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37 years after the chernobyl: the current radiation status in Kocaeli, Turkey

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Abstract
This study aims to assess the artificial and natural radiation dose levels in certain districts of Kocaeli province within the Marmara region, 37 years after the Chernobyl nuclear accident, and evaluate the current status prior to potential nuclear leakage events from Zaporijya or other nuclear power plants. Radioactive concentrations of ^{232}Th, ^{238}U, ^{40}K and ^{137}Cs were determined using HPGe gamma spectrometry in 26 soil samples collected from the region of interest. The average concentrations were found to be 22.35 Bqkg^{-1} for ^{238}U, 26.36 Bqkg^{-1} for ^{232}Th, 368.34 Bqkg^{-1} for ^{40}K, and 2.44 Bqkg^{-1} for ^{137}Cs. Furthermore, the study revealed an absorbed dose rate of 41.73 nGyh^{-1}, an annual effective dose equivalent of 51.18 μSvy^{-1}, and an excess lifetime cancer risk of 0.00018.

Keywords Natural radiation · ^{137}Cs · Gamma-ray spectrometry · Annual effective dose · Soil pollution

Introduction

Radiation is the emission of energy from the atom through various mechanisms. This energy may originate from both natural and artificial sources. Natural radiation has persisted since the inception of the universe, existing independent of human intervention. Natural radiation consists of a combination of terrestrial and cosmic radiations. Terrestrial natural radiation is emitted by uranium (^{238}U), thorium (^{232}Th) and their daughters and by ^{40}K. Cosmic radiation is the radiation that originates from extraterrestrial particles, such as photons and muons, and secondary radionuclides (e.g., ^{3}H, ^{7}Be, ^{10}Be, ^{14}C, and ^{26}Al) that are formed as a result of the reactions of these particles with isotopes in the atmosphere. People are not only exposed to terrestrial natural radiation when they are on the surface of the Earth, but they are also exposed to radiation from buildings they live, since most of the construction materials in their living spaces are terrestrial-based materials. Therefore, the determination of the natural radiation level is very important in terms of radiation exposure. For this reason, natural and artificial radiation levels in soil have been studied by many researchers around the world in the last three decades [1–9].

Artificial radiation is a type of radiation produced by man and not found in nature before. Sources of artificial radiation can include fallout after nuclear weapon tests and nuclear accidents, nuclear power plants, radioisotope production, nuclear medicine waste. Due to the nuclear power plant accidents that occurred in Fukushima Daiichi (2011), Chernobyl (1986), and Three-Mile Island (1979), a large number of artificial radionuclides was released into the environment. Some long-lived radioactive nuclides have spread to both the marine and terrestrial environment. The region of Turkey's Black Sea north was the most affected by the Chernobyl accident due to the accumulation of radioactive contaminants caused by the rains in April of that year in the area surrounding the plantation. In addition, a study conducted between 1987 and 1989 reported that ^{137}Cs activities in the Eastern Black Sea region ranged from 270 Bqkg^{-1} to 5495 Bqkg^{-1} [10]. For this reason, since 1986, many studies have been carried out to determine the level of radioactive nuclides both in our country and in neighboring countries of Chernobyl [11–18]. One of the important radionuclides

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emitted to the terrestrial environment as a result of radioactive fallout is ^{137}Cs. Since ^{137}Cs has a long half-life of 30 years, it is a good predictor of the behavior of the radionuclide in the natural environment.

The main objectives of this study are to determine and map the levels of natural radioactivity (^{238}U, ^{232}Th, ^{40}K) and artificial radioactivity (^{137}Cs) in the western part of the Kocaeli province, in the northwestern part of Turkey. In this study, radiological assessment (absorbed dose rate, annual effective dose equivalent (AEDE), radium equivalent activity (Ra_{eq}), excess lifetime cancer risk (ELCR), external hazard index, internal hazard index and gamma representative level index) arising from natural radiation were determined. ^{137}Cs levels measured in soil were compared with the results of previous studies, and ^{137}Cs activity behavior in the region was evaluated. The results of this work can be used as a reference data in order to determine possible changes in the radioactivity levels in the future. This study's significance lies in its potential as a reference point and as a snapshot of the current situation in the event of possible nuclear leaks, such as from Zaporijya or other locations.

Study area

Kocaeli province is in the northwestern part of Turkey (Fig. 1), with Istanbul in the west, Sakarya in the east, Bursa in the south, and the Black Sea in the north. Kocaeli province stands from 40° 44′ 17″ to 41° 13′ 28″ north latitudes and from 29° 19′ 53″ to 30° 22′ 10″ east longitudes. The distance between Kocaeli and Chernobyl is approximately 1100 km (Fig. 1).

The sample sites of the area is the Marmara Sea environment between 40° 44′ 58′ to 40° 48′ 25″ north latitudes and from 29° 22′ 19″ to 29° 50′ 53″ in the western part of Kocaeli. There are five different districts in the study area of Kocaeli which are named Darıca, Gebze, Dilovası, Körfez, and Derince. Sample sites were determined along the borders of the districts to the Marmara Sea. Considering the coastal lengths of the Marmara Sea, a total of 26 sampling points were determined: 3 in Darıca, 5 in Gebze, 4 in Dilovası, 9 in the Körfez, and 5 in Derince (Fig. 2).

Experimental methods

At each sampling point, approximately 1 kg of soil sample was obtained by taking four different sub-samples from a 1 m^2 area, each collected at a depth of 0–5 cm. Samples were collected during the summer of 2021 and measured in the following months. Soil samples collected from a total of 26 different points were dried at 105 °C for 36 h and then passed through a 1 mm mesh sieve to purify them. Subsequently, each soil sample was thoroughly mixed to achieve homogeneity. These samples were placed in PVC containers with a volume of 170 cm^3, and the containers were tightly

Fig. 1 Study area (Kocaeli province stands from 40° 44′ 17″ to 41° 13′ 28″ north latitudes and from 29° 19′ 53″ to 30° 22′ 10″ east longitudes)

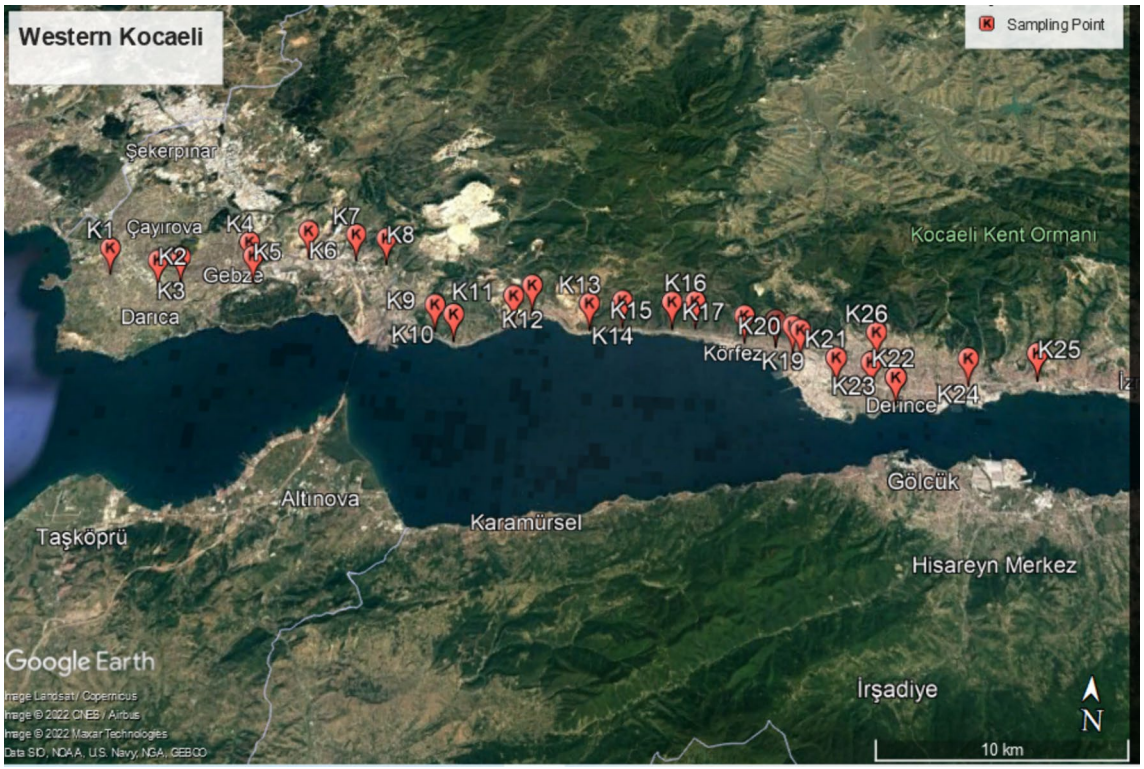

Fig. 2 Sample sites in Kocaeli were determined along the borders of the districts to the Marmara Sea

sealed with parafilm to prevent air from entering or exiting. The mass of the samples in the airtight containers is approximately 230 g. These 26 prepared soil samples were stored in the laboratory for 5 weeks to achieve secular equilibrium between ^{226}Ra and its progeny.

The samples were measured at the Kocaeli University Nuclear Physics Research Laboratory. A coaxial HPGe detector (GEM25P4-70 model, ORTEC) with a relative efficiency of 25% and a resolution of 1.71 keV at the 1332 keV gamma energy of ^{60}Co was used for the measurements. To reduce background radiation, the detector was placed within a 10 cm thick lead shield internally lined with 1 mm thick Sn and 1.5 mm thick Cu. Energy and efficiency calibrations of the detector were established using a multi-nuclide standard source (Eckert&Zeigler Company Isotopes Products), which covered an energy range from 47 to 1836 keV, including peaks of ^{210}Pb, ^{241}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{203}Hg, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{88}Y, and ^{60}Co, in a 170 mL PVC container that has the same geometry as the sample containers.

Each sample was measured for varying durations ranging from 70,000 s to 200,000 s to ensure a good counting statistic. The analysis of gamma spectra was performed using the GammaVision-326.02 software (MCA, EG&G ORTEC). In Fig. 3, a gamma-ray spectrum of a sample taken from Derince (sample no K-22) is shown. This spectrum displays gamma lines from various daughter radionuclides of the ^{238}U and ^{232}Th series, ^{40}K, and ^{137}Cs. The activity of ^{238}U was determined from gamma rays at 609.32 keV and 1120.29 keV from the ^{214}Bi peak, as well as 295.22 keV, and 351.93 keV from the ^{214}Pb peak. The activity of ^{232}Th was evaluated from the gamma rays at 338.32 keV and 911.20 keV originating from ^{228}Ac, and 583.19 keV from the ^{208}Tl peak. Weighted averages of the measured activities for ^{238}U and ^{232}Th from different gamma lines were calculated. ^{40}K activity was directly determined from the 1460.8 keV peak, and ^{137}Cs activity was determined using the 661.66 keV peak. When calculating the uncertainty of specific activity measurements, factors such as the net area of the photo peak, absolute peak efficiency, accumulation time, gamma-ray emission probability, and sample mass were taken into account.

To determine the radiological assessment, absorbed dose rate, AEDE, Ra_{eq}, ELCR, External hazard index (H_{ex}), Internal hazard index (H_{in}) and Gamma representative level index ($I_{\gamma r}$) were calculated using the ^{238}U, ^{232}Th, ^{40}K, concentrations.

The calculation of the absorbed gamma dose rate D (nGy h^{-1}) in the atmosphere at a height of 1 m above the ground surface, considering the uniform dispersion of radionuclides, was conducted through the utilization of the subsequent equation: [19]

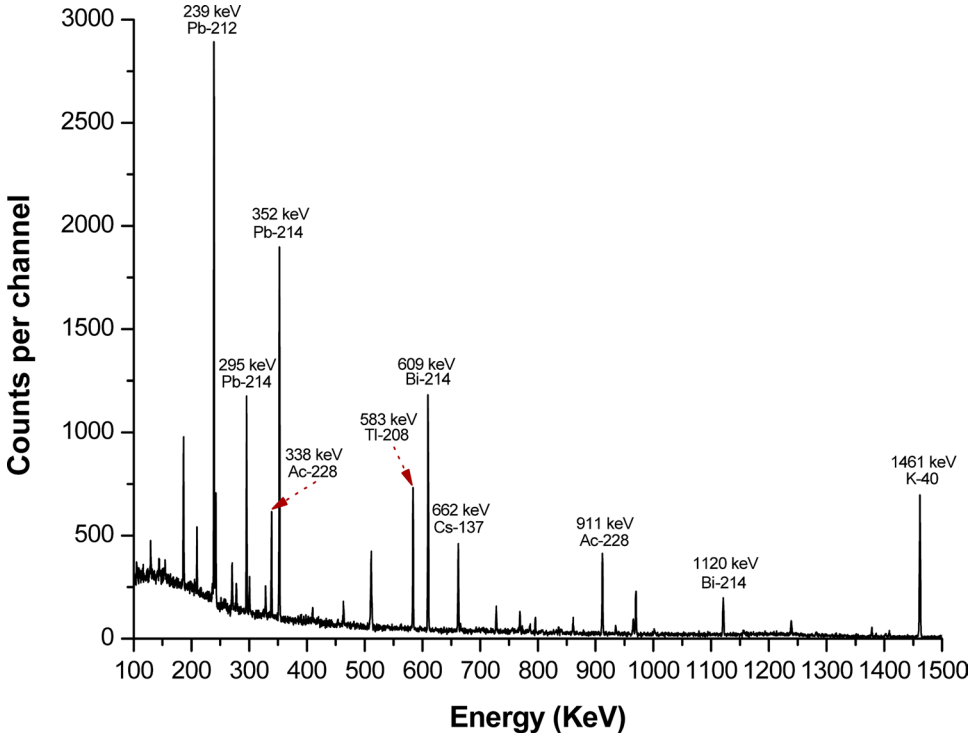

Fig. 3 Gamma-ray spectrum of sample taken from the Derince (sample no K-22) that counted for about 90,000 s

$$D\left(nGyh^{-1}\right) = 0.0417 \times C_K + 0.462 \times CU + 0.604 \times C_{Th} \quad (1)$$

where, D is gamma dose rate ($nGyh^{-1}$), C_K is ^{40}K concentration ($Bqkg^{-1}$), C_U is ^{238}U concentration ($Bqkg^{-1}$), C_{Th} is ^{232}Th concentration ($Bqkg^{-1}$).

AEDE serves as a key parameter in assessing the radiological hazards associated with the absorption of these radiation doses. AEDE was calculated using following equation [19],

$$AEDE(\mu Svy^{-1}) = D \times 0.2 \times 0.7 \times 8760 \times 10^{-3} \quad (2)$$

where, D is Gamma dose rate ($nGyh^{-1}$), 0.2 is outdoor occupancy factor (according to UNSCEAR[19]), 0.7 is conversion factor from D (absorbed dose) in air to effective dose, 8760 is number of hours in 1 year (hy^{-1}), 10^{-3} is nano to micro conversion factor (μn^{-1}).

Due to the uneven distribution of radium, thorium, and potassium in the soil, the true activity levels of ^{238}U, ^{232}Th, and.^{40}K in the samples can be determined using a common radiological index denoted in terms of Ra_{eq}. This index is extensively employed for the evaluation of radiation risks and is expressed by the following equation: [20]

$$Ra_{eq} = C_U + 0.077 \times C_K + 1.43 \times C_{Th} \quad (3)$$

The concept of ELCR pertains to the probability of cancer incidence in a given population resulting from radiation exposure. ELCR were calculated using following equation [21],

$$ELCR = AEDE \times RF \times DL \quad (4)$$

where, AEDE is Annual effective dose rate (μSvy^{-1}), RF is risk factor ($0.05\ sv^{-1}$), DL is duration of life (Aproximation 70 years).

The External Hazard Index (H_{ex}) is a radiological parameter used to assess the potential radiation hazard to individuals from external exposure to gamma radiation emitted by natural radionuclides in the surrounding environment. H_{ex} quantifies the contribution of external gamma radiation exposure to the overall radiation hazard. It takes into account the gamma dose rate in the vicinity of a specific location and helps estimate the potential health risks associated with external radiation exposure.

The Internal Hazard Index (H_{in}) is a radiological index that evaluates the potential radiation hazard arising from the inhalation or ingestion of radioactive materials, particularly those containing uranium and thorium decay products. H_{in} is crucial for assessing the risk of internal radiation exposure due to the presence of radioactive particles in the environment. It considers the radioactive decay of inhaled or ingested materials, which can lead to the irradiation of internal organs and tissues.

The Gamma Representative Level Index ($I_{\gamma r}$) is an indicator used to characterize the typical or average gamma radiation

level within a specific area or region. This index provides insight into the prevailing gamma radiation environment and is instrumental in radiation monitoring and risk assessment. It represents the expected gamma radiation dose from natural radionuclides and helps in determining the level of radiological safety in a given location.

These indices play a crucial role in radiological studies and assessments, aiding researchers and authorities in understanding the potential radiation risks associated with natural radioactivity in a specific area.

H_{ex}, H_{in}, $I_{\gamma r}$ were calculated using following equation respectively [20, 22, 23].

$$H_{ex} = \frac{C_{Th}}{259} + \frac{C_U}{370} + \frac{C_K}{4810} \quad (5)$$

$$H_{in} = \frac{C_{Th}}{259} + \frac{C_U}{185} + \frac{C_K}{4810} \quad (6)$$

$$I_{\gamma r} = \frac{C_{Th}}{100} + \frac{C_U}{150} + \frac{C_K}{1500} \quad (7)$$

Results and discussion

The results of activity concentrations for natural radiation (^{40}K, ^{238}U, and ^{232}Th) as well as the anthropogenic radionuclide (^{137}Cs) in the soil samples are summarized in Table 1. Within the study area, activity concentrations for natural radiation were observed to range from 178 ± 80 to 717 ± 30 Bqkg^{-1} for ^{40}K, from 10.9 ± 0.3 to 39.3 ± 1.0 Bqkg^{-1} for ^{238}U, and from 13.5 ± 0.6 to 43.9 ± 1.9 Bqkg^{-1} for ^{232}Th. As for the anthropogenic radionuclide ^{137}Cs, its activity concentration was found to vary between the minimum detectable activity MDA and 8.6 ± 0.5 Bqkg^{-1}. No decay correction was applied to the results.

Among these, the highest activity concentration of ^{40}K was observed at sampling point K-10 (717 ± 30 Bqkg^{-1}), while the lowest was recorded at K-20 (178 ± 8 Bqkg^{-1}). The mean concentration of ^{40}K across the sampled locations was determined to be 368 ± 22 Bqkg^{-1}.

For ^{238}U, the lowest activity concentration was detected at sampling point K-12 (10.9 ± 0.3 Bqkg^{-1}), while the two sampling points with the highest ^{238}U activity concentrations

Table 1 Activity concentration (^{137}Cs, ^{40}K, ^{238}U, ^{232}Th)

Sample no	^{137}Cs(Bqkg^{-1})	^{40}K(Bqkg^{-1})	^{238}U(Bqkg^{-1})	^{232}Th(Bqkg^{-1})
K-1	0.7 ± 0.2	460 ± 19	33.0 ± 0.9	41 ± 2
K-2	4.0 ± 0.3	444 ± 19	26.9 ± 0.8	34 ± 2
K-3	3.2 ± 0.2	316 ± 13	26.0 ± 0.7	28 ± 2
K-4	1.3 ± 0.2	457 ± 19	29.7 ± 0.8	33 ± 2
K-5	< MDA*	489 ± 21	39.0 ± 1.0	44 ± 2
K-6	0.6 ± 0.2	257 ± 11	24.4 ± 0.7	40 ± 2
K-7	1.2 ± 0.2	295 ± 13	18.8 ± 0.5	29 ± 2
K-8	1.8 ± 0.2	375 ± 16	20.0 ± 0.6	25 ± 2
K-9	4.2 ± 0.3	246 ± 11	13.5 ± 0.4	17 ± 1
K-10	0.9 ± 0.2	717 ± 30	25.2 ± 0.7	26 ± 2
K-11	1.1 ± 0.2	196 ± 90	13.7 ± 0.4	15 ± 1
K-12	5.5 ± 0.3	211 ± 90	10.9 ± 0.3	14 ± 1
K-13	1.8 ± 0.2	482 ± 20	17.0 ± 0.5	23 ± 2
K-14	0.40 ± 0.2	351 ± 15	18.2 ± 0.5	22 ± 2
K-15	7.6 ± 0.4	385 ± 16	20.0 ± 0.6	22 ± 2
K-16	3.7 ± 0.3	469 ± 20	23.5 ± 0.7	26 ± 2
K-17	0.8 ± 0.2	431 ± 18	21.2 ± 0.6	24 ± 2
K-18	< MDA*	239 ± 11	12.4 ± 0.4	15 ± 1
K-19	1.6 ± 0.2	403 ± 17	23.2 ± 0.7	28 ± 2
K-20	1.4 ± 0.2	178 ± 80	18.9 ± 0.6	20 ± 1
K-21	2.6 ± 0.2	300 ± 13	20.1 ± 0.6	24 ± 2
K-22	8.6 ± 0.5	249 ± 11	39.3 ± 1.0	32 ± 2
K-23	< MDA*	259 ± 11	11.6 ± 0.4	15 ± 1
K-24	0.7 ± 0.2	450 ± 19	22.9 ± 0.7	27 ± 2
K-25	< MDA*	520 ± 22	29.4 ± 0.8	36 ± 2
K-26	< MDA*	398 ± 16	22.2 ± 0.6	27 ± 1

*Minimum Detectable Activity (MDA) for ^{137}Cs is 0.35 Bqkg^{-1}

were K-5 (39 ± 1 Bqkg^{-1}) and K-22 (39 ± 1 Bqkg^{-1}). The mean concentration of ^{238}U across the sampled locations was calculated to be 23 ± 2 Bqkg^{-1}.

Among the sampled locations, the highest ^{232}Th activity concentration was found at K-5 (44 ± 2 Bqkg^{-1}), whereas the lowest ^{232}Th activity concentration was observed at K-12 (13.5 ± 0.6 Bqkg^{-1}). The mean concentration of ^{232}Th across the sampled locations was determined to be 26 ± 2 Bqkg^{-1}.

Upon analyzing the soil samples collected from 26 different sampling points in this study, it was observed that the activity concentration of ^{137}Cs, an artificial radionuclide, was below the minimum detectable activity at 4 distinct sampling points. In 14 out of the 26 sampling points, ^{137}Cs activity concentration is less than 2 Bqkg^{-1}. At 4 sampling points, the ^{137}Cs activity concentration was calculated to be between 2 and 4 Bqkg^{-1}, while in 4 of the 26 sampling points, the activity exceeded 4 Bqkg^{-1}. The highest ^{137}Cs activity concentration was recorded at sample point K-22, with a value of 8.6 ± 0.5 Bqkg^{-1}. Following closely, the second highest ^{137}Cs activity concentration was found at sample point K-15, measuring 7.6 ± 0.4 Bqkg^{-1}. The mean ^{137}Cs activity concentration across all sampled points was determined to be 2.4 ± 0.3 Bqkg^{-1}.

The study revealed a wide range of absorbed dose rates, ranging from 21.98 to 64.92 nGyh^{-1}, with a mean value of 41.73 nGyh^{-1}, as illustrated in Fig. 4. Notably, the lowest absorbed gamma dose rate was observed at the K-12 sampling point, while the highest was observed at the K-5 sampling point.

In terms of the AEDE, the minimum value was calculated to be 26.96 μSv y^{-1} at the K-12 sampling point, while the maximum value reached 79.62 μSv y^{-1} at the K-5 sampling point, as depicted in Fig. 5. The overall mean annual

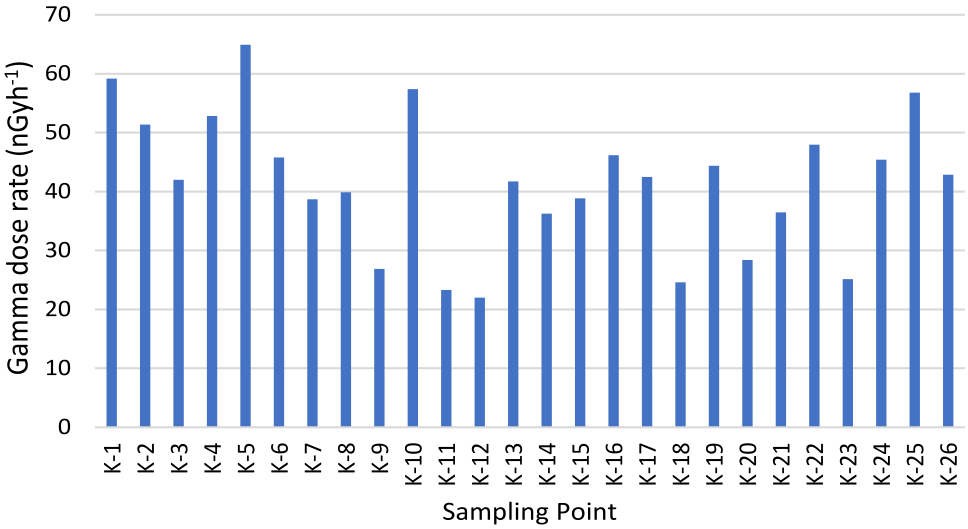

Fig. 4 Absorbed gamma dose rate according to sampling sites

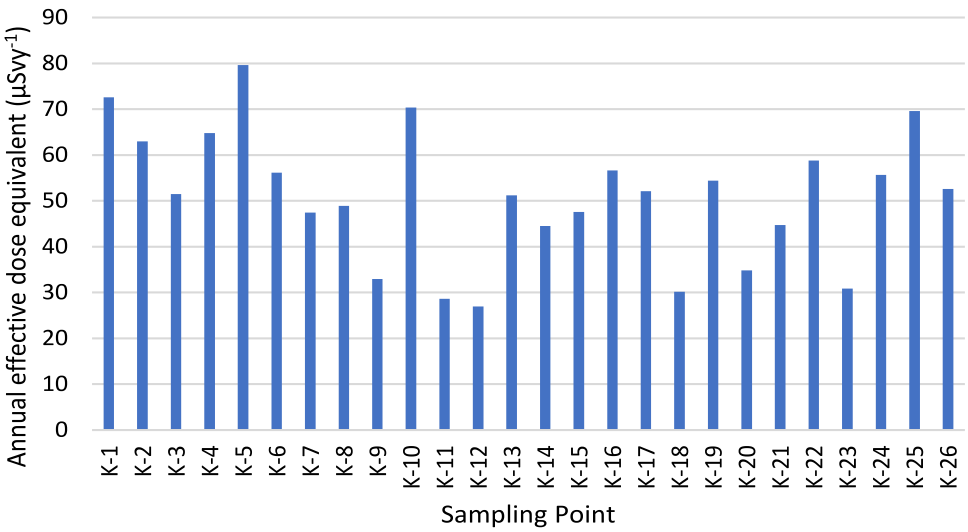

Fig. 5 Annual effective dose equivalent (AEDE) according to sampling sites

effective dose equivalent across all sampling points was determined to be 51.18 μSvy^{-1}.

The mean Ra_{eq} was found to be 88.72 $Bqkg^{-1}$, with the highest observed value being 139.43 $Bqkg^{-1}$, as shown in Fig. 6. Importantly, this maximum value remains below the established safe limit of 370 $Bqkg^{-1}$.

The maximum ELCR was calculated to be 0.28×10^{-3}, with H_{ex}, H_{in}, and $I_{\gamma r}$ presented in Figs. 7, 8, and 9. Conversely, the lowest excess lifetime cancer risk was determined to be 0.09×10^{-3} at the K-12 sampling point. The mean values for excess lifetime cancer risk, H_{ex}, H_{in} and $I_{\gamma r}$ were calculated as 0.18×10^{-3}, 0.24, 0.30, and 0.66, respectively. These comprehensive findings provide a detailed assessment of radiation exposure and associated risks in the studied region, contributing to our understanding of the radiological landscape and its potential implications for public health and safety.

The distribution of natural radionuclides in soil is influenced by various factors, including the geological and geographical characteristics of the region and the extent of fertilizer application in agricultural areas [19, 24]. Activity concentration levels of radionuclides tend to be higher in salt rocks, granite, and phosphorus-rich soils compared to sedimentary rocks [25]. Existing literature suggests that soils with a slips-debris type composition, characterized by abundant raw materials, minerals, lower clay content, and reduced organic matter, tend to exhibit higher average activity concentrations of ^{232}Th, ^{226}Ra, and ^{238}U [25, 26]. The presence of minerals and organic matter in soil samples can be attributed to the elevated activity concentrations of ^{232}Th and ^{226}Ra. Additionally, the use of artificial fertilizers, especially phosphate fertilizers, in agricultural lands to enhance macronutrient levels may contribute to higher activity concentrations of ^{40}K and ^{232}Th [27, 28]. These findings

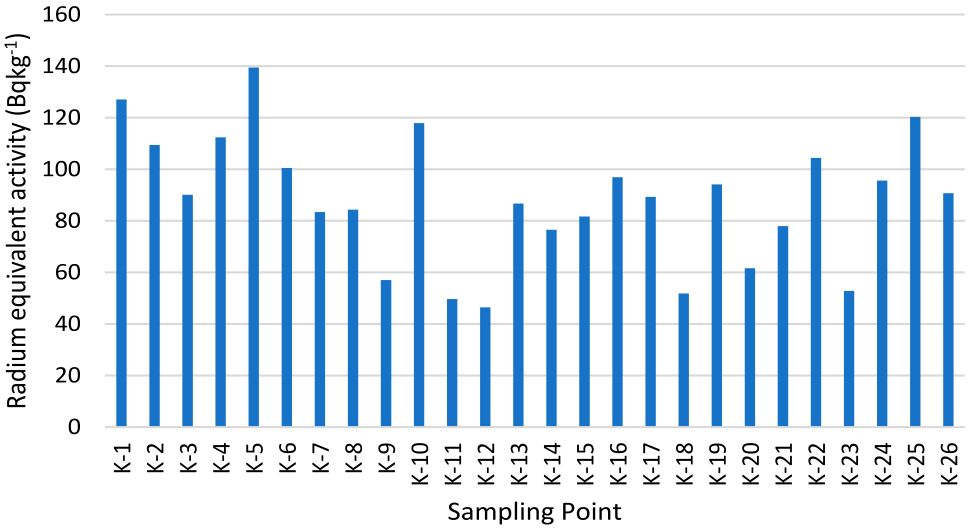

Fig. 6 Radium equivalent activity (Ra_{eq}), according to sampling sites

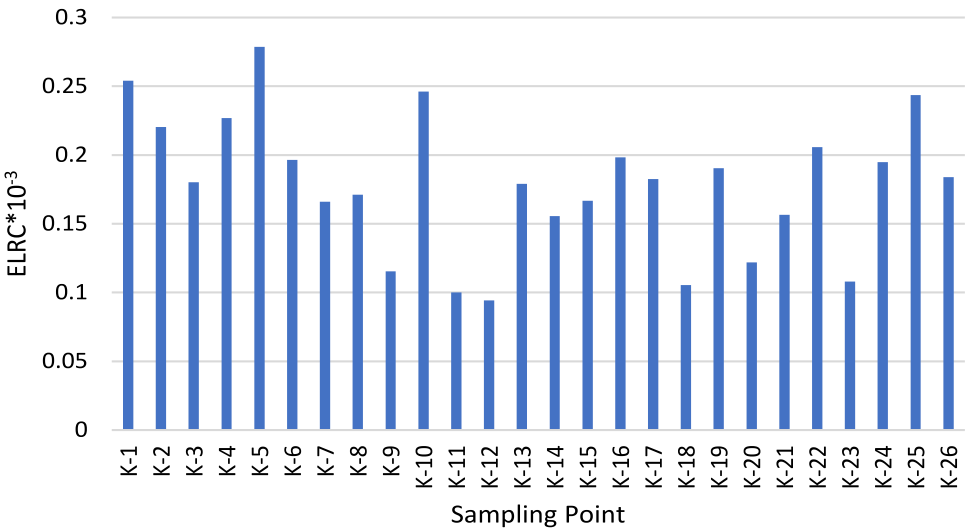

Fig. 7 Excess lifetime cancer risk (ELCR) according to sampling sites

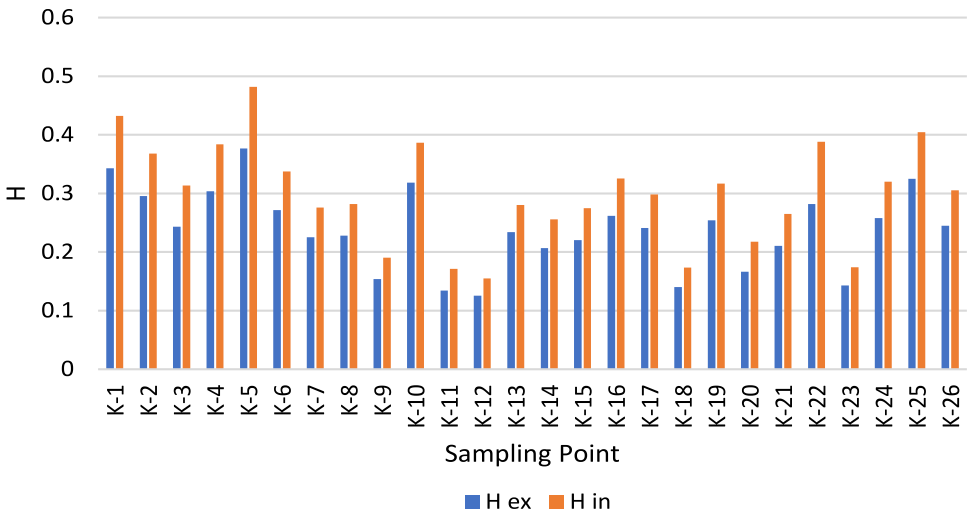

Fig. 8 External hazard index (H_{ex}) and internal hazard index(H_{in}) according to sampling sites

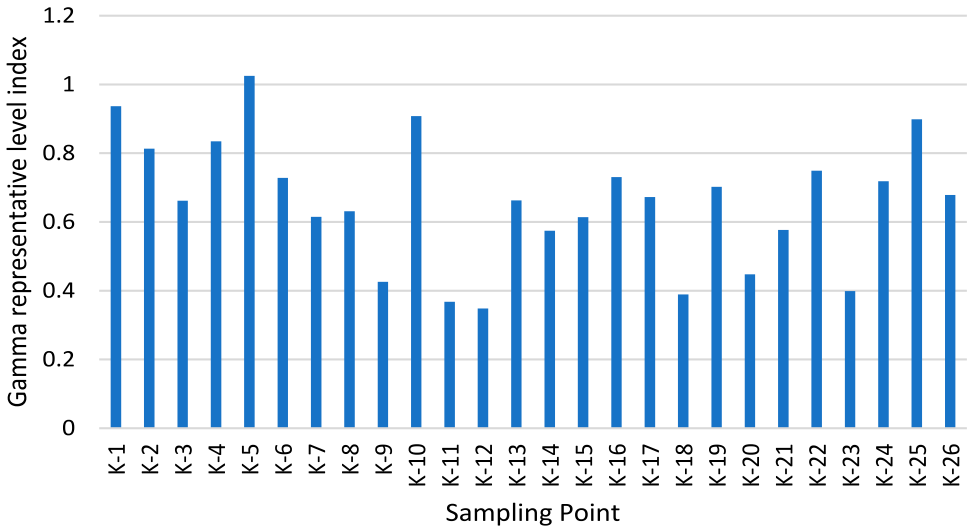

Fig. 9 Gamma representative level index according to sampling sites

underscore the multifaceted nature of natural radionuclide distribution in soil and the various factors that shape it.

The sampling area is one of the most intensive industrial zones in Turkey. There are many factories such as fertilizer, petrochemical, cement, paint and construction materials, iron-steel and paper, and many ports used to transport raw materials to these factories. In addition, Turkey's largest paper mill, SEKA Paper Mill, operated here for 70 years (1955–2005). The trees supplied as raw material for this factory came from the Black Sea coastal regions of Turkey and Russia, which were heavily affected by the Chernobyl accident [10]. For this reason, a high concentration of ^{137}Cs were observed on the shores of the factory, especially in the Gulf of Izmit, where the paper mill's wastewater has been mixed for many years [29]. In addition, a very destructive earthquake (magnitude 7.4) occurred in the region in 1999. Tons of debris were transported and some of it was used as fill material. For example, it is known that the debris from the Seka Paper factory was used as coastal fill on the beaches of Derince and Körfez districts [30]. The relatively high value of Cs-137 concentration in sample K-22 may be caused by the raw materials used in the SEKA paper factory.

There are also two fertilizer factories in the sampling area. The high potassium concentration found in sample K-10 may be the result of local contamination during transportation of raw materials to these factories or temporary storage activities. These results are in agreement with the findings of Ergül et al. in the marine sediments of the Bay of Izmit.

Numerous studies conducted worldwide and Turkey on natural radioactivity have demonstrated significant variations in radioactivity levels (Table 2). The average of activity concentration measurements performed worldwide is 35 $Bqkg^{-1}$, 30 $Bqkg^{-1}$, and 400 $Bqkg^{-1}$ for U, Th and K, respectively [UNSCEAR]. In 1990, four years after the Chernobyl accident, Yeşin and Güray conducted a study on

Table 2 Comparison of natural and artificial radioactivity concentration with soil samples in Turkey and other countries

Location	^{40}K(Bqkg^{-1})	^{238}U(Bqkg^{-1})	^{232}Th(Bqkg^{-1})	^{137}Cs(Bqkg^{-1})	References
Kocaeli / Turkey	161–964	11–49	10–58	2–25	Karakelle 2002 [35]
Kocaeli Bay / Turkey	568	18	24	21	Ergül 2013 [29]
Sakarya / Turkey	371	23.2	21.0	-	Tabar 2017 [36]
İstanbul / Turkey	342	21	37	18	Karahan 2000 [38]
İstanbul / Turkey	620	31	34	-	Günay 2018 [39]
Thrace region / Turkey	1319	43	23	21	Aközcan 2014 [40]
Black Sea coast / Turkey	–	–	–	100- 12,000	Yeşin 1993 [17]
Eastern Black Sea region / Turkey	204–1295	12 to 120	13 to 121	27 to 775	Çelik 2009 [31]
Eastern Black Sea region / Turkey	266–460	11–26	12–33	2–37	Baltaş 2015 [32]
Rize / Turkey	36–914	7–80	10–171	0.6–154	Durusoy [33]
Black Sea Region / Turkey	341–664	25–125	17- 40	2–144	Hafızoğlu 2023[34]
Nortwestern Turkey	363–829	12–44	3–88	–	Özden 2024 [37]
Iğdır / Turkey	437.7	19.1	21.9	11.8	Turhan 2018 [41]
Mersin / Turkey				18.6	Karataşlı 2016 [46]
İstanbul / Turkey				3.3	Günay 2018 [47]
Red Sea / Egypt				0.25–2.3	Harb 2008 [42]
Khrami Massif / Georgia				4–33	Kapanadze 2019 [34]
Mtskheta-Mtianeti region / Georgia				0–53	Kekelidze 2017 [35]
Worldwide Average	400	35	30	–	UNSCEAR [19]
Kocaeli /Turkey	178–717	10.9–39.3	14–44	MDA-8.6	This Study

the eastern side of the Black Sea coast and measured ^{137}Cs concentrations ranging from 100 to 12,000 Bqkg^{-1} in a total of 147 samples [17]. Recent studies have measured not only the artificial radioactive isotope ^{137}Cs, but also natural radioactive isotopes. In a 2009 study conducted by Çelik et al. in the Eastern Black Sea region, activity concentrations of ^{238}U ranged from 12 to 120 Bq kg^{-1}, ^{232}Th ranged from 13 to 121 Bq kg^{-1}, ^{40}K ranged from 204 to 1295 Bqkg^{-1}, and ^{137}Cs ranged from 27 to 775 Bq kg^{-1}[31]. In 2015, Baltaş et al. determined the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in marine sediment samples in the eastern Black Sea region. The measured activity concentrations ranged between 10.94–25.95, 12.14–33.05, 265.74–459.89, and 2.08–37.45 Bq kg^{-1} for ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs, respectively [32]. Durusoy and Yıldırım measured the concentrations of natural and artificial radioactivity in surface soils in the city of Rize, located in the eastern Black Sea. The activity concentrations in the soil samples varied from 7.4–79.8 Bq kg^{-1} for ^{238}U, 9.5–170.8 Bq kg^{-1} for ^{232}Th, 35.7–913.8 Bq kg^{-1} for ^{40}K, and 0.6–154.3 Bq kg^{-1} for ^{137}Cs [33]. In 2023, Hafızoğlu conducted a study in the Black Sea region of Turkey to measure the concentrations of natural and anthropogenic radioactivity in tea, plant, and soil samples. The study used a high-resolution HPGe gamma ray detector to measure the concentrations of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs. The activity concentrations measured in the soils ranged from 25 ± 1 to 125 ± 14 Bq kg^{-1} for the ^{238}U nuclide, from 18 ± 1 to 49 ± 6 Bq kg^{-1} for the ^{232}Th nuclide, 341 ± 9 to 664 ± 13 Bq kg^{-1} for the ^{40}K nuclide, and 2.1 ± 0.8 to 144 ± 2 Bq kg^{-1} for the anthropogenic ^{137}Cs radionuclide. Even 35 years after the Chernobyl accident, there are still residues of ^{137}Cs in the region of the eastern Black Sea [34].

The consequences of the accident at the Chernobyl nuclear power plant were not limited to the eastern Black Sea region of Turkey; the region of Thrace and Marmara were also affected. Ergül et al. (2013) conducted a study on surface sediments from the northeastern shores of the Marmara Sea, which is the closest study to the region we examined. The study reported an average activity concentration of 21 Bq kg^{-1} for ^{137}Cs, and 568 Bq kg^{-1}, 18 Bq kg^{-1}, and 24 Bq kg^{-1} for naturally occurring radioisotopes ^{40}K, ^{226}Ra, and ^{228}Ra, respectively, in surface sediments. It was concluded that natural radionuclide activities were highest in the vicinity of petrochemical, phosphate, and fertilizer processing plants in the region. On average, ^{137}Cs activities were generally up to ten times higher than in Middle Eastern marine sediments and lower than in Northern European sediments [29]. Notably, in a study conducted by Karakelle and colleagues within the same region as our study but in different districts in 2002, ^{137}Cs levels were found to vary between 2 and 25 Bqkg^{-1} [35]. In contrast, our study reports ^{137}Cs activity levels ranging from MDA to 8.56 Bqkg^{-1}, with an average of 2.44 Bqkg^{-1}. The decrease in ^{137}Cs radioactivity levels from 2002 to the present can be attributed to the approximately 30-year decay period of ^{137}Cs.

Tabar et al. conducted an assessment of environmental radioactivity levels in soil samples from Sakarya province to create a comprehensive radiological map of Sakarya, the eastern neighbor of Kocaeli. A NaI(Tl) gamma-ray spectrometer was used to analyze 85 soil samples collected from various locations throughout the city. The activity concentrations of the natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K were measured to be 23.2 ± 2.5, 21.0 ± 3.4, and 371 ± 25.9 Bq/kg^{-1}, respectively [36].

Özden (2024) conducted a study to measure the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in surface soil samples collected from northwestern Turkey using an HPGe gamma-spectroscopy system. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soils ranged from 12–44, 3–88, and 363–829 Bqkg^{-1}, respectively [37].

Closer to our study area, two separate studies conducted in Istanbul reported ^{238}U activity concentrations of 21 and 31 Bqkg^{-1} and for ^{232}Th activity concentrations of 34 and 37 Bqkg^{-1} [38, 39]. In Turkey, specifically in the Thrace region, another study found the ^{40}K activity concentration to be 1319 Bqkg^{-1} [40].

Turhan et al. measured the average activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in soil samples collected in Igdir province, located in the Eastern Anatolian region of Turkey on the border with Armenia and 20 km away from the Metsamor nuclear power plant. In this study, the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs were found to be 19.1 ± 0.6 Bq kg^{-1}, 21.9 ± 0.6 Bq kg^{-1}, 437.7 ± 10.3 Bq kg^{-1} and 11.8 ± 1.1 Bq kg^{-1} respectively [41].

On a global scale, studies investigating artificial radioactivity, particularly ^{137}Cs, have revealed varying levels in different countries, as depicted in Table 2. In studies conducted in Egypt, ^{137}Cs activity levels ranged from 0.25 to 2.3 Bqkg^{-1} [42], whereas in Georgia, one study reported values between 4 and 33 Bqkg^{-1} [43], and another study indicated a range of 0 to 53 Bqkg^{-1} [44].

Conclusion

In this study, the concentrations of natural and artificial radioactivity in soil samples from the districts of Darıca, Gebze, Dilovası, Körfez, and Derince within Kocaeli province in the Marmara region were determined, and several radiological parameters were calculated. Taking into consideration the land area and population density of these districts, soil samples were collected from 26 different locations and analyzed using HPGe gamma spectrometry to measure the concentrations of ^{238}U, ^{232}Th, ^{40}K, and ^{137}Cs radioactivity. The average concentrations were found to be 22.35 Bqkg^{-1} for ^{238}U, 26.36 Bqkg^{-1}for ^{232}Th, 368.34 Bqkg^{-1}for ^{40}K, and 2.44 Bqkg^{-1}for ^{137}Cs. Additionally, the study revealed an absorbed dose rate of 41.73 nGyh^{-1}, an annual effective dose equivalent of 51.18 μSv y^{-1}, and a mean radium equivalent activity of 88.72 Bqkg^{-1}, which was well below the safe limit value of 370 Bqkg^{-1}. The excess lifetime cancer risk was determined to be 0.00018. Moreover, the mean H_{ex}, H_{in}, and gamma representative level indices were found to be 0.24, 0.30, and 0.66, respectively. The study indicates that the average natural radioactivity levels in the region are lower than the global average. This research provides valuable insights into the levels of natural and artificial radioactivity in Kocaeli and its districts, and the obtained results will remain relevant until a potential nuclear (e.g., Zaporijya) leakage event occurs.

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Declarations

Conflict of interest The author declare that they have no confict of interest.

References

1. Ribeiro FC, Silva JI, Lima ES, do Amaral-Sobrinho NM, Perez DV, Lauria DC (2018) Natural radioactivity in soils of the state of Rio de Janeiro (Brazil): Radiological characterization and relationships to geological formation, soil types and soil properties. J Environ Radioact 182:34–43
2. Hannan MA, Nguyen N, Rivas M (2013) Natural radioactivity and its gamma dose rate in Mission (Texas) soils. J Radioanal Nucl Chem 295:729–736. https://doi.org/10.1007/s10967-012-1840-9
3. Bouhila G, Benrachi F (2017) Radioactivity investigation of sediment samples from BeniHaroun dam using high-resolution gamma-ray spectroscopy. Acta Phys Pol A 132(3II):889–891. https://doi.org/10.12693/APhysPolA.132.889
4. Aközcan S, Külahcı F, Mercan Y (2018) A suggestion to radiological hazards characterization of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs: spatial distribution modelling. J Hazard Mater 353:476–489

5. Aközcan S, Külahcı F, Günay O, Özden S (2021) Radiological risk from activity concentrations of natural radionuclides: cumulative hazard index. J Radioanal Nucl Chem 327(1):105–122
6. Külahcı F, Aközcan S, Günay O (2020) Monte Carlo simulations and forecasting of Radium-226, Thorium-232, and Potassium-40 radioactivity concentrations. J Radioanal Nucl Chem 324(1):55–70
7. Günay O, Eke C (2019) Determination of terrestrial radiation level and radiological parameters of soil samples from Sariyer-Istanbul in Turkey. Arab J Geosci 12(20):1–10
8. Arnedo MA, Rubiano JG, Alonso H, Tejera A, González A, González J, Bolivar JP (2017) Mapping natural radioactivity of soils in the eastern Canary Islands. J Environ Radioact 166:242–258. https://doi.org/10.1016/j.jenvrad.2016.07.010
9. Öksüz İ, Güray, RT, Özkan N, Yalçın C, Ergül HA, Aksan S (2016) Measurement of natural and 137Cs radioactivity concentrations at Izmit Bay (Marmara Sea), Turkey. In: *AIP Conference Proceedings* (Vol. 1722, No. 1). AIP Publishing.
10. Turkish Atomic Energy Authority (TAEA) Çernobil Serisi No 6, 20. Yılında Çernobil, Türkiye'de Çernobil Sonrası Radyasyon ve Radyoaktivite Ölçümleri, Ankara, (2006)
11. Zhidkin AP, Shamshurina EN, Golosov VN, Komissarov MA, Ivanova NN, Ivanov MM (2020) Detailed study of post-Chernobyl 137Cs redistribution in the soils of a small agricultural catchment (Tula region, Russia). J Environ Radioact 223:106386
12. Oolbekkink GT, Kuyper TW (1989) Radioactive caesium from Chernobyl in fungi. Mycologist 3(1):3–6
13. Panin AV, Walling DE, Golosov VN (2001) The role of soil erosion and fluvial processes in the post-fallout redistribution of Chernobyl-derived caesium-137: a case study of the Lapki catchment. Central Russia Geomorphol 40(3–4):185–204
14. Spezzano P (2005) Distribution of pre-and post-Chernobyl radiocaesium with particle size fractions of soils. J Environ Radioact 83(2):117–127
15. Schimmack W, Bunzl K, Zelles L (1989) Initial rates of migration of radionuclides from the Chernobyl fallout in undisturbed soils. Geoderma 44(2–3):211–218
16. Andersson KG, Roed J (1994) The behaviour of Chernobyl 137Cs, 134Cs and 106Ru in undisturbed soil: implications for external radiation. J Environ Radioact 22(3):183–196
17. Yeşin T, Güray RT (1993) Caesium-137 levels in surface soils over the black sea coast of Turkey. Turk J Eng Environ Sci 17:213
18. Duran S, Güray RT, Yalçın C, Özkan N (2007) A Recent Study on 137Cs Activities in Surface Soils over the Eastern Part of the Black Sea Coast of Turkey. In: *AIP Conference Proceedings* (Vol. 899, No. 1, pp. 731–731). American Institute of Physics.
19. UNSCEAR (2000) United nations scientific committee on the effects of atomic radiation, sources and biological effects of ionizing radiation. United Nations, New York
20. Beretka JJ, Mathew P (1985) Natural radioactivity of Australian building materials, industrial wastes and by products. J Health Physics 48:87–95
21. Ravisankar R, Sivakumar S, Chandrasekaran A, Prince P, Jebakumar J, Vijayalakshmi I, Vijayagopal P, Venkatraman B (2014) Spatial distribution of gamma radioactivity level sand radiological hazard indices in the East Coastal sediments of Tamilnadu, India with statistical approach. Radiat Phys Chem 103:89
22. Taskin H, Karavus M, Ay P, Topuzoglu A, Hindiroglu S, Karahan G (2009) Radionuclide concentrations in soil and lifetime cancer risk due to the gamma radioactivity in Kirklareli, Turkey. J Environ Radioact 100:49–53
23. ICRP (1990) Recommendations of the International Commission on Radiological Protection. Ann ICRP 21(1–3):publication 60
24. Najam LA, Younis SA, Kithah FH (2015) Natural radioactivity in soil samples in Nineveh Province and the associated radiation hazards. Int J Phys 3:126–132
25. Kayakökü H, Doğru M (2017) Radioactivity analysis of soil samples taken from the western and northern shores of Lake Van, Turkiye. Appl Radiat Isot 128:231–236
26. Thu HNP, Van Thang N, Loan TTH, Van Dong N (2019) Natural radioactivity and radon emanation coefficient in the soil of Ninh Son region. Vietnam Appl Geochem 104:176–183
27. Alajeeli A, Elmahroug Y, Mohammed S, Trabelsi A (2019) Determination of natural radioactivity and radiological hazards in soil samples: Alhadba and Abuscabh agriculture projects in Libya. Environ Earth Sci 78(6):194
28. da Conceição FT, Bonotto DM, Jiménez-Rueda JR, Roveda JAF (2009) Distribution of 226Ra, 232Th and 40K in soils and sugar cane crops at Corumbataí river basin, São Paulo State. Brazil Appl Radiat Isotopes 67(6):1114–1120
29. Ergül HA, Belivermiş M, Kılıç Ö, Topcuoğlu S, Çotuk Y (2013). Natural and artificial radionuclide activity concentrations in surface sediments of Izmit Bay, Turkey. Journal of environmental radioactivity, 126, 125–132.https://doi.org/10.1016/j.jenvrad.2013.07.015.
30. Project Report, 2018, "Reuse of Industrial Areas: The Case of Kocaeli-SEKA Factory in terms of Spatial, Ecological, Social Transformations and Heritage Production", KODA (Kocaeli Solidarity Academy), History Foundation and Heinrich Böll Stiftung (HBS). https://www.izmitteseka.com
31. Celik N, Cevik U, Celik A, Koz B (2009) Natural and artificial radioactivity measurements in Eastern Black Sea region of Turkey. J Hazard Mater 162(1):146–153. https://doi.org/10.1016/j.jhazmat.2008.05.017
32. Baltas H, Sirin M, Dalgic G, Cevik U (2018) An overview of the ecological half-life of the 137Cs radioisotope and a determination of radioactivity levels in sediment samples after Chernobyl in the Eastern Black Sea, Turkey. J Mar Syst 177:21–27. https://doi.org/10.1016/j.jmarsys.2017.09.005
33. Durusoy A, Yildirim M (2017) Determination of radioactivity concentrations in soil samples and dose assessment for Rize Province. Turkey, J Radiat Res Appl Sci 10(4):348–352. https://doi.org/10.1016/j.jrras.2017.09.005
34. Hafızoğlu N (2023) Radioactivity transfer factors and distribution of the natural and anthropogenic radionuclides in tea, plant and soil samples from the Black Sea Region in Turkey. Eur Phys J Plus 138:353
35. Karakelle B, Öztürk N, Köse A, Varinlioğbrevelu A, Erkol AY, Yilmaz F (2002) Natural radioactivity in soil samples of Kocaeli basin, Turkey. J Radioanal Nucl Chem 254(3):649–651
36. Tabar E, Yakut H, Saç MM, Taşköprü C, İçhedef M, Kuş A (2017) Natural radioactivity levels and related risk assessment in soil samples from Sakarya, Turkey. J Radioanal Nucl Chem 313:249–259. https://doi.org/10.1007/s10967-017-5266-2
37. Özden S (2024) Radioactivity of ^{226}Ra, ^{232}Th and ^{40}K in soil in Northwest part of Turkey: assessment of radiological impacts. Radiochim Acta 112(2):117–126. https://doi.org/10.1515/ract-2023-0219
38. Karahan G, Bayulken A (2000) Assessment of gamma dose rates around Istanbul (Turkey). J Environ Radioact 47(2):213–221
39. Günay O (2018) Assessment of lifetime cancer risk from natural radioactivity levels in Kadikoy and Uskudar District of Istanbul. Arab J Geosci 11(24):1–6
40. Aközcan S, Yılmaz M, Külahcı F (2014) Dose rate and seasonal variations of ^{238}U,^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs radionuclides in soils along Thrace, Turkey. J Radioanal Nucl Chem 299:95–101. https://doi.org/10.1007/s10967-013-2730-5
41. Turhan Ş, Gören E, Uğur FA, Karataşlı M, Yeğingil Z (2018) Study of the radioactivity in environmental soil samples from

Eastern Anatolia Region of Turkey. Radiochim Acta 106(2):161–168. https://doi.org/10.1515/ract-2017-2845
42. Harb S (2008) Natural radioactivity and external gamma radiation exposure at the coastal Red Seain Egypt. Radiat Prot Dosimetry 130:376–384
43. Kapanadze K, Magalashvili A, Imnadze P (2019) Distribution of natural radionuclides in the soils and assessment of radiation hazards in the Khrami Late Variscan crystal massif (Georgia). Heliyon 5(3):e01377. https://doi.org/10.1016/j.heliyon.2019.e01377
44. Kekelidze N, Jakhutashvili T, Tutberidze B, Tulashvili E, Akhalkatsishvili M, Mtsariashvili L (2017) Radioactivity of soils in Mtskheta-Mtianeti region (Georgia). Ann Agrar Sci 15(3):304–311
45. Montes M, Mercader R, Taylor M, Runco J, Imbellone P, Rivas P, Desimoni J (2011) Radiological and hyperfne characterization of soils from the Northeastern region of the Province of Buenos Aires. Argentina Hyperfne Interact 202(1–3):5–16
46. Karataslı M, Turhan S, Varinlioglu A, Yegingil Z (2016) Natural and fallout radioactivity levels and radiation hazard evaluation in soil samples. Environ Earth Sci 75:424. https://doi.org/10.1007/s12665-016-5414-y
47. Günay O, Aközcan S (2018) İstanbul Boğazı'nda ^{137}Cs Konsantrasyonun Belirlenmesi. Avrupa Bilim ve Teknoloji Dergisi 14(2018):54–60