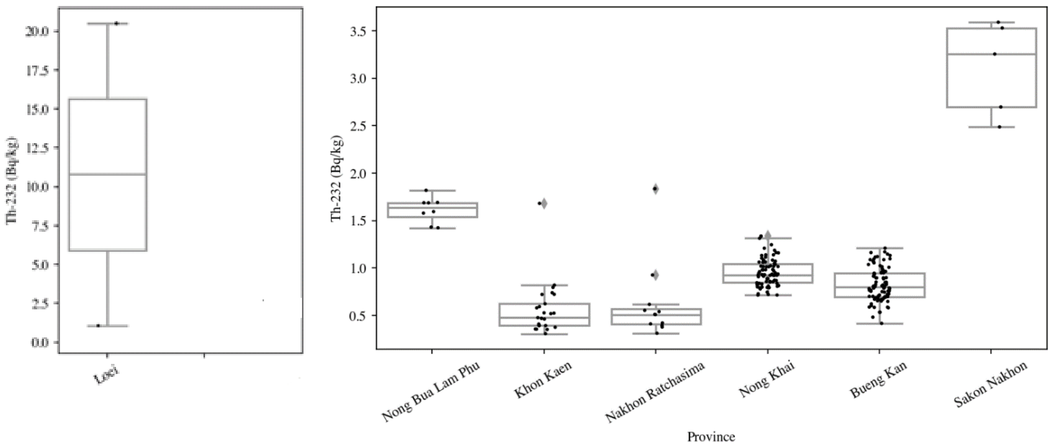
where $AEDE$ is the annual effective dose equivalent (mSv/y), DL is an average duration of life (70 y), and RF is a risk factor (Sv^{-1}), the fatal cancer risk per Sievert. For stochastic effects, ICRP60 uses the value of 0.05 for the public [4].

3. Results and Discussion

The activity concentrations of Ra-226, Th-232, and K-40 in sand samples are shown as a box distribution (Figure 3). Loei has only two samples. For Loei, Th-232 values are quite different.



(**a**)



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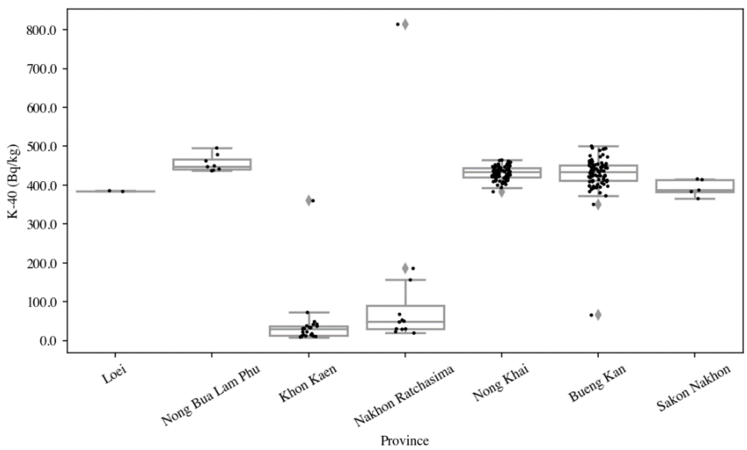
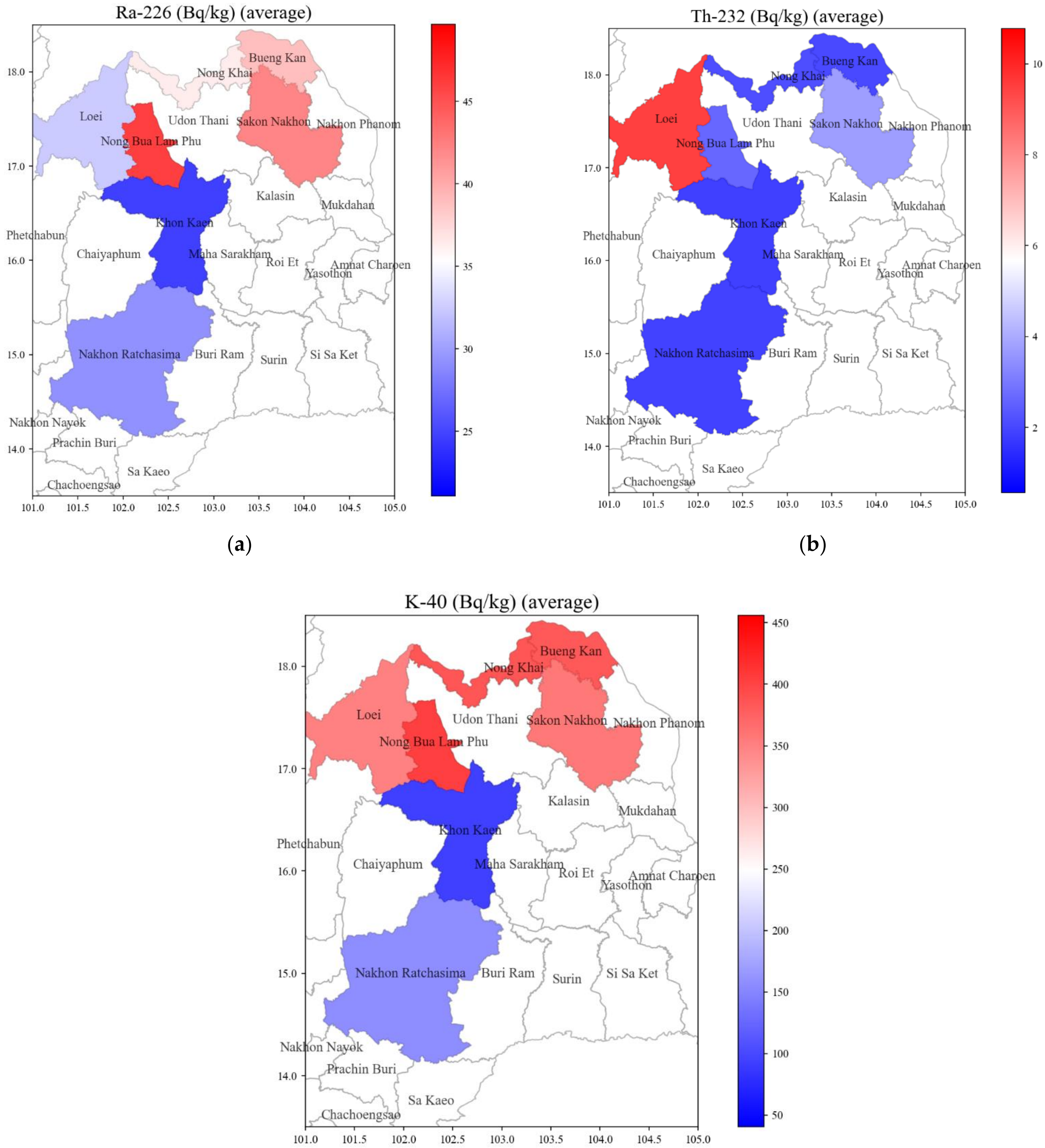


(**c**)

Figure 3. The activity concentrations of Ra-226 (**a**), Th-232 (**b**), and K-40 (**c**) in sand samples. The box represents the middle 50% of measurements (2nd and 3rd quartiles). The middle line represents the median dividing those quartiles. The whiskers represent the bounds of the remaining two quartiles. Data points outside the whisker range are outliers.

The activity concentrations of Ra-226, Th-232, and K-40 are reported in map format to report the level of NORM concentration in sand samples used in building construction in different provinces (Figure 4). This map with the data of radionuclides from every province of Thailand will be complete in 2022. The map will be useful for selecting building materials in Thailand in the future.



(**a**) (**b**)

(**c**)

Figure 4. The activity concentrations of Ra-226 (**a**), Th-232 (**b**), and K-40 (**c**) in sand samples are shown in the maps.

The average results of the activity concentrations of Ra-226, Th-232, and K-40 (C) are shown in Table 2 and the indoor external dose rates (D_{in}), the annual indoor effective dose (E_{in}), the activity concentration index (I) the radium equivalent activity (Ra_{eq}), the external hazard index (H_{ex}), the internal haphazard index (H_{in}), and the excess lifetime cancer risk ($ELCR$) are shown in Table 3.

The average results of this study were compared with reports of Ra-226, Th-232, and K-40 concentrations and D_{in}, E_{in}, I, Ra_{eq}, H_{ex} and H_{in} values from sand samples in the different countries, the world averages, and the guideline levels (Table 4).

Table 2. The average activity concentration (Bq/kg) from sand samples collected from Loei, Nong Bua Lam Phu, Khon Kaen, Nakhon Ratchasima, Nong Khai, Bueng Kan, and Sakon Nakhon provinces in Northeastern Thailand.

Provinces	**No. of Sample**	**Activity Concentration (Bq/kg)**					
		Ra-226		**Th-232**		**K-40**	
		Avg ± SD	**Min–Max**	**Avg ± SD**	**Min–Max**	**Avg ± SD**	**Min–Max**
Loei	2	32 ± 7	30–34	10.78 ± 1.86	1.07–20.49	385 ± 11	384–386
Nong Bua Lum Phu	8	50 ± 8	42–62	1.61 ± 0.14	1.42–1.82	456 ± 21	437–496
Khon Kaen	25	21 ± 10	2–42	0.56 ± 0.28	0.31–1.68	40 ± 68	9–360
Nakhon Ratchasima	12	27 ± 12	16–62	0.62 ± 0.42	0.31–1.84	125 ± 283	19–814
Nong Khai	80	37 ± 12	14–73	0.96 ± 0.14	0.71–1.34	432 ± 18	383–465
Bueng Kan	91	40 ± 15	8–89	0.83 ± 0.18	0.42–1.21	429 ± 48	65–500
Sakon Nakhon	5	44 ± 13	21–62	3.11 ± 0.50	2.49–3.59	393 ± 22	365–393
Total/Average/Range	223	36 ± 10	2–89	2.64 ± 0.58	0.31–20.49	323 ± 168	9–814

Table 3. The average D_{in}, E_{in}, I, Ra_{eq}, H_{ex}, H_{in}, and ELCR from sand samples collected from Loei, Nong Bua Lam Phu, Khon Kaen, Nakhon Ratchasima, Nong Khai, Bueng Kan, and Sakon Nakhon provinces in Northeastern Thailand. Assume that the sand is used indoor as construction materials (also check Appendix A).

Provinces	D_{in}	E_{in}	I	Ra_{eq}	H_{ex}	H_{in}	*ELCR*
	nGy/h	**mSv/y**		**Bq/kg**			**(1 × 10^{-3})**
Loei	72 ± 9	0.35 ± 0.03	0.29 ± 0.03	77 ± 10	0.21 ± 0.03	0.29 ± 0.03	1.23 ± 0.15
Nong Bua Lum Phu	84 ± 9	0.41 ± 0.05	0.33 ± 0.03	87 ± 10	0.24 ± 0.03	0.32 ± 0.05	1.44 ± 0.16
Khon Kaen	23 ± 13	0.11 ± 0.07	0.09 ± 0.05	25 ± 14	0.07 ± 0.04	0.12 ± 0.07	0.40 ± 0.23
Nakhon Ratchasima	36 ± 29	0.18 ± 0.14	0.14 ± 0.11	38 ± 29	0.10 ± 0.08	0.18 ± 0.11	0.62 ± 0.49
Nong Khai	69 ± 112	0.34 ± 0.06	0.27 ± 0.04	71 ± 12	0.19 ± 0.03	0.29 ± 0.07	1.19 ± 0.20
Bueng Kan	72 ± 16	0.35 ± 0.08	0.28 ± 0.06	74 ± 17	0.20 ± 0.05	0.31 ± 0.09	1.24 ± 0.27
Sakon Nakhon	76 ± 11	0.37 ± 0.05	0.29 ± 0.04	79 ± 12	0.21 ± 0.03	0.33 ± 0.07	1.30 ± 0.19
Average	62 ± 23	0.30 ± 0.11	0.24 ± 0.09	64 ± 23	0.17 ± 0.06	0.26 ± 0.08	1.06 ± 0.39

Table 4. Comparison of the average results of Ra-226, Th-232, and K-40 concentrations and D_{in}, E_{in}, I, Ra_{eq}, H_{ex} and H_{in} values from sand samples in this study with reports in the different countries and the world averages and the guideline levels.

Country	**Ra-226**	**Th-232**	**K-40**	D_{in}	E_{in}	I	Ra_{eq}	H_{ex}	H_{in}	**Ref.**
	Bq/kg	**Bq/kg**	**Bq/kg**	**nGy/h**	**mSv/y**		**Bq/kg**			
USA	5 ± 1	17 ± 2	457 ± 44	33	0.03	0.51	65	0.18		Radenkovic et al. 2009 [18]
Brazil	2 ± 0.36	6 ± 0.75	19 ± 2	6	0.01	0.09	13	0.03		Radenkovic et al. 2009 [18]
Saudi Arabia	23 ± 4	30 ± 6	380 ± 65	46 ± 6	0.28 ± 0.04		95 ± 13	0.26 ± 0.03	0.32 ± 0.04	Alaamer, 2012 [19]
Bangladesh	49 ± 5	126 ± 3	292 ± 18	131	0.64		238	0.64	0.77	Ahmed et al. 2016 [20]
Thailand	41 ± 5	64 ± 7	248 ± 44	69			152 ± 18			Kessaratikoon et al. 2007 [21]
Thailand	36 ± 10	2.64 ± 0.58	323 ± 168	62 ± 23	0.30 ± 0.11	0.24 ± 0.09	64 ± 23	0.17 ± 0.06	0.26 ± 0.08	This study
World averages	35	30	400	51	0.50					UNSCEAR, 2000 [3]
Guideline levels					1	<1	370	<1	<1	UNSCEAR, 2000 [3]

The lowest activity concentrations of Ra-226 and K-40 were 2, 0.31, and 9 Bq/kg, respectively, found at Khon Kaen; the lowest activity concentrations were found at Nakhon Ratchasima for Th-232 (0.31 Bq/kg). The highest activity concentrations of Ra-226, Th-232, and K-40 were found at Bueng Kan (89 Bq/kg), Loei (20 Bq/kg), and Nakhon Ratchasima (814 Bq/kg), respectively. Sand samples for building materials brought from Khon Kaen were found to have low activity concentrations of Ra-226, Th-232, and K-40. The lowest and highest values of E_{in}, I, Ra_{eq}, H_{ex}, H_{in}, and $ELCR$ are consistent with the D_{in} value. The lowest values of D_{in}, E_{in}, I, Ra_{eq}, H_{ex}, H_{in}, and $ELCR$ were 23 $\pm$ 13 nGy/h, 0.11 $\pm$ 0.07 mSv/y, 0.09 $\pm$ 0.05, 25 $\pm$ 14 Bq/kg, 0.07 $\pm$ 0.04, 0.12 $\pm$ 0.07, and 0.40 $\pm$ 0.23, respectively, found at Khon Kaen. The highest values of D_{in}, E_{in}, I, Ra_{eq}, H_{ex}, H_{in}, and $ELCR$ were 84 $\pm$ 9 nGy/h, 0.41 $\pm$ 0.05 mSv/y, 0.33 $\pm$ 0.03, 87 $\pm$ 10 Bq/kg, 0.24 $\pm$ 0.03, 0.32 $\pm$ 0.05, and 1.44 $\times$ 10^{-3} respectively, found at Nong Bua Lum Phu. The four measured quantities (activity concentrations of Ra-226, Th-232, and K-40, and the annual indoor effective dose) are used to cluster the data from each province (excluding Loei due to low number of measurements) into two dimensions by principal component analysis (PCA) (see Figure 5). Because the values from the provinces are not that different, the province clusters are not clearly separated. The PCA diagram shows that radioactive (Ra-226, Th-232, K-40, and E_{in}) levels in sand samples collected from the neighboring provinces are in the same range, with Sakon Nakhon results being perhaps the most different from others.

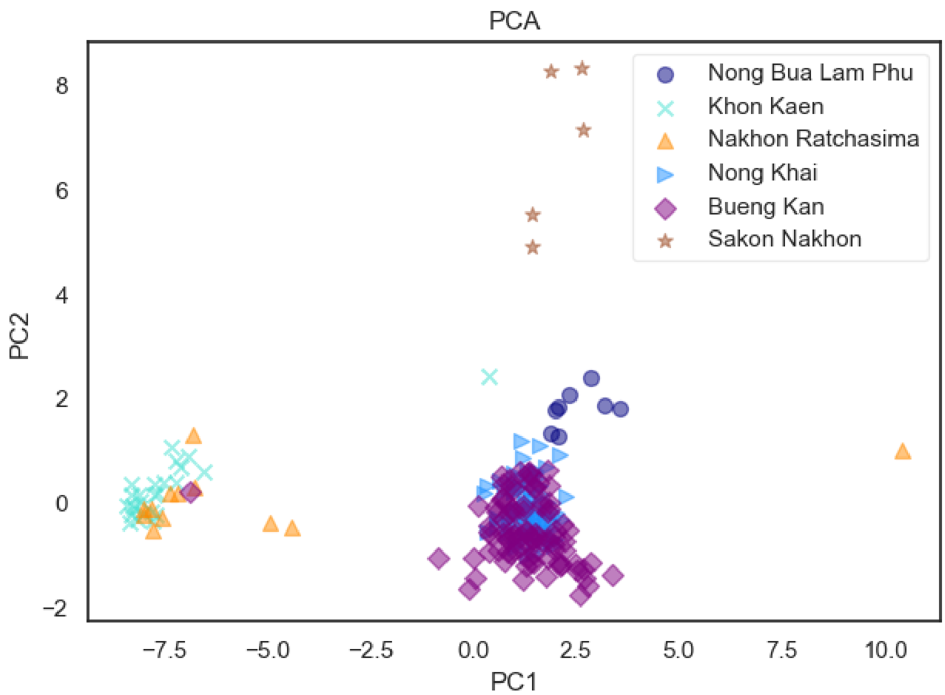


Figure 5. Grouping of the sand sample from six provinces (excluding Loei) using the activity concentrations of Ra-226, Th-232, K-40 and the annual indoor effective dose levels using principal component analysis.

The mean values of activity concentrations from seven province in Northeastern Thailand (C) were 36 $\pm$ 10, 2.64 $\pm$ 0.58, and 323 $\pm$ 168 Bq/kg for Ra-226, Th-232, and K-40, respectively. The mean indoor external dose rates value (D_{in}) is 62 $\pm$ 23 nGy/h. The world averages are 35, 30, and 400 Bq/kg, and 51 nGy/h for Ra-226, Th-232, K-40, and the absorbed dose rates, respectively, as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) [3]. The mean values of Ra-226 and K-40 in the sand samples are close to the world averages; whereas, the mean value of Th-232 in sand samples is much lower than the world average.

The average indoor annual effective dose (E_{in}) is 0.30 $\pm$ 0.11 mSv/y which is lower than the dose limit of 1 mSv/y recommended by the International Commission on Radiological Protection (ICRP) (ICRP, 2007) [5]. The index (I) was found to be 0.24 $\pm$ 0.09. These results were within the guideline levels of the EU-BSS: $I \leq 1$ for materials used in bulk, and $I \leq 6$ for superficial materials (Council of the European Union, 2013). An I lower than 1 indicates that the annual effective dose is less than 1 mSv. The radium equivalent activity (Ra_{eq}) was 64 $\pm$ 23 Bq/kg which does not exceed the limit of 370 Bq/kg recommended by UNSCEAR, 2000. The external hazard index and the internal haphazard index values are 0.17 $\pm$ 0.06 and 0.26 $\pm$ 0.08. The value of the index H_{ex} should be $\leq$1, the maximum level of H_{ex} corresponds to the upper limit of Ra_{eq} (370 Bq/kg) to hold the radiation hazard as insignificant. The value of the index H_{in} should be $\leq$1 to keep the radon and its daughter concentrations safe enough for human respiratory organs. The excess lifetime cancer risk ($ELCR$) was found to be 1.06 $\times$ 10^{-3}. The world average value of $ELCR$ was 0.29 $\times$ 10^{-3} reported by UNSCEAR, 2000 [3].

The results can be used to develop the standard guideline levels for choosing building materials in Thailand.

4. Conclusions

Sand samples collected from Loei, Nong Bua Lam Phu, Khon Kaen, Nakhon Ratchasima, Nong Khai, Bueng Kan, and Sakon Nakhon provinces of Northeastern Thailand were measured using an HPGe gamma-ray detector to determine the activity concentrations, dose and hazard index values. The average activity concentrations are found to be 36 $\pm$ 10 Bq/kg for Ra-226, 2.64 $\pm$ 0.58 Bq/kg for Th-232, and 323 $\pm$ 168 Bq/kg for K-40. The indoor external dose rate (D_{in}) is 62 $\pm$ 23 nGy/h. The world averages are 40, 40, and 370 Bq/kg and 51 nGy/h for Ra-226, Th-232, and K-40 concentrations, and the absorbed dose rates, respectively (UNSCEAR2000). The average indoor annual effective dose (E_{in}) is 0.30 $\pm$ 0.11 mSv/y which is lower than the dose limit of 1 mSv/y recommended by ICRP. The index (I) and radium equivalent activity (Ra_{eq}) were 0.24 $\pm$ 0.09 Bq/kg and 64 $\pm$ 23 Bq/kg, respectively. The results showed that the index (I) is lower than the standard levels of the EU-BSS: $I \leq 1$, indicating the radium equivalent activity (Ra_{eq}) does not exceed 370 Bq/kg as recommended by UNSCEAR 2000. The results of radiation hazard indices H_{ex}, H_{in} are 0.17 $\pm$ 0.06, and 0.26 $\pm$ 0.08, respectively. The values of the indices H_{ex} and H_{in} are within the guideline level of 1 recommended by EU. The excess lifetime cancer risk ($ELCR$) if the sand is used indoor was found to be 1.06 $\times$ 10^{-3} which is higher than the world average value of $ELCR$ (0.29 $\times$ 10^{-3}). It can be implied from the results that using sand in a large quantity in a closed room may increase the risk of lung cancer and mitigation measures should be applied. The project will collect more samples to measure and add to the database. The results will be used to develop the standard guideline levels for choosing building materials in Thailand.

Author Contributions: P.S. is responsible for measurement the naturally occurring radioactive materials in this research, as well as designing the experiment, calculating, interpreting the data and wrote the manuscript. R.P. is responsible for data analysis, visualization, and manuscript revision. S.T. and C.K. (Chutima Kranrod) designed, reviewed, and made recommendations on this manuscript. U.I. and C.K. (Chunyapuk Kukusamude) are responsible for sample preparation and measurement of naturally occurring radioactive materials and calculated the net count of radionuclides from all samples in this research. All authors have read and agreed to the published version of the manuscript.

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Appendix A

From the data from Table 2, if the sand samples were used outdoor instead of indoor (as shown in Table 3), the average values of D_{out}, E_{out}, I_{α} and $ELCR$ are lower, as shown in Table A1. The average outdoor $ELCR$ (0.14×10^{-3}) is lower than the world average $ELCR$.

Table A1. The average D_{out}, E_{out}, I_{α}, $ELCR$ from sand samples collected from Loei, Nong Bua Lam Phu, Khon Kaen, Nakhon Ratchasima, Nong Khai, Bueng Kan, and Sakon Nakhon provinces in Northeastern Thailand. Assume that the sand is used outside residential buildings.

Province	D_{out}	E_{out}	I_{α}	$ELCR$
	nGy/h	mSv/y		(1×10^{-3})
Loei	37 ± 5	0.05 ± 0.01	0.16 ± 0.03	0.16 ± 0.02
Nong Bua Lum Phu	43 ± 5	0.05 ± 0.01	0.25 ± 0.04	0.18 ± 0.02
Khon Kaen	12 ± 7	0.01 ± 0.01	0.11 ± 0.05	0.05 ± 0.03
Nakhon Ratchasima	18 ± 0	0.02 ± 0.02	0.14 ± 0.06	0.08 ± 0.06
Nong Khai	35 ± 6	0.04 ± 0.01	0.18 ± 0.06	0.15 ± 0.02
Bueng Kan	37 ± 8	0.05 ± 0.01	0.20 ± 0.08	0.16 ± 0.03
Sakon Nakhon	39 ± 5	0.05 ± 0.01	0.22 ± 0.06	0.17 ± 0.02
Average	32 ± 12	0.04 ± 0.02	0.18 ± 0.05	0.14 ± 0.05

References

1. Raghu, Y.; Ravisankar, R.; Chandrasekarn, A.; Vijayagopal, P.; Venkatraman, B. Assessment of natural radioactivity and radiological hazards in building materials used in the Tiruvannamalai District, Tamilnadu, India, using a statistical approach. *J. Taibah Univ. Sci.* **2017**, *11*, 523–533. [CrossRef]
2. Klepeis, N.E.; Nelson, W.C.; Ott, W.R.; Robinson, J.P.; Tsang, A.M.; Switzer, P. The National Human Activity Pattern Survey (NHAPS) A Resource for Assessing Exposure to Environmental Pollutants. *J. Expo. Sci. Environ. Epidemiol.* **2001**, *11*, 231–252. [CrossRef] [PubMed]
3. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation*; UNSCEAR 2000 Report to the General Assembly with Scientific Annex B. Exposures from Natural Radiation Sources; United Nations: New York, NY, USA, 2000; Volume I.
4. The International Commission on Radiological Protection. *Annals of the ICRP.1990, Recommendations of the International Commission on Radiological Protection. ICRP Publication 60*; Pergamon Press: Oxford, UK, 1991.
5. International Commission on Radiological Protection. *The 2007 Recommendations of the International Commission on Radiological Protection*; ICRP Publication 103. Ann. ICRP 37; Elsevier: Amsterdam, The Netherlands, 2007.
6. Smetsers, R.C.G.M.; Tomas, J.M. A practical approach to limit the radiation dose from building materials applied in dwelling, in compliance with the Euratom Basic Safety Standards. *J. Environ. Radioact* **2018**, *196*, 40–49. [CrossRef] [PubMed]
7. CE 2014. *Council Directive 2013/59/Euratom of 5 Dec. 2013 Laying Down Basic Safety Standards for Protection against the Dangers Arising from Exposure to Ionising Radiation*; Office for Official Publications of the European Communities: Luxembourg, 2014; Volume 57.
8. European Commission (EC). *Radiation Protection 112, Radiological Protection Principles Concerning the Natural Radioactivity of Building Materials*; Office for Official Publications of the European Communities: Luxembourg, 1999.
9. Xinwei, L.; Xiaolan, Z. Measurement of natural radioactivity in sand samples collected from the Baoji Weihe Sands Park, China. *Environ. Geol.* **2006**, *50*, 977–982. [CrossRef]
10. Vasconcelos, D.C.; Pereira, C.; Oliveira, A.H.; Santos, T.O.; Rocha, Z.; Menezes, D.B.C.M.A. Determination of natural radioactivity in beach sand in the extreme south of Bahia, Brazil, using gamma spectrometry. *Radiat Prot. Environ.* **2011**, *34*, 178–184.
11. Malain, D.; Regan, P.H.; Bradley, D.A.; Matthews, M.; Santawamaitre, T.; Al-Sulaiti, H.A. Measurements of NORM in beach sand samples along the Andaman coast of Thailand after the 2004 tsunami. *Nucl. Instrum. Methods. Sect. A Accel. Spectrometers Detect. Assoc. Equip.* **2010**, *619*, 441–445. [CrossRef]
12. Dabayneh, K.; Mashal, L.; Hasan, F. Radioactivity concentration in soil samples in the southern part of the West Bank, Palestine. *Radiat. Prot. Dosim.* **2008**, *131*, 265–271. [CrossRef] [PubMed]
13. European Commission (EC). *Radiation Protection, 112 Radioactivity of Building Materials, Directorate-General Environment. Nuclear Safety and Civil Protection*; Office for Official Publications of the European Communities: Luxembourg, 1999.
14. Bereka, J.; Mathew, P.J. Natural radioactivity of Australian building material, industrial wastes and by products. *Health Phys.* **1985**, *48*, 87–95. [CrossRef] [PubMed]
15. El-Taher, A.; Makhut, S.; Nossair, A.; Halim, A.S.A. Assessment of natural radioactivity levels and radiation hazards due to cement industry. *Appl. Radiat. Isot.* **2012**, *68*, 169–174. [CrossRef] [PubMed]

16. Vaeth, M.; Pierce, D.A. Calculating excess lifetime risk in relative risk models. *Environ. Health Perspect.* **1990**, *87*, 83–94. [CrossRef] [PubMed]
17. Loan, T.T.H.; Ba, V.N.; Bang, N.V.T.; Thy, T.H.N.; Hong, H.T.Y.; Huy, N.Q. Natural radioactivity and radiological health hazard assessment of chemical fertilizers in Viet Nam. *J. Radioanal. Nucl. Chem.* **2018**, *316*, 111–117. [CrossRef]
18. Radenkovic, M.B.; Alshikh, S.M.; Andric, V.D.; Miljanic, S.S. Radioactivity of sand from several renowned public beaches and assessment of the corresponding en-vironmental risks. *J. Serb. Chem. Soc.* **2009**, *74*, 461–470. [CrossRef]
19. Alaamer, A.S. Measurement of natural radioactivity in sand samples collected from Ad-Dahna desert in Saudi Arabia. *World J. Nuclear Sci. Technol.* **2012**, *2*, 187–191. [CrossRef]
20. Ahmed, M.M.; Das, S.K.; Sariful; Yeasmin, S. Natural radioactivity and dose assessment in sand and sediment samples from Kuakata beach, Bangladesh. *J. Bangladesh Acad. Sci.* **2016**, *40*, 45–55. [CrossRef]
21. Kessaratikoon, P.; Benjakul, S.; Udomsomporn, S. Distribution of Natural radionuclides in Songkla beach sand. *Kasatsart J. (Nat. Sci.)* **2007**, *41*, 157–164.