Environ Geochem Health (2025) 47:374
https://doi.org/10.1007/s10653-025-02668-6

ORIGINAL PAPER

Technologically enhanced natural radioactivity level in fly ash produced in lignite-fired thermal power plant and assessment of radiological hazards

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Received: 27 May 2025 / Accepted: 15 July 2025 / Published online: 13 August 2025

Abstract Lignite coal is the primary local energy source in Türkiye. The inevitable result of the utilization of lignite coal in thermal power plants for electricity generation is the formation of large amounts of ash (bottom ash and fly ash) as industrial solid waste. These wastes contain technologically enhanced natural radionuclides in the uranium (^{238}U) and thorium (^{232}Th) decay series and radio-potassium (^{40}K). Seyitömer lignite-fired thermal power plant (4×150 MW) located in the Central Western Anatolia Region of Türkiye produces approximately 1.6 million tons of siliceous fly ash per year. In this study, the utilization of these fly ashes in the construction industry and their storage in ash landfill areas were assessed by estimating radiological parameters and using the RESRAD Onsite 7.2 computer code. For this, the enhanced natural radioactivity levels of fly ash samples were determined by gamma-ray spectrometry with a high-purity germanium detector. The average activity concentrations of the natural radionuclides measured in fly ash samples were 621 ± 25 (^{40}K), 150 ± 7 (^{226}Ra), and 96 ± 3 (^{232}Th) Bq/kg. The assessment results confirm that the studied fly ash samples are radiologically safe to be used in cement and concrete production in accordance with international and national standards without significant effects of radiological hazards. The RESRAD simulation results revealed that the total annual effective dose rate in the uncovered ash storage area reached its maximum (0.11 mSv/y) at 18.97 years, and the covering of the protective materials on top of the area significantly attenuated the gamma radiation in the decreasing order: concrete > soil > PVC > zeolite.

Keywords Fly ash · Radioactivity · Annual effective dose · Cancer risk · RESRAD software

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Introduction

All developed and developing countries strive to meet their energy demand primarily by using their highly secure resources. In this context, the fact that it is abundant, easy, and safe to transport makes coal important for energy security worldwide. The utilization of coal in world electrical energy production has always been higher than other primary resources, and almost half of the world's total electrical power is provided by coal-fired thermal power plants (Turhan & Jamasali, 2024). Coal-fired thermal power plants are a critical component of Türkiye's electric energy production. Currently, Türkiye's installed electric capacity has reached 116.5 gigawatts (GW), and one-fifth of this power comes from a total of 69 coal-fired thermal power plants (1 asphaltite-fired, 48 lignite-fired, 4 hard coal-fired, and 16 imported coal-fired thermal power plants) (MERN, 2025). Türkiye's total coal reserves are approximately 22 billion tons (Bt), including 20.5 Bt of lignite and asphaltite and 1.5 Bt of hard coal (MERN, 2025). The calorific values of lignite coals ranged from 1000 to 4200 kcal/kg, and approximately 79% of them have a lower heating value below 2500 kcal/kg; therefore, a large portion of lignite is utilized as fuel in thermal power plants (MERN, 2025). Thus, lignite coal plays a very important role in maintaining a stable and sustainable energy supply by fueling many thermal power plants in Türkiye.

As a result of the combustion of coal in thermal power plants, volatile organic compounds, gases, and solid wastes, known as environmental pollutants, are inevitably formed. The most important of these solid wastes is fly ash. Approximately 99% of fly ash is collected by electrostatic precipitators and disposed of in ash dumps or landfill areas either as wet or in dry form, while 1% is released into the atmosphere together with volatile and gaseous wastes (Altıkulaç et al., 2022; Jayaranjan et al., 2014; Turhan & Jamasali, 2024; Turhan et al., 2010). Thus, significant amounts of fly ash particles can be released into the atmosphere each year with the burning of Bt coal. Coal contains varying trace amounts of radionuclides in the uranium (^{238}U) and thorium (^{232}Th) decay series, and radio-potassium (^{40}K) depending on its geological formation, geochemical structure, and organic matter composition (Dinis et al., 2021; Turhan & Jamasali, 2024; Turhan et al., 2010). When coal is fired, organic components are removed while the radionuclides accumulate in the ashes (bottom and FYA) at levels up to 3–10 times higher than the typical values of the fired coal (Dinis et al., 2021; Turhan & Jamasali, 2024; Turhan et al., 2010). Therefore, fly ash is the so-called naturally occurring radioactive material (NORM) since coal combustion technically leads to an increase in the concentration of these radionuclides in the fly ash (Janković et al., 2024; Turhan & Jamasali, 2024).

The global coal ash production in the energy sector is approximately 1.1 Bt, of which 75–80% is coal fly ash, and 25–30% of the fly ash is re-utilized in various sectors (Mathapati et al., 2022; Putilova, 2023). In 2022, the waste of fly ash, bottom ash, and slag from the coal-fired thermal power plants operated in Türkiye was approximately 23 million tons (Mt), and the majority of these were disposed of in landfill areas or ash dams (TÜİK, 2025). The radionuclides and other toxic pollutants that can adversely affect human health and pollute soil, air, and water resources are released into the atmosphere and the environment together with the large quantities of fly ash. This situation creates a worldwide serious environmental concern with economic and technological effects. Therefore, the management of fly ash, including its transportation, storage, reuse, and recovery, remains a challenging economic and environmental issue (Turhan & Jamasali, 2024). However, some fly ashes are utilized as the main component in the production of construction materials (especially cement and concrete) or as alternative raw materials or substitutes for these materials due to their inherent pozzolanic or hydraulic properties (TS EN 197-1, 2002; Türker et al., 2009; Turhan & Jamasali, 2024). Hence, people are exposed to ionizing radiations emitted from NORM in indoor (home, workplace, school, etc.) environments where building materials containing fly ash are utilized and outdoor environments (ash storage areas). Therefore, the knowledge of the activity levels of the radionuclides in fly ash and these building materials is important to assess the external and internal exposure to which people may be exposed. So far, in numerous studies, the activity levels of the radionuclides in fly ashes obtained as waste in different countries and building materials with fly ash have been determined and assessed the radiological hazard due to the utilization of these building materials (Ahmed, 2020; Fidanchevski et al., 2021; Hassan, 2023; Ignjatovic et al., 2017; Jalil & Rashid, 2015; Kovler, 2009; Łata & Danielowska, 2020; Loan et al., 2022; Mishra et al., 2023; Mohamed et al., 2023; Mudiwa et al., 2020; Ozden et al., 2018; Parami et al., 2010; Sahu et al., 2016; Suarez-Navarro et al., 2024). However, according to our literature research, there is no detailed research on the radiological assessment of Seyitömer fly ash resulting from its utilization in the construction industry.

The primary aim of this study is to assess the radiological hazards caused by the NORM in Seyitömer fly ash, which is utilized in significant amounts in the construction industry in Türkiye. Therefore, in this study (i) the radiometric measurement of thirty-seven fly ash samples collected from units of Seyitömer lignite-fired thermal power plant was performed by using a gamma-ray spectrometer with a high purity germanium (HPGe) detector, (ii) from a radiological point of view, the utilization of fly ash samples in CEM II and concrete production was assessed by estimating the activity concentration index, (iii) the radiological hazards caused by indoor external exposure due to gamma radiations from the radionuclides measured in fly ash samples was assessed by estimating the indoor annual effective dose and the corresponding excess lifetime cancer risk and (iv) effective dose rates for workers working in ash storage area were estimated by the RESRAD Onsite 7.2 computer code.

Materials and methods

Collection and preparation

Seyitömer basin, which is located approximately 25 km northwest of Kütahya province center, is one of the most productive coal basins in Western Anatolia-Türkiye (Celik & Karayigit, 2004). It contains lower and upper seams, within the Lower-Middle Miocene lacustrine Seyitömer Formation (Celik & Karayigit, 2004). The upper layer in this basin has no economic value. The lower layer, which is an average of 15 m in the basin, contains about 200 Mt of lignite reserves and is exploited by an open mining with a dragline, excavator, and truck system. Lower-Middle Miocene coal-bearing Seyitömer Formation is conformably underlain by fluvial beds of Egrioz Formation and overlain by the Kepez Formation of Miocene-Pliocene age (Celik & Karayigit, 2004). The coal-bearing Seyitömer Formation is represented from the bottom upwards by green claystone, lower coal seam, mudstone, and bituminous marl containing sapropelic coal lenses, upper coal seam, carbonaceous claystone with interbedded diatomite and fossiliferous marl. Most of the lignite produced in this layer is consumed in the thermal power plant installed at Seyitömer (Celik & Karayigit, 2004). The installed capacity of the Seyitömer lignite-fired thermal power plant is 600 MW, which has four boiler units of 150 MW each. It burns approximately 6.6 Mt of lignite per year and produces approximately 1.6 Mt of fly ash per year (Celik & Karayigit, 2004). Seyitömer fly ash is siliceous fly ash and has pozzolanic properties. Seyitömer fly ash is utilized in the production of Portland-fly ash cement (CEM II) and concrete as it complies with TS EN 197-1, TS EN 450-1, and ASTM C618 standards (Akgül & Yoncacı, 2021; Türker et al., 2009).

A total of thirty-seven fly ash samples were collected from the electrostatic precipitators of the Seyitömer lignite-fired thermal power plant shown in Fig. 1. After each fly ash sample was subjected to the

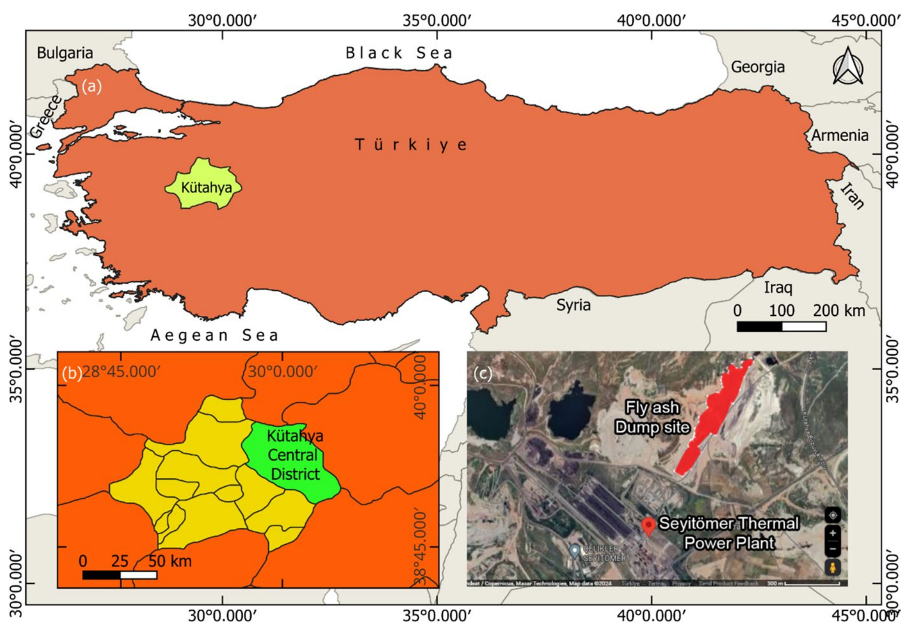


Fig. 1 Geographical map of Seyitömer lignite-fired thermal power plant and its fly ash dump site (marked as red)

drying process and coded as FASH, it was transferred to cylindrical sample containers of the same size and geometry as the reference material containers used for the calibration of the gamma-ray spectrometer. After each sample was weighed, the sample containers were sealed to prevent the leakage of radon gas and kept in the laboratory for at least four weeks until the radioactivity measurement process to ensure the radioactive secular equilibrium between the radon and its decay products (Turhan & Jamasali, 2024).

Radiometric measurement

The activity concentrations (ACs) of the enhanced natural radionuclides (^{40}K, ^{226}Ra, and ^{232}Th) in the fly ash samples were determined using a gamma-ray spectrometer with a coaxial p-type high-purity HPGe detector. The HPGe detector has a relative efficiency of 50% and an energy resolution of 2 keV (Turhan & Jamasali, 2024). To minimize background radiation, the HPGe detector is housed in an ultra-low-background lead shield. A vacuum cryogenic liquid nitrogen Dewar tank (30 L) was used to minimize electronic noise. The AC of ^{40}K was measured directly by its gamma-ray photopeak with 1460.8 keV. The AC of ^{226}Ra was determined using the gamma-ray photopeaks with 609.3 and 1764.5 keV from ^{214}Bi. The AC of ^{232}Th was determined using the gamma-ray photopeaks with 911.2 keV from ^{228}Ac and 583.2 keV from ^{208}Tl. The net counts of the photopeak in the region of interest were obtained by subtracting the counts of the relevant gamma-ray photopeak from the background gamma-ray. The ACs of the radionuclides in the fly ash samples were determined as follows:

$$A = \frac{C}{\varepsilon(E_\gamma) \cdot P_\gamma \cdot M \cdot t} \tag{1}$$

where A is the AC of the radionuclide (in Bq/kg), C is the net count gamma-ray photopeak of interest, ε (E_γ) is the efficiency found for the gamma-ray photopeak of interest, P_γ is the emission probability of the gamma-ray of interest, t is the count time (s) and M is the mass of the sample (kg). The full energy photopeak efficiency calibration of the system was carried out by the reference materials (RGTh-1, RGU-1, and RGK-1) prepared by the International Atomic Energy Authority. The minimum detectable activity (*MDA* in Bq/kg) concentration of the gamma-ray spectrometer at a 95% confidence level was determined as follows (Currie, 1968):

$$MDA = \frac{1.64 \cdot \sigma_B}{\varepsilon_\gamma \cdot P_\gamma \cdot t \cdot M} \tag{2}$$

where σ_B is the standard deviation of the background value of the gamma-ray photopeak of interest. The average *MDA* values were 6.7 (^{40}K), 0.3 (^{226}Ra), and 0.4 (^{232}Th) Bq/kg, respectively. Uncertainty of the measurement was found by the following formula (Turhan & Jamasali, 2024):

$$\frac{\Delta A}{A} = \sqrt{\left(\frac{\Delta\varepsilon}{\varepsilon}\right)^2 + \left(\frac{\Delta P_\gamma}{P_\gamma}\right)^2 + \left(\frac{\Delta C}{C}\right)^2 + \left(\frac{\Delta M}{M}\right)^2} \tag{3}$$

where ΔA, $\Delta\varepsilon$, ΔP, ΔC and ΔM are the uncertainty of the AC, detector efficiency, emission probability, photopeak net count and sample mass, respectively.

Utilization of fly ash samples in building materials

The European Commission (EC) has recommended the activity concentration index (*I*) as a screening tool to limit the annual effective dose (E_{Ind}) caused by external exposure from natural radioactivity in building materials in indoor (home, workplace, school, etc.) (EC, 1999). In the EC report, the criterion for E_{Ind} is 1 mSv/y, and dose values exceeding this criterion cannot be neglected from the radiation protection point of view. Therefore, *I* is based on the ACs of natural radionuclides and the criterion of E_{Ind} and is estimated by the formula given below (EC, 1999):

$$I = \left(\frac{A_{Ra}}{300\,(Bq/kg)} + \frac{A_{Th}}{200\,(Bq/kg)} + \frac{A_K}{3000\,(Bq/kg)}\right) \times FC \tag{4}$$

where A_{Ra} (^{226}Ra) and A_{Th} (^{232}Th), and A_K (^{40}K) are the AC (Bq/kg) of the radionuclides measured in the sample. *FC* is the utilization fraction of industrial wastes such as blast furnace slag, phosphogypsum, bauxite, fly ash, etc., utilized as raw materials in the production of building materials. $I \leq 1$ corresponds to $E_{Ind} \leq 1$ mSv/y and $I \leq 0.5$ corresponds to $E_{Ind} \leq 0.3$ mSv/y for building materials utilized in bulk amounts such as concrete, brick, cement, etc. (EC, 1999). $I \leq 6$ corresponds to $E_{Ind} \leq 1$ mSv/y and $I \leq 2$ corresponds to $E_{Ind} \leq 0.3$ mSv/y for superficial and restricted building materials such as marble, granite, tiles, etc. (EC, 1999).

Assessment of radiological hazards

Radiological hazards associated with the utilization of the studied fly ash samples as a building material were assessed by estimating E_{Ind} and the corresponding excess lifetime cancer risk (*ELCR*). In this study, the E_{Ind} was estimated by using the CEN formula based on the Markkanen model (MMod) (CEN, 2017; Markkanen, 1995; Smetsers & Tomas, 2019). In the MMod, the dose assessment is based on the geometry of the room of interest, construction layer thickness, and material properties such as mass density and the ACs of radionuclides measured in the material. Two material layers are considered in this model, thus taking into account the effect of the shielding of gamma radiation from the underlying construction layer by the upper construction layer (Markkanen, 1995; Smetsers & Tomas, 2019). In the MMod, ^{40}K, ^{226}Ra (and its daughters), and ^{232}Th (and its daughters) are considered as the main radionuclides contributing to the gamma dose (Markkanen, 1995; Smetsers & Tomas, 2019). Based on the results obtained with the MMod, CEN has derived a formula that estimates the E_{Ind} due to the gamma radiation in the centre of a reference room (3.0 m × 4.0 m × 2.5 m) with no windows or doors (CEN, 2017; Smetsers & Tomas, 2019). It is assumed that (i) the room shields all outdoor exposure, (ii) a dose conversion factor utilized to convert the absorbed dose in air into the effective dose is 0.7 Sv/Gy and (iii) the average indoor occupancy time is 7,000 h/y (CEN, 2017; Smetsers & Tomas, 2019). The E_{Ind} was estimated using the CEN formula as follows (Smetsers & Thomas, 2019):

$$E_{Ind} = \begin{bmatrix} (281 + 16.3 \times \rho d - 0.0161 \times (\rho d)^2) \times A_{Ra} + \\ (319 + 18.5 \times \rho d - 0.0178 \times (\rho d)^2) \times A_{Th} + \\ (22.3 + 1.28 \times \rho d - 0.00114 \times (\rho d)^2) \times A_K \end{bmatrix} \times 10^{-6} \quad (5)$$

where ρ is the mass density of concrete with fly ash (in kg/m^3) and d is the model room thickness (0.2 m). In this study, the background correction factor (0.29 mSv/y) is subtracted from the E_{Ind} values estimated with this formula.

The corresponding *ELCR* is related to the lifetime probability of cancer development associated with E_{Ind} and estimated as follows (Turhan & Jamasali, 2024):

$$ELCR = E_{Ind} \times RF \times AL \quad (6)$$

where RF is the fatal risk factor of 0.057/Sv (ICRP60, 1990) and AL is the average life of 70 years (y).

RESRAD onsite

Detailed information about the RESRAD onsite code 7.2 software used in this study was given in detail in previous studies (Jamasali & Turhan, 2024; Turhan & Jamasali, 2024). In the RESRAD onsite code, it is assumed that the industrial worker is exposed to radiation through two different pathways: external exposure due to gamma radiation and internal exposure due to the inhalation of dust and ingestion of soil. The effective dose from external exposure is estimated using the dose to which the receptor is exposed at a height of one meter above the ground area and applying correction factors such as the area, thickness, shape, and shielding of the contaminated site. In this study, the exposure of workers working directly in the ash landfill site of Seyitömer lignite-fired thermal power plant was assessed by the aforementioned computer code using the input parameters given in Table 1. Exposure in scenarios wherein the landfill site is covered by four different materials (zeolite, PVC, soil, and concrete) of different thicknesses (0.10 m, 0.25 m, and 0.50 m) was considered to obtain their shielding effect.

Results and discussion

Activity concentration

The ACs with the uncertainty of the radionuclides measured in each fly ash sample are given in Table 2. Figure 2 shows a boxplot comparing the ACs of ^{40}K, ^{226}Ra, and ^{232}Th. The frequency distributions of the ACs of the radionuclides are exhibited in Fig. 3. The comparison of the average ACs of the radionuclides with those measured in fly ash samples from coal-fired thermal power plants in various countries is presented in Table 3. From Table 2, the average ACs of the radionuclides in the fly ash samples are 621 ± 25 Bq/kg for ^{40}K

Table 1 Input parameters for RESRAD onsite software

Parameters	Unit	Value	
Area of contaminated zone	m^2	82,130	
Thickness of the contaminated zone	m	2	
Density of contaminated zone*	g/cm^3	0.58	
Density of saturated zone	g/cm^3	1.50	
Cover depth	m	0	
		0.10	
		0.25	
		0.50	
			Material
Density of cover	g/cm^3	0.7	Zeolite
		1.0	PVC
		1.2	Soil
		2.3	Concrete
Wind speed	m/s	3.48	
Precipitation rate	m/y	1	
Well-pump intake depth	m	10	
Indoor time factor		0.17 (0.20)	
Outdoor time factor		0.06 (0.0285)	
			Radionuclides
Average Activity Concentration	Bq/kg	621	^{40}K
		150	^{226}Ra
		96	^{232}Th

*Density of fly ash is based on bulk density (Yılmaz, 2015)

(242 ± 15–880 ± 42 Bq/kg), 150 ± 7 Bq/kg for ^{226}Ra (100 ± 4–282 ± 10 Bq/kg) and 96 ± 3 Bq/kg for ^{32}Th (71 ± 2–127 ± 4 Bq/kg). According to Fig. 2, ^{40}K exhibits the highest AC, but with a large spread and outliers, suggesting variability in the samples. In addition, ^{226}Ra has a moderate AC but still some outliers. ^{232}Th has the lowest AC, with a very tight distribution and no apparent outliers. From Fig. 3, the AC distribution of ^{40}K looks near normal, and the highest frequency is around 600–700 Bq/kg. The AC distribution of ^{226}Ra is skewed to the right, and the highest frequency is in the 100–120 Bq/kg. On the other hand, the AC distribution of ^{232}Th appears to be roughly normal or slightly skewed to the right, and the highest frequency is in the 90–100 Bq/kg. From Table 3, it can be seen that the average ACs of the radionuclides in fly ash samples from coal-fired thermal power plants in different countries vary depending on various parameters such as type, origin, and radionuclide concentration of coal, combustion conditions, etc.. However, it is significant to note that the findings of the study regarding radionuclides in fly ash samples appear to be comparable to other countries, as presented in Table 3.

Radiological hazard assessment

As stated before, Seyitömer fly ashes are utilized as the main Pozzolanic component in the production of CEM II (Portland-fly ash cement) at a rate of 5–35% following the TSE EN 197-1 (2002) standard. At the same time, Seyitömer fly ashes are also utilized as a cement substitute up to 30% in concrete production following the TS EN 450-1 (2015) and ASTM C618 (2012) standards. Therefore, radiological parameters were estimated by considering these utilizing ratios (or fractions). The mean and range (minimum–maximum) values of the radiological parameters estimated for the utilization of Seyitömer fly ash samples in cement and concrete production and the radiological hazards caused by the external exposure in indoor areas are given in Table 4. Figure 4 depicts a scatter plot of the estimated *I* values for different fly ash percentages. Values of *I* ranged from 0.04 to 0.08 for

Table 2 Activity concentration of radionuclides measured in Seyitömer fly ashes

Sample code	Activity concentration (Bq/kg)		
	^{40}K	^{226}Ra	^{232}Th
FASH-1	365 ± 22	150 ± 5	76 ± 3
FASH-2	242 ± 15	194 ± 6	95 ± 4
FASH-3	585 ± 37	270 ± 9	97 ± 3
FASH-4	375 ± 24	200 ± 6	110 ± 5
FASH-5	674 ± 47	165 ± 6	78 ± 3
FASH-6	636 ± 35	156 ± 6	127 ± 4
FASH-7	649 ± 43	282 ± 10	94 ± 3
FASH-8	585 ± 32	106 ± 4	80 ± 4
FASH-9	695 ± 44	100 ± 4	83 ± 4
FASH-10	663 ± 46	105 ± 5	101 ± 4
FASH-11	733 ± 47	145 ± 6	91 ± 3
FASH-12	631 ± 43	141 ± 6	98 ± 4
FASH-13	796 ± 45	123 ± 6	110 ± 4
FASH-14	806 ± 48	145 ± 6	81 ± 3
FASH-15	250 ± 13	121 ± 5	71 ± 3
FASH-16	712 ± 48	114 ± 4	101 ± 4
FASH-17	608 ± 39	121 ± 4	100 ± 3
FASH-18	680 ± 49	162 ± 6	117 ± 4
FASH-19	714 ± 39	109 ± 4	88 ± 3
FASH-20	610 ± 34	115 ± 3	85 ± 3
FASH-21	690 ± 44	120 ± 5	94 ± 3
FASH-22	690 ± 36	120 ± 4	94 ± 3
FASH-23	743 ± 49	117 ± 4	75 ± 3
FASH-24	688 ± 39	127 ± 4	96 ± 3
FASH-25	576 ± 36	133 ± 6	124 ± 5
FASH-26	615 ± 31	134 ± 5	106 ± 4
FASH-27	559 ± 26	115 ± 5	91 ± 4
FASH-28	766 ± 42	134 ± 6	107 ± 5
FASH-29	701 ± 37	150 ± 5	125 ± 4
FASH-30	350 ± 18	152 ± 5	71 ± 2
FASH-31	649 ± 35	183 ± 6	101 ± 3
FASH-32	455 ± 21	102 ± 4	80 ± 3
FASH-33	880 ± 42	235 ± 9	121 ± 5
FASH-34	688 ± 33	205 ± 6	105 ± 3
FASH-35	494 ± 24	132 ± 4	83 ± 2
FASH-36	568 ± 33	218 ± 6	98 ± 3
FASH-37	872 ± 49	165 ± 4	112 ± 3
Average	621	150	96
Median	649	134	96
Standard deviation	152	45	15
Standard error	25	7	3
Kurtosis	0.7	1.6	− 0.6
Skewness	− 0.9	1.4	0.3
Minimum	242	100	71
Maximum	880	282	127

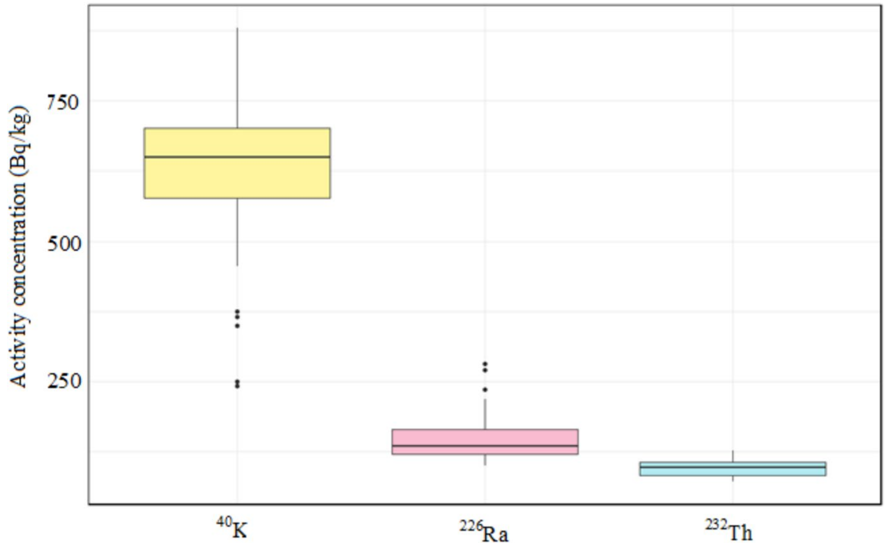
5%, 0.08–0.16 for 10%, 0.13–0.24 for 15%, 0.17–0.33 for 20%, 0.21–0.41 for 35%, 0.25–0.49 for 30% and 0.29–0.57 for 35%. As seen in Fig. 4, all *I* values are lower than the criterion of unity. Also, all values are below the exemption level of 0.5, except for three fly ash samples (coded as FASH3, FASH7, and FASH33).

Values of E_{Ind} ranged from 0.03 to 0.08 mSv/y for 5%, 0.07–0.17 mSv/y for 10%, 0.10–0.25 mSv/y for 15%, 0.14–0.33 mSv/y for 20%, 0.17–0.41 mSv/y for 25% and 0.21–0.50 mSv/y for 30% and 024–0.58 mSv/y for 35%. As shown in Fig. 5, all E_{Ind} values satisfy the criterion value of 1 mSv/y recommended by the EC (EC, 1999). The mean value of the corresponding *ELCR* were estimated as 2.1×10^{-4} for 5%, 4.2×10^{-4} for 10%, 6.3×10^{-4} for 15%, 8.4×10^{-4} for 20%, 1.0×10^{-4} for 25%, 1.3×10^{-4} for 30% and 1.5×10^{-4} for 35%. All *ELCR* values are lower than the world average value of 1.6×10^{-3} (UNSCEAR, 2000).

RESRAD Onsite assessment

The contributions of each radionuclide (^{226}Ra, ^{232}Th, and ^{40}K) and exposure route (external, inhalation and ingestion) to the estimated effective dose rate (E_R) without shielding to which workers working at the Seyitömer lignite-fired thermal power plant ash storage site (or dumpsite) may be exposed are shown in Fig. 6. It can be seen from Fig. 6a that the maximum E_R is 0.12 mSv/y at 18.97 years, in which the contributions of ^{226}Ra, ^{232}Th, and ^{40}K are 5.97×10^{-2}, 4.97×10^{-2}, and 6.46×10^{-3} mSv/y, respectively. From the beginning until 33.11 years, the main contributor is ^{226}Ra, wherein it is gradually decreasing, and then in later years, ^{232}Th becomes the main contributor. As can be seen from Fig. 6b, the exposure routes are ranked as external gamma exposure > ingestion of soil > inhalation of dust. At 18.97 years which the total E_R is maximum, 96.66% of which was through external gamma exposure, 2.99% through soil ingestion, and 0.35% through inhalation of dust. The

Fig. 2 A box plot comparing activity concentrations of radionuclides



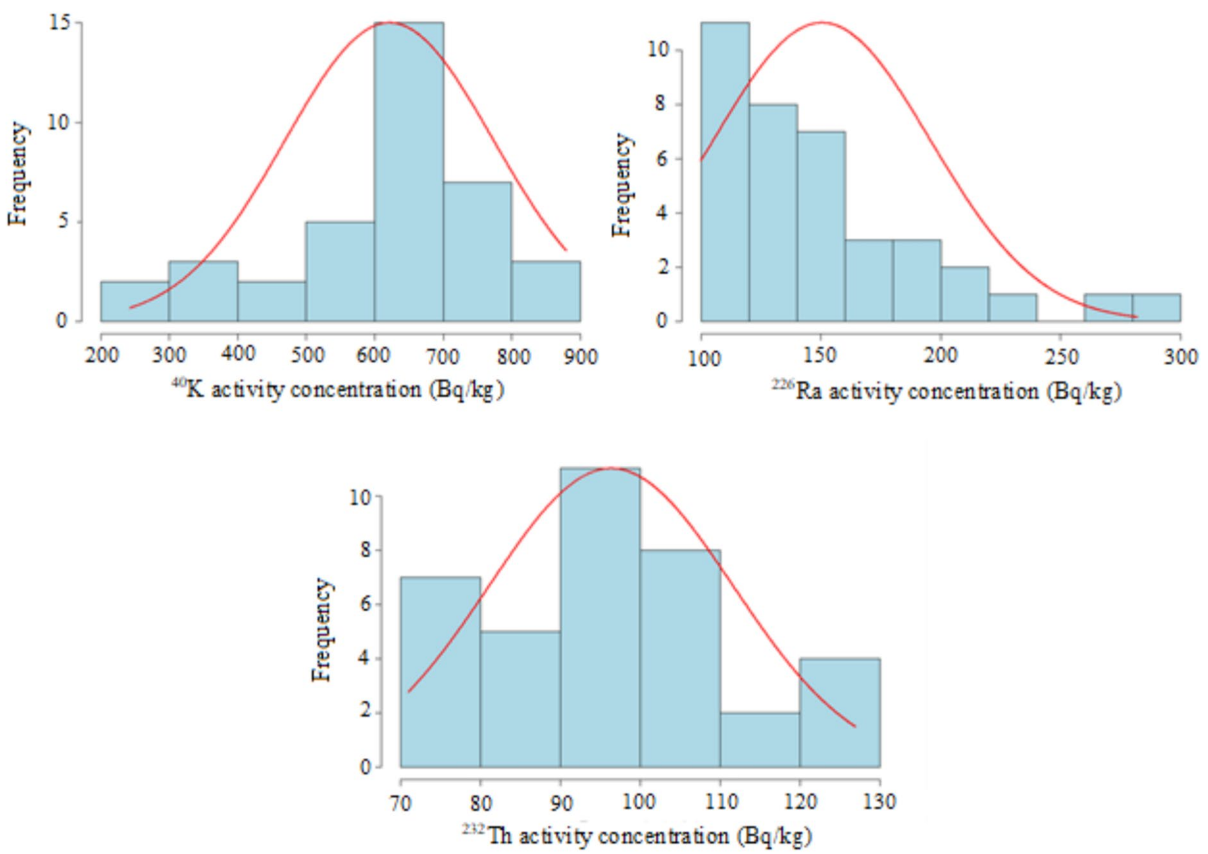


Fig. 3 The frequency distributions of activity concentrations of radionuclides

Table 3 Comparison of average activity concentrations of radionuclides with those measured in fly ashes from different countries

Country	Activity concentration (Bq/kg)			References
	^{40}K	^{226}Ra	^{232}Th	
Brazil	489	661	80	Fungaro et al. (2019)
China	235	83	87	Lu et al. (2012)
European Union countries	650	180	100	EC (1999)
India (average)	360	89	144	Mishra et al. (2023)
Kosovo	133	30	30	Hasani et al. (2014)
Malaysia	299	48	44	Jalil and Rashid (2015)
Morocco	348	149	104	Boukhair et al. (2016)
Nigeria	321	41	49	Ademola and Onyema (2014)
Serbia	360	120	72	Janković et al. (2011)
Republic of North Macedonia	719	143	116	Fidanchevski et al. (2021)
Türkiye (Average)	517	360	102	Turhan et al. (2010)
Viet Nam	938	77	92	Loan et al. (2022)
Türkiye (Seyitömer)	621	150	96	This study

Table 4 Values of radiological parameters (activity concentration index (*I*), annual effective dose (E_{Ind}) and excess lifetime cancer risk (*ELCR*) estimated for the indoor external exposure

Utilization fraction (%)	Radiological parameter			
	I		E_{Ind} (mSv/y)	ELCR
5	Average	0.06	0.05	2.1×10^{-4}
	Range	0.04–0.08	0.03–0.08	1.4×10^{-4}–3.3×10^{-4}
10	Average	0.12	0.11	4.2×10^{-4}
	Range	0.08–0.16	0.07–0.17	2.8×10^{-4}–6.6×10^{-4}
15	Average	0.17	0.16	6.3×10^{-4}
	Range	0.13–0.24	0.10–0.25	4.1×10^{-4}–9.9×10^{-4}
20	Average	0.23	0.21	8.4×10^{-4}
	Range	0.17–0.33	0.14–0.33	5.5×10^{-4}–1.3×10^{-3}
25	Average	0.29	0.26	1.0×10^{-3}
	Range	0.21–0.41	0.17–0.41	6.9×10^{-4}–1.7×10^{-3}
30	Average	0.35	0.32	1.3×10^{-3}
	Range	0.25–0.49	0.21–0.50	8.3×10^{-4}–2.0×10^{-3}
35	Average	0.41	0.37	1.5×10^{-3}
	Range	0.29–0.57	0.24–0.58	9.7×10^{-4}–2.3×10^{-3}

external gamma exposure pathway is the major pathway, with an average of 96.91% contribution to the dose rate in the entire 100-year time span.

Figure 7 shows the changes in the total E_R values that workers may be exposed to when the Seyitömer ash waste storage is shielded with different materials. The results reveal that the total E_R values decrease due to the influence of the composition and thickness of the shielding material. Effective shielding is ranked as concrete > soil > PVC > zeolite. It is observed that in the first year in 0.10-m cover scenarios, E_R values are reduced to 61% (zeolite), 49% (PVC), 42% (soil), and 19% (concrete) of the E_R value in the no cover scenario. E_R values in these scenarios gradually climb up to the value of E_R in the no cover scenario until reaching over 80% at $t=57.54$ years, at $t=69.18$ years, at $t=75.00$ years, and at $t=90.00$ years, for zeolite, PVC, soil and concrete, respectively. In 0.25-m cover scenarios, the rise in E_R value is less, with 27.76% in the first year to 45.20% in the 100th year for zeolite, 16.09–32.82% for PVC, 11.20–26.56% for soil, and 1.56–8.48% for concrete. In the 0.50-m cover scenarios, the increase in E_R value is the least,

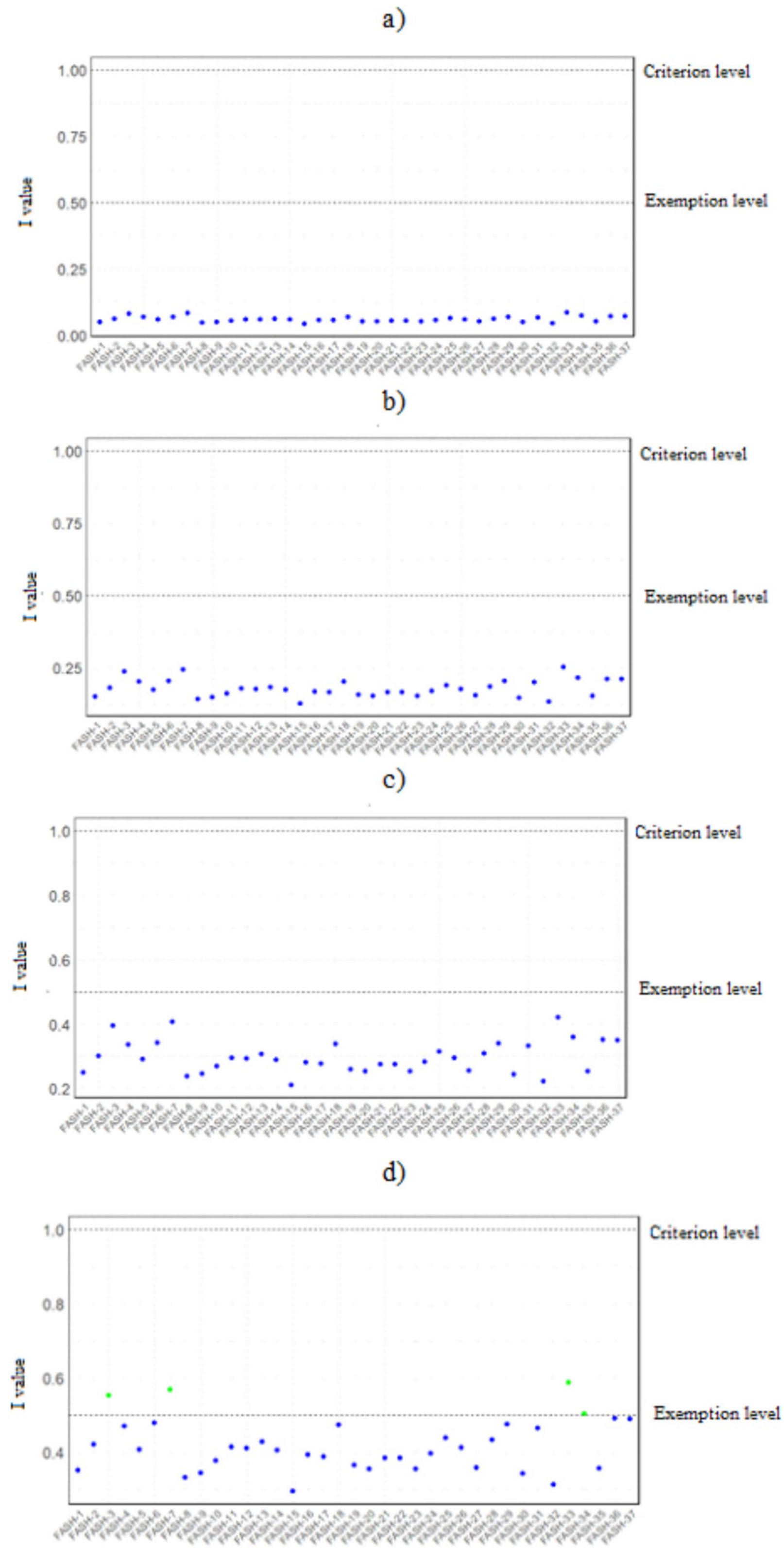


Fig. 4 A scatter plot of values of activity concentration index (*I*) estimated for different fly ash percentages. **a** 5%, **b** 15%, **c** 25 **d** 35%

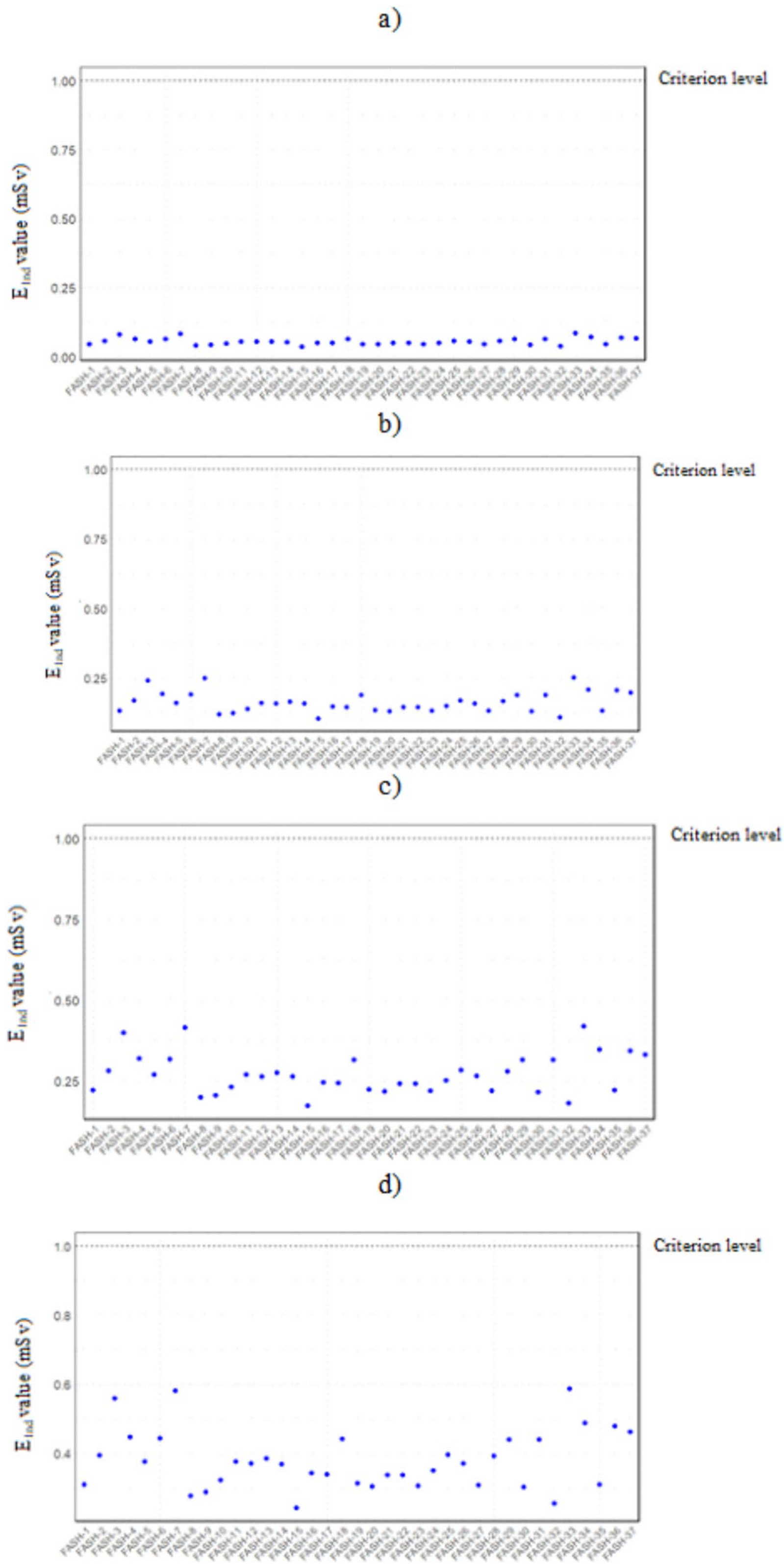


Fig. 5 A scatter plot of values of indoor annual effective dose (E_{Ind}) estimated for different fly ash percentages. **a** 5%, **b** 15%, **c** 25 **d** 35%

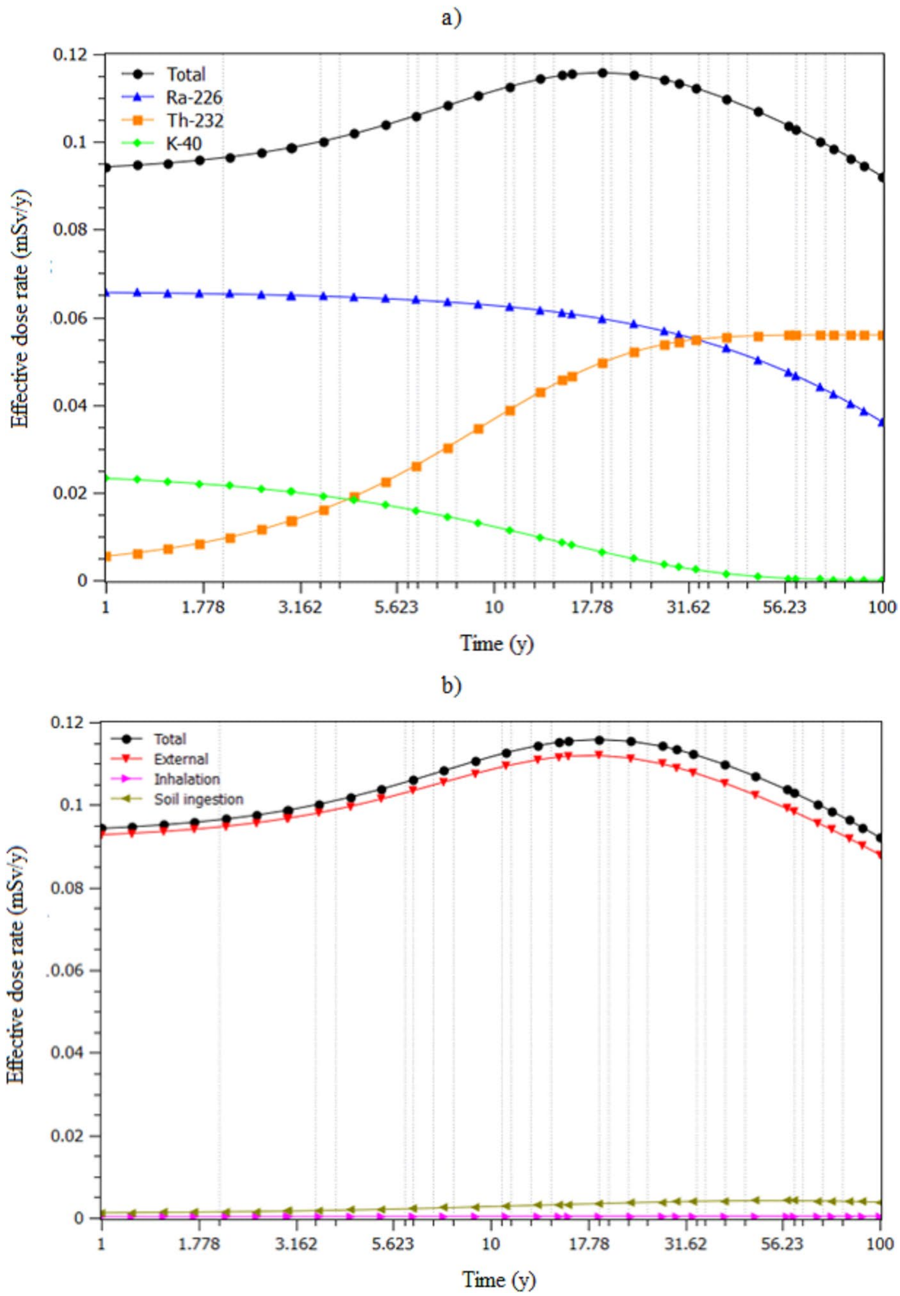


Fig. 6 Effective dose rates estimated for each radionuclide (**a**) and exposure pathways (**b**) for no cover scenario

with 7.75% in the first year to 13.17% in the 100th year for zeolite, 2.64–5.79% for PVC, 1.29–3.37% for soil, and 0.03–0.19% for concrete. The least of the maximum E_R values in all the scenarios is 1.70×10^{-4} mSv/y of 0.5-m concrete. Hence, concrete exhibits the highest shielding capacity among the four shielding materials. However, its cost makes it impractical for covering an area as large as the dumpsite. Therefore, soil is considered the most suitable option due to its widespread availability.

Conclusion

The measurement indicates that, on average, the ACs of ^{40}K, ^{226}Ra, and ^{232}Th in Seyitömer fly ash samples

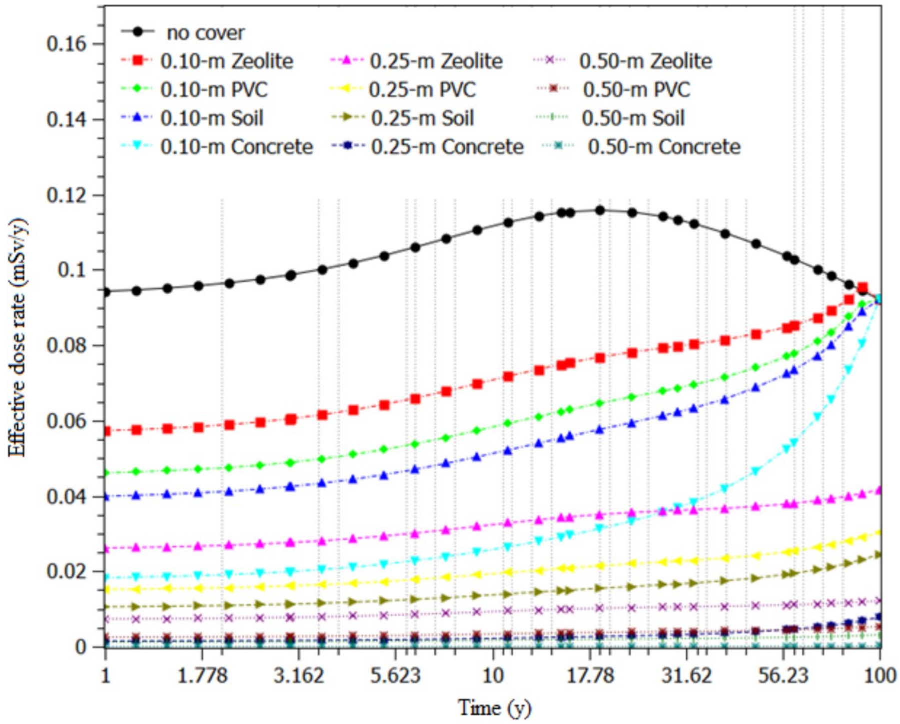


Fig. 7 Total effective dose rates estimated for without cover and with various covering materials of different thickness

are lower than those measured in fly ash samples from European Union countries. The radiological hazard assessment reveals that the studied fly ash samples can be utilized in cement and concrete production at a maximum rate of 35%, and in this case, the utilization of fly ash samples as a building material will not pose a significant radiological health hazard. The RESRAD simulation results show that the total E_R value in the uncovered fly ash storage area reached its maximum value of 0.11 mSv/y at 18.97 years, and the covering of the protective materials on top of the area significantly attenuated the gamma radiation in the decreasing order: concrete > soil > PVC > zeolite.

Acknowledgements The authors thank Prof. Dr. Ergin Murat Altuner for his assistance.

Author contributions The design and conceptualization of the study was done by Ş.T. Analysis was performed by Şeref Turhan and Yusof-den Jamasali. The first draft of the manuscript was written by Şeref Turhan and Y.J. All authors read and approved the final manuscript.

Funding This is not applicable.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Consent to participate This is not applicable.

Consent to publish This is not applicable.

Ethical approval This is not applicable.

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