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Original Article

Activity concentrations and radiological hazard assessments of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in soil samples obtained from the Dongnam Institute of Radiological & Medical Science, Korea

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ABSTRACT

The radioactivity concentration of environmental radionuclides was analyzed for soil and sand at eight locations within a radius of 255 m centered on the Dongnam Institute of Radiological & Medical Science (DIRAMS), Korea. The average activity concentrations of ^{40}K, ^{137}Cs, ^{226}Ra, and ^{232}Th were 661.1 Bq/kg-dry, 0.9 Bq/kg-dry, 21.9 Bq/kg-dry, and 11.1 Bq/kg-dry, respectively. The activity of ^{40}K and ^{137}Cs was lower than the 3-year (2017–2019) average reported by the Korea Institute of Nuclear Safety, respectively. Due to the nature of granite-rich soil, the radioactivity of ^{40}K was 0.6-fold higher than in other countries, while ^{137}Cs was in the normal fluctuation range (15–30 Bq/kg-dry) of the concentration of radioactive fallout from nuclear tests. The activity of ^{226}Ra and ^{232}Th was lower than in Korean soils reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The average activity concentrations of ^{232}Th and ^{40}K for the soil and sand samples from DIRAMS were within the range specified by UNSCEAR in 2000. The radium equivalent activity and internal and external hazard index values were below the recommended limits (1 mSv/y). These radionuclide concentration (^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs) data can be used for regional environmental monitoring and ecological impact assessments of nuclear power plant accidents.

1. Introduction

The Earth's crust contains naturally occurring radionuclides, including ^{40}K, ^{226}Ra, and ^{232}Th, which are universally found in soil, sediment, and water in the environment [1]. Natural radioactivity investigations are essential to understand human exposure to natural radiation. Gamma radiation due to natural radioactivity accounts for 85% of the total global annual average ionizing radiation [2]. Natural radiation can damage living cells and cell transformation due to DNA damage [3]. The determination of radionuclides in soil and sand provides valuable insight into human exposure to background radiation and the potential impact of natural radioactivity on human health [4]. The study of natural radiation from soil has received considerable attention in recent years, with numerous papers published in this field [5–9] In addition, soil material and heavy metals may accumulate in living organisms through direct absorption or through the food chain, and are subsequently passed on to the human food chain, leading to diseases [10–12] in human beings. Some researchers have widely studied pollution in the soil and the Mediterranean Sea [13,14]. Soil serves as a typical environmental sample for detecting environmental fallout. However, it is pertinent to note that the concentrations of radionuclides present in soil are constantly fluctuating due to decay and other environmental factors, as well as varying according to region based on factors such as rainfall, soil type, and plants [15].

The naturally occurring radionuclide ^{40}K ($T_{1/2} = 1.28 \times 10^9$ *years*) accounts for 2.59% of the ground surface and is abundant in soil. The concentration of ^{40}K in Korean soil is estimated to be 17–1500 Bq/kg-dry, with an average value of 670 Bq/kg-dry [16]. It is a major component of the Earth's crust and mantle and is the largest source of natural radiation of all animal and plant body components. The Cs

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isotopes, such as ^{134}Cs ($T_{1/2} = 2.06\ years$) and ^{137}Cs ($T_{1/2} = 30.5\ years$), have chemical properties similar to those of K, and represent a large proportion of the artificial gamma-emitting radioisotopes released through nuclear tests and nuclear accidents. The Cs isotope ^{137}Cs was leaked into the ocean and the atmosphere during the Chernobyl Nuclear Power Plant (NPP) accident (ca. 85 PBq) in the former Soviet Union and the Fukushima NPP accident (13–20 PBq) [17,18]. Also, in the case of future NPP accidents, accurate estimation of radionuclide concentrations of ^{40}K and ^{137}Cs is necessary for regional environmental monitoring and ecological impact assessments. Radon is a gas radionuclide that is naturally generated from the decay of ^{238}U, ^{232}Th, and ^{235}U, and natural radioactive elements originating from rocks, and is found in rocks, soil, and groundwater. ^{226}Ra ($T_{1/2} = 1600\ years$) has a long half-life in the uranium/radium decay chain. ^{232}Th ($T_{1/2} = 1.41 \times 10^{10}\ years$) is the parent radionuclide of the thorium decay chain. Determination of the decay radionuclides ^{228}Ac, ^{212}Pb, and ^{208}Tl can be performed based on the assumption that these radionuclides are in radioactive equilibrium with each other and with ^{232}Th [19].

The presence of radionuclides above a certain permissible level in soil is a health hazard. Proximity to nuclear facilities increases the risk of radiation exposure. In particular, the Dongnam Institute of Radiological and Medical Science (DIRAMS), located approximately 5 km from a nuclear facility, would be affected by a nuclear accident at the facility. Therefore, it is necessary to study the concentrations and characteristics of major radionuclides in this area. We conducted a basic study to evaluate environmental radiation in the premises of the DIRAMS. Soil and sand were collected from eight locations within a radius of 255 m, with DIRAMS as the center. Environmental radioactivity concentrations and external and internal hazards were analyzed.

2. Material and methods

2.1. Sample collection and preparation

DIRAMS is situated in an area within 5 km of the nuclear facility. A sampling area and a sampling strategy were formulated to characterize the radioactivity in the environment. According to the Korea Institute of Geoscience and Mineral Resources (KIGAM), the soil in the study area is divided into two layers: the alluvial layer generated in the 4th stage of the Cenozoic and a recurrent andesite undercurrent layer generated in the Cretaceous period of the Mesozoic era [20]. The alluvial layer is a representative sill composed of stations, companies, and clay. In the case of ordinary andesite undercurrents, andesite and trachyandesite are the main constituents. For this study, soil and sand samples were collected from eight locations within a radius of 255 m of DIRAMS from April to August 2021; two samples were collected for each branch. A flat location without any soil disturbance, erosion, or exposed surface was selected for sampling. Systematic random sampling methods were applied, and the topsoil was sampled at a depth of 5 cm in a square area of 0.5 × 0.5 m. The soil sampling locations are presented in Fig. 1 and Table 1. Locations #1, #2, #7, and #8 corresponds to the recurrent andesitic undercurrent layer, and locations #3, #4, #5, and #6 corresponds to the alluvial layer. The exact geological characteristics of the soil at location #1 could not be confirmed because its origin was unknown. For sampling and analysis procedures, refer to IOS 18589–3, the International Standards Document [19].

2.2. Calibration and radioactivity measurements

Stones, gravel, and residues of plants and roots were removed from the samples, and the samples were dried at 110 °C for 24 h to remove any moisture present in the soil. Then, the samples were crushed and sieved using a 200-μm sieve, homogenized, weighed, and placed in U8 polyethylene bottles of the same size as the mixed standard calibration source and tightly sealed. Care was taken to avoid contamination during sample crushing. Gamma spectroscopy was used to measure the activity concentration of the soil samples because it is less time consuming and non-destructive. As a rule, when estimating the waiting period, if the severity of the interference with the equilibrium is not known, one should initially assume that there are practically no daughter radionuclides. In the case of a long-life parent radionuclide and a short-life decay product, this means that the waiting period should be at least six half-lives of the decay product. Before gamma-ray spectroscopy, the samples were labeled with codes and stored for approximately 1 month such that radioactive equilibrium of ^{226}Ra with its daughter products could be achieved. The ^{40}K, ^{137}Cs, ^{226}Ra, and ^{232}Th samples were analyzed using a high-purity germanium detector (GC 4018, Canberra Inc., USA) and a multiple pulse height analyzer (Canberra Inc., USA). The relative efficiency was 40%, and the diameter of the detector was 63 mm. A certified reference material (CRM) from the Korea Institute of Standards Science (KRISS) was used for the energy and efficiency calibration of the detector. The radioactively CRM containing a 90 mL solid-phase source and gamma-emitting mixed radionuclides in a cylindrical beaker (U8). Each soil sample was measured at 80,000 s. The spectra and radioactivity were evaluated using the software Genie 2000 (Canberra Inc., USA).

2.3. Measurement of other parameters

2.3.1. Gamma dose rate

The gamma dose rate in the air can be calculated from the measured concentration of the radionuclide in the soil. For virtually uniformly distributed radionuclides, the gamma dose rate at 1 m above the ground surface can be calculated using the following equation:

$$\mathrm{D}(nGy/h) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (2)$$

where D is the gamma dose rate, A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, and 0.462, 0.604, and 0.0417 are the absorbed dose conversion factors, respectively, as described by United Nations Scientific Committee on the effects of Atomic Radiation (UNSCEAR) report [16].

2.3.2. Annual effective dose

The annual effective dose in the study area was calculated using the conversion coefficient and occupancy factor, as discussed in the UNSCEAR report. In the UNSCEAR 1993 report, the committee used 0.7 Sv/Gy for the conversion coefficient from absorbed dose in air to effective dose received by adults and 0.8 for the indoor occupancy factor, i.e. the fraction of time spent indoors and outdoors is 0.8 and 0.2, respectively [16]. The annual effective dose were calculated from absorbed dose values using equations (3) and (4),

$$\text{Indoors} : D\left(\frac{\text{nGy}}{\text{h}}\right) \times 8760\ \text{h} \times 0.8 \times 0.7\left(\frac{\text{Sv}}{\text{Gy}}\right) \quad (3)$$

$$\text{Outdoors} : D\left(\frac{\text{nGy}}{\text{h}}\right) \times 8760\ \text{h} \times 0.2 \times 0.7\left(\frac{\text{Sv}}{\text{Gy}}\right) \quad (4)$$

2.3.3. Radium equivalent activity and hazard index

The radium equivalent activity was calculated by converting

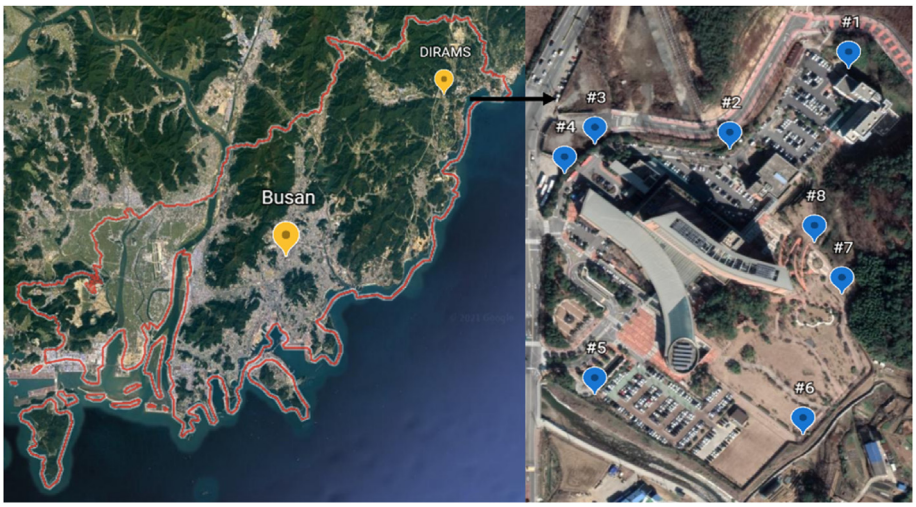

Fig. 1. Location of sampling stations around the DIRAMS. Points #1, #2, #7, and #8 are sedimentary rocks, and points #3, #4, #5, and #6 are andesitic rocks and alluvium regions.

Table 1
Sampling location and activity concentration of ^{40}K, ^{137}Cs, ^{226}Ra, and ^{232}Th.

Sample location	Direction	Activity concentration (Bq/kg-dry)			
		^{40}K	^{137}Cs	^{226}Ra	^{232}Th
1	35°19'21.7" N	899.8 ± 55.8	< MDA	6.1 ± 0.7	4.7 ± 0.4
	129°14'41.4" E	901.9 ± 56.0	< MDA	11.0 ± 1.0	6.9 ± 0.6
2	35°19'19.4" N	665.9 ± 43.0	0.8 ± 0.2	24.3 ± 1.9	11.2 ± 0.9
	129°14'38.1" E	662.4 ± 42.9	< MDA	21.6 ± 1.7	11.4 ± 0.9
3	35°19'19.6" N	746.8 ± 47.8	< MDA	20.4 ± 1.6	11.7 ± 0.9
	129°14'34.4" E	657.5 ± 42.6	1.0 ± 0.2	19.5 ± 1.6	10.8 ± 0.8
4	35°19'18.8" N	676.2 ± 43.6	0.7 ± 0.2	23.8 ± 1.8	12.3 ± 0.9
	129°14'33.2" E	672.6 ± 43.4	1.4 ± 0.2	20.8 ± 1.7	11.4 ± 0.9
5	35°19'12.2" N	626.5 ± 40.8	< MDA	24.9 ± 1.9	13.2 ± 1.0
	129°14'34.1" E	599.2 ± 39.2	< MDA	21.7 ± 1.7	10.4 ± 0.8
6	35°19'11.2" N	577.9 ± 37.9	1.1 ± 0.2	29.3 ± 2.1	14.1 ± 1.0
	129°14'40.3" E	629.7 ± 40.9	1.0 ± 0.2	28.7 ± 2.1	14.6 ± 1.1
7	35°19'15.3" N	636.1 ± 41.3	< MDA	26.7 ± 2.0	12.9 ± 1.0
	129°14'41.7" E	619.2 ± 40.3	< MDA	26.3 ± 2.0	12.8 ± 0.9
8	35°19'16.7" N	462.0 ± 31.2	0.6 ± 0.2	21.8 ± 1.7	9.9 ± 0.8
	129°14'40.7" E	544.2 ± 35.9	<MDA	24.1 ± 1.8	10.0 ± 0.8
Mean	–	661.1 ± 42.7	0.9 ± 0.2	21.9 ± 1.7	11.1 ± 0.8

MDA, minimum detectable activity.

^{232}Th and ^{40}K into the radioactivity concentration that corresponded to the same dose as the gamma radiation emitted from the daughter nuclei of ^{226}Ra and combining it with the ^{226}Ra radioactivity concentration. The hazard index is the amount used to measure the external exposure dose to the human body. The characteristic gamma peaks selected for the determination of ^{226}Ra were estimated from the weighted activities of the photopeak of ^{214}Bi (609.3 keV). The characteristic gamma peaks selected for the determination of ^{232}Th were estimated from the weighted activities of the photo peak of ^{208}Tl (583 keV), that of ^{40}K was estimated from its characteristic gamma line (1460.8 keV), and two indices were used to assess risk. The radium equivalent activity Ra_{eq} (in Bq/kg) was defined to assess the potential hazards of exposure to gamma radiation associated with materials that contain ^{226}Ra, ^{232}Th, and ^{40}K radionuclides, and was calculated by equation (5) [21]:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \tag{5}$$

The external hazard index is obtained from R_{eq} expression through the supposition that its maximum values allowed corresponds to the upper limit of 370 Bq/kg This index value must be less than unity in order to keep the radiation hazard insignificant. It is defined as the evaluation index when the annual effective dose from building materials is assumed to be 1 mSv/y. The external hazard index can be defined as:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1, \tag{6}$$

where A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (in Bq/kg), respectively.

The internal hazard index H_{int} must be less than 1 to maintain the radiation hazard [7]. The internal hazard index can be defined as:

$$H_{int} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1, \tag{7}$$

where A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (in Bq/kg), respectively.

$H^*(10)$ is a measurable quantity that provides a conservative assessment of the effective dose, which quantifies the risk to human health caused by radiation exposure. The ambient dose equivalent rate of ^{40}K, ^{226}Ra, ^{232}Th and ^{137}Cs in the surface at 1 m

aboveground was computed. The ambient dose equivalent rate is calculated using the following equation [22].

$$H^*(10) = (nSv/h) = 0.674A_{Ra} + 0.749A_{Th} + 0.0512A_K + 0.192A_{Cs}$$

where A_{Ra}, A_{Th}, A_K, and A_{Cs} (Bq/kg) are the activity concentration of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs, respectively.

2.3.4. Gamma level index

In samples, the gamma level index (I_γ) was used to estimate the level of gamma radiation hazard associated with natural radionuclides. This index is also used to correlate the annual dose rate due to the excess external gamma radiation caused by superficial materials [23]. The gamma level index in the soil samples was calculated using equation (8) given by the European Commission [23]:

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000}. \quad (8)$$

2.3.5. Excess lifetime cancer risk (ELCR)

The ELCR was assessed using equation (9) [23]:

$$\mathrm{ELCR} = D \times T \times RF, \quad (9)$$

where D is the annual effective dose, T is the duration of life in years (70 years) as specified by the World Health Organization (WHO) in 2014, and RF is the risk factor and fatal cancer risk per sievert. The standard proposed by the International Commission on Radiological Protection, ICRP-60, considers a value of 0.05 for stochastic effects of ionizing radiation.

3. Experimental results and discussion

3.1. Environmental radionuclide activity concentrations

The radioactivity of the radionuclides in the environment analyzed by the high-purity germanium detector is shown in Table 1 and Fig. 2. As shown in Table 1, the ^{40}K average activity concentration in soil was the highest at location #1 (900.8 Bq/kg-dry) and the lowest at location #8 (503.1 Bq/kg-dry). Moreover, the ^{40}K activity concentration in DIRAMS ranged from 462.0 to 901.9 Bq/kg-dry, with an average value of 661.1 Bq/kg-dry. The activity concentration in the soil in DIRAMS showed a trend of being approximately 1.1 times lower than that in the soil of KINS as reported during 2017–2019 [24–26]. The value was similar to the Korean average ^{40}K radioactivity concentration (670 Bq/kg-dry) shown in the UNSCEAR report [16]. As shown in Table 2, the ^{137}Cs average radioactivity concentration of soil was the highest at locations #3, #4, and #6 (1.0 Bq/kg-dry) and the lowest at locations #1, #5, and #7 at minimum detectable activity (MDA) (0.58 Bq/kg-dry). The range of ^{137}Cs activity concentration in DIRAMS was <MDA–1.4 Bq/kg-dry, with an average of 0.9 Bq/kg-dry. The ^{137}Cs activity concentration in DIRAMS showed a trend of being about 2.8 times lower than that in the soil of KINS as reported during 2017–2019 [24–26]. ^{131}I and ^{134}Cs were not detected. Compared to the ^{137}Cs radioactivity concentration range (<MDA-15.8 Bq/kg-dry) in the nationwide soil shown in the "Environmental Radioactivity Survey in Korea", the radioactivity concentration detected at the DIRAMS site is as low as 0.9 indicates. As shown in Table 1, the ^{226}Ra average radioactivity concentration of soil was the highest at location #6 (29.0 Bq/kg-dry) and the lowest at location #1 (8.6 Bq/kg-dry). The range of ^{226}Ra in DIRAMS was 6.1–29.3 Bq/kg-dry, with an average of 21.9 Bq/kg-dry. The ^{232}Th average radioactivity concentration of soil was the highest at location #6 (14.4 Bq/kg-dry) and the lowest at location #1 (5.8 Bq/kg-dry). The range of ^{232}Th in DIRAMS was 4.7–14.6 Bq/kg-dry, with an average value of 11.1 Bq/kg-dry.

Fig. 3 shows a comparison of the environmental radionuclide activity data from DIRAMS and Korean soils We compared the DIRAMS data with the data of 42 countries in nine regions: Africa, North America, South America, East Asia, West Asia, North Europe, West Europe, East Europe, and South Europe. The range of ^{40}K in the 42 countries was 140–850 Bq/kg, with a population-weighted average of 420 Bq/kg, and that in DIRAMS, Argentina, Korea, Iran, and Denmark tended to be 1.04–1.59 times higher than the average. The range of ^{226}Ra in the 42 countries was 17–60 Bq/kg, with a population-weighted average of 32 Bq/kg, and that of ^{232}Th was 11–64 Bq/kg, with a population-weighted average of 45 Bq/kg. It was confirmed that ^{226}Ra and ^{232}Th in DIRAMS were lower than the population-weighted average reported in the UNSCEAR [16] report. The ^{137}Cs/^{40}K concentration ratio difference can be explained by local characteristics (rainfall and soil characteristics). The data in Table 1 and Fig. 4 show the relationship between the ^{40}K and ^{137}Cs radiation concentrations. This correlation can be expressed as follows [15]:

$$C_{C_s} = 0.0014xC_K + 0.0459 \quad (10)$$

C_{C_s} : Specific radioactivity of ^{137}Cs in soil, Bq/kg − dry, .

C_K : Specific radioactivity of ^{40}Kin soil, Bq/kg − dry..

Fig. 4 shows that the radioactivity concentration ratio of ^{137}Cs and ^{40}K does not have a significant correlation. The concentrations of radionuclides ^{40}K and ^{137}Cs in the soil depend on the types of rocks and formations that make up the soil. Both the soil layers in the present study were composed of sand, mud, clay, and gravel, and were mostly granite. It is considered that the radioactivity concentrations of ^{40}K and ^{137}Cs were lower than the national average.

3.2. Gamma dose rate assessment and estimation of annual effective dose

External exposures arise from terrestrial radionuclides, which are present at trace levels in all soils. All the spectrometric measurements of gamma-emitting radionuclides indicate that the series of ^{226}Ra, ^{232}Th, and the non-decay series of ^{40}K provide approximately equivalent contributions to the outdoor external gamma radiation dose in typical situations. The activity concentrations of ^{40}K, ^{232}Th, ^{226}Ra, and ^{137}Cs were used to estimate the percentage contribution to the gamma dose rate in air. ^{226}Ra activity concentrations are generally higher than ^{232}Th activity concentrations; therefore, ^{226}Ra was found to be the most important contributor to the terrestrial gamma dose rate. The relative contributions were 22.3%, 14.8%, 60.8%, and 2.1%, with values of 10.13, 6.73, 27.57, and 0.94 nGy/h to the gamma dose rate, respectively.

The estimated annual effective dose is tabulated in Table 2. The corresponding indoor and outdoor annual effective doses varied from 0.18 mSv to 0.23 and 0.05 mSv–0.06 mSv, with average values of 0.22 mSv and 0.05 mSv, respectively. The total average annual effective dose was estimated to be 0.27 mSv, which is lower than the dose of 0.48 mSv, as recommended by the UNSCEAR report [16].

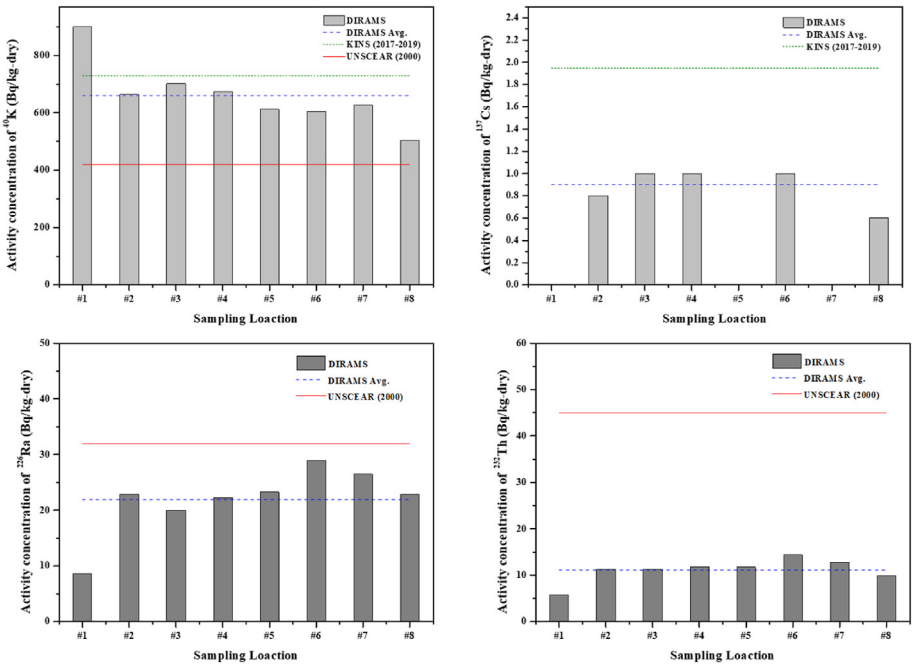

Fig. 2. Activity concentrations of ^{40}K, ^{137}Cs, ^{226}Ra, and ^{232}Th in soil samples. DIRAMS Avg. indicates the average sample activity concentration of eight sites. UNSCEAR data are the population-weighted average of the respective data obtained from 42 countries.

Table 2
Gamma dose rates of ^{226}Ra, ^{232}Th, and ^{40}K and annual effective indoor and outdoor doses.

Location	Gamma dose rate (nGy/h)				Annual effective dose (mSv)	
	^{226}Ra	^{232}Th	^{40}K	Total	Indoor	Outdoor
#1	3.97	3.50	37.57	45.03	0.22	0.06
#2	10.59	6.82	27.69	45.10	0.22	0.06
#3	9.22	6.81	29.28	45.31	0.22	0.06
#4	10.30	7.18	28.12	45.60	0.22	0.06
#5	10.78	7.11	25.56	43.44	0.21	0.05
#6	13.40	8.68	25.18	47.26	0.23	0.06
#7	12.22	7.75	26.17	46.15	0.23	0.06
#8	10.59	6.01	20.98	37.58	0.18	0.05

3.3. Gamma-ray radiation hazard indices in soils

The radium equivalent activity and hazard index due to the natural radioactivity of the soil were evaluated. The results of Ra_{eq}, H_{ex}, and H_{int} are shown in Table 3. The Ra_{eq} range was 71.49–98.10 Bq/kg, with an average value of 88.77 Bq/kg. The H_{ex} range was 0.19–0.26, with an average value of 0.24. The H_{int} range was 0.24–0.34, with an average value of 0.30. The values of radium equivalent activity, and external and internal hazard indices are given to show a wide diversification. Values of <1 indicate a very low probability of radiation hazard to the people. The range of I_r was 0.28–0.38 Bq/kg, with an average value of 0.35 Bq/kg. An I_r value of less than or equal to 0.5 corresponds to the dose rate criterion of 1 mSv/y, implying that materials with $I_r \geq 1.0$ should be avoided in building construction [23]. The $H^*(10)$ values of each sample were calculated. The obtained average value for the studied samples was 56.9 nSv/h. The Spearman correlation coefficient was estimated to understand the possible relationship between natural radionuclides and the radiological hazard index (see Table 4). The high correlation between these two parameters indicate a direct relationship. The relationship between Ra_{eq} and H_{in} was strong with a correlation coefficient (r = 0.99). Significant correlations exist between Ra_{eq}-H_{ex} (r = 0.93), Ra_{eq}-I_r (r = 0.87), H_{ex}-H_{in} (r = 0.9), H_{ex}-I_r (r = 0.75), H_{in}-I_r (r = 0.85). Weak negative correlations were observed between ^{40}K-^{226}Ra (r = −0.83) and ^{40}K–^{232}Th (r = −0.38).

3.4. Excess lifetime cancer risk (ELCR)

The average $ELCR_{in}$, $ELCR_{out}$, and $ELCR_{tot}$ values for DIRAMS are calculated to be 0.38×10^{-3}, 0.19×10^{-3}, and 0.95×10^{-3}, which are higher than the world's mean $ELCR_{in}$, $ELCR_{tot}$ (UNSCEAR). The calculated range of ELCR varied from 0.807×10^{-3} to 1.014×10^{-3}. Also, the ELCR study by M. Abbaspour et al., 2010, was 0.26×10^{-3}, in Iran by Antović et al., 2012, was 0.28×10^{-3}, in Montenegro and by Dizman et al., 2016, was 0.48×10^{-3} in Turkey [27–29]. Spearman correlation coefficients among variable are shown in Table 5. A strong positive correlation was observed between the activity concentration of ^{232}Th in soil with AEDE (r = 0.79), ELCR (r = 0.79), and $H^*(10)$ (r = 0.98) due to thorium series radionuclides. According to the Spearman correlation, analyzes ^{40}K has the lowest correlation in hazard indices compared to ^{232}Th and ^{226}Ra in Tables 4 and 5 The average value of ELCR in the investigation area was higher than the global average value of 0.29×10^{-3}. This is due to the presence of relatively high concentrations of uranium and thorium in the granite and andesite-based soils [30]. These soil types are known to exhibit higher average environmental radionuclide activity than that of other soils. Therefore, due to the characteristics of the site, which consists of granite and andesite, the ELCR was rated higher than the global average value. Additionally, the outdoor variations in gamma dose rates observed across different locations can be attributed to changes in weather conditions, such as fluctuations in radon progeny concentration in the air, which can result from factors such as rainfall, soil moisture, and snow cover.

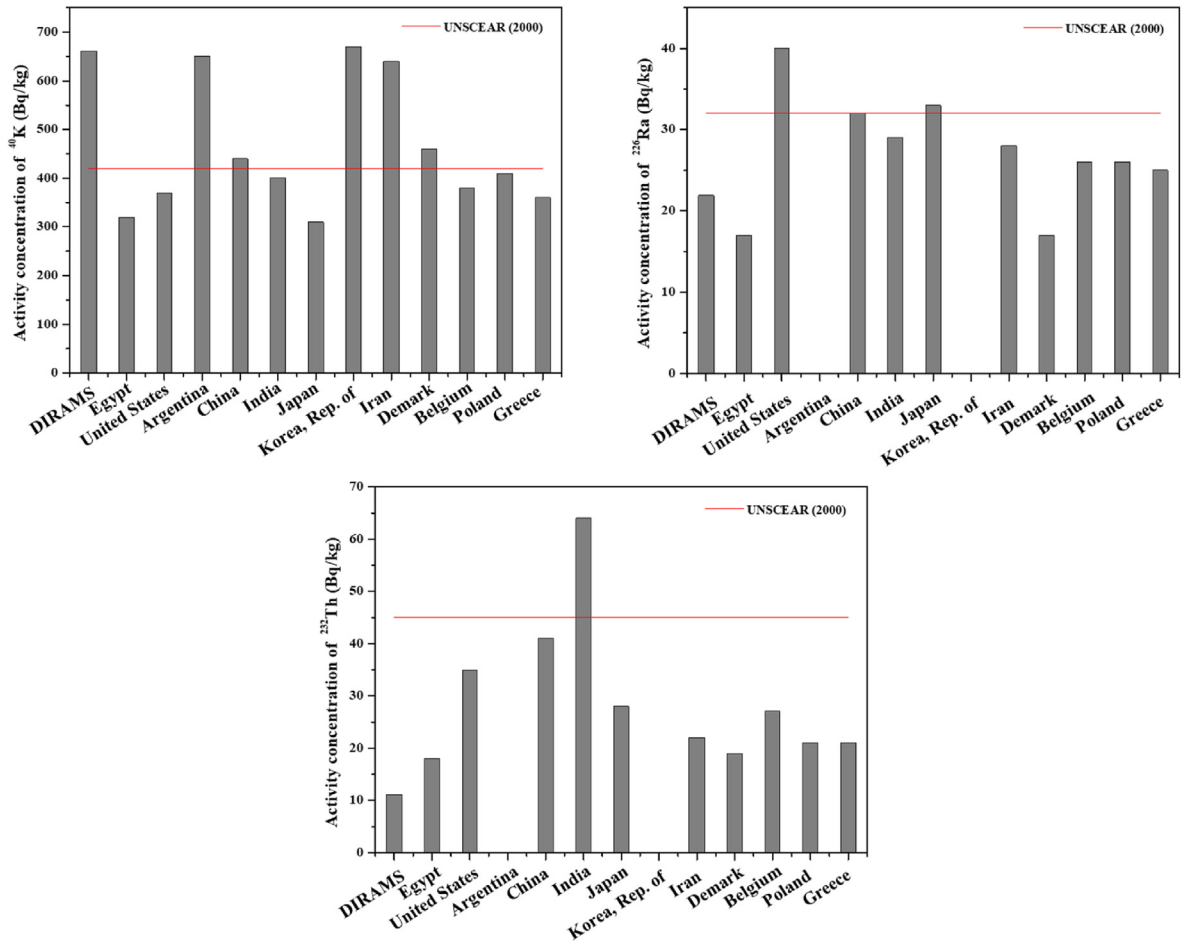

Fig. 3. Activity concentration of ^{40}K, ^{226}Ra, and ^{232}Th in soil samples from various country. UNSCEAR data are the population-weighted average of the respective data obtained from 42 countries.

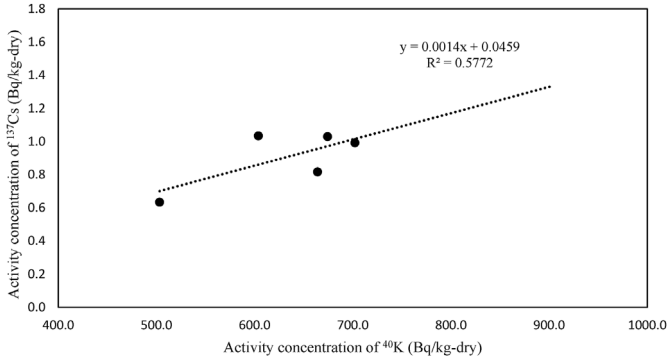

Fig. 4. Activity concentrations of ^{137}Cs versus that of ^{40}K in soils around the DIRAMS area.

4. Conclusions

In this study, environmental radioactivity of four environmental radionuclides, ^{40}K, ^{137}Cs, ^{226}Ra, and ^{232}Th, was measured in sand and soil samples from the DIRAMS premises. The average activity concentrations were 661.1 Bq/kg-dry, 0.9 Bq/kg-dry, 21.9 Bq/kg-dry, and 11.1 Bq/kg-dry for ^{40}K, ^{137}Cs, ^{226}Ra, and ^{232}Th, respectively. The concentrations of ^{137}Cs, ^{226}Ra, and ^{232}Th in the soil were lower than the global average activity concentrations reported by UNSCEAR,

Table 3
Radium equivalent activity Ra_{eq} (Bq/kg), external and internal hazard indices (H_{ex} and H_{int}), and Gamma level index (I_r) for soil samples in DIRAMS.

Location	Ra_{eq} (Bq/kg)		H_{ex}		H_{int}		I_r	
#1	82.17	90.31	0.22	0.24	0.24	0.27	0.34	0.37
#2	91.53	88.84.	0.25	0.24	0.31	0.30	0.36	0.35
#3	94.66	85.60	0.26	0.23	0.31	0.28	0.38	0.34
#4	93.54	88.86	0.25	0.24	0.32	0.30	0.37	0.35
#5	91.97	82.70	0.25	0.22	0.32	0.28	0.36	0.32
#6	93.97	98.10	0.25	0.26	0.33	0.34	0.36	0.38
#7	94.07	92.18	0.25	0.25	0.33	0.32	0.37	0.36
#8	71.49	80.27	0.19	0.22	0.25	0.20	0.28	0.31
Mean.	88.77		0.24		0.30		0.35	

Table 4
Correlations of ^{40}K, ^{226}Ra, ^{232}Th, and radiological hazards in the soil samples (Spearman's correlation coefficients).

Parameters	^{40}K	^{226}Ra	^{232}Th	Ra_{eq}	H_{ex}	H_{in}	I_r
^{40}K	**1.00**						
^{226}Ra	**−0.83**	**1.00**					
^{232}Th	**−0.38**	**0.76**	**1.00**				
Ra_{eq}	**−0.07**	**0.52**	**0.88**	**1.00**			
H_{ex}	**−0.14**	**0.55**	**0.88**	**0.93**	**1.00**		
H_{in}	**−0.13**	**0.59**	**0.92**	**0.99**	**0.96**	**1.00**	
I_r	**0.18**	**0.32**	**0.65**	**0.87**	**0.75**	**0.85**	**1.00**

Table 5
Correlations of ^{40}K, ^{226}Ra, and ^{232}Th activity concentration in the risk parameters (Spearman's correlation coefficients).

Parameters	^{40}K	^{226}Ra	^{232}Th	AEDE	ELCR	H*(10)
^{40}K	**1.00**					
^{226}Ra	**−0.83**	**1.00**				
^{232}Th	**−0.38**	**0.76**	**1.00**			
AEDE	**0.10**	**0.36**	**0.79**	**1.00**		
ELCR	**0.10**	**0.36**	**0.79**	**1.00**	**1.00**	
***H**(10)**	**0.05**	**0.41**	**0.8**	**0.98**	**0.98**	**1.00**

whereas the concentration of ^{40}K in the soil was higher. Radium equivalent activity and internal and external hazard index values were below the recommended limits. The effects of long exposure are indicated by major parameters such as Ra_{eq}, H_{ex}, and H_{in}, which were well within the recommended limits. The calculated ELCR was higher than the reference level reported to UNSCEAR. Geology influenced the activity concentrations of ^{232}Th, ^{40}K, and ^{137}Cs but did not have an impact on the concentration of ^{226}Ra in DIRAMS. Values of the ambient dose equivalent rate, H*(10) were obtained for all the soil samples. The mean value of H*(10) was within the range of the worldwide average. Results of this study can be used as baseline data for the observation of any possible change in DIRAMS in the future. We believe that our study makes a significant contribution to the literature by offering measurements of the concentrations of radionuclides ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs, which are pertinent for regional environmental monitoring and ecological impact assessments in any future cases of NPP accidents.

Declaration of competing interest

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

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