Natural and Artificial Radioactivity Concentrations and Health Risks due to Radionuclides in the Soil of Nevşehir (Cappadocia)

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Abstract: - Natural and artificial radionuclides in the surface soil samples collected from the Nevşehir (Cappadocia) region were analyzed using gamma spectrometry employing an HPGe detector. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K range from 58.31 to 77.40 Bq kg^{-1}, 60.56 to 90.97 Bq kg^{-1}, and 796.42 to 1142.8 Bq kg^{-1}, respectively. The values indicate that the activity concentrations of the natural radionuclides in the soil samples were higher than the world average. Since Turkey is a country greatly affected by the Chernobyl accident, ^{137}Cs activity concentration was measured to determine whether its effect continues. The activity concentration of ^{137}Cs ranges from Minimum Detectable Activity (MDA) to 6.88 Bq kg^{-1}. In addition, the radium equivalent activity, the absorbed dose rate, the annual effective dose equivalent, and the excess lifetime cancer risk parameters were calculated to determine the radiological effect of natural and artificial radionuclides on the population in the study area. All values except the radium equivalent activity were found to be above the world average.

Key-Words: - Radionuclide, Soil, Radioactivity, Gamma spectrometry, Health risks, Pollution

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1 Introduction

The main known source of natural radiation is from radionuclides in the soil to which humans are constantly exposed [1]. Concentrations of natural radionuclides vary depending on geological and geographic features [2, 3]. Terrestrial radionuclides are dispersed throughout the Earth's crust. Outdoor exposures from terrestrial radiation sources mainly originate from the top layer of the soil [3].

The main natural radioactive isotopes ^{238}U, and ^{232}Th, and their decay products, and ^{40}K produce significant outdoor exposure [4, 5]. Natural radionuclides naturally expose humans to radiation. However, agricultural practices such as fertilization processes and agrochemical inputs applied to increase productivity contribute to the increase in the radioactivity content of the soil [4]. In addition, radionuclides in phosphate rocks can increase radioactivity due to phosphogypsum used in building construction [6]. The distribution of natural radionuclides in soil depends on the distribution of radionuclides in rocks. Higher radiation levels are generally seen in areas with igneous rocks and lower levels in areas with sedimentary rocks [7].

People are exposed to artificial radiation due to reasons such as nuclear weapons tests and reactor accidents. ^{137}Cs is one of the fallout radionuclides (FRNs) that should be examined due to its half-life ($t_{1/2}$=30.2 years) [8]. As a result of the Chernobyl accident, Turkey is one of the countries exposed to artificial radionuclide pollution [9]. Determining the radioactivity in the soil and assessing the long-term exposure to humans is an important step in taking precautions. Natural and artificial radionuclides threaten food safety and harm human health by transferring from soil to plant [4, 10]. There are studies on these subjects in the literature in different regions of the world [11-16]. However, since radionuclide concentrations differ from region to region, radionuclide activity concentration and radiological parameters should be evaluated separately for each region. The behavior of artificial radionuclides depends on their chemical form in the fallout and environmental properties [17]. In addition to natural radiation, the identification of artificial radionuclides by Gamma measurements is an important factor in predicting the fate of current and future nuclear fallout.

In this study, concentrations of the natural radionuclides and ^{137}C associated with the Chernobyl accident in soil were determined for soil samples (0-8 cm) collected from Nevşehir (Cappadocia), Turkey.

Radiological parameters were calculated to estimate the impact of these health-threatening radionuclides to which humans are exposed.

2 Materials and Methods

2.1 Sampling and Activity Analysis

Nevşehir (Cappadocia) region was preferred as the study area as it is one of the most touristic and important regions of Turkey. Nevşehir province is located at 38° 37' north latitude and 34° 42' east longitude. It was formed as a result of the eruption of Cappadocia, Erciyes, Hasandağ and Güllüdağ volcanoes [18, 19].

Various flint and siliceous layers are concentrated in places close to Mount Erciyes. Nevşehir soil consists of volcanic tuffs. There are metamorphic, volcanic, and sedimentary rocks in Nevşehir province [20].

Soil samples were collected randomly from the Nevşehir (Cappadocia) region (Fig. 1). The samples were dried at 105 °C for approximately 2 days to lose moisture. Before gamma spectrometry analysis, 250 g soil samples were placed in containers for more than 30 days to allow ^{226}Ra and daughter products to reach equilibrium [21].

Gamma spectra were obtained using Maestro and and GammaVision software program. Gamma-ray spectrometry measurements were performed with a p−type HPGe detector. A soil-mixed source (Isotope Product Laboratories) was used as a reference material for calibration. Each sample was counted for at least a day. The gamma-ray peak energies and daughter radionuclides used for measurements are listed in Table 1.

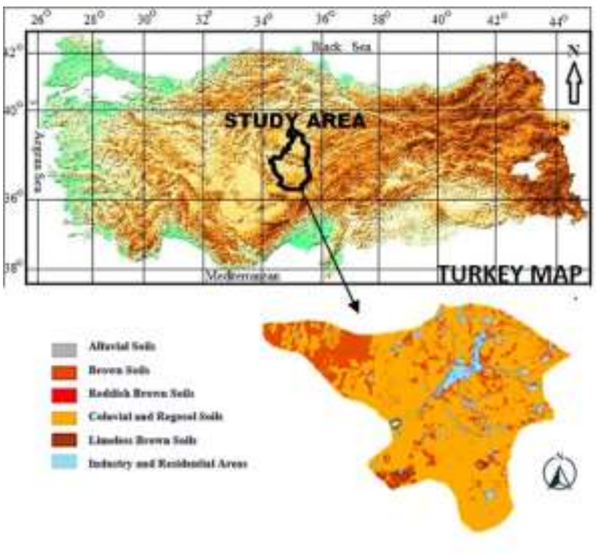

Fig. 1: Study area (Nevşehir, Cappadocia Region, Turkey)

Table 1. The gamma-ray peak energies and daughter radionuclides used for the measurement

Radionuclide	Daughter nuclide	ɤ-ray energies (keV)
^{226}Ra	^{214}Pb	351.9
	^{214}Bi	609.3
^{232}Th	^{228}Ac	911.2
	^{208}Tl	583.1
^{40}K	-	1460.8
^{137}Cs	-	661.66

The activity concentrations (A) were calculated in Bq kg^{-1} by the following equation:

$$A = \frac{C}{\varepsilon x I_\gamma x m} \quad (1)$$

In equation C, m, ε, Iγ, are the net gamma counting rate, the sample mass (kg), the detector efficiency, and the gamma-ray emission probability, respectively.

2.2 Radiological Hazards

Radiological parameters were investigated to the dose rates received by people living in the Nevşehir (Cappadocia) region and to estimate the radiological hazard. The radium equivalent activity (Ra_{eq}) (Bq kg^{-1}), the absorbed dose rate (D) (nGy h^{-1}), the annual effective dose equivalent (AEDE) (μSv y^{-1}) and the excess lifetime cancer risk (ELCR) were calculated using the following equations:

$$\mathrm{Ra_{eq}} = \mathrm{A_{Ra}} + 1.43\mathrm{A_{Th}} + 0.077\mathrm{A_K} \quad (2)$$

$$\mathrm{D} = 0.462\mathrm{A_{Ra}} + 0.604\mathrm{A_{Th}} + 0.0417\mathrm{A_K} + 0.03A_{Cs} \quad (3)$$

$$\mathrm{AEDE} = \mathrm{D}\ (\mathrm{nGy\,h^{-1}}) \times 8760\ (\mathrm{h\,y^{-1}}) \times 0.2 \times 0.7\ (\mathrm{SvGy^{-1}}) \times 10^{-3} \quad (4)$$

$$\mathrm{ELCR} = \mathrm{AEDExDLxRF} \quad (5)$$

where A_{Ra}, A_{Th}, and A_K are the activities of ^{226}Ra, ^{232}Th, and ^{40}K, respectively. RF is the risk factor (0.057) and DL is the average lifetime duration (70 years).

3 Results and Discussion

^{226}Ra and ^{232}Th activity concentrations are shown in Fig. 2. The average ^{226}Ra activity concentration was found to be 66.99 Bq kg^{-1}. ^{226}Ra activity concentration varies between 58.31 and 77.40 Bq kg^{-1}. All ^{226}Ra activity concentrations found for soil samples were higher than the world average value of 35 Bq kg^{-1} [22]. The average ^{232}Th activity concentration was found to be 72.54 Bq kg^{-1}. ^{232}Th activity concentration varies between 60.56 and 90.97 Bq kg^{-1}. The average ^{232}Th activity concentration and ^{232}Th activity concentration values were higher than the world average value of 30 Bq kg^{-1} [22]. ^{226}Ra and ^{232}Th activity concentrations were observed in almost the same value range, which represents the similarities in the geological features. The correlation of ^{232}Th and ^{226}Ra is applied to evaluate the maintenance of proportionality within the ^{238}U decay series [23]. A significant positive correlation (R = 0.82, R^2=0.67) was obtained between ^{226}Ra and ^{232}Th (Fig. 3).

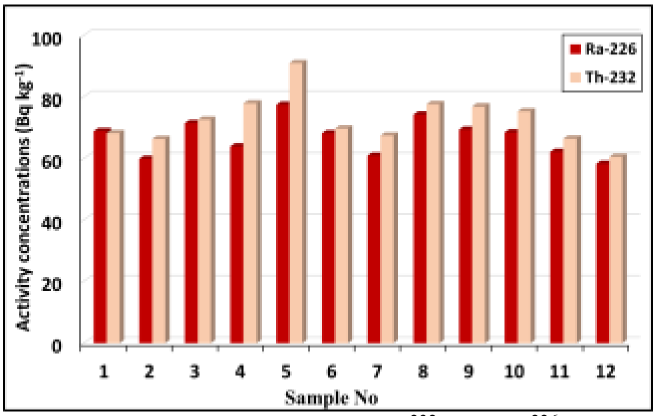

Fig. 2: Activity concentrations of ^{232}Th and ^{226}Ra in Nevşehir (Cappadocia) Region

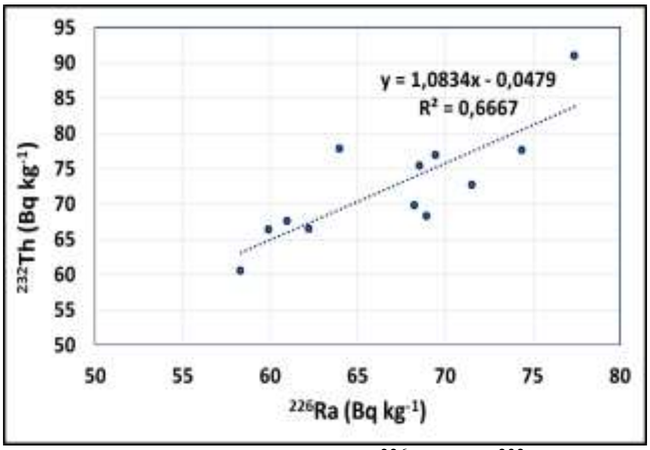

Fig. 3: The correlation between ^{226}Ra and ^{232}Th

The ^{40}K activity concentration values are shown in Fig. 4. The highest activity concentration was found to be 1142.8 Bq kg^{-1} and the lowest activity concentration was 796.42 Bq kg^{-1}. The average ^{40}K activity concentration was found to be 966.65 Bq kg^{-1}. All calculated ^{40}K activity concentration values are higher than the world average (400 Bq kg^{-1}) [22]. The geological structure of the studied region consists of volcanic rocks, which are especially rich in natural radionuclides [24]. The high concentration of ^{40}K activity in the region is due to the high presence of this radionuclide in volcanic rocks [25]. The use of inorganic fertilizers also increases the activity [4, 26]. It is estimated that lower radionuclide concentrations were sampled from regions with sedimentary rocks [27].

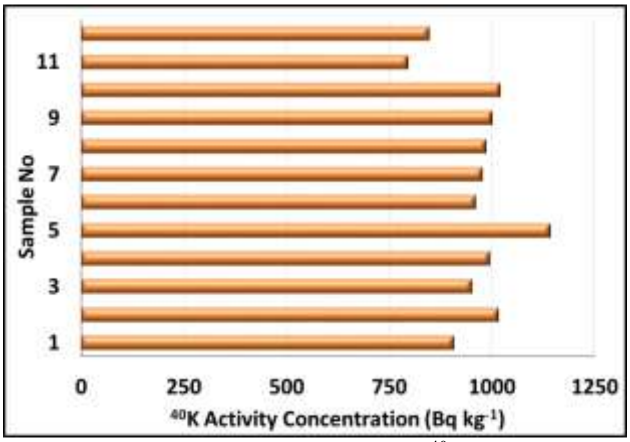

Fig. 4: Activity concentrations of ^{40}K in Nevşehir (Cappadocia) Region

In addition to natural radionuclides, artificial radionuclide analysis was also performed for the studied region. ^{137}Cs artificial radionuclide varies between MDA and 6.88 Bq kg^{-1} (Fig. 5). The distribution of ^{137}Cs depends on regional topography and meteorological factors. The fact that the ^{137}Cs radionuclide is in a certain range is due to the small size of the study area and the topography does not change significantly in the region. High levels of ^{137}Cs may depend on the following features: migration, soil organic matter substance, and soil texture [25].

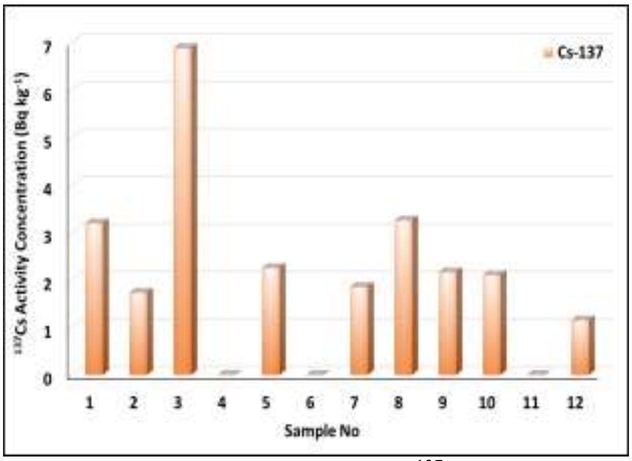

Fig. 5: Activity concentrations of ^{137}Cs in Nevşehir (Cappadocia) Region

In a study performed in Nevşehir, the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were found to be in the range of 7.40–193.90, <2.8–122.50, 37.67–1370.20, and 0.10–52.60 Bq kg^{-1}, respectively [28]. In this study, the activity concentration in most soil samples was found to be higher than in the study conducted in 2020. In Küçük Menderes Basin-Turkey, the activity concentrations were found to be in the range of 12.63 – 72.51 (^{26}Ra), 11.45 –58.12 (^{232}Th), 234.8 – 1058.52 (^{40}K), 2.31 – 7.75 (^{137}Cs) Bq kg^{-1} [29]. In Bolu-Turkey, the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in soil samples were found to be 3.8–49.9, 4.1–37.9, 64.6–518.9, and 0.6–43.6 Bq kg^{-1}, respectively [30]. In a study performed in Ankara-Turkey, the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were determined as in the range of 6–186, 2–181, 23–1355, 0.5–20.9 Bq kg^{-1}, respectively [31]. The activity concentrations in this study are almost in the same range as those obtained in Küçük Menderes Basin, Ankara, and Bolu. The highest values of ^{226}Ra and ^{232}Th activity concentrations in this study are higher than the highest values obtained in Bolu and Küçük Menderes Basin. The highest ^{40}K activity concentration in this study is lower than the highest ^{40}K activity concentration calculated for the soil samples in Ankara.

The activity concentrations of ^{226}Ra in this study were found to be higher than the study performed in Yerevan-Armenia (0.02-18.20 Bq kg^{-1}), Toplica-South Serbia (3.3-48.2 Bq kg^{-1}), India (14.59-50.49 Bq kg^{-1}), Gorgan Region-Iran (10.59-29.54 Bq kg^{-1}) and Lahore-Pakistan (24.73-28.17 Bq kg^{-1}) [32-36]. ^{232}Th activity concentrations in this study were found higher than in Yerevan-Armenia (0.02-58.19 Bq kg^{-1}), Gorgan Region-Iran (11.16-43.19 Bq kg^{-1}), Toplica-South Serbia (0.9-58.9 Bq kg^{-1}) and Lahore-Pakistan (45.46-52.61 Bq kg^{-1}) [32-33, 35-36]. The highest ^{232}Th activity concentration in this study was found lower than the ^{232}Th activity concentration in India (116.12 Bq kg^{-1}) and Ethiopia (167 Bq kg^{-1}) [34, 37]. The activity concentrations of ^{40}K in this study were found to be higher than the study determined in Yerevan-Armenia (0.35-374.80 Bq kg^{-1}), Gorgan Region-Iran (261.69-562.88 Bq kg^{-1}), Lahore-Pakistan (524.84-601.62 Bq kg^{-1}), and Ethiopia (94-540 Bq kg^{-1}) [32, 35-37]. The highest activity concentration of ^{40}K in the present study was found lower than the ^{40}K activity concentration in India (1563 Bq kg^{-1}) [34]. The highest activity concentration of ^{137}Cs in soil samples in Toplica-South Serbia (83.3 Bq kg^{-1}), Yerevan-Armenia (80.45 Bq kg^{-1}), Gorgan Region-Iran (12.72 Bq kg^{-1}) were found higher than the highest activity concentration of ^{137}Cs in this study [32-33, 35].

The average natural radionuclide activity concentrations in this study were found to be higher than the average activity concentrations in Saudi Arabia (7.64 Bq kg^{-1} for ^{226}Ra, 3.76 Bq kg^{-1} for ^{232}Th, and 174 Bq kg^{-1} for ^{40}K), in Wadi Al-Hussini Yemen (61.95 Bq kg^{-1} for ^{226}Ra, 32.33 and for ^{232}Th), in Tuban Yemen (65.20 Bq kg^{-1} for ^{226}Ra, and 50.95 Bq kg^{-1} for ^{232}Th), in Iraq (11.17 Bq kg^{-1} for ^{226}Ra, 13.38 Bq kg^{-1} for ^{232}Th, and 158.36 Bq kg^{-1} for ^{40}K), in North-central Sicily, Italy (30 Bq kg^{-1} for ^{226}Ra and 227 Bq kg^{-1} for ^{40}K), Greece (28.3 Bq kg^{-1} for ^{226}Ra, 35.4 Bq kg^{-1} for ^{232}Th, and 444.2 Bq kg^{-1} for ^{40}K), and Bulgaria (31.7 Bq kg^{-1} for ^{226}Ra, 39.9 Bq kg^{-1} for ^{232}Th, and 467.2 Bq kg^{-1} for ^{40}K) [38-42]. Some activity concentration values in this study were found to be lower than in soil samples analyzed in Italy, Greece and Spain. In a study performed in the Calabria region (South of Italy), ^{226}Ra activity concentration varied between 52.9 and 885.9 Bq kg^{-1} [43]. In a study performed in Italy (Caprarola municipality), ^{226}Ra, ^{232}Th and ^{40}K concentrations range from 83 to 318 Bq kg^{-1}, from 146 to 481 Bq kg^{-1} and from 317 to 1236 Bq kg^{-1}, respectively [44]. Studies showed that high radionuclide concentrations occur in tuffs, phreatomagmatic facies and volcanic rocks [44, 45]. High activity concentrations were observed due to the volcanic nature of Lesvos, Greece (90 Bq kg^{-1} for ^{226}Ra, 190 Bq kg^{-1} for ^{232}Th, 960 Bq kg^{-1} for ^{40}K, and 70 Bq kg^{-1} for ^{137}Cs) [46]. In addition, in a study performed in Western Canary Islands (Spain), which has a basaltic and felsic volcanic rock structure, activity concentrations ^{40}K, ^{226}Ra and ^{232}Th were determined as in the range of 52.0–1240.1, 7.0–71.0, 8.1–147.5 Bq kg^{-1}, respectively [47].

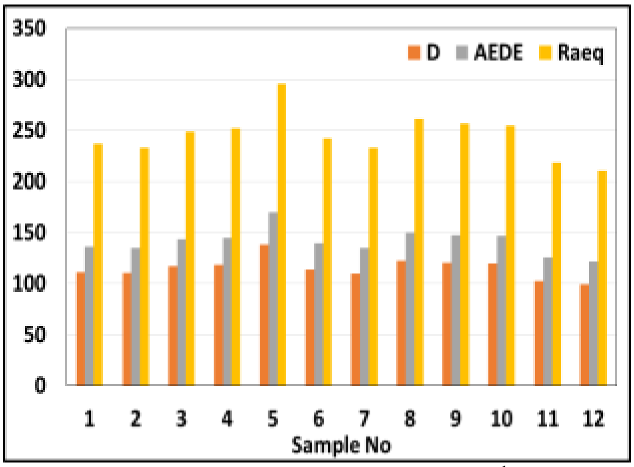

Fig. 6: Radiological hazards Raeq (Bq kg^{-1}), D (nGy h^{-1}), and AEDE (μSv y^{-1}) in soils

Radiological hazard parameters were calculated to obtain the potential threat due to radioactivity in soil. Radiological hazard values are shown in Fig.6 and Fig. 7. R_{aeq} was calculated to determine the total amount of radiation exposure from the natural radionuclides. R_{aeq} ranged from 210.16 to 295.48 Bq kg^{-1} and the average was calculated as 245.16 Bq kg^{-1}. The average of R_{aeq} and all estimated values of Ra_{eq} were less than the recommended value (370 Bq kg^{-1}). The lowest and highest values of the radiological parameter D, calculated using activity concentration values, were calculated as 98.89 nGy h^{-1} and 138.43 nGy h^{-1}, respectively.

The average of D (115.14 nGy h^{-1}) and all calculated values of D were higher than the world average (57 nGy h^{-1}). In addition, AEDE was calculated to evaluate the level of health effects. AEDE ranged from 121.27 to 169.77 μSv y^{-1}, and the average of AEDE determined as 141.20 μSv y^{-1}. All AEDE results calculated for soil samples were higher than the world average of 70 μSv y^{-1}. ELCR was used to estimate the amount of cancer risk caused by exposure to ionizing radiation. As seen in Fig. 7, all ELCR values were higher than the world average (0.29×10^{-3}) [22]. The fact that D, AEDE, and ELCR parameters were found higher than the world average and recommended safety values that soil use in the study area is not radiologically safe and can lead to comparatively higher gamma doses for the population of that area. Therefore, continuous radiological monitoring of the soil to protect the health of the population is necessary.

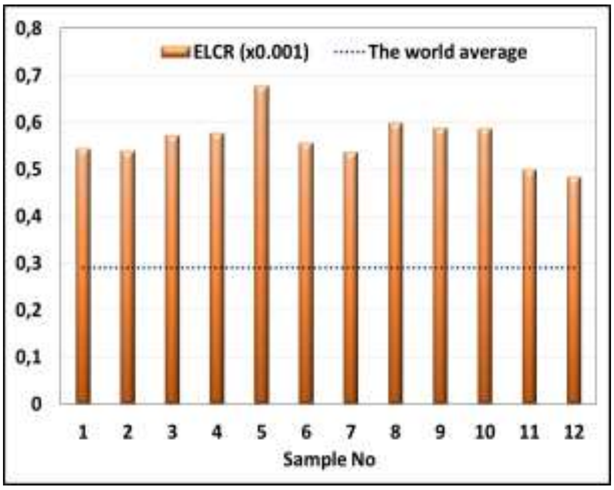

Fig. 7: ELCR values in soils and the world average

4 Conclusion

Natural and artificial radionuclide analyses of surface soil samples were carried out for the Nevşehir (Cappadocia) region, which is one of the most touristic regions of Turkey and has volcanic and sedimentary soil characteristics. Natural radioactivity concentrations were above the world average. The reason why natural radionuclides are found above the world average is that volcanic rocks are dominant in the geological structure of the study area. ^{137}Cs, an artificial radionuclide, is not found in high amounts compared to other studies in the literature, but its presence in small amounts in the region indicates that it may have harmful effects on health. In addition, the calculated radiological parameters (D, AEDE, and ELCR) are above the world average, indicating that the population in this region is in radiological danger and will pose a health risk with long-term exposure.

The main result of the present study is that the results obtained constitute the first data on the Cappadocia region, which still has a volcanic and complex geological structure. As a preliminary study in this region, the present study shows that the natural radionuclide concentrations in the soils of the region are higher than the permissible limit values and it should not be forgotten that many studies on radioactivity should be carried out in this area. However, continuous radiological monitoring of the regions is encouraged to control variations in radionuclide concentrations due to different factors such as seasonal variations, geological structure, etc. Radioactivity monitoring studies should be carried out in important tourism regions of Turkey such as Cappadocia. It is thought that the presented results will constitute reference data and will be useful for the future radioactivity map of Turkey.

In our future studies, we plan to use ARIMA and Monte Carlo Simulation (MCS) methods together. This is because the use of MCS saves time, financial resources, and effort by avoiding the preparation of standard solutions with various isotopes. Also the proposed simulation models are useful for other hazardous substances in environmental systems. In addition, ARIMA and MCS have been shown to work well even for low-activity radionuclides in our previous studies.

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