Environmental Radioactivity Concentrations and Assessment of Radiological Hazards in Soil Around Bandung Nuclear Area

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Abstract. *Bandung nuclear area is an area which is nuclear reactor named TRIGA 2000 and research laboratory located. The reactor and research laboratory are utilized for training, researching and radioisotopes production that has potential to contaminate the environment. Environmental radioactivity monitoring is done periodically to find out potential radioactive release from activities inside Bandung nuclear area to surroundings. However, the assessment of radiological hazards to determine the potential radiological dangers to humans and environment around Bandung nuclear area is not done yet. The objective of this study is assessing the radiological hazards in Bandung nuclear area by comparing the data from soil samples taken in environment radiological monitoring activity with the recommendation data based on UNSCEAR and other references to find out the radiological hazards that potentially affect to humans, where this assessment has never been carried out in this area. The assessment of radiological hazards in this study is limited to Ra-226, Th-232 and K-40 nuclides because contributing to radiation dose received by human. The study was conducted by collecting soil samples from several sampling points inside and outside Bandung nuclear area. Then, the nuclides of Ra-226, Th-232 and K-40 contained in soil samples are measured by using the gamma-ray spectrometry method with high resolution detector that is HPGe (High Purity Germanium) and a computer-based Multichannel Analyzer (MCA). The results indicated that the concentration of environmental radioactivity ranged between 11.02 to 32.66 Bq/kg for Ra-226; 19.44 to 43.83 Bq/kg for Th-232 and 56.00 to 183.39 Bq/kg for K-40. This study also obtained results that the radiological hazard of the gamma dose rate ranged from 23.54 to 40.23 nGy/h, the radium equivalent was 51.77 to 89.78 Bq/kg; the external hazard index was 0.14 to 0.24 and the internal from 0.18 to 0.33; the index of radioactivity level was 0.37 to 0.63. The annual effective dose equivalent for outdoor ranged from 0.03 to 0.05 mSv/y and indoor was 0.12 to 0.20 mSv/y. The lifetime cancer risk for outdoors ranged from 0.10×10^{-3} to 0.17×10^{-3} and indoor was 0.4×10^{-3} to 0.69×10^{-3}. The values of radiological hazard were below the international requirements. There is no potential risk of natural radiation of gamma ionizing radiation exposure in soil samples around the Bandung nuclear area for workers, the public, and the environment.*

Keywords: Environment, Radiological, Hazard, Gamma, Spectrometry

Introduction

Radiation has always been present in nature, and all living organisms are constantly exposed to it. Cosmic rays, terrestrial radionuclides, and radionuclides in the human body are the origins of that exposure. Cosmic rays (or extraterrestrial radionuclides) come from outer space and the sun's surface, but terrestrial or primordial radionuclides are found in the Earth's crust, construction materials, air or atmosphere, water, and foods. The human body receives radiation from sources in the earth's crust that enter by inhalation of air, water consumption, or food consumption [1]. Background radiation is another name for natural radiation.

There was artificial radiation in addition to natural radiation. Artificial radiation comes from radiation sources originating due to human activities. For example: radiation from radionuclides

Sr-90 and Cs-137. The presence of artificial radionuclides contributes to an increase in the radiation already present in the environment [1].

Bandung nuclear area is an area which is nuclear reactor named TRIGA 2000 located. The TRIGA 2000 reactor is utilized for training, researching and radioisotopes production. Also, in Bandung nuclear area there is laboratories used to radioisotopes researching. If the research activities in reactor and laboratory are not held well, the artificial radioactive are potential to release and contaminate the surrounding environmental. The radioactive release also increasing the natural radiation has been present in nature. Environmental radioactivity caused by artificial radioactive could affect the organism health and growth. Therefore, the environmental radioactivity monitoring around Bandung nuclear area is done routinely with the intention to observe the potential radioactivity release from radioactive research facilities inside Bandung nuclear area to environment.

Environmental radioactivity monitoring around Bandung nuclear area is held periodically 4 times a year every 3 month. The environmental radioactivity monitoring performed by collecting sample (soil, plant, air particulate, water and sediment) from several sampling locations. Then the samples are prepared and the radioactivity contained in samples are measured by using gamma-ray spectrometry.

Assessment of Radiological Hazards in Bandung nuclear area is not conducted yet. So, the objective of this study is assessing the radiological hazards around Bandung nuclear area. The limitation of this study is comparing the values of Ra-226, Th-232 and K-40 measured in soil samples taken around Bandung nuclear area in 2020 with recommended value provided by UNSCEAR 2000. Because natural radioactivity concentrations are usually determined from the contents of Ra-226, Th-232, and K-40 [2], and because the dominant radiological effects are from radium and its progenies, rather than from its precursors [3], the radionuclides measured are primarily Ra-226, Th-232, and K-40.

The measurements were made with a computer-based Multichannel Analyzer (MCA) and Genie2000 software, employing the gamma-ray spectrometry method with a High Purity Germanium (HPGe) detector.

Theoretical Background

Natural radionuclides such as U-238, Th-232, and their decay products, as well as K-40, are already present in the earth's crust. The natural radionuclide, including natural radiation from U-238 and its decay products, contributes significantly to human natural radiation [4]. Natural radiation is the most significant contribution to the external dose, and it can be found in soil, rocks, plants, water, and air [1].

The U-238 is one of the most abundant substances in the earth's crust and can be found in trail amounts in rocks and soil. Natural and human processes contribute to its reallocation in the environment, and it will gain stability by relieving energy from the nucleus. One of the decay products of U-238 is Rn-222 (Radon), which is a naturally occurring gas that independently migrate and distribute far away to locations and trending to accumulate within certain environments. The inhalation of radon is the main cause of lung cancer after smoking, and become the main origin of natural radioactivity exposure worldwide [5].
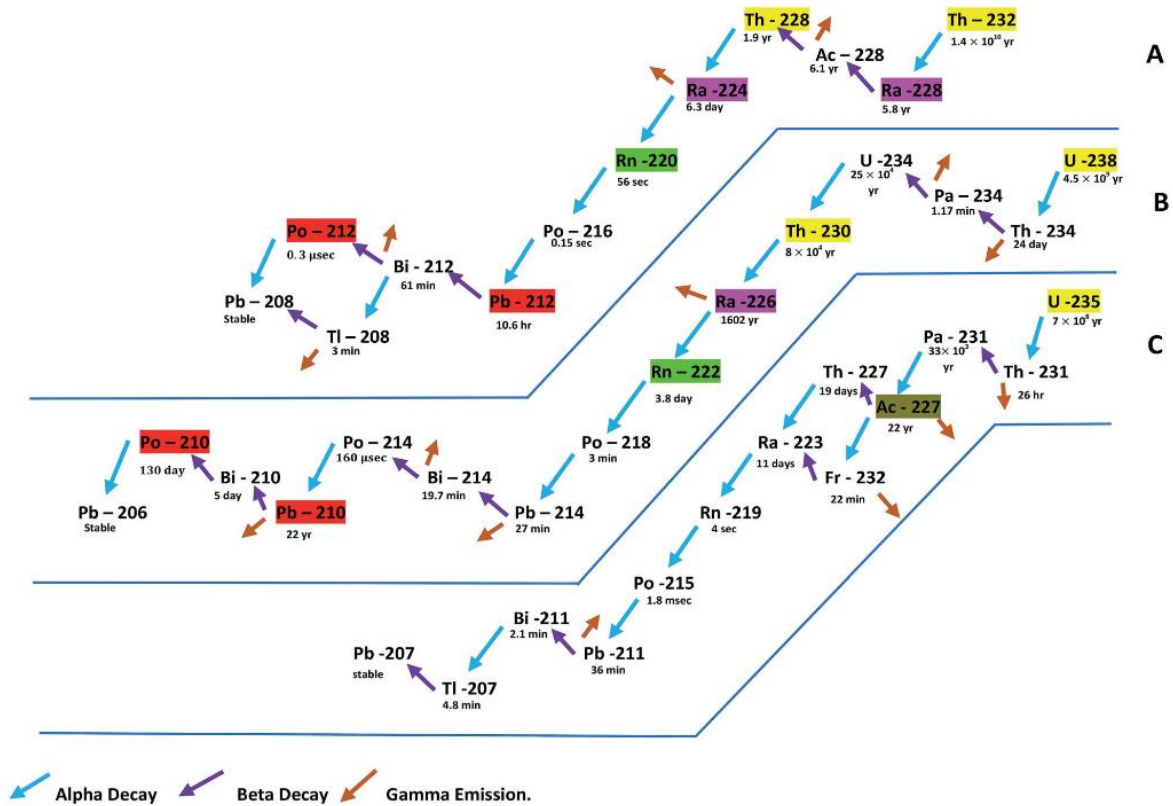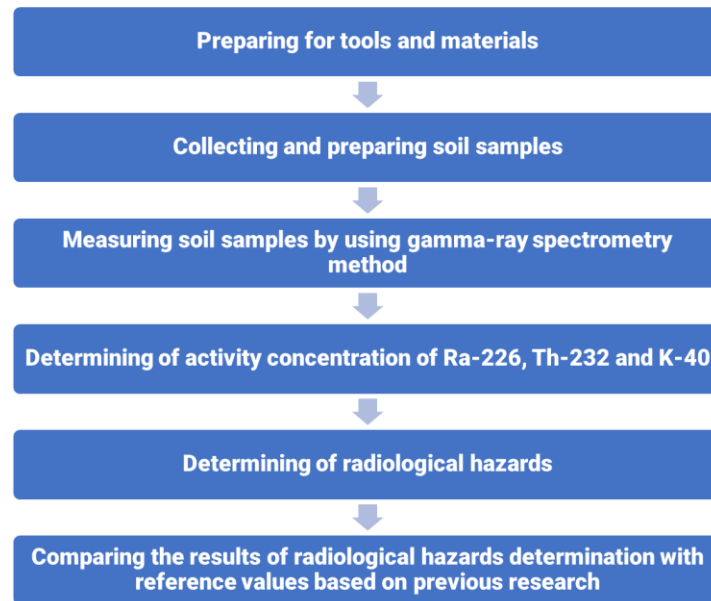
Figure 1.   Primordial radioactive decay series (A) [232]Th, (B) [238]U and (C) [235]U [6].

Materials and Methods

The method of radiological hazards assessment in soil around Bandung nuclear area is illustrated in Figure 2 below.

Figure 2. Method of radiological hazards assessment in soil around Bandung nuclear area

Collecting and Preparing Soil Samples

The soil has been collected for 43 (forty-three) samples around the Bandung nuclear area. Soil samples were taken at a radius of 100 meters, 200 meters, 500 meters, 1000 meters, and 2000 meters from the Bandung nuclear reactor. This reactor type is TRIGA Mark II nuclear reactor with an administrative area 100 meters from the reactor and surrounded by perimeter fence. For each radius of 100 m, 200 m, and 500 m, soil samples were collected at 4 (four) locations. The samples of soil were taken at 5 (five) different locations for each radius of 1000 m and 2000 m. Each location is monitoring points on environmental radioactivity monitoring around Bandung nuclear area which are sampled routinely once in 3 months. Figure 3 depicts the location of the soil sampling.

The collected samples are surface soil in widely opened area unobstructed by high buildings and trees. The surface soil samples taken based on NCRP report (National Council on Protection and Measurement) that 80% radon gasses released to atmosphere came from surface soil. Then the impurities (such as gravel, tree branches, and so on) carried during sampling collection at the site were removed from the soil samples. The soil samples were sun-dried. A soil grinder was used to grind the dried soil samples. Before grinding other soil samples, the tools must be clean of the most recent impurities residual soil. The soil sample was sieved through a 200 meshes sieve to achieve uniform grain size, affine grain size, and homogeneity [7]. A digital scale was used to weigh 500 g of soil samples, which were then placed in a 500 mL Marinelli beaker. The samples were sealed to prevent radon gas escape and stored for approximately 28 days before being measured and analyzed to determine the secular equilibrium of radon and its progenies [8].
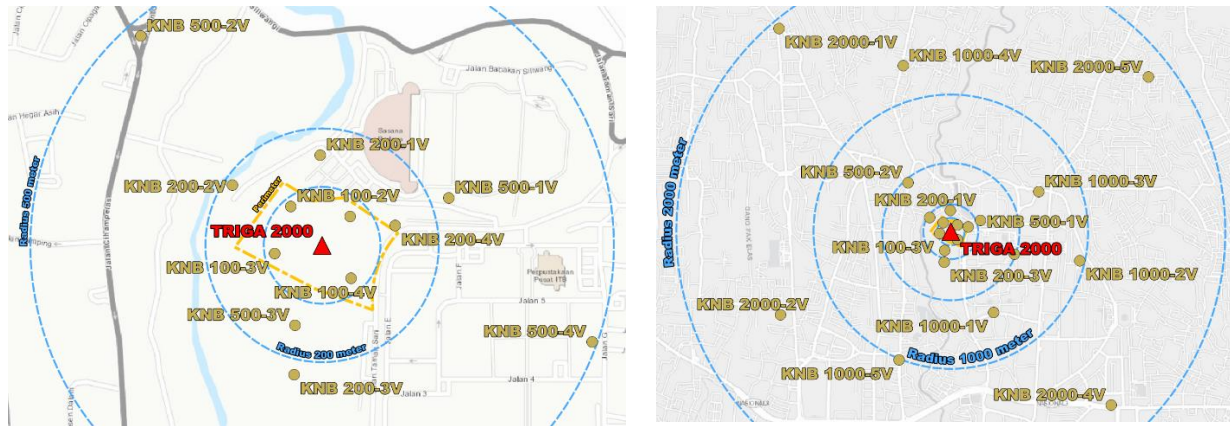
Figure 3. The geographic site of sampling, radius of 100 m, 200 m, 500 m, 1000 m, and 2000 m of Bandung nuclear area

Measurement of Soil Samples

Gamma radiation is emitted by naturally occurring radioactivity in the soil. Gamma radiation was measured in soil samples using gamma-ray spectrometry, which was calibrated and equipped with a High Purity Germanium (HPGe) detector. The detector was linked to a computer-based Multichannel Analyzer (MCA) and Genie2000 software. The program was used to analyze the gamma spectrum as well as the data collected by the detector. The gamma radiation background was measured using an empty Marinelli beaker prior to the sample measurement and analysis. For 10,000 seconds, the soil samples were measured.

Determination of Activity Concentration Ra-226, Th-232, and K-40

The radioactivity concentration of each nuclide was calculated using the gamma radiation measurement results from the soil sample. The concentrations of Ra-226 and Th-232 were calculated using the energy of their progenies as they decayed.

The net count of the sample was calculated by subtracting the value of the soil count from the background count. After subtracting the background, the activity of Ra-226 was specified using the average gamma-ray peak intensity of Pb-214 (at 351.93 keV) and Bi-214 (at 609.31 keV and 1120.29 keV), and the activity of Th-232 was specified using the gamma-line of Ac-228 (at 338.40 keV, 911.20 keV, and 968.96 keV), Pb-212 at 238.63 keV, and Tl-208 (at 583.19 keV and 860.53 keV). The K-40 activity was specified directly from its gamma-line at 1.46082 MeV [9].

The concentrations of each radionuclide Ra-226, Th-232, and K-40 in the soil sample were determined by using the formula [9]:

$$A = \frac{N_s}{\varepsilon P_\gamma \, mt}$$

(1)

where: A is radioactivity concentration of radionuclides (Bq/kg), N_s is count per second netto (cps) = net count of sample – net count of background, ε is the measured peak efficiency (%), P_γ is the

emission probability (the gamma-ray intensity), m is the mass of the sample (kg), and t is the sample measurement time (seconds).

According to UNSCEAR 2000, the average radioactivity concentrations of radium, thorium, and potassium in the crust of the earth are approximately 33, 45, and 420 Bq/kg, respectively.

Determination of Radiological Hazards

The radiological hazard potential of natural radionuclides was assessed by evaluating the parameter values of the absorbed dose rate (D), radium equivalent (Ra_{eq}), internal and external hazard index (H_{in} and H_{ex}), index of radioactivity level (I_γ), annual effective dose equivalent ($AEDE$) for indoor and outdoor, and excess lifetime cancer risk ($ELCR$).

Absorbed Dose Rate (D)

The absorbed dose rate denotes the rate at which radiation emitted by radionuclides in environmental materials is received outside. The gamma dose rate (absorbed) in air was measured at one meter above the surface of the ground and calculated using the contribution of natural radionuclide activity concentrations Ra-226, Th-232, and K-40 in the soil sample. The Ra-226 decay product took the place of the U-238.

The gamma absorption dose rate (D) was counted up by using this formula [1]: [10]

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \tag{2}$$

where: The absorbed gamma dose rate at one meter above the ground level (D) in nGy/h; A_{Ra}, A_{Th} and A_K are the specific activity concentrations of Ra-226, Th-232, and K-40 in soil sample (Bq/kg); 0.462, 0.604 and 0.0417 are conversion factors for Ra-226, Th-232, and K-40 (nGyh^{-1}/Bqkg^{-1}).

According to UNSCEAR, the maximum allowable absorbed gamma dose rate from soil is 59 nGy/h, with a median of 57 nGy/h and a maximum of 55 nGy/h in Indonesia.

Radium Equivalent (Ra_eq)

Natural radionuclides are distributed unevenly in the environment, depending on where they are found. As a result, the radium equivalent activities (Ra_{eq}) [11] have been used to determine the uniformity of radiation exposure. The radium equivalent activity was used to compare the radium, thorium, and potassium radioactivity in materials; the number of activities is expressed in the amount. The radium equivalent activities of soil samples are calculated using the assumption that 10 pCi/g Ra-226, 7 pCi/g Th-232, and 130 pCi/g K-40 produce the similar dose rate of gamma-ray. The conversion of 1 pCi/g is equal to 37 Bq/kg [12] [13].

Radium equivalent (Ra_{eq}) was counted up by using this formula: [14]

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \tag{3}$$
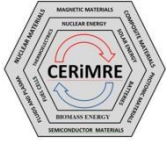
where: Ra_{eq} is radium equivalent activities (Bq/kg); A_{Ra}, A_{Th} dan A_K are the specific concentrations of Ra-226, Th-232, and K-40 (Bq/kg); 1.43 and 0.077 are the conversion factors for Th-232 and K-40.

The radium equivalent activity was used to assess the radiation risk associated with building materials such as soil. To keep the annual dose below 1.5 mGy/y or 1.5 mSv/y, the Ra_{eq} limit in building materials must be less than 370 Bq/kg [8] [15].

External Hazard Index (H_{ex})

The index of external hazard is a measure of the risk of gamma ray exposure from natural radionuclides [16].

The external hazard index (H_{ex}) was counted up by using this formula:

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

(4)

where: H_{ex} is external hazard index; A_{Ra}, A_{Th} and A_K are the specific concentrations of Ra-226, Th-232, and K-40 (Bq/kg).

To reduce the risk of external radiation received by the population, the external hazard index must be less than 1. This equates to a maximum radium equivalent value of 370 Bq/kg.

Internal Hazard Index (H_{in})

Radon and thoron are the progenies of natural radionuclides decay series. Radon and thoron are available in huge amount in the soil and can be released into the air and water. Internal radiation exposure occurs from breathing air or consuming water or food containing radon or other nuclides.

The index of internal hazard is one of the parameters used to assess the potential radiological hazards associated with natural radionuclide decay product exposure to internal radiation. Radiation hazard must be negligible in the population if the values of the internal hazard index are less than one [17].

The index of internal hazard (H_{in}) was calculated using the following formula:

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

(5)

where: H_{in} is internal hazard index; A_{Ra}, A_{Th} and A_K are the specific concentrations of Ra-226, Th-232, and K-40 (Bq/kg).

Radiological Level Index (I_γ)

The index of radioactivity level (I_γ) is used for estimation of radiation risk level by gamma-ray from natural radionuclides [18].

The radioactivity level index (I_γ) were counted up by using this formula:

$$I_\gamma = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500}$$

(6)

where: I_γ is radioactivity level index; A_{Ra}, A_{Th} and A_K are the specific concentrations of Ra-226, Th-232, and K-40 (Bq/kg).

The radioactivity level index value for this index must be less than 1. Values of index $I_\gamma \leq 2$ correspond to an absorbed gamma dose rate of 0.3 mSvy^{-1}, where as $2 < \gamma \leq 6$ corresponds to an absorbed gamma dose rate of 1mSvy^{-1}, and $I_\gamma > 6$ correspond to dose rates higher than 1 mSvy^{-1}, which is the highest dose rate value recommended for the population [19].

The value of radioactivity level index must be less than one. Index $I_\gamma \leq 2$ values correspond to gamma dose rate (absorbed) of 0.3 mSv/y, index $2 < I_\gamma \leq 6$ correspond to gamma dose rate (absorbed) of 1 mSv/y, and index $I_\gamma > 6$ correspond to gamma dose rates greater than 1 mSv/y, which is the population's highest radiation dose limit according to IAEA [19].

Annual Effective Dose Equivalent (AEDE)

The absorbed dose's health effects are assessed using the annual effective dose. Thus, using a conversion coefficient of 0.7 Sv/Gy, the annual effective dose equivalent received by humans can be calculated from the gamma absorbed dose in air. The conversion factor from the absorbed dose in air to the effective dose is thus 0.7 Sv/Gy. For the purposes of estimating effective dose rates in a year (1 year = 8760 hours), it is assumed that adults spend approximately 80% of their time indoors and 20% of their time outdoors. As a result, the values for the indoor and outdoor occupancy factors were 0.8 and 0.2, respectively. The population's indoor and outdoor annual effective dose rates (AEDE) were counted up by using the formulas listed below [1] [23]:

For indoor: $AEDE(mSv/y) = D(nGy/h) \; x \; 8760 \; (h/y) \; x \; 0.8 \; x \; 0.7 \; (Sv/Gy) \; x \; 10^{-6}$ (7)

For outdoor: $AEDE(mSv/y) = D(nGy/h) \; x \; 8760 \; (h/y) \; x \; 0.2 \; x \; 0.7 \; (Sv/Gy) \; x \; 10^{-6}$ (8)

where: *AEDE* is the effective dose *equivalent* in a year (mSv/y), *D* is the dose rate (absorbed) in air (nGy/h); 0.7 is the dose conversion factor, which converts the absorbed dose rate in air to human effective dose (Sv/Gy); 0.8 is the indoor occupancy factors; 0.2 is the outdoor occupancy factor, and 10^{-6} is the conversion factor of measurements.

The world average effective dose rate (annual) for outdoor is 70 µSv/y (or 0.07 mSv/y) [1].

Excess Lifetime Cancer Risk (ELCR)

The annual effective dose equivalent (AEDE) can be used for calculating the cancer risk. The equation is as follow. [21]:

$$ELCR = AEDE \; x \; DL \; x \; RF$$

(9)

where: DL is the duration of life (70 years in average); and RF is the factor of risk, given as 0.05 Sv^{-1} [20] [21]. It is assumed that the average age of the population is 70 years.

The ELCR global value was 0.29×10^{-3} and 1.16×10^{-3} for indoor and outdoor, respectively, given by UNSCEAR [1].

Results and Discussion

Table 1 shows the results of the radioactivity concentrations of Ra-226, Th-232, and K-40 measured in soil samples. The activity concentration of these natural radioactive then be calculated using certain formula to obtain the radiological hazard parameters that showed in Table 2. As shown in Table 1, sample ID/Location represent the distance from TRIGA Mark II research reactor facility. The effect of this difference in activity concentration values for each radioisotope are not affected by the distance from the presence of the reactor. Natural radiation is the radioactive which already exist in nature, so they are not affected by the presence or the distance of nuclear reactors. The differences in activity concentration for each natural radionuclide in every sample depend on several factors, like composition of the soil, terrain condition, geomorphology and lithology. The activity concentration of Ra-226 at location 1000-1 is slightly higher than other location possibly due to the characteristic of soil and several other factors mentioned above. Therefore, the further research related to those factors is needed to do if we are willing to know the reason of difference activity concentration in samples taken from every single location.

Table 1. Ra-226, Th-232, and K-40 activity concentrations in soil samples

Sample ID / Location	Activity concentration (Bqkg^{-1})		
	^{226}Ra	^{232}Th	^{40}K
100-1	16.07 ± 3.71	36.24 ± 17.29	121.10 ± 13.38
100-2	13.33 ± 7.79	31.10 ± 15.01	87.53 ± 104.05
100-3	14.83 ± 1.61	19.44 ± 16.62	118.67 ±146.98
100-4	15.26 ± 3.50	31.01 ± 15.02	56.00 ± 68.08
200-1	13.51 ± 5.21	31.37 ± 14.15	166.42 ± 60.13
200-2	15.54 ± 3.11	28.14 ± 14.38	183.39 ± 50.09
200-3	12.44 ± 1.54	28.83 ± 13.58	102.77 ± 6.26
200-4	16.14 ± 2.31	33.77 ± 15.34	90.36 ± 6.87
500-1	15.56 ± 1.84	34.05 ± 16.29	89.92 ± 6.39
500-2	14.92 ± 1.31	39.74 ± 17.92	123.65 ± 32.80
500-3	13.36 ± 2.04	31.04 ± 20.76	137.98 ± 5.43
500-4	16.48 ± 2.06	32.00 ± 17.01	66.82 ± 94.49
1000-1	32.66 ± 37.02	34.01 ± 16.09	110.17 ± 16.76
1000-2	11.02 ± 2.03	24.48 ± 17.98	104.39 ± 4.60
1000-3	14.49 ± 1.97	32.35 ± 16.47	163.50 ± 66.48
1000-4	12.92 ± 1.34	32.43 ± 15.02	115.40 ± 0.90
1000-5	13.01 ± 1.01	33.81 ± 15.81	155.30 ± 5.12
2000-1	14.81 ± 1.19	33.27 ± 15.67	101.12 ± 4.92
2000-2	13.71 ± 2.33	31.50 ± 15.38	130.62 ± 14.53
2000-3	14.23 ± 2.48	37.39 ± 20.92	140.09 ± 1.50
2000-4	19.34 ± 1.98	43.83 ± 21.52	96.50 ± 24.61
2000-5	15.85 ± 2.64	32.86 ± 15.60	136.44 ± 24.82
Minimum	11.02	19.44	56.00
Maximum	32.66	43.83	183.39

Sample ID / Location	Activity concentration (Bqkg^{-1})		
	^{226}Ra	^{232}Th	^{40}K
Average	15.43	32.39	118.10
Stdev	4.22	4.90	32.14
UNSCEAR 2000	**33**	**45**	**420**

Table 2 summarizes the calculation results of radiological hazard parameters in soil samples. There are seven parameters that represent the radiological hazard from natural radionuclides that can affect human body, both workers and the surrounding community.

Table 2. Summary the result of calculation radiological hazard parameters

Sample ID/ location	D (nGyh^{-1})	Ra_{eq} (Bqkg^{-1})	H_{ex}	H_{in}	I_{γ}	Annual Effective Dose Equivalent (mSv/y)		Excess Lifetime Cancer Risk (x 10^{-3})	
						Outdoor	*Indoor*	*Outdoor*	*Indoor*
100-1	34.36	77.21	0.21	0.25	0.55	0.04	0.17	0.15	0.59
100-2	28.59	64.54	0.17	0.21	0.46	0.04	0.14	0.12	0.49
100-3	23.54	51.77	0.14	0.18	0.37	0.03	0.12	0.10	0.40
100-4	28.11	63.91	0.17	0.21	0.45	0.03	0.14	0.12	0.48
200-1	32.13	71.19	0.19	0.23	0.51	0.04	0.16	0.14	0.55
200-2	31.82	69.90	0.19	0.23	0.51	0.04	0.16	0.14	0.55
200-3	27.44	61.57	0.17	0.20	0.44	0.03	0.13	0.12	0.47
200-4	31.62	71.38	0.19	0.24	0.51	0.04	0.16	0.14	0.54
500-1	31.50	71.18	0.19	0.23	0.50	0.04	0.15	0.14	0.54
500-2	36.05	81.27	0.22	0.26	0.58	0.04	0.18	0.15	0.62
500-3	30.67	68.37	0.18	0.22	0.49	0.04	0.15	0.13	0.53
500-4	29.73	67.38	0.18	0.23	0.47	0.04	0.15	0.13	0.51
1000-1	40.23	89.78	0.24	0.33	0.63	0.05	0.20	0.17	0.69
1000-2	24.23	54.06	0.15	0.18	0.39	0.03	0.12	0.10	0.42
1000-3	33.05	73.34	0.20	0.24	0.53	0.04	0.16	0.14	0.57
1000-4	30.37	68.18	0.18	0.22	0.49	0.04	0.15	0.13	0.52
1000-5	32.91	73.31	0.20	0.23	0.53	0.04	0.16	0.14	0.56
2000-1	31.15	70.17	0.19	0.23	0.50	0.04	0.15	0.13	0.53
2000-2	30.81	68.81	0.19	0.22	0.49	0.04	0.15	0.13	0.53
2000-3	35.00	78.48	0.21	0.25	0.56	0.04	0.17	0.15	0.60
2000-4	39.43	89.45	0.24	0.29	0.63	0.05	0.19	0.17	0.68
2000-5	32.86	73.35	0.20	0.24	0.53	0.04	0.16	0.14	0.56
Minimum	23.54	51.77	0.14	0.18	0.37	0.03	0.12	0.10	0.40
Maximum	40.23	89.78	0.24	0.33	0.63	0.05	0.20	0.17	0.69
Average	31.62	70.85	0.19	0.23	0.51	0.04	0.16	0.14	0.54
Stdev	4.05	9.21	0.02	0.03	0.06	0.005	0.02	0.02	0.07
UNSCEAR 2000	**55**	**≤ 370**	**< 1**	**< 1**	**< 1**	**0.5 mSvy^{-1}**	**0.5 mSvy^{-1}**		

Table 1 showed the Ra-226, Th-232, and K-40 radioactivity concentrations quantified from the samples of soil. The activity concentrations of Ra-226 is in the range from 11.02 to 32.66 Bq/kg; Th-232 is 19.44 to 43.83 Bq/kg; and K-40 is 56.00 to 183.39 Bq/kg. The highest concentration of Ra-226 was found in locations 1000-1 and Th-232 was found in location 2000-4 (Table 1). While locations 200-2 had the highest level of K-40 activity. The average activity concentrations of Ra-226, Th-232, and K-40 in soil samples were 15.43 ± 4.22 Bq/kg, 32.39 ± 4.90 Bq/kg, and 118.10
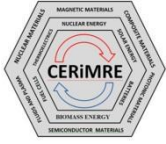
± 32.14 Bq/kg, respectively. These levels are lower than the UNSCEAR requirement of average activity concentration.

Table 2 showed the results of the calculation of the radiological hazard parameters of Ra-226, Th-232, and K-40 in soil sample, which include the parameters Absorbed dose rate (D), Radium equivalent (Ra_{eq}), External Hazard Index (H_{ex}), Internal Hazard Index (H_{in}), Radioactivity Level Index (I_γ), Annual Effective Dose Equivalent ($AEDE$) and Excess Lifetime Cancer Risk ($ELCR$). The radiological hazard of natural radioactivity concentration was assessed by comparing the calculated parameter values to approved international values.

Table 2 showed the gamma absorption dose rate (D) in the air was in the range of 23.54 to 40.23nGyh^{-1} with an average of 31.62 ± 4.05nGyh^{-1}. The air absorption dose rate was lower than the population-weighted average of global terrestrial or primordial radiation, which was 59 nGy/h. Under normal conditions, the dose rate from terrestrial gamma-rays in air is approximately 60 nGy/h, with a median value of 51 nGy/h. The average absorbed dose rate of gamma radiation in the vicinity of the Bandung research reactor is less than 59 nGy/h, and thus less than the UNSCEAR 2000 average limit value [1]. The radium equivalent activity (Ra_{eq}) in soil samples ranged from 51.77 to 89.78 Bq/kg, with an average of 70.85 ± 9.21 Bq/kg. The radium equivalent value (Ra_{eq}) was less than 370 Bq/kg, which was still below the allowable limits (recommended by the Organization for Economic Cooperation and Development).

External hazard index (H_{ex}) values for soil samples ranged from 0.14 to 0.24 with an average value of 0.19 ± 0.02. The external hazard index (H_{ex}) value was less than one, and less than the allowable limits, indicated that there was no possible radiation risk. Internal hazard index (H_{in}) values for soil samples ranged from 0.18 to 0.33 with an average values of 0.23 ± 0.03. The value of the internal hazard index (H_{in}) was less then one, and less than the allowable limits, indicating that there is no potential radiation risk. The value of effective dose per year (1 mSv/y) indicated that the internal risk was less than the suggested value. Radioactivity level index (I_γ) values for soil samples ranged from 0.37 to 0.63 with an average of 0.51 ± 0.06. The value of the radioactivity level index (I_γ) was less than one, it was lower than the recommended limits and does not pose a potential radiation hazard.

The outdoor annual effective dose equivalent ($AEDE$) in soil samples ranged between 0.03 to 0.05 mSv/y with the average values of 0.04 ± 0.005 mSv/y and for the indoor ranged between 0.12 to 0.20 mSv/y with the average of 0.16 ± 0.02 mSv/y. The average outdoor and indoor effective dose equivalent (annual) were below the UNSCEAR average value. In average, the outdoor effective dose (annual) was less than the global value of 70 µSv/y (or 0.07 mSv/y). Also, in average, the effective dose for outdoor and indoor per year was 0.04 and 0.16 mSv/y. Thus, the total effective dose (annual) was 0.10 mSv/y. It was less than the International Commission on Radiological Protection's (ICRP) permissible value for individual members of the public [22].

The excess lifetime cancer risk ($ELCR$) in outdoor ranged from 0.10 x 10^{-3} to 0.17 x 10^{-3} with the average values was (0.14 ± 0.02) x 10^{-3} and for the indoor ranged from 0.40 x 10^{-3} to 0.69 x 10^{-3} with an average was (0.54 ± 0.07) x 10^{-3}. In average, the excess lifetimes cancer risk was less than the global value set by UNSCEAR.

Conclusions

In this present work, the calculation for assessing the radiological hazard from natural radioactivity into human body has been studied. The three radioisotopes Ra-226, Th-232, and K-40 exist in the environmental soil samples around the Bandung nuclear area have been quantified and analyzed. The average activity concentrations obtained from Ra-226, Th-232, and K-40 in soil of Bandung nuclear area were less than the UNSCEAR and other references recommendation. The calculated radiological hazard values were below the value of the international requirement. This means that there is no potential risk of gamma radiation exposure from the natural radioactivity of the soil around the environmental of Bandung nuclear area. Therefore, the public health around the Bandung nuclear area is protected from radiological hazard originating from terrestrial or primordial radionuclides in soil.

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