Journal of Food Composition and Analysis 151 (2026) 108958

Contents lists available at ScienceDirect

Journal of Food Composition and Analysis

journal homepage: www.elsevier.com/locate/jfca

Analysis of toxic and radiotoxic heavy metals in some cereal grains consumed in Türkiye and assessment of potential health risk

Şeref Turhan [a,*], Ergin Murat Altuner [b], Aslı Kurnaz [a], Kenan Akyol [c], Aybaba Hançerlioğulları [a], Aydan Altıkulaç [d]

[a] Department of Physics, Faculty of Science, Kastamonu University, Kuzeykent, Kastamonu 37150, Türkiye
[b] Department of Biology, Faculty of Science, Kastamonu University, Kuzeykent, Kastamonu 37150, Türkiye
[c] Department of Physics, Institute of Graduate Education, Kastamonu University, Kuzeykent, Kastamonu 37150, Türkiye
[d] Muğla Sıtkı Koçman University, Ula Ali Koçman Vocational School, Ula, Muğla 48640, Türkiye

A R T I C L E I N F O

Keywords:
Cereal grains
Health risk assessment
Heavy metal
Natural radioactivity
Thorium
Uranium

A B S T R A C T

This study analyzed the concentrations of toxic (Cr, Co, Cu, etc.) and radiotoxic (U, Th) heavy metals (HMs) in 40 commercial cereal samples consumed in Türkiye by using an energy dispersive X-ray fluorescence spectrometer. Health risks caused by ingestion of cereal samples were assessed using the hazard index (HI), annual effective dose (E_{Eff}), and the excess lifetime cancer risk (LCR) models. The average concentrations (mg/kg dry weight) of HMs analyzed in the samples were 2.7 (Cr), 6.4 (Co), 7.9 (Cu), 49.8 (Fe), 49.4 (Mn), 7.6 (Ni), 40.4 (Zn), 1.0 (U), and 1.4 (Th). Wheat and maize showed HI $>$ 1, indicating potential concern for consumers. The total annual effective dose exceeded global averages primarily due to Th in cereal samples. Findings highlight the need for monitoring and consumer guidance.

1. Introduction

Cereal grains (wheat, corn, rice, barley, rye, oats, etc.) are an important source of nutrition because they provide essential nutrients for the human body. Wheat is particularly important due to its suitability for bread-making. Türkiye is a suitable country for growing a variety of grain crops due to its diverse climate and soil conditions. The most commonly grown grains in Türkiye are wheat, barley, corn, rye, oats, and rice. Food safety, which means the presence or absence of harmful pollutants in food at acceptable levels for the health of consumers, is one of the crucial issues for consumers, producers, and governments (Amarloei et al., 2025). Toxic heavy metal (HM) pollution has become a major global environmental issue due to its permanence, irreversibility, invisibility, and non-degradability (Luo et al., 2024). The pollution of HMs can originate from lithogenic processes (volcanic activity, soil erosion, etc.) and anthropogenic activities such as mining, metal-containing chemicals used in agriculture (artificial fertilizers, pesticides, and herbicides), etc. (Ali et al., 2019; Briffa et al., 2020). The greatest risk posed by toxic HMs to human health is related to exposure to hazardous metals found in staple foods such as cereal grains and legumes (Adam et al., 2022). Toxic HMs can enter the human body through various routes such as ingestion, inhalation, and dermal contact. Plant-based foods contain terrestrial radionuclides in naturally occurring uranium (^{238}U) and thorium (^{232}Th) radioactive series, and potassium radioisotope (^{40}K) (UNSCEAR, 2000). ^{238}U and ^{232}Th are both radiotoxic HMs and chemotoxic to humans due to the effects of ionizing radiation caused by their radioactive decay and chemical toxicity from absorption into the body (Turhan, 2020).

Analysis and regular monitoring of toxic and radiotoxic HMs and other contaminants in foods is vital to ensure and maintain food safety. To date, numerous studies have been conducted to determine the levels of toxic or radiotoxic HMs in cereal grains grown in different countries (Hosseini et al., 2006; Jibiri et al., 2007; Lindahl et al., 2011; Tawalbeh et al., 2011; Ali and Al-Qahtani, 2012; Lenka et al., 2013; Baz and Alamoudi, 2017; Ercilla-Montserrat et al., 2018; Salih, 2018; Obasi et al., 2022; Hasan et al., 2022; Vasilachi et al., 2023; Madomguia et al., 2024; Wang et al., 2024; Amarloei et al., 2025; Bedoya-Perales et al., 2025; Kumar et al., 2025; Rafaqat et al., 2025; Oudh et al., 2025). According to our literature review, very few studies were conducted on the analysis of toxic and/or radiotoxic HMs in cereal grain products grown in Türkiye and on the assessment of health risks arising from HMs, and these studies are generally related to wheat (Tekin et al., 2018; Sultan

* Corresponding author.
E-mail addresses: serefturhan63@gmail.com, sturhan@kastamonu.edu.tr (Ş. Turhan).

https://doi.org/10.1016/j.jfca.2026.108958

Available online 29 January 2026

Table 1
Information on commercial cereal grains consumed in Türkiye.

Sample code	Cereal type	Location of production	Consumption (kg/y) *
CER1–1	Wheat	İzmir	178.6
CER1–2		Kastamonu (İhsangazi)	
CER1–3		Samsun (Çarşamba)	
CER1–4		Kastamonu (Ilgaz)	
CER1–5		Kastamonu	
CER1–6		Gaziantep	
CER1–7		Sakarya	
CER1–8		Nevşehir	
CER1–9		Kastamonu	
CER1–10		Kastamonu	
CER1–11		Samsun	
CER1–12		Sivas	
CER1–13		İzmir	
CER1–14		Gaziantep	
CER1–15		Kastamonu	
CER1–16		Kastamonu	
CER1–17		Gaziantep	
CER1–18		Siirt	
CER1–19		Gaziantep	
CER1–20		Gaziantep	
CER2–1	Rice	Kastamonu (Tosya)	8.8
CER2–2		Pakistan (Imported)	
CER2–3		Samsun (Bafra)	
CER2–4		Çorum (Osmancık)	
CER2–5		China (Imported)	
CER2–6		Italy (Imported)	
CER2–7		Thailand (Imported)	
CER2–8		Kastamonu (Tosya)	
CER2–9		Kastamonu (Tosya)	
CER2–10		Bolu	
CER3–1	Maize	Samsun (Çarşamba)	19
CER3–2		Kahramanmaraş	
CER3–3		Kastamonu (İhsangazi)	
CER3–4		Samsun (Çarşamba)	
CER3–5		Aydın	
CER4–1	Barley	Kastamonu (Araç)	0.9
CER4–2		Kastamonu (İhsangazi)	
CER5–1	Oats	Germany (Imported)	1.3
CER5–2		Russia (Imported)	
CER5–3		Mersin	

*Taken from Akyol (2024) and TÜİK (2025)

et al., 2020; Cengiz and Çağlar, 2021; Ozturk and Arici, 2021; Karapınar, 2023).

Keeping all these in mind, the purpose of this study is to determine the concentrations of toxic and radiotoxic HMs in cereal grains and assess potential health risks (PHRs). For this purpose, i) the concentrations of toxic (Cr, Co, Cu, Fe, Mn, Ni, and Zn) and radiotoxic (U and Th) HMs in the most consumed commercial cereal grain (wheat, rice, maize, barley, and oats) samples in Türkiye were analyzed by using an energy dispersive X-ray fluorescence (EDXRF) spectrometer, ii) the contents of U and Th were converted into activity concentrations of ^{238}U and ^{232}Th, and iii) non-carcinogenic and radiological PHRs were assessed for adults consumers by estimating hazard index, and total annual effective dose and the corresponding excess lifetime cancer risk. This is the first study in Türkiye to simultaneously quantify toxic and radiotoxic metals in multiple cereal types and assess both non-carcinogenic and radiological risks.

2. Materials and methods

2.1. Sample collection and preparation

Forty cereal grain samples, some of which are commonly consumed and grown in different regions of Türkiye, and some of which are imported, were purchased from supermarkets. Information on the cereal grain samples is provided in Table 1. Samples were not selected to represent specific regions; the study reflects commercial availability rather than geographic distribution. Samples brought to the laboratory were removed from their original packaging, and each sample was coded as CER. The sample preparation procedure for analysis was given in previous studies (Sultan et al., 2020; Turhan et al., 2024). Each sample was dried again at a constant temperature to remove moisture and ground into a powder using a ceramic mortar. Approximately 3 g of each homogenized sample was used for EDXRF analysis.

2.2. Analysis of toxic heavy metals

The elemental analysis of toxic and radiotoxic HMs in the samples was performed by an EDXRF spectrometer (SPECTRO XEPOS, Analytical Instruments GmbH). The technical specifications of the EDXRF spectrometer were presented in Table S1 (Sultan et al., 2020; Altıkulaç, Turhan, 2023; Turhan et al., 2024; Turhan, 2025). Quality assurance of EDXRF spectrometric analyses was performed using NIST SRM 2709 certified soil reference material (Table S2). The EDXRF spectrometer's target modifier, which optimizes excitation using polarization and secondary targets, has many different excitation conditions that guarantee the best determination of all elements from Na to U, ranging from less than mg/kg to percentages. Measurements were performed in a He gas environment. Samples for analysis were placed in 12 simultaneous sampling devices, and the analysis time was set to 1800 s. The overall uncertainty of the analytical procedure varied from 0.1 % to 16.6 %. The limit of detection (LOD) was calculated as follows (Van Grieken, Markowicz. 2001; Turhan et al., 2026):

$$\mathrm{LOD} = \frac{3 \times C_i}{N_C} \times \sqrt{\frac{N_B}{t}} \quad (1)$$

where C is the ith elemental concentration, N_B is the background count ratio, N_C is the net count ratio, and t is the counting time (Turhan et al., 2026). The LOD (in /kg) of toxic and radiotoxic HMs is found to be As 0.7; Cd 2.0; Cr 1.0; Co 3.0; Cu 0.6; Fe 1.3; Hg 1.0; Mn 1.1; Ni 1.0; Pb 1.0; Zn 0.6; Th 0.3; U 0.2. The limit of quantification (LOQ) of toxic and radiotoxic HMs is given as maximum values in Tables 2 and 4. The lowest and highest LOQ values were determined as 1.6 mg/kg (U) and 154.1 mg/kg (Fe), respectively.

2.3. Activity concentration of radiotoxic HM

The elemental concentration of U and Th analyzed in each cereal grain sample was converted into the activity concentration of ^{238}U and ^{232}Th as follows (Turhan, 2025):

$$\mathrm{A} = \frac{\mathrm{C} \times \lambda \times \mathrm{N_{Av}} \times \mathrm{h}}{\mathrm{M} \times F} \quad (2)$$

where A is the activity concentration of radiotoxic HM (Bq/kg); C is the elemental concentration of element (mg/kg); λ is the decay constant (1/s) of each radiotoxic HM; N_{AV} is Avogadro's number (6.023 ×1023 atoms/mol); h is the atomic abundance (%) (99.275 for ^{238}U and 99.98 for ^{232}Th); M is the atomic mass (kg/mol) (238.050 for ^{238}U and 232.038 for ^{232}Th) and F is a factor with a value of 1000,000 for ^{238}U and ^{232}Th.

2.4. Non-carcinogenic PHR assessment

Health risk assessment is conducted using the method developed by the United States Environmental Protection Agency (USEPA, 1989) to assess the degree and likelihood of adverse health effects in individuals exposed to toxic substances through ingestion, inhalation, and dermal contact (Turhan et al., 2024). PHR assessment is generally based on the estimation of carcinogenic and non-carcinogenic risks for various age groups (Miletić et al., 2023; Turhan et al., 2024). In this study, the non-carcinogenic PHR due to the ingestion of toxic HMs in the samples examined cereal grain samples was assessed for adult consumers by estimating the average daily dose (ADD in mg /kg·d), hazard quotient (HQ), and hazard index (HI). The ADD, HQ and HI were calculated as

Table 2
Elemental concentrations of toxic heavy metals in cereal grain samples.

Sample code	Elemental concentration (mg/kg)						
	Cr	Mn	Fe	Co	Ni	Cu	Zn
CER1–1	2.1 ± 0.2	68.2 ± 1.2	58.1 ± 1.2	4.1 ± 0.6	7.3 ± 0.3	8.7 ± 0.3	40.1 ± 0.3
CER1–2	2.4 ± 0.2	65.8 ± 1.3	56.0 ± 1.2	< LOD	7.3 ± 0.3	8.2 ± 0.2	38.4 ± 0.3
CER1–3	2.2 ± 0.2	57.7 ± 1.3	33.4 ± 0.8	5.3 ± 0.8	7.0 ± 0.3	6.7 ± 0.2	46.3 ± 0.4
CER1–4	2.3 ± 0.2	81.7 ± 1.5	44.0 ± 1.1	4.2 ± 0.6	6.5 ± 0.2	9.9 ± 0.2	39.9 ± 0.3
CER1–5	2.6 ± 0.3	72.2 ± 1.2	48.9 ± 1.1	9.0 ± 1.3	7.7 ± 0.3	10.1 ± 0.3	52.3 ± 0.4
CER1–6	< LOD	32.8 ± 0.6	45.6 ± 1.0	5.5 ± 0.8	8.7 ± 0.3	7.1 ± 0.2	26.6 ± 0.2
CER1–7	< LOD	23.2 ± 0.3	21.6 ± 0.5	< LOD	4.7 ± 0.2	7.3 ± 0.2	19.6 ± 0.2
CER1–8	3.5 ± 0.4	87.7 ± 1.0	87.7 ± 1.9	9.0 ± 1.3	7.0 ± 0.3	11.5 ± 0.4	63.5 ± 0.6
CER1–9	3.4 ± 0.4	91.3 ± 1.5	154.1 ± 3.3	12.4 ± 1.7	10.9 ± 0.4	8.1 ± 0.3	61.8 ± 0.5
CER1–10	3.3 ± 0.3	82.7 ± 1.6	94.4 ± 2.0	15.7 ± 2.2	12.4 ± 0.5	9.1 ± 0.3	68.6 ± 0.7
CER1–11	2.8 ± 0.3	73.3 ± 1.5	39.3 ± 0.8	< LOD	6.1 ± 0.2	7.4 ± 2.2	49.6 ± 0.5
CER1–12	2.9 ± 0.3	40.0 ± 0.8	39.5 ± 0.9	< LOD	13.6 ± 0.5	10.7 ± 0.4	44.9 ± 0.4
CER1–13	2.2 ± 0.2	64.1 ± 1.2	35.0 ± 0.7	6.9 ± 1.0	7.5 ± 0.3	6.9 ± 0.2	42.3 ± 0.3
CER1–14	1.6 ± 0.2	33.5 ± 0.6	17.2 ± 0.4	< LOD	5.6 ± 0.2	7.8 ± 0.2	35.7 ± 0.3
CER1–15	< LOD	80.4 ± 1.5	70.4 ± 1.5	< LOD	5.6 ± 0.2	10.0 ± 0.2	88.4 ± 0.9
CER1–16	2.3 ± 0.2	65.0 ± 1.2	58.6 ± 1.3	4.3 ± 0.6	5.8 ± 0.2	8.8 ± 0.3	62.8 ± 0.6
CER1–17	2.5 ± 0.2	63.3 ± 1.2	37.9 ± 0.8	< LOD	6.3 ± 0.2	10.4 ± 0.3	44.4 ± 0.4
CER1–18	1.8 ± 0.1	30.7 ± 0.6	12.1 ± 0.3	< LOD	4.7 ± 0.2	8.1 ± 0.3	28.0 ± 0.3
CER1–19	2.7 ± 0.2	85.2 ± 1.6	60.4 ± 1.3	4.2 ± 0.6	5.6 ± 0.2	9.1 ± 0.3	47.2 ± 0.4
CER1–20	1.7 ± 0.1	31.2 ± 0.6	17.6 ± 0.4	4.0 ± 0.6	5.8 ± 0.2	8.2 ± 0.2	33.6 ± 0.3
CER2–1	< LOD	17.1 ± 0.3	< LOD	4.3 ± 0.5	5.2 ± 0.2	9.5 ± 0.3	23.7 ± 0.2
CER2–2		7.8 ± 0.1	< LOD	< LOD	5.2 ± 0.2	7.2 ± 0.2	8.6 ± 0.1
CER2–3		25.3 ± 0.5	5.1 ± 0.1	5.9 ± 0.8	6.7 ± 0.3	5.6 ± 0.2	28.7 ± 0.3
CER2–4		21.5 ± 0.4	< LOD	4.2 ± 0.6	5.4 ± 0.2	4.6 ± 0.1	24.9 ± 0.2
CER2–5		20.4 ± 0.4	< LOD	< LOD	5.2 ± 0.2	7.5 ± 0.2	29.1 ± 0.2
CER2–6		14.6 ± 0.3	< LOD	< LOD	5.4 ± 0.2	5.9 ± 0.2	28.5 ± 0.2
CER2–7		17.4 ± 0.3	< LOD	4.4 ± 0.6	6.0 ± 0.2	6.0 ± 0.2	28.0 ± 0.2
CER2–8		31.8 ± 0.6	5.5 ± 0.1	6.8 ± 1.0	6.6 ± 0.3	7.2 ± 0.2	22.8 ± 0.2
CER2–9		18.5 ± 0.3	< LOD	4.1 ± 0.6	5.7 ± 0.2	5.0 ± 0.2	23.2 ± 0.2
CER2–10		45.4 ± 0.8	< LOD	4.2 ± 0.6	6.3 ± 0.2	8.3 ± 0.2	30.0 ± 0.2
CER3–1	< LOD	6.2 ± 0.1	10.8 ± 0.2	4.0 ± 0.6	6.4 ± 0.2	3.3 ± 0.1	7.9 ± 0.1
CER3–2	1.5 ± 0.1	31.4 ± 0.6	34.6 ± 0.7	4.2 ± 0.6	7.0 ± 0.3	7.0 ± 0.2	60.8 ± 0.5
CER3–3	3.9 ± 0.3	33.0 ± 0.6	48.1 ± 1.0	4.4 ± 0.6	7.4 ± 0.3	5.2 ± 0.2	48.3 ± 0.4
CER3–4	< LOD	5.6 ± 0.1	< LOD	7.7 ± 1.1	6.9 ± 0.3	3.8 ± 0.1	7.2 ± 0.1
CER3–5	4.4 ± 0.5	27.1 ± 0.5	38.8 ± 0.8	< LOD	7.1 ± 0.3	5.2 ± 0.2	46.6 ± 0.4
CER4–1	1.9 ± 0.2	57.6 ± 1.0	26.9 ± 0.6	5.5 ± 0.8	7.7 ± 0.3	7.2 ± 0.2	35.0 ± 0.3
CER4–2	3.4 ± 0.3	58.1 ± 1.0	137.0 ± 2.9	10.0 ± 1.4	7.9 ± 0.3	10.0 ± 0.3	55.5 ± 0.5
CER5–1	2.7 ± 0.2	106.9 ± 1.9	106.8 ± 2.2	8.1 ± 1.1	13.1 ± 0.5	12.9 ± 0.4	75.0 ± 0.6
CER5–2	3.0 ± 0.2	114.4 ± 2.1	52.9 ± 1.1	10.6 ± 1.5	27.6 ± 1.1	12.2 ± 0.4	55.1 ± 0.5
CER5–3	3.2 ± 0.3	86.7 ± 1.6	44.6 ± 0.9	7.2 ± 1.0	8.8 ± 0.4	8.9 ± 0.3	44.8 ± 0.4
Average	2.7	49.4	49.8	6.4	7.6	7.9	40.4
SE	0.1	4.7	5.6	0.5	0.6	0.3	2.9
Median	2.6	42.7	44.0	5.4	6.7	8.0	40.0
SD	0.7	29.7	35.4	3.0	3.9	2.2	18.2
Kurtosis	-0.2	-1.0	2.1	2.3	18.6	-0.1	0.1
Skewness	0.5	0.3	1.4	1.5	3.9	0.1	0.4
Min	< LOD	5.6	< LOD	< LOD	4.7	3.3	7.2
Max	4.4	114.4	154.1	15.7	27.6	12.9	88.4

SE: standard error; SD: standard deviation

follows (Miletić et al. 2023; Turhan et al. 2024):

$$ADD = \frac{C \times DI}{BM} \tag{3}$$

$$HQ = \frac{ADD}{R_f D} \tag{4}$$

$$HI = \sum_{i=1}^{n} HQ_i i = 1, 2, 3, \ldots n \tag{5}$$

where n is the number of toxic HMs; C is the elemental concentration (mg/kg) of toxic HM analyzed in the samples; DI is the daily intake amount for each type of grain, given in kg/y in the last column of Table 1 and it was converted to kg/d; BM is the average body mass (70 kg) and $R_f D$ is the oral reference dose (mg/kg·d). The values of $R_f D$ were taken as 14×10^{-2} (Co), 3×10^{-3} (Cr-VI), 5×10^{-3} (Cu), 7×10^{-1} (Fe), 1.4×10^{-1} (Mn), 2×10^{-2} (Ni), and 3×10^{-1} (Zn) (Miletić et al., 2023; Turhan et al., 2024). If HQ or HI > 1, there is a serious PHR for humans, and if HQ or HI < 1, the effect of toxic HMs is negligible (Miletić et al., 2023; Turhan et al., 2024).

2.5. *Radiological PHR assessment*

Radionuclides taken into the human body can move throughout the

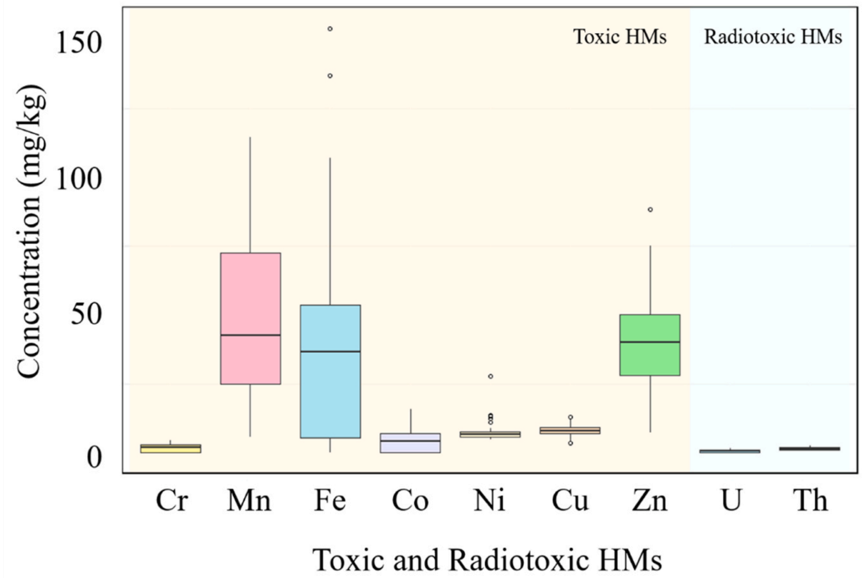

Fig. 1. Distributions of toxic (in the yellow area) and radiotoxic (in the blue area) heavy metals. The hierarchy of elemental concentrations highlights the prevalence of essential yet toxic trace elements compared to the relatively low but persistent presence of terrestrial radionuclides across all analyzed cereal samples.

body via the blood or lymph. Internal organs and tissues have unique propensities to retain certain types of radionuclides. Accumulation and retention of U in organs or tissues (liver, kidney, and bone) can persist for days or even years, potentially resulting in unpredictable deleterious health effects (Ma et al., 2020). They can accumulate in the lungs, liver, or bones (Popoola et al., 2024). Internal exposure results from the irradiation of organs and tissues with ionizing radiation emitted by these radionuclides, and their effects on tissues are influenced by their biological and physical half-lives over time (Shuaibu et al., 2023). In this study, the radiological PHR was assessed for adult consumers by estimating the annual effective dose and excess lifetime cancer risk. The annual effective dose was estimated as follows (UNSCEAR, 2000):

$$E_{Eff} = CR \times \sum_{j} A_j \times DCF_j \tag{6}$$

where E_{Eff} is the annual effective dose (μSv/y); CR is the annual consumption of cereal grain per capita (kg/y) given in the last column of Table 1; A is the activity concentration (Bq/kg) of radiotoxic HM, and DCF_j is the dose conversion factor of radiotoxic HM given as 0.045 and 0.23 μSv/Bq for ^{238}U and ^{232}Th (ICRP, 2012; UNSCEAR, 2000). The corresponding lifetime cancer risk is estimated as follows (Altamemi et al., 2021):

$$LCR = E_{Eff} \times ALT \times RC \tag{7}$$

where LCR is the excess lifetime cancer risk; ALT is the average lifetime

Table 3
Comparison of concentrations of toxic heavy metals in cereal grain samples with other studies available in the literature.

Country	Cereal type	Concentration of toxic heavy metal (mg/kg)							Ref.
		Cr	Mn	Fe	Co	Ni	Cu	Zn	
Ethiopia	Wheat	0.4	7.7	10.6	0.4	0.3	1.7	8.5	Tegegne, 2015
Nigeria	Wheat	0.4	63.3	48.1	0.2	0.7	4.9	26.1	Ikem et al., 2023
Italy	Wheat	-	-	-	-	0.7	4.3	57.7	Brizio et al., 2016
Iran	Wheat	78.3	-	-	0.1	-	-	-	Amarloei et al., 2025
Asia countries	Wheat	2.5	81.6	0.03	4.4	3.1	5.6	25.7	Kerketta et al., 2023
Saudi Arabia	Wheat	-	13.9	128.8	-	-	4.9	24.4	Ali and Al-Qahtani, 2012
Türkiye	Wheat	2.5	61.5	51.6	7.1	7.3	8.7	46.7	This study
Italy	Rice	-	-	-	-	0.2	1.4	27.8	Brizio et al., 2016
Iran	Rice	87.6	-	-	0.1	-	-	-	Amarloei et al., 2025
USA	Rice	-	-	25.0	-	-	-	24.0	TatahMentan et al., 2023
Asia countries	Rice	2.2	-	89.0	3.0	2.7	7.3	19.8	Kerketta et al., 2023
Saudi Arabia	Rice	-	9.8	84.1	-	-	7.8	27.8	Ali and Al-Qahtani, 2012
Türkiye	Rice	-	22.0	5.3	4.8	5.8	6.7	24.8	This study
Ethiopia	Maize	0.5	0.4	0.4	0.2	0.1	0.1	0.7	Getu et al., 2022
Nigeria	Maize	0.3	10.0	33.8	0.3	0.5	9.3	24.0	Ikem et al., 2023
Italy	Maize	-	-	-	-	0.7	2.0	37.1	Brizio et al., 2016
Iran	Maize	93.8	-	-	0.002	-	-	-	Amarloei et al., 2025
Asia countries	Maize	1.4	-	68.6	15.1	1.4	6.1	30.1	Kerketta et al., 2023
China	Maize	2.4	-	-	-	-	1.0	17.0	Liu et al., 2020
Türkiye	Maize	3.5	20.7	33.1	5.1	7.0	4.9	34.2	This study
Ethiopia	Barley	0.1	1.7	31.9	0.2	-	0.2	3.9	Tegegne, 2015
Italy	Barley	-	-	-	-	0.2	5.0	63.5	Brizio et al., 2016
Türkiye	Barley	2.7	57.9	82.0	7.8	7.8	8.6	45.3	This study
Italy	Oats	-	-	-	-	4.7	3.8	51.3	Brizio et al., 2016
Türkiye	Oats	3.0	102.7	68.1	8.6	16.5	11.3	58.3	This study

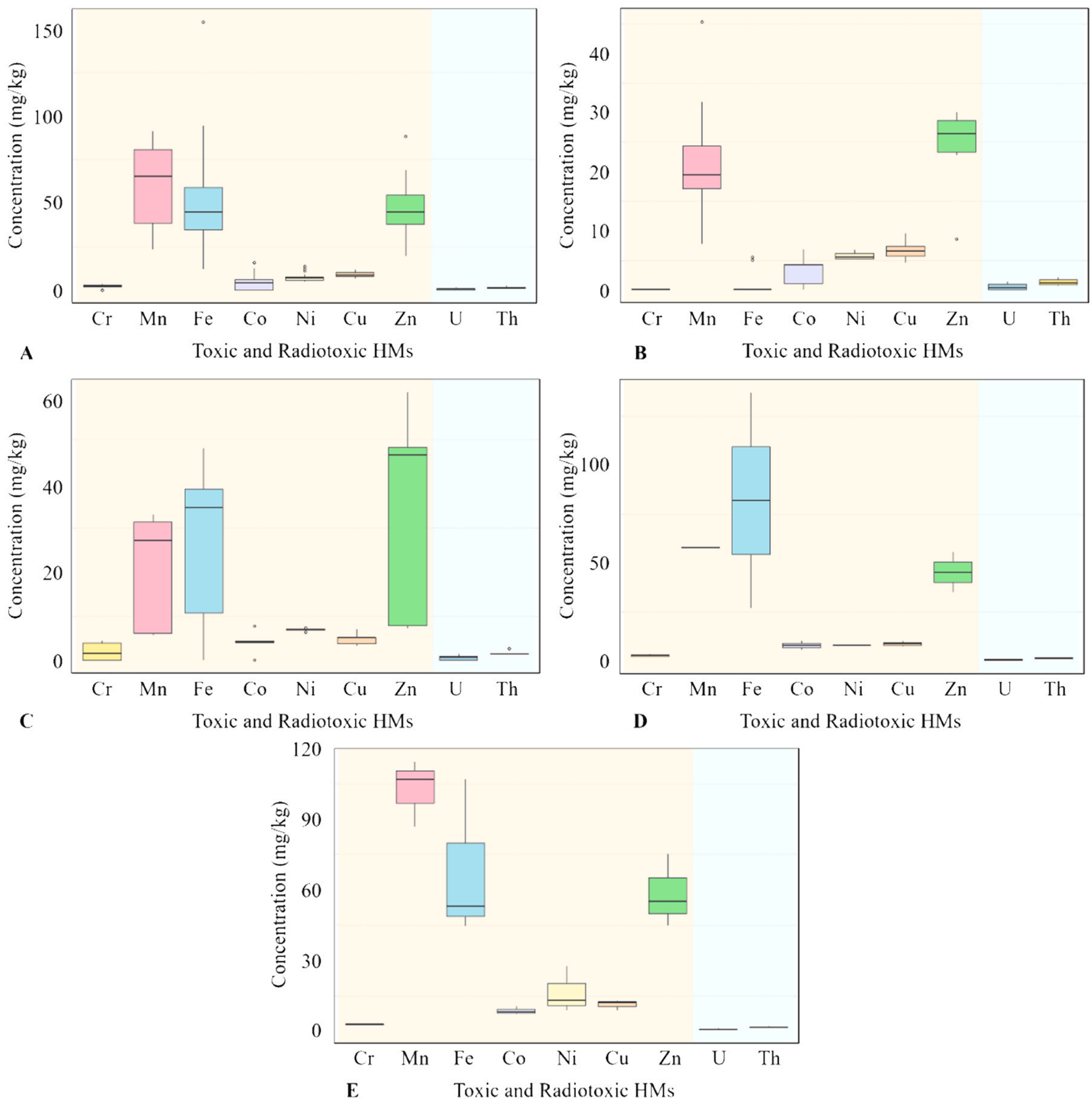

Fig. 2. Box plot showing comparison of toxic (in the yellow area) and radiotoxic (in the blue area) heavy metals analyzed in cereal products: (A) Wheat (CER1), (B) Rice (CER2), (C) Maize (CER3), (D) Barley (CER4), and (E) Oat (CER5). The significant variability observed in element-specific accumulation suggests that metal uptake is highly dependent on cereal species and soil-plant transfer characteristics.

(70 y) for adult consumers, and RC is the fatal cancer risk factor per Sv (0.057/Sv) for the public (ICRP, 1990; Altamemi et al., 2021).

2.6. Statistical analysis

To identify statistically significant distinctions across the analyzed data, a rigorous preliminary assessment of the data's distributional attributes was performed. This involved utilizing the Shapiro-Wilk test for normality and Levene's test for assessing variance homogeneity. Although various transformations were explored to improve normality and homogeneity of variance, the data continued to deviate from a normal distribution. Therefore, the non-parametric Kruskal-Wallis test ($\alpha = 0.05$) was performed on the raw (untransformed) data to identify statistically significant differences. For variables exhibiting a significant Kruskal-Wallis result, a Dunn's post-hoc test, employing a Bonferroni adjustment for multiple comparisons, was subsequently conducted to identify the specific pairs driving these differences. Additionally, Pearson correlation coefficients were calculated to investigate correlations between toxic and radiotoxic HMs in the samples. All analyses were conducted in R Studio, version 2023.06 (R Core Team R, 2023).

3. Results and discussion

3.1. Toxic and radiotoxic HM contents of cereal grains

The strengths of this study are the novel integration of toxic and radiotoxic heavy metals in cereals in Türkiye, the inclusion of non-carcinogenic and radiological risk assessments, and a clear comparison with literature data in the discussion section. A limitation of this study is that differences in toxic and radiotoxic metal concentrations in the samples were not related to the soil characteristics in which the crops were grown.

The contents of arsenic (As), Cd, mercury (Hg), and Pb, which are considered to be in the carcinogenic HMs class, were found below the detection limit (As < 0.7 mg/kg; Cd < 2.0 mg/kg; Hg < 1.0 mg/kg and Pb < 1.1 mg/kg). The elemental concentrations and some descriptive statistical data of toxic HMs analyzed in cereal grain samples are given in Table 2. The frequency distributions of each HM after the square root transformation are shown in Fig. 1. Fig. 1 is a boxplot, which provides a comprehensive overview of the concentrations of the investigated toxic and radiotoxic HMs, aggregated across all analyzed cereal products. Each box plot summarizes the median, interquartile range (IQR), and presence of potential outliers for each HM. A distinct hierarchy in elemental concentrations is clearly observable. Mn, Fe, and Zn consistently exhibited the highest median concentrations among all analyzed HMs. Furthermore, these elements displayed substantial variability, characterized by notably wider interquartile ranges. Conversely, Cr, Co, Ni, Cu, U, and Th generally presented much lower median concentrations. U, in particular, registered the lowest levels and a relatively narrow interquartile range, indicating its consistently low presence across the majority of samples. The Kruskal-Wallis and subsequent Dunn's post-hoc test revealed significant differences for the elemental concentrations of Mn, Fe, Ni, Cu, and Zn when compared to other toxic HMs ($p < 0.05$). Table 3 represents a comparison of concentrations of toxic HMs with those in similar investigations in other countries. From Table 2, toxic HM contents of cereal grain samples varied depending on the geological, geochemical structure, and natural processes of the region where the samples were produced. Cr was observed below the detection limit (1.0 mg/kg) in all rice samples. According to their average contents, toxic HMs analyzed above the detection limit in cereal grain samples were listed as follows: Cr < Co < Ni < Cu < Zn < Mn < Fe. The comparison of toxic and radiotoxic HMs in cereal products (groups) is presented in Fig. 2. From Fig. 2, overall, the concentration levels of Mn, Fe, and Zn appear higher across most cereal types when compared to other analyzed HMs. In contrast, elements such as Cr, Co, Ni, Cu, and the radiotoxic isotopes U and Th generally exhibit much lower concentration ranges. Significant variability in concentrations is observed both within specific HMs across different cereal types and for certain HMs within individual cereal products, as indicated by the spread of the boxes and presence of outliers.

According to their average contents, toxic HMs analyzed in the cereal grain groups were listed as follows: Cr < Co < Ni < Cu < Zn < Fe < Mn (CER1); Co < Fe < Ni < Cu < Mn < Zn (CER2); Cr < Cu < Co < Ni < Mn < Fe < Zn (CER3); Cr < Co < Ni < Cu < Zn < Mn < Fe (CER4) and Cr < Co < Cu < Ni < Zn < Fe < Mn (CER5).

3.1.1. Chromium

Cr is both an essential and toxic HM for the human body. Cr(III) is a biologically essential element due to its role in carbohydrate and sugar metabolism and protein, while Cr(VI) is potentially toxic (Tchounwou et al., 2012). The contents of Cr analyzed in the cereal grain samples varied from < LOD to 4.4 ± 0.5 mg/kg with an average of 2.7 ± 0.1 mg/kg. The highest content of Cr was analyzed in sample CER3–5 (maize from Aydın province). Statistical analysis revealed significant differences in Cr content between CER1 and CER2, and also between CER2 and CER5 ($p < 0.05$). From Table 3, the average Cr in CER1 is similar to the average concentration in wheat consumed in eleven Asian countries (China, India, Pakistan, Bangladesh, etc.). The average Cr is significantly lower than that in Iranian wheat, while it is higher than that in Nigerian and Ethiopian wheat samples. The average Cr in CER3 is significantly lower than that in Iranian maize, while it is higher than that in maize samples consumed in Asian countries, Nigeria, and Ethiopia. The average Cr in CER4 is higher than that in Ethiopian barley.

3.1.2. Manganese

Mn is an essential nutrient for many indispensable biochemical processes in the human body and is an important cofactor in many enzyme-related processes (Kulshreshtha et al., 2021). Adverse health effects can occur due to insufficient intake or excessive exposure. Mn toxicity can lead to serious pathologies in the central nervous system, and the typical symptom of Mn overexposure is Parkinsonism (Kulshreshtha et al., 2021). The contents of Mn varied from 5.6 ± 0.1–114.4 ± 2.1 mg/kg with an average of 49.4 ± 4.7 mg/kg. The highest Mn content was found in sample CER5–2 (oats imported from Russia), and the lowest in sample CER3–4 (corn from Samsun province). The statistical analysis indicated that the Mn content differed significantly when comparing CER1 with CER2, and similarly, when comparing CER1 with CER3, CER2 with CER5, and CER3 with CER5 ($p < 0.05$). From Table 3, the average Mn in CER1 is in agreement with that in Nigerian wheat. The average Mn is higher than that in wheat samples consumed in Saudi Arabia and Ethiopia, while it is lower than that in wheat samples consumed in Asian countries. The average Mn in CER2 is higher than that in Saudi Arabian rice. The average Mn in CER3 is higher than that in maize samples consumed in Nigeria and Ethiopia. The average Mn in CER4 is significantly higher than that in Ethiopian barley.

3.1.3. Iron

Fe is both an essential micronutrient for the human body and a toxic HM due to its ability to produce free radicals that can damage biological systems (Yadav and Singh, 2022). On the other hand, Fe deficiency is the most common nutritional deficiency and the primary trigger of anaemia. However, excess Fe can accumulate in organs such as the heart, liver, and endocrine glands (Yadav and Singh, 2022). The contents of Fe varied from < LOD to 154.1 ± 3.3 mg/kg with an average of 49.8 ± 5.6 mg/kg. The highest Fe content was analyzed in sample CER1–9 (wheat from Kastamonu province). Statistical analysis presented significant differences in Fe content between CER1 and CER2, and also between CER2 and CER5 ($p < 0.05$). From Table 3, the average Fe in CER1 is lower than that in Saudi Arabian wheat, while it is higher than that in wheat samples consumed in Asian countries, Nigeria, and Ethiopia. The average Fe in CER2 is significantly lower than that in rice samples consumed in Asian countries, the USA, and Saudi Arabia. The average Fe in CER3 is in agreement with that in Nigerian maize. The average Fe in CER3 is lower than that in maize samples consumed in Asian countries, while it is significantly higher than that in Ethiopian maize. The average Fe in CER4 is higher than that in Ethiopian barley. Higher Mn and Fe levels may reflect natural abundance in Turkish soils and their high mobility in plant uptake systems.

3.1.4. Cobalt

Co is both an essential element constituent of vitamin B12 and a toxic HM (Leyssens et al., 2017). Excessive Co exposure causes a complex clinical syndrome that includes various cardiovascular, neurological, and endocrine deficiencies (Leyssens et al., 2017). The contents of Co varied from < LOD to 15.7 ± 2.2 mg/kg with an average of 6.4 ± 0.5 mg/kg. The highest content of Co was found in sample CER1–10 (wheat from Kastamonu province). Statistical analysis indicated no significant difference in Co content across all CER samples ($p > 0.05$). The average Co in CER1 and CER2 is higher than that in wheat and rice samples consumed in the countries given in Table 3. The average Co in CER3 is higher than that in maize samples consumed in Iran, Nigeria, and Ethiopia, while it is lower than that in maize samples consumed in Asian countries. The average Co in CER4 is significantly higher than that in Nigerian barley.

3.1.5. Nickel

Ni is both an essential mineral that can prevent anaemia, regulate prolactin, and stabilize DNA and RNA structures, and a toxic HM that can affect many organs (Nematollahi et al., 2021). The contents of Ni varied from 4.7 ± 0.2–27.6 ± 1.1 mg/kg with an average of 7.6 ± 0.6 mg/kg. The highest content of Ni was found in sample CER5–2 (oats imported from Russia), and the lowest in sample CER1–7 (wheat from Sakarya province). Significant statistical differences in Ni content were observed for the comparisons between CER2 and CER5 ($p < 0.05$). The average Ni in CER1 and CER2, CER3, and CER4 is higher than that in wheat, rice, maize, and barley samples consumed in the countries given in Table 3.

Table 4
Elemental and activity concentrations of radiotoxic heavy metals in cereal grain samples.

Sample code	Elemental concentration (mg/kg)						Activity concentration (Bq/kg)					
	U			Th			^{238}U			^{232}Th		
CER1–1	< LOD			1.4	±	0.2	< LOD			5.7	±	0.6
CER1–2	< LOD			0.7	±	0.1	< LOD			2.8	±	0.3
CER1–3	0.8	±	0.1	1.2	±	0.1	9.9	±	0.7	4.9	±	0.5
CER1–4	< LOD			0.7	±	0.1	< LOD			2.8	±	0.3
CER1–5	0.6	±	0.1	1.6	±	0.2	7.4	±	0.1	6.5	±	0.7
CER1–6	1.6	±	0.1	1.6	±	0.2	19.8	±	1.5	6.5	±	0.7
CER1–7	1.0	±	0.1	0.5	±	0.1	12.3	±	0.9	2.0	±	0.2
CER1–8	0.6	±	0.1	1.6	±	0.2	7.4	±	0.1	6.5	±	0.7
CER1–9	1.4	±	0.1	1.9	±	0.2	17.3	±	1.2	7.7	±	0.8
CER1–10	1.2	±	0.1	2.4	±	0.3	14.8	±	1.0	9.7	±	1.1
CER1–11	1.0	±	0.1	1.1	±	0.1	12.3	±	0.9	4.5	±	0.5
CER1–12	1.0	±	0.1	1.0	±	0.1	12.3	±	0.9	4.1	±	0.4
CER1–13	1.5	±	0.1	2.3	±	0.3	18.5	±	1.3	9.3	±	1.0
CER1–14	< LOD			1.1	±	0.1	< LOD			4.5	±	0.5
CER1–15	0.6	±	0.1	1.1	±	0.1	7.4	±	0.1	4.5	±	0.5
CER1–16	1.0	±	0.1	2.1	±	0.2	12.3	±	0.9	8.5	±	0.9
CER1–17	0.6	±	0.1	1.2	±	0.1	7.4	±	0.1	4.9	±	0.5
CER1–18	0.9	±	0.1	0.9	±	0.1	11.1	±	0.8	3.7	±	0.4
CER1–19	< LOD			1.1	±	0.1	< LOD			4.5	±	0.5
CER1–20	< LOD			0.8	±	0.1	< LOD			3.2	±	0.4
CER2–1	< LOD			0.9	±	0.1	< LOD			3.7	±	0.4
CER2–2	< LOD			1.2	±	0.1	< LOD			4.9	±	0.5
CER2–3	1.4	±	0.1	1.9	±	0.2	17.3	±	1.2	7.7	±	0.8
CER2–4	< LOD			1.3	±	0.1	< LOD			5.3	±	0.6
CER2–5	< LOD			0.9	±	0.1	< LOD			3.7	±	0.4
CER2–6	1.0	±	0.1	0.7	±	0.1	12.3	±	0.9	2.8	±	0.3
CER2–7	0.9	±	0.1	1.9	±	0.2	11.1	±	0.8	7.7	±	0.8
CER2–8	1.4	±	0.1	2.1	±	0.2	17.3	±	1.2	8.5	±	0.9
CER2–9	< LOD			1.0	±	0.1	< LOD			4.1	±	0.4
CER2–10	0.6	±	0.1	1.1	±	0.1	7.4	±	0.1	4.5	±	0.5
CER3–1	0.7	±	0.1	1.4	±	0.2	8.6	±	0.1	5.7	±	0.6
CER3–2	< LOD			1.4	±	0.2	< LOD			5.7	±	0.6
CER3–3	0.9	±	0.1	1.4	±	0.2	11.1	±	0.8	5.7	±	0.6
CER3–4	1.4	±	0.1	2.6	±	0.3	17.3	±	1.2	10.5	±	1.2
CER3–5	< LOD			1.5	±	0.2	< LOD			6.1	±	0.7
CER4–1	0.9	±	0.1	1.8	±	0.2	11.1	±	0.8	7.3	±	0.8
CER4–2	< LOD			1.0	±	0.1	< LOD			4.1	±	0.4
CER5–1	0.6	±	0.1	1.7	±	0.2	7.4	±	0.1	6.9	±	0.8
CER5–2	1.2	±	0.1	2.1	±	0.2	14.8	±	1.0	8.5	±	0.9
CER5–3	0.8	±	0.1	1.7	±	0.2	9.9	±	0.7	6.9	±	0.8
Average	1.0			1.4			12.2			5.7		
SE	0.1			0.1			0.6			0.3		
Median	1.0			1.4			11.7			5.5		
SD	0.3			0.5			3.9			2.1		
Kurtosis	-1.0			-0.5			-1.0			-0.5		
Skewness	0.4			0.5			0.4			0.5		
Min	< LOD			0.5			< LOD			2.0		
Max	1.6			2.6			19.8			10.5		

3.1.6. Copper

Cu is both an essential element that plays a role in many physiological processes, such as infant development and growth, fetal brain development, bone strength, cholesterol metabolism, and immune function, and a toxic HM that can negatively affect the functions of important organs such as the brain, kidneys, and liver at high exposure (Taylor et al., 2020). The contents of Cu varied from 3.3 ± 0.1–12.9 ± 0.9 with an average of 7.9 ± 0.3 mg/kg. The highest Cu content was found in sample CER5–1 (oats imported from Germany), and the lowest in sample CER3–1 (corn from Samsun province). The statistical analysis showed that the Cu content differed significantly when comparing CER1 with CER3, and similarly, when comparing CER2 with CER5 and CER3 with CER5 ($p < 0.05$). The average Cu in CER1 is higher than that in wheat samples consumed in the countries given in Table 3. The average Cu in CER2 is lower than that in rice samples consumed in Asian countries and Saudi Arabia, while it is higher than that in Italian maize. The average Cu in CER3 is lower than that in maize samples consumed in Asian countries and Nigeria, while it is higher than that in maize samples consumed in Ethiopia, Italy, and China. The average Cu in CER4 is higher than that in barley samples consumed in Ethiopia and Italy. The average Cu in CER5 is higher than that in Italian oats.

3.1.7. Zinc

Zn is both an important essential element that can bind to more than 300 enzymes and more than 2000 transcriptional factors, and a toxic HM that excessive doses can cause gastrointestinal disorders (Chasapis et al., 2020; Nematollahi et al., 2021). The contents of Zn varied from 7.2 ± 0.1–88.4 ± 0.9 mg/kg with an average of 40.4 ± 2.9 mg/kg. The highest content of Zn was found in sample CER1–15 (wheat from Kastamonu province), and the lowest content was found in sample CER3–4 (maize from Samsun province). Statistical analysis revealed significant differences in Zn content between CER1 and CER2, and also between CER2 and CER5. The average Zn in CER1 is higher than that in wheat samples consumed in countries given in Table 3, except for Italy. The average Zn in CER2 is in agreement with that in rice samples consumed in the USA. The average Zn in CER2 is higher than that in rice samples consumed in Asian countries, while it is lower than that in rice samples consumed in Italy and Saudi Arabia. The average Zn in CER3 is higher than that in maize samples consumed in countries given in Table 3, except for Italy. The average Zn in CER4 is higher than that in Ethiopian barley, while it is lower than that in Italian barley. The average Zn in CER5 is in agreement with that in Italian oats.

3.1.8. Uranium and thorium

The elemental and activity concentrations and some descriptive statistical data of radiotoxic HMs analyzed in cereal grain samples are given in Table 4. The activity concentration of ^{238}U analyzed in the cereal grain samples varied from < LOD to 19.8 ± 1.5 Bq/kg with an average of 12.2 ± 0.6 Bq/kg. The highest activity concentration of ^{238}U was found in sample CER1–6 (wheat from Gaziantep province). According to the average activity contents of ^{238}U, the cereal grain groups were ranked as follows: CER2 (13.1 Bq/kg) > CER3 (12.3 Bq/kg) > CER1 (12.2 Bq/kg) > CER4 (11.1 Bq/kg) > CER5 (10.7 Bq/kg). The activity concentration of ^{232}Th analyzed in the cereal grain samples varied from 2.0 ± 0.2–10.5 ± 1.2 Bq/kg with an average of 5.7 ± 0.3 Bq/kg. The highest activity concentration of ^{232}Th was found in sample CER3–4 (maize from Samsun province), and the lowest activity concentration was found in sample CER1–7 (wheat from Sakarya province). According to the average activity contents of ^{232}Th, the cereal grain groups were ranked as follows: CER5 (7.4 Bq/kg) > CER3 (6.7 Bq/kg) > CER4 (5.7 Bq/kg) > CER1 (5.3 Bq/kg) > CER2 (5.27 Bq/kg). Statistical analysis revealed no significant difference in the content of ^{238}U and ^{232}Th across any of the CER samples ($p > 0.05$). Lower U and Th uptake is consistent with limited plant transfer coefficients reported in previous studies.

In addition to these analyses, Pearson correlation analysis was conducted to examine pairwise correlations among toxic and radiotoxic HMs in the samples. Fig. 3 presents a correlation matrix illustrating the pairwise relationships among concentrations of various toxic and radiotoxic HMs. The upper triangle of the matrix displays the Pearson correlation coefficients via a color scale (blue for positive, red for negative, darker shades indicating stronger correlations), with asterisks (*) denoting statistically significant correlations ($p < 0.05$). The lower triangle visually represents the strength and direction of these correlations using pie charts. A prominent pattern observed is the strong, positive, and statistically significant intercorrelations among most of the toxic HMs. For instance, Cr shows significant positive correlations with Mn, Fe, Co, Ni, Cu, and Zn, while Mn and Fe exhibit particularly strong positive relationships with each other and with Co, Ni, Cu, and Zn. These widespread positive correlations strongly suggest common geological origins or shared anthropogenic inputs for these elements within the study area. Furthermore, it could imply similar geochemical behavior in soils, such as comparable mobility under specific pH or redox conditions, or shared adsorption characteristics with soil organic matter and clay particles. From a biological perspective, these correlations might also point to non-specific or shared uptake mechanisms by cereal plants, where common transporters facilitate the acquisition of multiple divalent or trivalent metal ions from the soil solution. In contrast, the radiotoxic HMs generally displayed weaker and non-significant correlations with the majority of the toxic heavy metals, with a notable exception. Both ^{238}U and ^{232}Th showed a statistically significant and moderately positive correlation with Ni, and a moderate positive correlation was observed between Co and ^{232}Th. This distinct behavior for the radionuclides suggests different primary geochemical controls or unique speciation compared to the other toxic metals. ^{238}U and ^{232}Th are often associated with specific mineral phases, such as phosphates, silicates or exhibit lower mobility under typical environmental conditions than many HMs (Lefebvre et al., 2021). The significant correlation with Co might indicate a localized geochemical association, where these three elements are co-mobilized or co-precipitated from specific mineralizations present in the soil. Alternatively, it could imply a less common, shared uptake pathway in plants that is distinct from the primary routes for other heavy metals. In addition, there is also a significant correlation between two radiotoxic HMs.

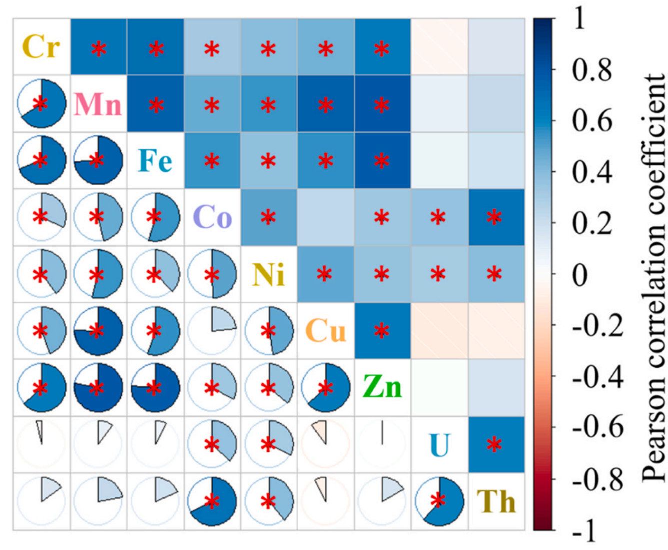

Fig. 3. Correlation plot for toxic and radiotoxic heavy metals ("*" denotes statistically significant correlation). Strong positive correlations among Cr, Mn, and Fe suggest shared geogenic origins or common anthropogenic inputs such as fertilizers, whereas the distinct correlation profiles for radionuclides imply unique geochemical controls or different biological uptake mechanisms by the cereal plants.

Table 5
Values of hazard quotient (HQ) and hazard index (HI) estimated to assess non-carcinogenic health risks from heavy metals analyzed in cereal groups (CER1: wheat; CER: rice; CER3: maize; CER4: barley, and CER5: oats).

Heavy metal		Values of hazard quotient (HQ)				
		CER1	CER2	CER3	CER4	CER5
Cr	Average	5.8165	-	0.8092	0.0311	0.0503
	Min	3.7402		0.3716	0.0223	0.0458
	Max	8.1816		1.0899	0.0399	0.0542
Mn	Average	3.0806	0.0540	0.1097	0.0145	0.0373
	Min	1.1621	0.0192	0.0297	0.0145	0.0315
	Max	4.5734	0.1116	0.1752	0.0146	0.0415
Fe	Average	0.5168	0.0026	0.0351	0.0041	0.0049
	Min	0.1212	0.0025	0.0115	0.0014	0.0032
	Max	1.5438	0.0027	0.0511	0.0069	0.0078
Co	Average	0.3531	0.0119	0.0269	0.0019	0.0031
	Min	0.2004	0.0101	0.0212	0.0014	0.0026
	Max	0.7864	0.0167	0.0409	0.0025	0.0038
Ni	Average	2.5614	0.0993	0.2586	0.0137	0.0419
	Min	1.6480	0.0895	0.2378	0.0136	0.0224
	Max	4.7687	0.1153	0.2750	0.0139	0.0702
Cu	Average	12.2093	0.4598	0.7283	0.0605	0.1153
	Min	9.3972	0.3167	0.4905	0.0507	0.0905
	Max	16.1295	0.6540	1.0404	0.0704	0.1312
Zn	Average	1.0917	0.0284	0.0846	0.0053	0.0099
	Min	0.4582	0.0099	0.0178	0.0041	0.0076
	Max	2.0664	0.0344	0.1506	0.0065	0.0127
HI=SHQ	Average	24.6	0.7	1.7	0.1	0.3
	Min	13.7	0.5	0.8	0.1	0.2
	Max	34.0	0.8	2.4	0.2	0.3

Overall, the correlation analysis reveals a complex interplay of environmental factors influencing heavy metal accumulation in cereal products. The strong intercorrelations among most toxic HMs highlight common source-sink relationships and similar biogeochemical cycling, whereas the distinct correlation profile of radiotoxic HMs with Ni and Co points to more specific geochemical or biological interactions for these radionuclides.

3.2. Non-carcinogenic PHR risk assessment

The ADD values (in mg/kg·d) varied from 6.7×10^{-5} (Cr in CER4–1) to 1.1 (Fe in CER1–9) mg/kg·d. The average ADD values (mg/ kg·d) of the toxic HMs are ranked as Fe (0.237) > Mn (0.220) > Zn (0.169) > Cu (0.032) > Ni(0.027) > Co (0.022) > Cr (0.012). The HQ values varied from 1.4×10^{-3} (Fe in CER4–1) to 16.1 (Cu in CER1–8). The HQ averages of the toxic HMs are listed as Cu (6.3) > Cr (2.5) > Mn (1.6) > Ni (1.3) > Zn (0.6) > Fe (0.3) > Co (0.1). The HQ averages of Cu, Cr, Mn, and Ni are higher than the risk limit of 1. The values of HI estimated for toxic HMs in all cereal grain samples varied from 0.1 to 34.0. Approximately 58 % of HI values are above the risk limit of 1. HQ and HI values estimated for cereal grain groups are given in Table 5. According to the average value of HI, the cereal grain groups were ranked as follows: CER1 (24.6) > CER3 (1.7) > CER2 (0.7) > CER5 (0.3) > CER4 (0.1). The statistical evaluation demonstrated that the HI values were significantly disparate across several pairwise comparisons, specifically between CER1 and CER2, CER1 and CER4, and CER1 and CER5 ($p < 0.05$).

3.3. Radiological PHR assessment

The total E_{Eff} values due to the ingestion of the investigated cereal grain samples varied from 0.8 to 530.8 μSv/y with an average value of 151.6 μSv/y. The contribution of ^{238}U and ^{232}Th to the total E_{Eff} values was 23 % (35.1 μSv/y) and 77 % (116.6 μSv/y), respectively. LCR values corresponding to the total annual effective dose varied from 3.4×10^{-6} to 2.1×10^{-3} with an average value of 6.0×10^{-4}. Total E_{Eff} and the corresponding LCR values estimated for cereal grain groups are given in Table 6. According to the average value of total E_{Eff} and LCR, the cereal grain groups were ranked as follows: CER4 (1.4 μSv/y and 5.6×10^{-6}) < CER5 (2.8 μSv/y and 1.1×10^{-5}) < CER2 (13.2 μSv/y and 5.3×10^{-5}) < CER 3 (35.6 μSv/y and 1.4×10^{-4}) < CER1 (287.2 μSv/y and 1.1×10^{-3}). Regarding LCR values, the statistical analysis indicated distinct differences between CER1 and CER2, CER1 and CER4, as well as CER1 and CER5 ($p < 0.05$).

The radar plots in Fig. 4 illustrate the relative magnitudes of the HI and LCR values observed for five different cereal crops. The radial axes represent proportional values of HI and LCR, with the outermost grid line indicating the maximum observed value within each risk category, thereby facilitating direct visual comparison of risk levels among cereals. A striking pattern is evident: Wheat (CER1) consistently demonstrates the highest contribution to both HI and LCR, forming the prominent peak in both radar profiles. In contrast, Rice (CER2) and Maize (CER3) generally exhibit the lowest HI and LCR values among the analyzed cereal types. The similar overall shape between the HI and LCR radar plots suggests a consistent relative risk profile across the cereals for both human health endpoints. Furthermore, according to the Kruskal-Wallis test, both HI and LCR indices displayed highly significant differences across cereal groups ($p < 0.001$), with post-hoc Dunn's tests identifying significant pairwise distinctions, particularly between wheat and other grains.

4. Conclusions

Non-carcinogenic potential health risk assessment revealed that the estimated hazard index values for toxic heavy metals analyzed in wheat samples were significantly greater than the safety limit of 1. This may be

Table 6
Values of radiological parameters estimated to assess radiological health risks from radiotoxic heavy metals analyzed in cereal groups (CER1: wheat; CER: rice; CER3: maize; CER4: barley, and CER5: oats).

Radiological parameter		Cereal grain group					World average (μSv/y)
		CER1	CER2	CER3	CER4	CER5	
Annual effective dose (μSv/y)							
^{238}U	Average	67.2	2.5	6.2	0.4	0.6	
	Min	58.4	2.9	7.2		0.4	
	Max	155.8	6.7	14.4		0.8	
^{232}Th	Average	220.0	10.7	29.4	1.2	2.2	
	Min	83.6	5.7	24.8	0.8	2.1	
	Max	401.5	17.2	46.1	1.5	2.5	
Total	Average	287.2	13.2	35.6	1.4	2.8	120.0
	Min	117.1	7.4	24.8	0.8	2.5	
	Max	530.8	23.9	60.5	2.0	3.4	
Lifetime cancer risk	Average	1.1×10^{-3}	5.3×10^{-5}	1.4×10^{-4}	5.6×10^{-6}	1.1×10^{-5}	4.8×10^{-4}
	Min	4.7×10^{-4}	2.9×10^{-5}	9.9×10^{-5}	3.4×10^{-6}	9.9×10^{-6}	
	Max	2.1×10^{-3}	9.5×10^{-5}	2.4×10^{-4}	7.8×10^{-6}	1.4×10^{-5}	

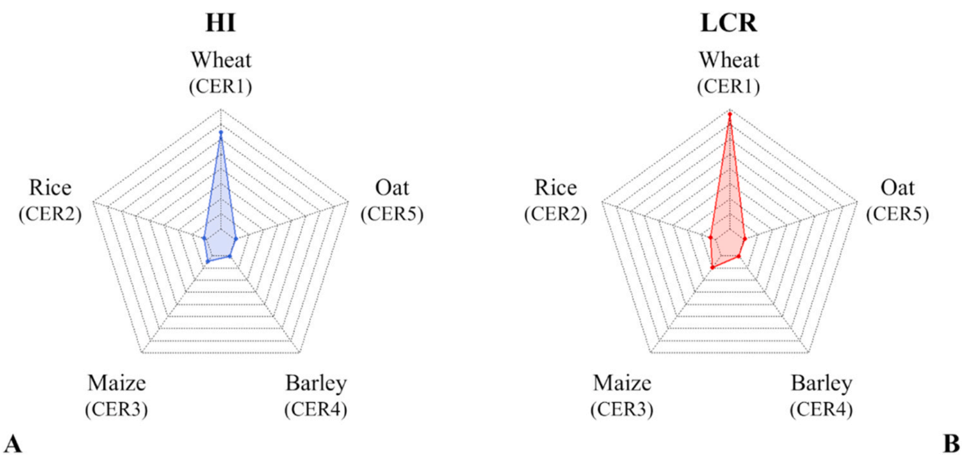

Fig. 4. Combined health risk assessment showing normalized HI (A) and LCR (B) values. Wheat (CER1) demonstrates the highest contribution to both HI and LCR, primarily reflecting higher Mn, Fe, and Zn concentrations combined with the high daily consumption rate of wheat-based products in Türkiye.

due to the high consumption of wheat compared to other grains, resulting in the high consumption of wheat-based bread in Türkiye. Therefore, it is recommended that relevant institutions and organizations implement policy measures, such as promoting dietary programs to reduce wheat consumption. The total average annual effective dose and the corresponding lifetime cancer risk are above the reported world averages of 120 μSv/y and 4.8×10^{-4} due to the ingestion of ^{238}U and ^{232}Th in foods.

In conclusion, the results obtained from this study will raise consumer awareness and contribute to the necessary attention to the safety of cereal grain products consumed in Türkiye. Results emphasize the importance of ongoing monitoring, strict regulation, and further research to understand the potential health effects of long-term exposure to toxic and radiotoxic heavy metals in food samples. Future studies should include geographically stratified sampling and multi-replicate analyses to improve representativeness and precision.

CRediT authorship contribution statement

Şeref Turhan: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Aslı Kurnaz:** Resources, Methodology. **Ergin Murat Altuner:** Writing – review & editing, Formal analysis. **Aybaba Hançerlioğulları:** Resources. **Kenan Akyol:** Resources. **Aydan Altıkulaç:** Data curation.

Ethics approval

Not applicable.

Funding

Not applicable.

Declaration of Competing 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 manuscript.

Acknowledgment

This study was conducted within the scope of a master's thesis. The authors would like to thank Serhat Karabıçak, a staff member of the Kastamonu University Central Research Laboratory, for her assistance during the analysis process.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jfca.2026.108958.

Data availability

Data will be made available on request.

References

Adam, A.A., Sackey, L.N.A., Ofori, L.A., 2022. Risk assessment of heavy metals concentration in cereals and legumes sold in the Tamale Aboabo market, Ghana. Heliyon 8, 1–6.
Akyol, K., 2024. Determination of potentially toxic element contents of cereal products consumed in Kastamonu and evaluation of health risk. Master's Thesis, Kastamonu University, Institute of Science, Department of Physics, Kastamonu (in Turkish).
Ali, M.H.H., Al-Qahtani, K.K., 2012. Assessment of some heavy metals in vegetables, cereals and fruits in Saudi Arabian markets. Egypt. J. Aquat. Res. 38, 31–37.
Ali, H., Khan, E., Ilahi, I., 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. J. Chem. 2019, 1–15.
Altamemi, R., Turhan, Ş., Kurnaz, A., 2021. Natural and anthropogenic radioactivity in some vegetables and fruits commonly consumed in the Western Black Sea region of Turkey. Radiochim. Acta 109 (12), 935–942.
Altıkulaç, A., Turhan, Ş., 2023. Assessment of the levels of potentially toxic elements contained in natural bentonites collected from quarries in Turkey. ACS Omega 8 (23), 20797–20986.
Amarloei, A., Nourmoradi, H., Nazmara, S., Heidari, M., Mohammadi-Moghadam, F., Mazloomi, S., 2025. Toxic heavy metals of agricultural products in developing countries and its human health risk assessment: a study from Iran. Heliyon 11 (1), 1–9.
Baz, S.S., Alamoudi, Z.M., 2017. Naturally occurring radioactive nuclides from cereal grains, legumes and some foodstuffs consumed in Saudi Arabia. Life Sci. J. 14 (7), 1–5.
Bedoya-Perales, N., Maus, D., Pumi, G., Dantas, S.V.A., Ferreira, S.L.C., 2025. Health risk assessment from heavy metals in crops grown and marketed by family farmers in the mining region of Moquegua, Peru. Food Res. Int. 217, 1–9.
Briffa, J., Sinagra, E., Blundell, R., 2020. Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon 6 (9), 1–26.
Brizio, P., Benedetto, A., Squadrone, S., Curcio, A., Pellegrino, M., Ferrero, M., Abete, M. C., 2016. Heavy metals and essential elements in Italian cereals. Food Addit. Contam. Part B 9 (4), 261–267.
Cengiz, G.B., Çağlar, İ., 2021. determination of the natural radioactivity distribution and consumption effective dose rate of cereal crops in Ardahan province, Turkey. J. Sci. Rep. A 047, 174–183.
Chasapis, C.T., Ntoupa, P.S.A., Spiliopoulou, C.A., Stefanidou, M.E., 2020. Recent aspects of the effects of zinc on human health. Arch. Toxicol. 94 (5), 1443–1460.
Ercilla-Montserrat, M., Muñoz, P., Montero, J.I., Gabarrell, X., Rieradevall, J., 2018. A study on air quality and heavy metals content of urban food produced in a Mediterranean city (Barcelona). J. Clean. Prod. 195, 385–395.
Getu, A., Seid, Y., Asrade, B., 2022. Determination of the level of heavy metals in the selected cereals from Debre Markos local market, Amhara region, Ethiopia. Int. J. Anal. Chem. 2022, 1–7.
Hasan, G.M.M.A., Das, A.K., Satter, M.A., 2022. Accumulation of heavy metals in rice (*Oryza sativa*. L) grains cultivated in three major industrial areas of Bangladesh. J. Environ. Public Health 2022, 1–8.

Hosseini, T., Fathivand, A.A., Barati, H., Karimi, M., 2006. Assessment of radionuclides in imported foodstuffs in Iran. Iran. J. Radiat. Res. 4, 149–153.
ICRP, 1990. International Commission on Radiological Protection (ICRU). Recommendations of the International Commission on radiological protection, 1990. Pergamon Press, Oxford (Annals of the ICRP; 21(1–3), ICRP Publication; 60).
ICRP, 2012. International Commission on Radiological Protection (ICRU). Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. In: Ann. ICRP, 41. Published by Elsevier Ltd.
Ikem, A., Odumosu, P.O., Udousoro, I., 2023. Elemental composition of cereal grains and the contribution to the dietary intake in the Nigerian population. J. Food Compos. Anal. 118, 1–13.
Jibiri, N.N., Farai, I.P., Alausa, S.K., 2007. Activity concentrations of ^{226}Ra, ^{228}Th, and ^{40}K in different food crops from a high background radiation area in Bitsichi, Jos Plateau, Nigeria. Radiat. Environ. Biophy 46, 53–59.
Karapınar, H.S., 2023. Composition of some trace elements in wheat plant and soil. Anat. J. Bot. 7 (1), 40–45.
Kerketta, A., Kumar, H., Powell, M.A., Sahoo, P.K., Kapoor, H.S., Mittal, S., 2023. Trace element occurrence in vegetable and cereal crops from parts of Asia: a meta-data analysis of crop-wise differences. Curr. Pollut. Rep. 9, 1–21.
Kulshreshtha, D., Ganguly, J., Jog, M., 2021. Manganese and movement disorders: A review. J. Mov. Disord. 14 (2), 93–102.
Kumar, U., Singh, P.K., Kumar, I., Sharma, R.K., 2025. Heavy metal accumulation, yield and health risk assessment of wheat crop grown in contaminated soil amended with bioash for sustainable agriculture. J. Food Compos. Anal. 139, 1–15.
Lefebvre, P., Gourgiotis, A., Mangeret, A., Sabatier, P., Le Pape, P., Diez, O., Louvat, P., Menguy, N., Merrot, P., Baya, C., Zebracki, M., 2021. Diagenetic formation of uranium-silica polymers in lake sediments over 3,300 years. Proc. Natl. Acad. Sci. 118 (4), 1–19.
Lenka, P., Sahoo, S.K., Mohapatra, S., Patra, A.C., Dubey, J.S., Vidyasagar, D., Tripathi, R.M., Puranik, V.D., 2013. Ingestion dose from ^{238}U, ^{232}Th, ^{226}Ra, ^{40}K and ^{137}Cs in cereals, pulses and drinking water to adult population in a high background radiation area, Odisha, India. Radiat. Prot. Dosim. 153 (3), 328–333.
Leyssens, L., Vinck, B., Van Der Straeten, C., Wuyts, F., Maes, L., 2017. Cobalt toxicity in humans-A review of the potential sources and systemic health effects. Toxicology 387, 43–56.
Lindahl, P., Maquet, A., Hult, M., Gasparro, J., Marissens, G., González de Orduña R. Natural radi Lindahl, P., Maquet, A., Hult, M., Gasparro, J., Marissens, G., González de Orduña, R., 2011. Natural radioactivity in winter wheat from organic and conventional agricultural systems. J. Environ. Radio. 102, 163–169.
Liu, P., Zhang, Y., Feng, N., Zhu, M., Tian, J., 2020. Potentially toxic element (PTE) levels in maize, soil, and irrigation water and health risks through maize consumption in northern Ningxia, China. BMC Public Health 20 (1), 1–13.
Luo, W., Zhang, Y., Wei, P., Sun, C., 2024. Assessment of heavy metal(loid) pollution and human health risks associated with a mineral (Zn, Cu, and Sn ores) processing plant in Yunnan, Southwest China. Minerals 14, 1–17.
Ma, M., Wang, R., Xu, L., Xu, M., Liu, S., 2020. Emerging health risks and underlying toxicological mechanisms of uranium contamination: Lessons from the past two decades. Environ. Int. 145, 1–15.
Madomguia, D., Basokdou, G.B., Appoline Isabelle, K.W., Dongo, P.K., Nya, E., Togouet, S.H.Z., 2024. Accumulation of heavy metals in maga-pouss rice fields (far-north region, Cameroon) and transfer to rice grains. Agric. Sci. 15, 311–326.
Miletić, A., Lučić, M., Onjia, A., 2023. Exposure factors in health risk assessment of heavy metal(loid)s in soil and sediment. Metals 13 (7), 1–28.
Nematollahi, A., Abdi, L., Abdi-Moghadam, Z., Fakhri, Y., Borzoei, M., Tajdar oranj, B., Thai, V.M., Linh, N.T.T., Khaneghah, A.M., 2021. The concentration of potentially toxic elements (PTEs) in sausages: a systematic review and meta-analysis study. Environ. Sci. Pollut. Res. 28, 55186–55201.
Obasi, N.A., Obasi, S.E., Ajala, L.O., Aloh, G.O., Aloke, C., Ogundapo, S.S., Onyeji, G.N., 2022. Nutrient interaction and health risk assessment of cereal grains on Nigerian's markets. J. Food Qual. Hazards Control 9, 137–146.
Oudh, A.J.A., Kadhim, M.J.H., Abdul-Hussein, A.K., Al-Khafaji, Z., 2025. Natural and anthropogenic radionuclides concentration and risk assessment in legumes and grains, which provides in a basket foodstuff in Iraq country. Nucl. Eng. Sci. 10 (1), 1–13.
Ozturk, A., Arici, O.K., 2021. Carcinogenic-potential ecological risk assessment of soils and wheat in the eastern region of Konya (Turkey). Environ. Sci. Pollut. Res. 28 (12), 15471–15484.
Popoola, F.A., Isola, O.B., Fakeye, O.D., Owolabi, T.A., Sanyaolu, M.E., Owoyemi, S.I., Elijah, I.O., 2024. Examination of medicinal plants for radionuclide absorption and their health implications. Pollution 10 (2), 700–711.
R Core Team R, 2023. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 〈https://www.R-project.org/〉.
Rafaqat, S., Aslam, A., Riaz, U., Alsudays, U.M., Javied, S., Hassan, N., Saleh, M.A., Alamer, K.H., Uz Zaman, Q., 2025. Health risk assessment of heavy metal accumulation in rice grains cultivated by industrial effluents. Appl. Environ. Soil Sci. 2025, 1–14.
Salih, N.F., 2018. Determination of natural radioactivity and radiological hazards of ^{226}Ra, ^{232}Th, and ^{40}K in the grains available at Penang markets, Malaysia, using high-purity germanium detector. Sci. J. Koya Univ. VI 71–77.
Shuaibu, H.K., Mohamed, F., Khandaker, M.U., Ismail, A.Z., Omar, R.S., 2023. Radioactivity and concomitant radiation dose from Malaysian herbal plants. Radiat. Phys. Chem. 211, 1–10.
Sultan, D., Turhan, Ş., Kurnaz, A., Hançerlioğulları, A., Kamberli, A., Emeksizoğlu, B., 2020. Investigation of natural radionuclide and essential metal contents of ancient wheat einkorn (Triticum monococcum L.) grown in Turkey. Radiochim. Acta 108 (12), 999–1007.
TatahMentan, M., Nyachoti, S., Okwori, O.F., Godebo, T.R., 2023. Elemental composition of rice and lentils from various countries: a probabilistic risk assessment of multiple life stages. J. Food Compos. Anal. 115, 1–14.
Tawalbeh, A.A., Abumurad, K.M., Samat, S.B., Yasir, M.S., 2011. A study of natural radionuclide activities and radiation hazard index in some grains consumed in Jordan. Malay. J. Anal. Sci. 15, 61–69.
Taylor, A.A., Tsuji, J.S., Garry, M.R., McArdle, M.E., Goodfellow, W.L., Jr, Adams, W.J., Menzie, C.A., 2020. Critical review of exposure and effects: implications for setting regulatory health criteria for ingested copper. Environ. Manag. 65 (1), 131–159.
Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K., Sutton, D.J., 2012. Heavy metal toxicity and the environment. Exp. Suppl. 101, 133–164.
Tegegne, W.A., 2015. Assessment of heavy metal concentration in selected cereals collected from local markets of Ambo city, Ethiopia. J. Cereals Oilseeds 6 (2), 8–13.
Tekin, M., Cengiz, M.F., Abbasov, M., Aksoy, A., Canci, H., Akar, T., 2018. Comparison of some mineral nutrients and vitamins in advanced hulled wheat lines. Cereal Chem. 95, 436–444.
TÜİK, 2025. Türk Standardları Enstitüsü (Turkish Statistical Institute) (TÜİK). Bitkisel Ürün Denge Tabloları; "Tahıllar ve Diğer Bitkisel Ürünler", 2000/'01-2023/'24. Web page: 〈https://data.tuik.gov.tr/Bulten/Index?p=Bitkisel-Uretim-Istatistikleri-2025-53939〉.
Turhan, Ş., 2020. Evaluation of agricultural soil radiotoxic element pollution around a lignite-burning thermal power plant. Radiochim. Acta 108 (1), 77–85.
Turhan, Ş., 2025. Health risk assessment caused by external and internal exposure to radiation dose from naturally occurring radioactive materials in outdoor dust. Environ. Geochem. Health 47, 1–13.
Turhan, Ş., Akata, I., Kumru, E., Altuner, E.M., 2024. Heavy metal analysis of wild edible mushrooms grown in Türkiye and assessment of possible carcinogenic and non-carcinogenic risk. J. Food Compos. Anal. 135, 1–14.
Turhan, Ş., Türkdoğan, S., Altuner, E.M., Kurnaz, A., Hançerlioğulları, A., 2026. Heavy metals in perlite quarries and exposure of worker. Environ. Earth Sci. 85 (58), 1–13.
UNSCEAR, 2000. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and Effects of Ionizing Radiation. Vol. I. Sources. Report to the General Assembly with Scientific Annexes. United Nations, New York.
USEPA, 1989. United States Environmental Protection Agency (USEPA). Risk assessment guidance for superfund. Volume I: Human health evaluation manual (Part A), EPA/540/1–89/002, Washington, DC.
Van Grieken, R., Markowicz, A., 2001. Handbook of X-Ray Spectrometry. CRC press.
Vasilachi, I.C., Stoleru, V., Gavrilescu, M., 2023. Analysis of heavy metal impacts on cereal crop growth and development in contaminated soils. Agriculture 13, 1–50.
Wang, P., Wang, X., Wang, H., Zhang, G., 2024. Health risk assessment of heavy metals from grains and grain products in Gansu Province, China, 2012-2020. J. Food Compos. Anal. 125, 1–11.
Yadav, P.K., Singh, A.K., 2022. A review of iron overload in beta-thalassemia major, and a discussion on alternative potent iron chelation targets. Plasmatology 16, 1–9.