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Assessment of radioactivity levels and radiation hazards using gamma spectrometry in soil samples of Edirne, Turkey

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Abstract This study assesses natural and artificial radioactivity concentrations in surface soil samples from nine different districts in Edirne province, Turkey, and examines the associated potential radiation hazards using gamma spectrometry. The average activity concentrations of radionuclides ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were measured as 39.73 ± 8.45, 55.85 ± 10.55, 407.12 ± 35.39, and 8.76 ± 0.74 Bq kg^{-1} respectively. The radiation hazard indices for natural activity were calculated. The evaluated data were compared with internationally approved values.

Keywords Radioactivity · Radiation hazard · Gamma spectrometry · Soil · Edirne · Turkey

Introduction

Natural environmental radioactivity is composed of cosmic rays and naturally occurring radioactive materials (NORM) in the earth [1]. Some of these materials are cosmogenic, some are primordial, and others come from natural sources through various mechanisms [1, 2]. Natural radionuclides from the cosmic radiation that continuously bombards the earth's atmosphere are retained by many materials in the environment, including soil. These natural radioactive sources are present at different concentration levels in the soils of each region in the earth's crust and emit gamma radiation [3, 4]. Higher radiation levels are associated with igneous rock such as granite and lower levels are associated with sedimentary rocks [5]. Such radiometric data is important for geological and environmental studies as well as for mineral and natural resources exploration [6].

Natural environmental radioactivity comes mainly from primordial radionuclides, which include ^{40}K and the nuclides from the ^{232}Th and ^{238}U series and their decay products, which are present at trace levels in all ground formations [7]. All kinds of rocks, soils, and minerals include the above-mentioned naturally existing radionuclides and their products [8].

Since radiation is ubiquitous and continuous, human beings and other living organisms are exposed to ionizing radiation from NORM composed of such nuclides found in the earth's crust [9]. The total emitted radiation from NORM in the earth's crust is referred to as terrestrial background radiation. The effect of this natural radioactivity on human beings is a continuing and inescapable feature of life on earth [5]. Besides natural radionuclides, artificial radionuclides can also arise from fallout from weapons testing and from nuclear accidents such as Chernobyl and Fukushima [9].

Measurements of natural environmental radioactivity have been of great research interest for many countries in the world over the last two decades. Such investigations are important for assessing public dose rates and for many fundamental scientific reasons, as well as for providing reference data for tracking changes in environmental radioactivity levels due to geological processes, artificial influences such as nuclear industry and other human activities, whenever the level is found to be above the recommended limits [7]. As a consequence, the investigation of gamma radiation levels from soil is particularly

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important for providing the baseline data that are increasingly being used in decision-making processes related to land use, the environment, agriculture, and public health [10, 11].

The aim of this study is to determine the natural and artificial radioactivity levels and associated radiological hazards present in soil samples from Edirne, Turkey. An assessment of the investigated average activity of natural radionuclides ^{226}Ra, ^{232}Th, ^{40}K, and artificial ^{137}Cs for each district in Edirne is presented in Table 1, along with their calculated errors. Table 2 shows the average values for Edirne calculated from the average values from nine districts and those of the comparison with Turkey and the world.

Materials and methods

Edirne province is located in the northwest border of Turkey with Maritza River that is shared by Turkey, Bulgaria and Greece, Fig. 1. Coal fired power plant and uranium mining activities in south-east of Bulgaria can enhance the radionuclide concentration of the Maritza River. The agricultural activities in three countries are also intense and the use of fertilizers and pesticides is widespread. Because Maritza is a trans-boundary river, it is important to monitor the activity concentration of radionuclides.

Edirne covers an area of 6272 km^2. The study region stretches between longitudes 26°04′–26°55′ and latitudes 40°36′–40°57′, with an average elevation of 41 m above sea level. Edirne borders the Strandzha Mountains to the north and extends to the Ergene Basin in the central region; is limited by mountains, a plateau, and the Maritza Delta to the south.

The geology of our study area is composed chiefly of young sedimentary rocks from the Neogene period and includes bentonite deposits, limestone and clay reserves, as well as fluoride, phosphate, and manganese. Moreover lignite deposits in the region hold an important place [12].

In order to measure natural and artificial concentrations of radioactivity from surface soil samples in Edirne city, nine districts were selected, Table 1 and Fig. 1. Ten samples were collected randomly from each district, for a total of 90 samples, in January 2014. A metal apparatus (20 × 20 × 20 cm) was used for holding the samples. After removing stones, gravel, and residues of plants and roots, about 1 kg of material from the first 20 cm of topsoil was packed in labelled polythene bags and transferred to the laboratory where the samples were dried at room temperature. Then, they were pulverized, homogenized, and strained through 2 mm mesh. Next, they were dried at 90 °C until they reached a constant weight. Then, they were placed in Marinelli beakers (150 ml capacity). The soil samples were weighed, carefully sealed, and stored in Marinelli beakers. Each beaker was sealed hermetically and externally as well, stored for at least 30 days in order to achieve secular equilibrium between parents in the decay chain and their short-lived progenies.

In all cases, the activity concentration of ^{40}K was determined from the peak related to photons with energy 1460.75 keV; the activity of ^{226}Ra was determined from the 1764.49 keV gamma line of ^{214}Bi, and that of ^{232}Th was determined from the 2614.53 keV gamma line of ^{208}Tl. For ^{137}Cs concentration was used 661.66 keV gamma transition energy.

Measurements of activity levels of radionuclides in the samples were achieved by comparing them with standardized samples of reference materials; IAEA-RGK-1, Potassium Sulphate; IAEA-RGTh-1, Thorium Ore; IAEA-RGU-1, Uranium Ore; and IAEA-375, Soil. All processing for measuring activity levels of radionuclides in the samples and the standards were applied under the same conditions. When performing the calculation for each radionuclide activity concentration, the net count rate of background with the related gamma ray line are subtracted from its net count rate (in count per second).

Gamma background levels were measured under the same conditions for the study samples and the reference materials at the counting laboratory, with the empty Marinelli beakers washed with dilute HCl and distilled water.

The minimum detectable radionuclide activity for ^{226}Ra, ^{232}Th, and ^{40}K was determined as 5, 6, and 32 Bq kg^{-1}, respectively, for 80,000 s counting time, for both the study samples and reference materials. Ten samples from each district, a total 90 samples from nine districts were analysed and the average values were calculated for each region, Tables 1 and 2.

The sample counting procedures were carried out using gamma ray spectrometry consisting of a 3 × 3 NaI(TI) (Model ORTEC) detector connected to a 16384-channel multichannel analyzer (MCA). The energy resolution of the spectrometer was 2.1 % for the 1332.51 keV gamma ray line ^{60}Co (FWHM is 70.44 %). This spectrum analysis was performed with the aid of computer software ORTEC Spectrum receiving and analysis software. To reduce the effect of background noise, the detector was shielded using 6 cm of lead on all sides. For the energy calibration of the system, ^{60}Co and ^{137}Cs point sources were used with gamma ray energies at 1173.24, 1332.51 and 661.66 keV, respectively.

Measurement of natural radioactivity

The activity concentration in each sample was calculated using Eq. (1):

Table 1 Radioactivity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in Bq kg^{-1}, as well as calculated absorbed dose rate, annual effective dose equivalent, Ra equivalent, external hazard index and excess lifetime cancer risk in soil samples at Edirne province

Locations	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	^{137}Cs (Bq kg^{-1})	Absorbed dose rate in air (D) (nGy h^{-1})	Annual effective dose equivalent (AEDE) (μSv/yıl)	Ra equivalent activity Ra_{eq} (Bq kg^{-1})	External hazard index (H_{ex})	Annual gonadal dose equivalent (AGDE) (μSv/yıl)	Excess lifetime cancer risk (ELCR)
Lalapaşa	47.03 ± 9.33 (SD = 5.87)	59.15 ± 9.08 (SD = 15.03)	423 ± 34.04 (SD = 88.74)	28.7 ± 2.90 (SD = 7.39)	74.17	91.00	156.01	0.43	512.18	3.18×10^{-4}
Süloğlu	41.05 ± 9.45 (SD = 0.75)	58.69 ± 9.63 (SD = 6.95)	445.10 ± 35.40 (SD = 83.38)	ND	73.97	91.00	156.13	0.43	511.93	3.18×10^{-4}
Edirne (center)	51.45 ± 12.00 (SD = 12.26)	57.96 ± 12.91 (SD = 11.46)	402.60 ± 37.60 (SD = 73.50)	4.07 ± 0.30 (SD = 0.60)	76.55	93.88	162.51	0.45	527.67	3.29×10^{-4}
Havsa	24.00 ± 2.70 (SD = 2.97)	53.37 ± 10.01 (SD = 11.01)	368.78 ± 32.16 (SD = 75.13)	ND	59.61	73.10	126.13	0.35	413.04	2.56×10^{-4}
Meriç	50.50 ± 4.70 (SD = 11.39)	55.39 ± 12.29 (SD = 11.08)	369.41 ± 36.03 (SD = 62.57)	10.53 ± 0.97 (SD = 4.58)	73.13	89.69	155.57	0.43	503.57	3.14×10^{-4}
İpsala	21.00 ± 1.07 (SD = 5.67)	50.53 ± 10.63 (SD = 7.96)	389.52 ± 34.83 (SD = 108.59)	29.71 ± 1.82 (SD = 7.78)	57.32	70.30	120.52	0.33	398.41	2.46×10^{-4}
Enez	37.80 ± 10.35 (SD = 3.30)	55.96 ± 10.29 (SD = 20.49)	498.4 ± 36.96 (SD = 84.54)	5.17 ± 1.34 (SD = 1.55)	72.99	89.53	152.71	0.42	507.21	3.13×10^{-4}
Keşan	48.28 ± 10.65 (SD = 7.75)	56.28 ± 9.33 (SD = 8.85)	370.16 ± 36.47 (SD = 119.16)	0.62 ± 0.30 (SD = 0.02)	72.69	89.15	154.67	0.42	500.67	3.12×10^{-4}
Uzunköprü	36.51 ± 11.49 (SD = 6.11)	55.25 ± 10.83 (SD = 8.25)	397.11 ± 35.09 (SD = 94.53)	ND	67.74	83.07	143.32	0.39	468.45	2.91×10^{-4}

SD Standard deviation, *ND* not detected

Table 2 Concentration of natural radionuclides, fission product and radiologic parameters in soil samples from different parts of Turkey and the world, compared with those of mean values of the present study

Region and Country	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	^{137}Cs (Bq kg^{-1})	Absorbed dose rate in air (D) (nGy h^{-1})	Annual effective dose equivalent (AEDE) (μSv/yıl)	Ra equivalent activity Ra_{eq} (Bq kg^{-1})	External hazard index (H_{ex})	Annual gonadal dose equivalent (AGDE) (μSv/yıl)	Excess lifetime cancer risk (ELCR)
Average value of Edirne province ± SDA	39.73 ± 10.51	55.85 ± 2.55	407.12 ± 40.44	8.76 ± 13.13	69.79 ± 6.46	85.64 ± 7.95	147.51 ± 13.82	0.41 ± 0.04	482.57 ± 47.32	3.06 ± 0.28 × 10^{-4}
Turkey (İstanbul) [27]	27.70	32.50	388.00	–	48.70	59.70	104.10	0.28	–	–
Turkey (Zonguldak) [28]	23.19	20.00	244.75	–	33.02	40.50	–	0.19	–	–
Turkey (Kayseri) [29]	35.51	37.27	429.66	11.53	59.75	73.28	–	–	–	–
Turkey (Rize) [33]	50.00	42.00	643.00	85.00	77.40	88.70	166.30	0.45	550.50	–
India (Rajasthan) [30]	24.00	55.00	549.00	–	68.00	–	141.00	0.40	–	–
Iran (Tehran) [31]	38.80	43.40	555.10	–	69.10	80.00	142.60	0.39	–	–
Mexican (radioactive waste-storage center) (other city) [32]	203.00	22.00	252.00	34.00	117.00	–	–	–	–	–
	26.00	23.00	294.00	1.50	38.00	–	–	–	–	–
Nigeria (Southwestern) [34]	54.50	91.10	286.50	–	95.03	117.00	203.63	0.52	–	–
Italy (Lombardia) [35]	72.00	48.00	617.00	25.00	–	–	–	–	–	–
Spain [36]	46.00	49.00	650.00	–	56.60	–	–	–	–	–
UNSCEAR 2000 [13]	35.00	30.00	400.00	–	60.00	70.00	370.00	<1	300.00	2.90 × 10^{-4}

SDA Standard deviation of average

Fig. 1 Google map showing location of Edirne with their sampling sites

$$A_{\text{sam}}\left(\frac{\text{Bq}}{\text{kg}}\right) = A_{\text{ref}}\left(\frac{\text{Bq}}{\text{kg}}\right)\frac{\frac{S_{\text{sam}}}{t_{\text{sam}}} - \frac{S_{\text{fon}}}{t_{\text{fon}}}}{\left(\frac{S_{\text{ref}}}{t_{\text{ref}}} - \frac{S_{\text{fon}}}{t_{\text{fon}}}\right)m_{\text{sam}}} \quad (1)$$

where A_{sam}, A_{ref} represent the activity of interest in Bq kg^{-1} in the sample and reference, respectively; S_{sam}, S_{ref} and S_{fon} represent the photo peak area of sample, reference, and background gamma ray peaks (dimensionless), respectively; and t_{sam}, t_{ref} and t_{fon} represent the duration of gamma ray counts in seconds for sample, reference, and background, respectively.

The uncertainty of the activation concentration was calculated by the following equation:

$$\text{U} = A_{\text{sam}}\sqrt{\left(u_{\text{A,ref}}\right)^2 + \frac{\left(u_{\text{sam}}\right)^2 + \left(u_{\text{fon}}\right)^2}{\left(C_{\text{sam}} - C_{\text{fon}}\right)^2} + \frac{\left(u_{\text{ref}}\right)^2 + \left(u_{\text{fon}}\right)^2}{\left(C_{\text{ref}} - C_{\text{fon}}\right)^2}} \quad (2)$$

where $u_{\text{A,ref}}$ is the relative uncertainty of reference activities, and u_{sam}, u_{ref} and u_{fon} are the uncertainty in the count rate for the sample, reference, and background, respectively. C_{sam}, C_{ref}, and C_{fon} stand for the net counts of gamma-ray peaks for the radionuclides in the samples, references and background respectively.

Absorbed dose rate in air (D)

For a uniform distribution of radionuclides ^{226}Ra, ^{232}Th and ^{40}K, the absorb dose rate in air at 1 m above the ground in each sampling location was calculated by using the conversion factors in Eq. (3), [13]. The conversion factors of D for ^{226}Ra, ^{232}Th and ^{40}K are 0.427; 0.662; and 0.043 nGy h^{-1} per Bq kg^{-1}, respectively,

$$D = (0.427 \times A_{\text{Ra}} + 0.662 \times A_{\text{Th}} + 0.043 \times A_{\text{K}})\ \text{nGy h}^{-1} \quad (3)$$

where A_{Ra}, A_{Th}, and A_{K} (in Bq kg^{-1}) represent the activity concentration in the samples, respectively.

Annual effective dose equivalent (AEDE)

In order to estimate the annual effective dose equivalent, 0.7 Sv Gy^{-1} for the conversion coefficient from absorbed dose in air to effective dose received by adults and 0.2 for outdoor occupancy factor, i.e. the fraction of time spent outdoors proposed by UNSCEAR is used [13], in Eq. (4)

$$\text{AEDE} = \left[D\left(\text{nGy h}^{-1}\right) \times 8760\left(\text{h}^{-1}\right) \times 0.2 \times 0.7(\text{Sv/Gy}) \times 10^{-3}\right]\mu\text{Sv year}^{-1} \quad (4)$$

where D is the absorbed dose rate in air (nGy h^{-1}).

Radium equivalent activity (Ra_{eq})

It is well known that natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K are not uniformly distributed in soil [6, 9]. In order to estimate uniform radiological exposure rates, the concentration of radionuclides has been defined in terms of radium equivalent activity (Ra_{eq}) units in Bq kg^{-1}, which takes into account the associated radiation hazards and provides a very useful guideline for regulating the safety standards for radiation protection of human populations [8, 14, 15].

It is assumed that 370 Bq kg^{-1} of ^{226}Ra, 259 Bq kg^{-1} of ^{232}Th, and 4810 Bq kg^{-1} of ^{40}K produce the same gamma-ray dose rate;

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (5)$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1}, respectively [16].

External hazard index (H_{ex})

As local soil is used for the construction of houses, the soil contributes to the external gamma dose rates in these houses. The external hazard index (H_{ex}) was calculated for the investigated samples using the model proposed by Ref. [17], assuming thick walls without windows and doors, where the H_{ex} was given by [18, 19] in Eq. (6),

$$H_{ex} = A_{Ra}/370 + A_{Th}/259 + A_K/4810 \leq 1 \quad (6)$$

This is a dimensionless quantity and the safety regulations for materials used for building construction is $H_{ex} \leq 1$ [20], where A_{Ra}, A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1}, respectively. When the value of H_{ex} is less than unity, the radiation received by occupants will be <1.5 mGy $year^{-1}$. The maximum value of H_{ex} equal to unity corresponds to the upper limit of Ra_{eq}; 370 Bq kg^{-1}.

Annual gonadal dose equivalent (AGDE)

Radiation effects are different on all living cells. These effects could result in the death or mutation of the cell, whereas there may be no effects on DNA. The gonads, the active bone marrow, and bone surface cells are considered the organs of interest by UNSCEAR [13]. It is important to measure the annual genetic dose equivalent (AGDE) of the yearly dose equivalent received by the population's reproductive organs (gonads) [21]. Therefore, the AGDE due to the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K was calculated using the Mamont-Ciesla et al.'s formula [22, 23]:

$$AGDE(\mu Sv\ year^{-1}) = 3.09A_{Ra} + 4.18A_{Th} + 0.314A_K \quad (7)$$

Excess lifetime cancer risk (ELCR)

Potential carcinogenic effects are determined by indices that are estimated by the probability of cancer in a population of individuals for a specific lifetime using predicted intakes and exposures and chemical-specific dose–response data (i.e., slope factors). Excess lifetime cancer risk (ELCR) is calculated using Eq. (8), stated by Ref. [24, 25]:

$$ELCR = AEDE \times DL \times RF \quad (8)$$

where AEDE, DL, and RF are the annual effective dose equivalent, duration of life (70 years), and risk factor (0.05 Sv^{-1}) (i.e., fatal cancer risk per Sievert), respectively [26].

Results and discussion

Table 1 summarizes the average values of activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs for each nine districts of Edirne province soil samples, with their standard deviation. The activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs ranges from 21.00 ± 1.07 to 51.45 ± 12.00 Bq kg^{-1}, 50.53 ± 10.63 to 59.15 ± 9.08 Bq kg^{-1}, 368.78 ± 32.16 to 498.40 ± 36.96 Bq kg^{-1}, and 0.62 ± 0.30 to 29.71 ± 0.82 Bq kg^{-1} respectively. For the entire study area, Edirne province, the average activity of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were given 39.73 ± 8.45, 55.85 ± 10.55, 407.12 ± 35.39, and 8.76 ± 0.74 Bq kg^{-1} with standard deviation of 10.51, 2.55, 40.44 and 13.13 Bq kg^{-1} respectively, in Table 2.

The worldwide average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K reported by UNSCEAR (2000) are 35, 30, and 400 Bq kg^{-1}, respectively [13].

While the average activity concentrations for ^{226}Ra in the soil samples of the study area excluding Havsa and İpsala are between 1.04 and 1.47 times higher than the worldwide figures, average value of Edirne province is 1.14 times higher than the same figures [13].

As shown in Table 2, among worldwide ^{226}Ra concentrations, while the average value of Edirne province is higher than average ^{226}Ra concentration of Istanbul, Zonguldak, and Kayseri in Turkey, as well as in India (Rajasthan), Iran (Tehran), and Mexico, it is lower than average ^{226}Ra concentration of Rize (Turkey), Nigeria (Southwestern), Northern Italy, and Spain [27–36].

All activities of ^{232}Th in the studied regions are higher than the world average and average value of Edirne

province is 1.86 times of the world average. Table 2 shows that the mean activity concentration obtained in this study for ^{232}Th is higher than Istanbul, Zonguldak, Kayseri, and Rize in Turkey, as well as in India (Rajasthan), Iran (Tehran), Mexico, Northern Italy, and Spain, while it is lower than Nigeria [27–36]. The highest amount of ^{232}Th (59.15 Bq kg^{-1}) was found at Lalapaşa, is about two times of the world average value. The result may be due to the geological structure. The activity concentrations of ^{232}Th in Edirne soil samples were higher than the activity concentrations of ^{226}Ra.

Among the ^{40}K concentrations, while our values are lower than the world average except Lalapaşa, Süloğlu, Edirne (center) and Enez, average value of Edirne is similar to the world average. The activity concentration values of ^{40}K obtained in Rize [33] and Kayseri [29], Turkey, as well as in India (Rajasthan) [30], Northern Italy [35], Iran [31], and Spain [36], are higher than Edirne in the present work.

The ^{137}Cs was also determined in the soil samples in six districts of Edirne (Lalapaşa, Edirne-center, Meriç, İpsala, Enez and Keşan). ^{137}Cs does not exist in soil naturally, this result may be due to Chernobyl nuclear power accident in 1986 or nuclear weapon testes. The concentrations of ^{137}Cs are consistent with the world average, as can be seen in Table 2.

Figure 2 shows the distribution of the ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs activity concentrations of soil in Edirne.

Absorbed dose rate in air (*D*)

The average absorbed dose rate for the nine districts under investigation compared to values from other areas of Turkey and the world are listed in Table 2. It can be seen that the calculated results range from 57.32 to 76.55 nGy h^{-1}, with a mean value of 69.79 nGy h^{-1} and a standard deviation of 6.46 nGy h^{-1}. The mean value is slightly higher than the global value of 60 nGy h^{-1} reported by Ref. [13]. As can be seen in Table 2, the mean *D* value obtained in the present study is higher than that other cities in Turkey except for Rize, and about twice that reported for Zonguldak.

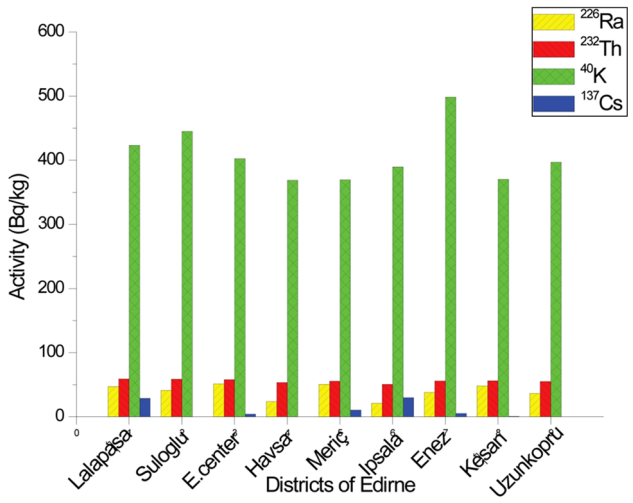

Fig. 2 Variation of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs concentrations of districts of Edirne, in vertical profiles

Annual effective dose equivalent (AEDE)

The annual effective dose equivalent values vary from 70.30 to 93.88 μSv year^{-1}, and the average value was found to be 85.64 μSv year^{-1} and a standard deviation of 7.95 μSv year^{-1}, Tables 1 and 2. The world average AEDE from outdoor terrestrial gamma radiation is 70 μSv year^{-1} [13]. So, the calculated values are higher than the world average value but lower than values of Rize [33], Nigeria [34].

Radium equivalent activity (Ra_{eq})

In the present study, the average value of Ra_{eq} was calculated as 147.51 Bq kg^{-1} and a standard deviation of 13.82 Bq kg^{-1}, which is lower than the limit value (370 Bq kg^{-1}) recommended by the Organization for Economic Cooperation and Development (OECD) [17, 18]. The Ra_{eq} in the soil samples tabulated in Table 1 ranges from 120.52 to 162.51 Bq kg^{-1}. The average value was found to be higher as compared with other places reported by Belivermiş et al. [27] (104.10 Bq kg^{-1} for Istanbul, Turkey), Asha et al. [30]. (141 Bq kg^{-1} for Rajasthan, India), Asgharizadeh et al. [31] (142.60 Bq kg^{-1} for Tehran, Iran).

External hazard index (H_{ex})

The calculated values of H_{ex} lie in the range of 0.33–0.45, with an average value of 0.41 and a standard deviation of 0.04. This value is less than unity, according to the Radiation Protection 112 report given by the European Commission (EC), [19]. The results for H_{ex} based on Eq. 6 are given in Table 1.

Annual gonadal dose equivalent (AGDE)

The average values for AGDE are presented in Table 2, 482.57 μSv year^{-1} and a standard deviation of 47.32 μSv year^{-1}. The AGDE values in soil samples from Edirne investigated in this work are determined to be higher than the world average (300 μSv year^{-1}) [37].

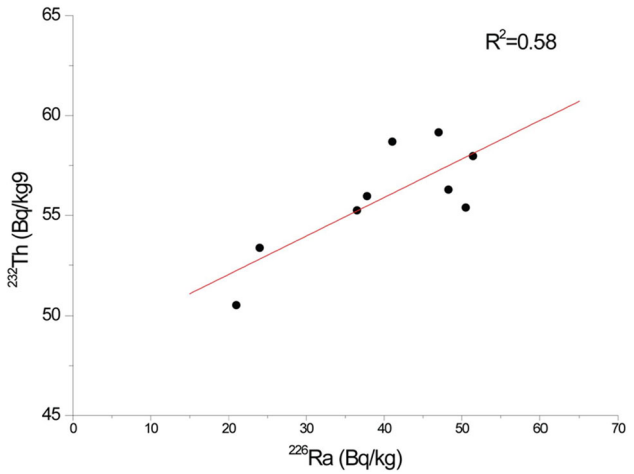

Fig. 3 The correlation between the activity concentrations of ^{226}Ra and ^{232}Th for the samples

Excess lifetime cancer risk (ELCR)

The calculated values vary from 2.46×10^{-4} to 3.29×10^{-4}, with an average of 3.06×10^{-4} and a standard deviation of 0.28. The present average is near the world average limit (2.9×10^{-4}) [13, 26, 38]. Only two of the sampling locations (Havsa, Ipsala) has ELCR values lower than the world average. The average values are calculated as 4.5×10^{-4} for Bursa, Turkey [39], 5×10^{-4} for Kirklareli, Turkey [40], 17×10^{-4} in Kerala, India [25], and 1.8×10^{-4} in Tamilnadu, India [38].

The correlation between the activity concentrations of ^{226}Ra and ^{232}Th for the samples is shown in Fig. 3. As shown in Fig. 3, there are positive correlations of 0.58 ($p = 0.094$) between ^{226}Ra and ^{232}Th concentrations. The positive correlation predicts the samples collected in this region are geochemically coherent [9].

Conclusion

It is important to determine natural radiation levels in order to evaluate health hazards. However, a survey of the literature shows that no attempt has been made at such a study in Edirne province, Turkey.

We have come to the following conclusions based on our assessments of the natural radioactivity and associated radiological hazards in Edirne province, Turkey.

1. The average activity concentration of ^{232}Th in the soil of these areas is higher than the world average value, while that of ^{226}Ra and ^{40}K is slightly higher. High activity concentration of ^{40}K might be due to the use of fertilizer rich in potassium. The average concentration of natural radionuclides ^{226}Ra is lower than that of ^{232}Th, and major contribution to the total activity is due to ^{40}K, with percentage of them 7.9, 11.11 and 80.99 %, respectively. The standard deviation values of all activity concentrations, except average value for ^{137}Cs are lower than the mean value. The result indicates that the present radioactivity variables show high degree of uniformity.
2. With respect to ^{137}Cs, the fall out ^{137}Cs was noted in soil. This can be attributed to the Chernobyl nuclear power plant accident and atmospheric nuclear weapon tests conducted by several countries.
3. The D and AEDE determined in the soil samples of the studied areas are higher than the recommended safe limits reported by UNSCEAR [13].
4. The highest and the average values of Ra_{eq} in our samples are 162.51 and 147.51 Bq kg^{-1}, respectively, significantly less than world average values from Ref. [13].
5. The results obtained from the H_{ex} for the studied soil samples are lower than unity, which is safe according to the Radiation Protection 112 European Commission report [19].
6. The values of AGDE and ELCR for the soil samples from Edirne studied in this work are also found to be higher than the world average (300 μSv year^{-1} and 2.9×10^{-4}).
7. A slight correlation has been found between ^{226}Ra and ^{232}Th activity concentration.

As can be seen, the average values do, in general, slightly exceed the permissible recommended limits; therefore, the hazardous effects of these radioactive substances should be considered with regard to inhabitants. In addition, this study has established baseline data for natural radioactivity levels in Edirne and will be consulted as reference information to determine any future changes in background radiation levels in the studied area.

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