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Radiological risk from natural radioactivity in cereal-based foods: age-specific assessment in Turkish consumers

Gülçin Bilgici Cengiz[1] · İlyas Çağlar[2] · Fatma Çifcibaşı[3]

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Abstract
This study evaluates the radiological health risks associated with naturally occurring radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in 10 breakfast cereal and 15 biscuit samples commonly consumed in Turkey. Activity concentrations were measured using a NaI(Tl) γ-ray spectrometer and ranged from 8.3 to 18.9, 4.1–16.4 and 49.1–125 Bq kg^{-1}, respectively. Estimated mean annual ingestion doses were 143 μSv y^{-1} (children) and 130 μSv y^{-1} (adults) from cereals, and 140 μSv y^{-1} (children) and 127 μSv y^{-1} (adults) from biscuits, all below the ICRP 1 mSv y^{-1} limit. Average ELCR values were 1.8×10^{-4} (children) and 3.4×10^{-4} (adults) for cereals, and 1.0×10^{-4} (children) and 3.3×10^{-4} (adults) for biscuits, aligning with UNSCEAR estimates. Although risks are low, regular surveillance of food radioactivity remains important.

Keywords Gamma spectrometry · Breakfast cereals · Annual ingestion dose · Excess lifetime cancer risk

Introduction

Naturally occurring radioactive materials (NORM), including radionuclides from the uranium-238 (^{238}U) and thorium-232 (^{232}Th) decay series, as well as potassium-40 (^{40}K), are ubiquitously present in soil, water, and air. These radionuclides can enter the human food chain through agricultural products, resulting in internal exposure upon ingestion. Because ingestion represents one of the main exposure pathways for the general population, monitoring natural radioactivity in foods is a key aspect of environmental radiation protection. Although the activity levels of natural radionuclides in foods are generally low, long-term exposure may cause potential health effects depending on dietary habits and consumption rates. Therefore, continuous monitoring of radionuclide concentrations in food products is essential for evaluating potential radiological health risks to the population [1–5]. Breakfast cereals have become a common dietary choice due to their convenience and nutritional benefits, being a source of fiber, vitamins, and minerals [6–9]. Their variety and popularity have expanded in recent years, with several studies emphasizing additional health benefits from antioxidants and phytoestrogens [10–12]. Similarly, bakery products, particularly biscuits, are widely consumed due to their affordability, long shelf life, and versatility as staple foods, snacks, or dietary supplements [13–17]. Given their nutritional and cultural significance, cereals and biscuits represent essential components of the Turkish diet.

From a radiological perspective, cereals and cereal-based products are important to monitor because they can accumulate naturally occurring radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) from soil, irrigation water, or phosphate fertilizers [18–20]. The radionuclide levels in these products depend on several factors such as soil geochemistry, fertilizer use, and climatic conditions, all of which affect plant uptake and transfer to edible grains. Food processing does not entirely eliminate these radionuclides, meaning both raw and processed foods may contribute to internal exposure [21, 22]. Reported activity concentrations in food are usually expressed in becquerels per kilogram (Bq kg^{-1}), while the potential dose to consumers is assessed as the annual ingestion dose (D_{AI}, in μSv y^{-1}) and the excess lifetime cancer risk (ELCR, dimensionless probability) [5, 23]. Although numerous studies worldwide have examined the levels of natural radioactivity

✉ Gülçin Bilgici Cengiz
gulcincengiz@kafkas.edu.tr

[1] Department of Physics, Faculty of Science and Letters, Kafkas University, Kars, Turkey

[2] Department of Electricity and Energy, Kazım Karabekir Vocational School of Technical Sciences, Kafkas University, Kars, Turkey

[3] Department of Physics, Institute of Science, Kafkas University, Kars, Turkey

in agricultural products and drinking water, comparatively fewer investigations have focused on processed foods such as packaged breakfast cereals and biscuits. For example, Alrefae et al. [24] reported that ^{226}Ra, ^{232}Th, and ^{40}K activities in cereals consumed in Kuwait were within internationally accepted limits, while Abojassim et al. [25] found higher radionuclide levels in biscuits marketed in Iraq. These studies indicate that differences in soil composition, fertilizer application, and manufacturing processes can influence the radionuclide content of processed foods.

In Turkey, despite the widespread daily consumption of cereals and biscuits, systematic data on their natural radioactivity content remain scarce. Existing assessments have mainly concentrated on raw food items or drinking water, leaving a gap in knowledge regarding processed foods that are widely distributed through nationwide supermarket chains [26–28]. Evaluating such products is essential to establish whether they comply with international radiological safety standards and to provide a scientific basis for public health protection. Therefore, the present study aims to determine the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40} K in selected breakfast cereals and biscuits commonly marketed in Turkey and to estimate the associated radiological health risks. The measurements were performed using a calibrated NaI(Tl) gamma-ray spectrometer (ORTEC, USA) at the Physics Laboratory of Kafkas University. The age-dependent annual ingestion dose (D_{AI}) and excess lifetime cancer risk (ELCR) were calculated in accordance with UNSCEAR, WHO, and ICRP guidelines [5, 29, 30]. This research provides the first comprehensive dataset on processed cereal-based foods in Turkey, contributing to national food-safety databases and international radiological comparisons.

Materials and method

Sampling procedure and preparation

A total of ten breakfast cereal samples and fifteen biscuit samples were collected from nationwide supermarket chains in Kars, Turkey (e.g., Migros, Şok). These chains distribute the same packaged products across the country; thus, the selected samples are representative of widely consumed cereal-based foods in Turkey. The brand names, countries of origin, and principal cereal ingredients for each product are presented in Tables 1 and 2.

All samples were ground into fine powder, sieved using a steel laboratory sieve of 2 mm-mesh size to obtain uniform particle size. Approximately 65 g each of homogenized samples was placed in airtight cylindrical plastic containers (5 cm in diameter and 5.5 cm in height) for subsequent analysis. To ensure representativeness and reproducibility, the same mass of each sample was used in the measurements. In order to achieve secular equilibrium between uranium- and thorium-series radionuclides and their short-lived progeny, the samples in sealed containers were stored for about 30 days before gamma spectrometric analysis [19, 21]. This procedure ensured the traceability of activity concentration results and reduced uncertainties associated with possible disequilibrium conditions [22].

Breakfast cereal samples predominantly consisted of oatmeal, corn-based ingredients (e.g., corn, corn flour, corn semolina), and wheat-based components (e.g., wheat flour, whole wheat, barley malt). For example, C1, C3, and C6 were exclusively oatmeal-based, while C2, C4, and C5 contained corn and wheat mixtures. Mixed cereal products such as C7 to C10 included combinations of oats, corn, and wheat (Table 1).

Table 1 Brand names, origins and the content of each breakfast cereal samples in this study

Food group	Sample ID	Brand name	Company	Origin	Main cereal ingredients of each sample
Cereals	C1	Lifalif finely ground oatmeal	Eti	Turkey	Oatmeal
	C2	Cornflakes	Kellogg's	Turkey	Corn, Wheat flour
	C3	Lifalif dried fruit and hazelnut muesli	Eti	Turkey	Oatmeal
	C4	Coco pops	Kellogg's	Turkey	Corn flour, Wheat flour
	C5	Gold corn flakes Strawberry flavoured	Nestlé	Turkey	Corn semolina, Whole corn, Barley malt
	C6	Oatmeal	Burch	Turkey	Oatmeal
	C7	Granola oatmeal Cocoa	Migros	Poland	Oats, Corn semolina, Whole wheat flour, Reduced fat cocoa powder
	C8	Nesquik chocolate cereal	Nestlé	Turkey	Whole wheat, Corn semolina, Corn starch, Rice, fat-reduced cocoa powder
	C9	Weetabix protein	Weetabix	England	Whole grain wheat, Rice flour, cocoa powder
	C10	Honey wheat pops	Richland	Poland	Wheat flakes, Barley malt extract

Table 2 The brand, country of origin, and primary grain components of each biscuit sample analyzed in this research

Food group	Sample ID	Brand name	Company	Origin	Main cereal ingredients of each sample
Biscuits	B1	Form bran diet	Eti	Turkey	Wheat flour, Bran, Whole wheat flour
	B2	Burcak oatmeal	Eti	Turkey	Oatmeal, Wheat flour, Whole wheat flour
	B3	Creamy oatmeal	Oylum	Turkey	Oatmeal, Wheat flour, Whole wheat flour
	B4	Whole wheat chocolate biscuits	Torku	Turkey	Whole wheat flour, Wheat flour, Wheat germ
	B5	Form lemon Fibber whole wheat	Eti	Turkey	Wheat Flour, Bran
	B6	Altınbaşak light Oatmeal	Ülker	Turkey	Wheat flour, Wheat bran, Whole wheat flour, Oatmeal
	B7	Burçak sultani Raisin Bran	Eti	Turkey	Wheat flour, Whole wheat flour, Bran
	B8	Full taste of Anatolia	Torku	Turkey	Wheat flour, Whole wheat flour, Bran
	B9	Fig and peanut cookies	XRoll	Turkey	Wheat flour, Whole wheat flour, Bran
	B10	Full cream cocoa cream	Torku	Turkey	Whole wheat flour, Wheat flour, Oatmeal
	B11	Full cream milk cream	Torku	Turkey	Whole wheat flour, Wheat flour, Oatmeal
	B12	Burçak cocoa cream	Eti	Turkey	Oatmeal, Wheat flour, Whole wheat flour, Corn starch
	B13	Saklıkoy milk cream biscuit	Ülker	Turkey	Oatmeal, Wheat flour, Whole wheat Flour
	B14	Whole wheat	Torku	Turkey	Wheat flour, Whole wheat flour
	B15	Burçak milk chocolate	Eti	Turkey	Wheat flour, Whole wheat flour

Similarly, the biscuit samples were primarily composed of wheat flour, whole wheat flour, bran, and oatmeal. Oatmeal was identified in multiple biscuits (B2, B3, B6, B13), while corn starch was present in only one sample (B12). Barley malt extract was not a prominent ingredient in the biscuits (Table 2).

This categorization by major cereal type (oat-based, corn-based, wheat-based) enabled subgroup analyses to evaluate potential ingredient-specific differences in radionuclide accumulation and associated radiological risk.

Gamma spectrometric analysis

All radioactivity measurements were carried out in the Physics Laboratory of the Faculty of Science, Kafkas University. Each powdered and sealed sample was measured continuously for approximately 86,000 s to obtain statistically reliable γ-ray spectra.

The natural radionuclide concentrations were determined using a NaI(Tl) scintillation detector (ORTEC, USA) integrated with a gamma spectrometry system. To minimize background interference, the detector was enclosed within a 5 cm thick lead shielding. Background spectra were recorded under the same conditions and subtracted from the sample spectra to determine net counts. The gamma spectra were processed using a Multi-Channel Analyzer (MCA) and MAESTRO-32 (A65-B32) software [19, 21]. The schematic arrangement of the detector and associated electronics is illustrated in Fig. 1.

Energy and efficiency calibrations of the gamma spectrometer were performed standard calibration material (IAEA-375), ensuring traceability of the measurements. The energy and relative efficiency calibrations of the spectrometer were previously described by Bilgici Cengiz [31]. The associated uncertainties of activity concentration values were calculated by propagating errors from counting

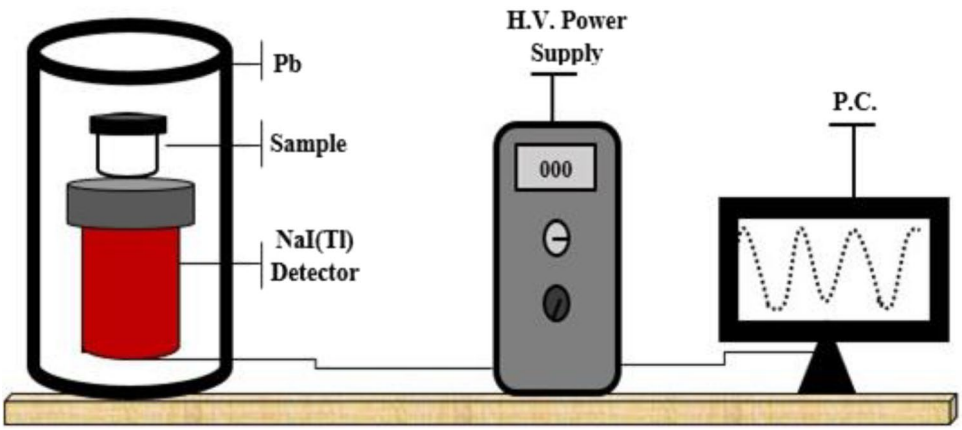


Fig. 1 Schematic diagram of the NaI(Tl) detector setup used for gamma-ray spectrometric measurements

statistics, detector efficiency, emission probabilities, and sample mass. In this study, reported values are given with one standard deviation (± 1σ), consistent with the significance of measurement uncertainties.

The activity concentrations of ^{40}K was evaluated directly by its own 1460.8 keV gamma peak. The ^{226}Ra concentration was determined by measuring 609.3 keV, 1120.3 keV, and 1764.5 keV gamma rays from ^{214}Bi and similarly, peaks at 583 and 2614.5 keV energies from ^{208}Tl were used to determine the activity concentration of ^{232}Th [21]. The net activity concentration of natural radionuclides ^{226}Ra, ^{232}Th and ^{40}K was calculated utilizing Eq. (1) [25].

$$A_{AS}(\text{Bq kg}^{-1}) = \frac{N_{Net}}{\varepsilon . I_{\gamma} . m . t} \quad (1)$$

where A_{AS} is the analysed sample activity concentration, N_{Net} (counts) is the net counts (measured under the photopeak after background subtraction), ε is the efficiency of the detector, I_γ is the transition probability of the emitted gamma ray, m (kg) is the mass of the sample, and t (s) is the counting time of the sample. All activity values are reported with one standard deviation (± 1σ).

Dose and risk calculations

To evaluate the potential radiological health effects due to ingestion of these radionuclides, the annual ingestion dose (D_{AI}) and excess lifetime cancer risk (ELCR) were calculated using Eqs. (2) and (3), respectively [24, 25, 27].

$$D_{AI} = A_{AS} \times C_R \times IDCF \quad (2)$$

where D_{AI} is the annual ingestion dose (Sv y^{-1}), A_{AS} is the activity concentration (Bq kg^{-1}) of the investigated radionuclides in the biscuits and breakfast cereals, C_R is the consumption rate (kg y^{-1}) and IDCF is the ingested dose conversion factor for radionuclides (Sv Bq^{-1}).

The IDCF values for children and adults were adopted from ICRP (1996) and are presented in Table 3 [32]. Differences in metabolic rate, body mass, and consumption habits influence the dose conversion and intake quantities by age. The annual consumption rates for breakfast cereals and biscuits were assumed to be 20 kg for adults and 10 kg for children, based on UNSCEAR (2000) and national consumption data [5, 33].

Table 3 Age-dependent ingestion dose conversion factors (IDCF) (in μSv Bq^{-1}) for selected radionuclides [32]

Age groups	^{226}Ra	^{232}Th	^{40}K
Children	0.8	0.29	0.013
Adults	0.28	0.23	0.0062

Excess lifetime cancer risk (ELCR) refers to the probability of individuals developing cancer as a result of prolonged exposure to low doses of ionizing radiation over a lifetime [28, 34]. In this study, the ELCR values due to ingestion of radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in cereals and biscuits were calculated using the Eq. (3) [35–37].

$$ELCR = DAI \times L \times RF \quad (3)$$

where D_T is the total ingestion dose (Sv y^{-1}), L is the average life expectancy (70 years), and RF is the risk factor for stochastic cancer effects per unit dose, taken as 5×10^{-2} Sv^{-1} for adults [5, 30, 32, 38]. The total ingestion dose (D_T) was obtained by summing annual doses over a 70 year lifespan.

The calculations accounted for age-dependent variations in consumption behaviour and dose conversion factors. The annual ingestion dose (D_{AI}) for each radionuclide was estimated separately for childhood and adulthood periods, and the cumulative ingestion dose over a 70 year lifetime was then used to evaluate the excess lifetime cancer risk (ELCR).

Results and discussion

Activity concentrations of natural radionuclides in breakfast cereals and biscuits

The measured activity concentrations of natural radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in breakfast cereals and biscuits are summarized in Tables 4 and 5. Reported values include associated uncertainties (± 1σ), reflecting statistical counting errors and detector efficiency. The results indicate variability across samples depending on grain type, ingredient composition, and possibly regional differences in raw material sources.

For breakfast cereals, ^{226}Ra ranged from 8.3 ± 0.9 to 18.9 ± 1.2 Bq kg^{-1} (mean: 12.6 ± 1.2 Bq kg^{-1}), ^{232}Th from 4.1 ± 0.1 to 14.3 ± 0.8 Bq kg^{-1} (mean: 10.6 ± 0.8 Bq kg^{-1}),

Table 4 Measured activity concentrations (Bq kg^{-1}) of natural radionuclides (^{226}Ra, ^{232}Th and ^{40}K) in selected breakfast cereal samples

Sample ID	^{226}Ra	^{232}Th	^{40}K
C1	18.9 ± 1.2	13.4 ± 1.0	117 ± 13
C2	16.6 ± 0.9	14.3 ± 0.8	71 ± 09
C3	13.6 ± 1.0	7.7 ± 0.8	75 ± 12
C4	8.5 ± 1.0	12.1 ± 1.0	80 ± 13
C5	8.7 ± 0.8	11.7 ± 0.3	65 ± 10
C6	13.7 ± 1.2	4.1 ± 0.1	79 ± 17
C7	9.50 ± 0.9	13.1 ± 0.3	72 ± 12
C8	8.3 ± 0.9	14.1 ± 0.3	90 ± 12
C9	13.8 ± 1.2	6.9 ± 1.0	99 ± 14
C10	14.2 ± 2.6	9.0 ± 2.4	125 ± 36

Table 5 Activity concentration (Bq kg^{-1}) of ^{226}Ra, ^{232}Th and ^{40}K in for examined biscuits samples

Sample ID	^{226}Ra	^{232}Th	^{40}K
B1	13.8 ± 1.2	6.4 ± 1.0	85 ± 15
B2	9.7 ± 0.9	6.0 ± 0.9	72 ± 13
B3	13.9 ± 1.1	10.5 ± 0.98	69 ± 13
B4	10.3 ± 1.2	14.5 ± 1.2	88 ± 15
B5	15.9 ± 1.2	16.4 ± 1.2	72 ± 14
B6	8.9 ± 1.2	9.2 ± 1.3	81 ± 17
B7	13.0 ± 1.1	4.3 ± 1.0	78 ± 14
B8	17.8 ± 1.1	9.8 ± 1.0	57 ± 12
B9	9.3 ± 1.0	6.1 ± 1.0	89 ± 14
B10	10.7 ± 1.5	12.9 ± 1.5	112 ± 21
B11	11.0 ± 1.2	10.0 ± 1.1	71 ± 16
B12	16.8 ± 1.3	14.5 ± 1.2	49 ± 14
B13	11.7 ± 1.1	11.5 ± 1.2	53 ± 15
B14	13.2 ± 1.1	9.9 ± 1.0	98 ± 14
B15	10.2 ± 1.0	15.0 ± 1.0	89 ± 13

and ^{40}K from 65 ± 10 to 125 ± 36 Bq kg^{-1} (mean: 87 ± 15 Bq kg^{-1}). Among the examined samples, C1 (Lifalif Finely Ground Oatmeal) contained the highest levels of ^{226}Ra and ^{40}K, whereas C2 (Cornflakes) showed the highest ^{232}Th concentration. Such variations are consistent with the known influence of grain type, soil mineral composition, and fertilizer use on radionuclide uptake [5, 29, 36–38].

Sample C10 recorded the highest ^{40}K activity concentration (125 ± 36 Bq kg^{-1}), likely due to the naturally high potassium content in wheat and honey, as reported in food composition data [29]. Conversely, samples containing cocoa (e.g., C4 and C7) exhibited relatively higher ^{232}Th levels, which may be attributed to the mineral-rich composition of cocoa. Previous studies have demonstrated elevated thorium and other radionuclide concentrations in cocoa beans and cocoa-based food products [39, 40]. The elevated ^{226}Ra activity observed in sample C6 (another oatmeal-based cereal) supports the hypothesis that oats may accumulate radium more readily, potentially due to their deeper root systems and high silica content [41, 42]. Overall, cereals formulated with oatmeal, corn, and whole grains tend to show higher levels of naturally occurring radionuclides, particularly ^{226}Ra and ^{40}K, whereas additives such as cocoa or other mineral-enriched ingredients may contribute to increased ^{232}Th activity.

Table 5 presents the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the analyzed biscuit samples. The measured concentrations ranged from 8.9 ± 1.2 to 17.8 ± 1.1 Bq kg^{-1} for ^{226}Ra, 4.3 ± 1.0–16.4 ± 1.2 Bq kg^{-1} for ^{232}Th, and 49 ± 14–112 ± 21 Bq kg^{-1} for ^{40}K. The variations observed among samples are primarily associated with the type and proportion of ingredients used in the formulations. Biscuits containing bran exhibited the highest mean ^{226}Ra activity (15.1 Bq kg^{-1}), whereas those prepared with invert sugar syrup showed the greatest ^{232}Th levels (11.97 Bq kg^{-1}). Samples enriched with malt extract and milk cream displayed elevated ^{40}K concentrations (85 Bq kg^{-1} and 83 Bq kg^{-1}, respectively). In contrast, basal components such as wheat flour, whole-wheat flour, and vegetable oils contributed only moderate radionuclide levels, consistent with previously reported activity ranges for cereal-based staples and edible oils [20, 40, 42–44].

These compositional influences are consistent with previous findings on biscuit and cereal-based products from Iraq and Turkey [25–28, 45]. Overall, ingredients rich in minerals and organic matter—such as bran, invert sugar syrup, milk cream, and malt extract—tend to enhance natural radionuclide contents compared with more neutral components like oatmeal or salt [39, 46, 47].

Table 6 presents the natural activity concentration values (Bq kg^{-1}) for breakfast cereals and biscuits reported in the literature. The observed radionuclide concentrations are consistent with previous food-related radiological studies from other countries, confirming that breakfast cereals and biscuits are not significant contributors to radiological health risk [24, 25, 27, 43–45].

Table 6 Natural activity concentration values (Bq kg^{-1}), D_T (μSv y^{-1}), and ELCR (10^{-3}) for breakfast cereals and biscuits reported in the literature

Study location	Sample type	Activity range			D_T	ELCR	References
		^{226}Ra	^{232}Th	^{40}K			
Kuwait	Breakfast cereals	0.33–1.07	0.16–0.4	15.96–93.29			[24]
Iraq	Biscuits	11.15 ± 0.72	16.31 ± 0.80	206.57 ± 2.87			[25]
Iraq (Imports)	Biscuits & baked products	4.9	26.8	178.8			[45]
Iraq	Breakfast cereals	18.19 ± 2.90	20.96 ± 5.47	796.59 ± 16.04	0.136	0.068	[27]
Italia	Grain products	3.0	3.24	144.1			[56]
Turkey	Breakfast cereals	12.6 ± 1.2	10.6 ± 0.8	87.1 ± 14.7	132.8	0.31	Current study
Turkey	Biscuits	12.4 ± 1.2	10.5 ± 1.1	77.5 ± 14.7	129.9	0.28	Current study

However, the slightly elevated activity levels observed in oat-based and multi-ingredient products suggest that ingredient composition can influence radionuclide content. Ingredients such as oats and whole wheat tend to accumulate higher levels of ^{226}Ra and ^{40}K due to their greater mineral uptake capacities [44, 45].

Radiological dose and risk evaluation

The radiological health risks associated with the consumption of breakfast cereals and biscuits were evaluated using three parameters: the annual ingestion dose (D_{AI}), total ingestion dose (D_T), and excess lifetime cancer risk (ELCR). These indicators reflect both the annual radiological burden and the potential long-term stochastic effects on human health, and the results are summarized in Tables 7 and 8.

Although neither the World Health Organization (WHO, 1996) nor the International Atomic Energy Agency (IAEA, 2006) has established specific permissible limits for natural radionuclides in foodstuffs, radiological protection assessments generally rely on effective dose criteria [23, 29]. According to the International Commission on Radiological Protection (ICRP, 2007) and UNSCEAR (2000), the recommended annual effective dose limit for the general public from ingestion is 1 mSv y^{-1} [5, 30].

Among the breakfast cereals analyzed, the highest total committed effective dose (D_T) and excess lifetime cancer risk (ELCR) were recorded in sample C1, with children receiving 205.3 μSv y^{-1} and an ELCR of 0.26×10^{-3}, and adults 181.9 μSv y^{-1} and 0.47×10^{-3}, respectively. These elevated values primarily reflect the higher concentrations of ^{226}Ra and ^{40}K in this sample. On average, the total ingestion doses from breakfast cereal consumption were 142.9 μSv y^{-1} for children and 130.2 μSv y^{1} for adults, corresponding to mean ELCR values of 0.18×10^{-3} and 0.34×10^{-3}, respectively.

All the calculated dose and risk values are well below the ICRP-recommended public dose limit of 1 mSv y^{-1}, indicating that the consumption of these products does not pose any significant radiological health concern [30]. These findings are consistent with global UNSCEAR (2000) report, which estimates ingestion doses from natural radionuclides in food to range between 100 and 300 μSv y^{-1} and lifetime cancer risks between 10^{-4} and 10^{-3}. [5].Therefore, the studied foods can be considered radiologically safe for human consumption.

Among the biscuits, the highest radiological doses and cancer risks were identified in samples B5 and B8, reflecting elevated ^{226}Ra and ^{232}Th concentrations. The mean total committed effective dose D_T from biscuit consumption was 139.8 μSv y^{-1} for children and 127.4 μSv y^{-1} for adults,

Table 7 D_{AI} (μSv y^{-1}), D_T (μSv y^{-1}) and ELCR (10^{-3}) from breakfast cereals consumption (Ages 3–70)

Samples	Ages	D_{AI}			D_T	ELCR
		^{226}Ra	^{232}Th	^{40}K		
C1	Child	151.4	38.7	15.2	205.3	0.26
	Adult	106.0	61.5	14.5	181.9	0.47
C2	Child	133.0	41.6	9.2	183.8	0.23
	Adult	93.08	65.9	8.8	167.8	0.44
C3	Child	109.1	22.2	9.8	141.1	0.18
	Adult	76.4	35.3	9.3	121.0	0.31
C4	Child	67.9	35.0	10.4	113.3	0.14
	Adult	47.5	55.6	9.9	112.9	0.29
C5	Child	69.4	33.9	8.4	111.7	0.14
	Adult	48.6	53.7	8.0	110.3	0.29
C6	Child	109.4	12.0	10.3	131.7	0.17
	Adult	76.6	19.1	9.8	105.4	0.27
C7	Child	76.0	38.1	9.3	123.4	0.16
	Adult	53.2	60.4	8.9	122.5	0.32
C8	Child	66.6	41.0	11.7	119.3	0.15
	Adult	46.6	65.0	11.1	122.8	0.32
C9	Child	110.7	20.0	12.8	143.5	0.18
	Adult	77.5	31.7	12.2	121.4	0.32
C10	Child	113.5	26.2	16.2	155.9	0.20
	Adult	79.5	41.5	15.5	136.4	0.35
Average	Child	100.7	30.9	11.3	142.9	0.18
	Adult	70.5	49.0	10.8	130.2	0.34

Table 8 D_{AI} (μSv y^{-1}), D_T (μSv y^{-1}) and ELCR (10^{-3}) from consuming biscuits in individuals aged 3–70

Samples	Ages	D_{AI}			D_T	ELCR
		^{226}Ra	^{232}Th	^{40}K		
B1	Child	110.0	18.6	11.0	139.6	0.12
	Adult	77.0	29.6	10.5	117.1	0.30
B2	Child	77.7	17.5	9.4	104.7	0.12
	Adult	54.4	27.8	9.0	91.2	0.24
B3	Child	111.4	30.3	9.0	150.7	0.12
	Adult	78.0	48.1	8.6	134.7	0.35
B4	Child	82.5	41.9	11.4	135.8	0.09
	Adult	57.8	66.5	10.9	135.1	0.35
B5	Child	126.8	47.4	9.4	183.6	0.13
	Adult	88.8	75.2	9.0	173.0	0.45
B6	Child	70.9	26.7	10.5	108.0	0.07
	Adult	49.6	42.3	10.0	102.0	0.27
B7	Child	104.5	12.4	10.1	127.0	0.11
	Adult	73.2	19.6	9.7	102.5	0.27
B8	Child	142.8	28.6	7.4	178,7	0.15
	Adult	99.9	45.3	7.1	152.3	0.40
B9	Child	74.0	17.8	11.6	103.5	0.08
	Adult	51.8	28.3	11.0	91.2	0.24
B10	Child	85.4	37.6	14.6	137.6	0.09
	Adult	59.8	59.6	13.9	133.3	0.35
B11	Child	88.0	29.2	9.2	126.4	0.09
	Adult	61.6	46.3	8.8	116.6	0.30
B12	Child	134.7	42.2	6.4	183.2	0.14
	Adult	94.3	66.9	6.1	167.2	0.43
B13	Child	93.9	33.3	6.9	134.1	0.10
	Adult	65.7	52.9	6.6	125.2	0.33
B14	Child	105.8	28.9	12.8	147.4	0.11
	Adult	74.0	45.8	12.2	132.0	0.34
B15	Child	81.5	43.7	11.6	136.7	0.09
	Adult	57.0	69.3	11.0	137.4	0.36
Average	Child	99.3	30.4	10.1	139.8	0.10
	Adult	69.5	48.2	9.6	127.4	0.33

with corresponding ELCRs of 0.10×10^{-3} and 0.33×10^{-3}, respectively.

All measured dose and risk values were well below the international safety threshold of 1 mSv y^{-1} and the global average lifetime cancer risk from natural background radiation (2.9×10^{-3}) [5]. Hence, the examined breakfast cereals and biscuits do not pose any significant radiological risk to consumers within the studied population.

Overall, the comparison shows that breakfast cereals exhibit slightly higher radionuclide activity concentrations and associated ingestion doses and ELCRs compared to biscuits, consistent with previous reports on cereal-based foods [25, 43–45, 48]. This difference is likely due to variations in raw ingredients, as cereals typically contain greater proportions of oats, whole grains, and mineral-rich additives known to enhance natural radionuclide uptake [40, 47]. Despite these differences, all calculated ELCR values for both product categories remain below international limits of concern [5, 30, 46], implying no significant radiological health hazard for consumers aged 3–70 years. Nevertheless, considering the cumulative nature of internal radiation exposure—especially among vulnerable groups such as children—regular surveillance and quality control of food products and raw ingredients are recommended to ensure ongoing consumer safety. These observations are consistent with current radiobiological evidence indicating that excess lifetime cancer risks remain very low at environmental dose levels, well below thresholds associated with measurable health effects [49].

These findings confirm that, although cereals and biscuits contribute to the dietary intake of natural radionuclides, their radiological impact is minimal and consistent with safe

global consumption levels. Comparable results regarding the distribution of natural radionuclides and ingestion doses have also been reported for other food categories, including oils, sugars, and meats, supporting the general consistency of natural radioactivity patterns across dietary products and related environmental media such as soils worldwide [20, 22, 28, 50–56].

Age-specific dose analysis

Figure 2 presents the total annual ingestion dose (D_T) from ^{226}Ra, ^{232}Th, ^{40}K for different age groups based on breakfast cereal consumption. The radionuclide-specific annual ingestion doses (D_{AI}) were calculated using age- and radionuclide-dependent ingestion dose coefficients provided by ICRP Publication 72 [32]. The highest total dose was observed in the 13–17 year age group (209.8 μSv y^{-1}), followed by the 8–12 years (199.7 μSv y^{-1}) and 3–7 year (192.6 μSv y^{-1}) groups. Despite lower breakfast cereal consumption compared to adults, children and adolescents received higher doses due to elevated age-specific IDCFs, especially for ^{226}Ra and 40K. For example, the IDCF for ^{226}Ra in children is 0.8 μSv Bq^{-1}, compared to only 0.28 μSv Bq^{-1} in adults.

Although adults aged 18–65 years consumed the largest amount of cereal (20 kg y^{-1}), their total DAI (127.4 μSv y^{-1}) was comparatively lower [13, 33]. This reduction can be attributed to both smaller DCF values and lower radionuclide concentrations in cereal types commonly consumed by adults. The lowest total dose (103.3 μSv y^{-1}) was recorded in the > 65 year age group, consistent with decreased consumption rates and reduced metabolic absorption efficiency.

These findings emphasize that children and adolescents are more susceptible to internal radiological exposure from cereal consumption due to physiological and metabolic differences, highlighting the need for age-specific considerations in dietary radiological risk assessments.

Statistical correlation analysis

In addition to the age-specific dose results, regression analyses were conducted to evaluate the relationships between radionuclide-specific ingestion doses (^{226}Ra, ^{232}Th, and ^{40}K) and the total annual committed effective dose (D_T) in children based on breakfast cereal and biscuit consumption. The strength of these associations is summarized in Table 9.

The ingestion dose from ^{226}Ra exhibited a very strong correlation with total DT in both food groups ($R^2 = 0.89$ for breakfast cereals; $R^2 = 0.83$ for biscuits), confirming that ^{226}Ra is the primary contributor to the overall dose. In contrast, ^{232}Th showed a weak correlation in cereals ($R^2 = 0.03$) but a moderate one in biscuits ($R^2 = 0.36$), indicating a relatively greater influence in the latter. The ingestion dose from ^{40}K demonstrated a moderate correlation in cereals ($R^2 = 0.27$) and a weak correlation in biscuits ($R^2 = 0.16$), reflecting its limited role in total dose variation.

These findings underscore the dominant role of ^{226}Ra in the radiological health risk associated with breakfast cereal and biscuit consumption, and emphasize the importance of monitoring radium levels in processed food products, particularly those consumed regularly by children. Figure 3 illustrates the percentage contribution of each age group to the total excess lifetime cancer risk (ELCR) resulting from biscuit consumption.

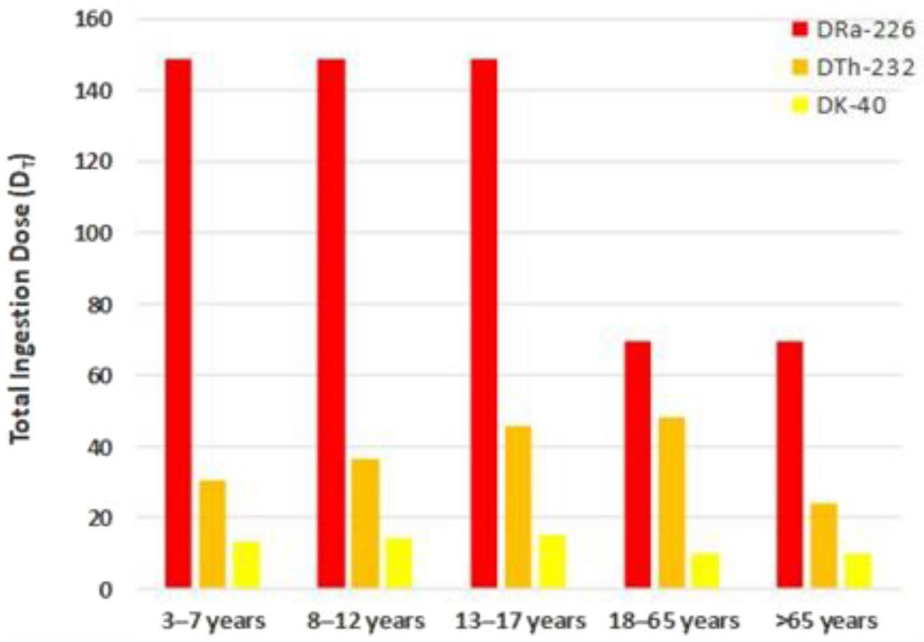


Fig. 2 D_T (μSv y^{-1}) from ^{226}Ra, ^{232}Th and ^{40}K in breakfast cereals by age group (ICRP 72 [32])

Table 9 Radionuclide dose contribution to total annual ingestion dose (DT) from breakfast cereal and biscuit consumption in children

Food type	Radionuclide	R^2 with D_T	Strength of correlation	Interpretation
Breakfast cereal	^{226}Ra	0.89	Very strong	^{226}Ra explains nearly 89% of the total dose variation
	^{232}Th	0.03	Weak	^{232}Th has minimal impact on total D_T variation
	^{40}K	0.27	Moderate	^{40}K contributes modestly to total D_T variability
Biscuits	^{226}Ra	0.83	Very strong	^{226}Ra is the dominant contributor to D_T
	^{232}Th	0.36	Moderate	^{232}Th has a more notable influence in biscuits
	^{40}K	0.16	Weak	^{40}K contributes minimally to total D_T variation

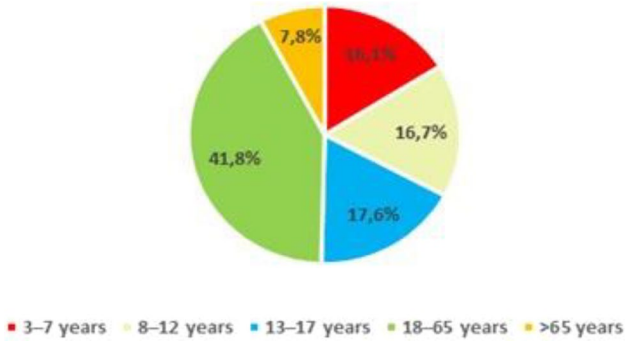


Fig. 3 Percentage contribution of each age group to the total excess lifetime cancer risk (ELCR) from biscuit consumption. (Based on data from Table 9 and age-specific ELCR calculations.)

The total excess lifetime cancer risk (ELCR) resulting from biscuit consumption across all age groups was estimated to be 0.335×10^{-3}. Adults aged 18–65 years contributed the largest proportion to the total ELCR (≈ 41.8%), followed by adolescents (13–17 years) and children (8–12 years), each accounting for approximately 16–18%. The lowest contribution was observed in the elderly group (> 65 years), with a share of 7.8% of the total risk.

These results highlight the substantial influence of adult consumption patterns and the importance of considering age-specific physiological sensitivity when evaluating lifetime radiological health risks. Such age-dependent variability in cancer risk assessment aligns with advanced modelling approaches emphasizing the integration of radiological parameters into excess lifetime cancer risk estimation frameworks [57].

Conclusion

This study assessed the radiological health risks associated with the consumption of breakfast cereals and biscuits commonly marketed in Turkey. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K varied depending on product type and ingredient composition but remained within internationally accepted safety limits. The estimated annual committed effective doses (D_T) and excess lifetime cancer risk (ELCR) values for both children and adults were below the recommended thresholds established by global health and radiological protection organizations, indicating no immediate radiological hazard from regular consumption.

Children and adolescents exhibited comparatively higher ingestion doses, underscoring the importance of age-specific assessments in evaluating dietary radiological exposure. Continuous monitoring is recommended, particularly for foods consumed frequently or in large quantities. Ingredient composition, agricultural practices, and the geographical origin of raw materials significantly influence radionuclide levels in processed foods. Overall, these findings provide valuable baseline data for national food safety frameworks and contribute to the advancement of future radiological risk assessments and public health policy development.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Fatma Çifcibaşı, İlyas Çağlar, and Gülçin Bilgici Cengiz. The manuscript was written by Gülçin Bilgici Cengiz, and all authors commented on previous versions of the manuscript. All authors read and approved the final version of the manuscript.

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Declarations

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

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