



Assessment of the radiological doses and health risk from natural and anthropogenic radionuclides in wheat samples near nuclear facilities in Dera Ghazi Khan

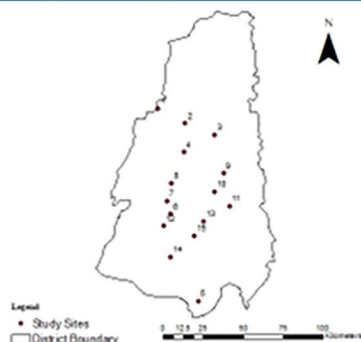
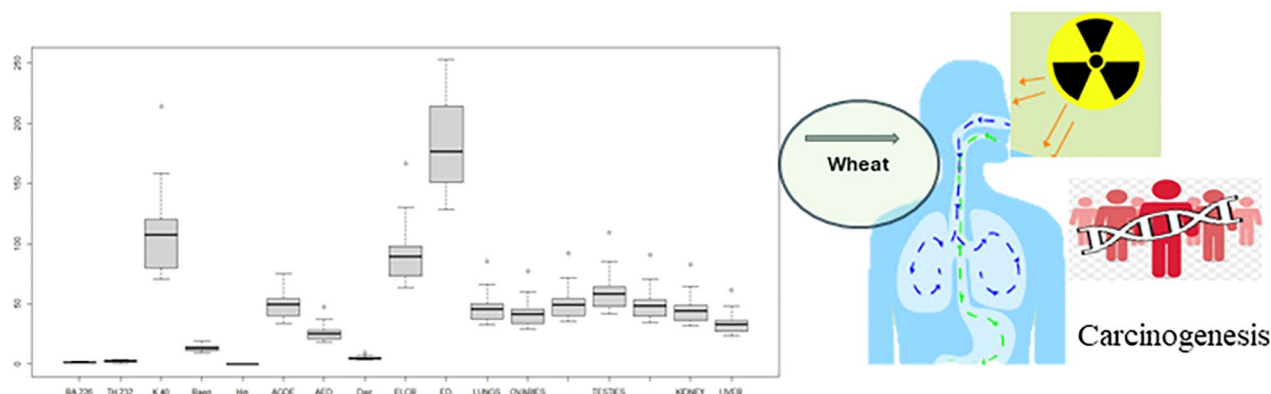
Sidra Ghias¹ · Khizer Hayat Satti² · Abdulaziz Al-Anazi³ · Waqas Niaz¹ · Muhammad Ibrahim⁴ · Abdul Jabbar² · Muhammad Aqeel⁵

Received: 13 July 2024 / Accepted: 4 December 2024 / Published online: 6 January 2025
 © Akadémiai Kiadó Zrt 2025

Abstract

The study evaluated the presence of anthropogenic and natural radionuclides in wheat samples close to nuclear facilities of Dera Ghazi Khan by using gamma ray spectrometry. The average activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K found to be 1.60, 2.41 and 108.22 Bq/kg, respectively. The estimated average values for the internal hazard index, radium equivalent, radiological doses and cancer risk factor were found to be within acceptable ranges. The study discovered no substantial health concerns from consuming edible grains because their concentrations were within the permissible limits established by UNSCEAR.

Graphical abstract



Extended author information available on the last page of the article

Keywords Radionuclides · Wheat · Radiological doses · Health risk assessment · Dera Ghazi Khan

Introduction

Naturally occurring radionuclides (NORMs) are found in all parts of the environment, including humans, air, water, soil and food. Vegetation absorbs radionuclides through foliar absorption, soil-to-plant transfer via root systems or external plant surfaces. In the biosphere, soil functions as a naturally occurring buffer system, regulating chemicals and other substances [1]. Plants may absorb both nutrients and dangerous substances, such as radionuclides, which may then accumulate in the food chain [2]. Many factors, such as soil properties, plant maturity, chelating ions, regulated influx across plasma membranes, binding ions to cell walls, and selective absorption by plants, impact the mobility of bioavailable radionuclides from rhizospheric soil to plants [3].

As per the international network of food safety authorities (INFOSAN) the plants are often used as food containing ^{232}Th , ^{40}K and ^{238}U and their progeny [4]. These long-lived, naturally occurring radionuclides may enter plants by mineral absorption and accumulate in different parts of the plant even into edible parts. Consuming these plants and their parts would expose humans to constant radiation exposure. Food from unpolluted surroundings makes a considerable contribution to the average radiation doses absorbed by various organs. Consuming contaminated food, whether as a result of nuclear accidents or accidental atmospheric emissions, is a major cause of long-term health risks [5, 6]. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the radionuclides in the naturally occurring ^{232}Th and ^{238}U decay series equate to internal radiation exposure/doses by 30–60% [7]. The International Agency for Research on Cancer (IARC) has classified all kinds of ionizing radiation as carcinogenic to humans [8]. Because radionuclides have a long half-life, even a minor concentration can influence the environment for a long time. The extended exposure of these radionuclides can cause nausea, vomiting, and headaches, fatigue, fever, weakness, dizziness, low blood pressure, hair loss, diarrhea, disorientation, blood in the stool, mental disability, underdeveloped eyes and smaller head or brain [7, 9–11]. Additionally, long-term exposure to radionuclides has been linked to increased risk for leukemia, leucopenia, renal damage, and genetic damage [12–14].

The implications of consuming radioactively contaminated food, particularly after Chernobyl in 1986, force many countries to implement food control and monitoring measures. The extensive presence of radionuclides in a variety of food products has been demonstrated by

recent studies [15–20] underscoring the urgent need for additional research on the effects of radionuclides on a variety of food products. The current study area is near a nuclear power station and a radioactive waste disposal facility, both of which have the potential to pose health risks to the local population. This emphasizes the important necessity for studying radioactive contamination in staple foods. Furthermore, previous research has primarily focused on determining radiation levels in the soil [21] and air [22] in areas adjacent to the current study sites. However, there are still no studies that assess the radiation levels of the wheat crop. This research gap must be filled and that's why the current study was designed to investigate the levels of the natural and artificial radionuclide concentrations in the wheat samples, assess the associated radiological doses and lifetime cancer risk factors. The findings of this study will help researchers, public health specialists and policymakers to establish evidence-based initiatives that prioritize the safety and well-being of these vulnerable populations. The results of the study can enrich the baseline radiometric data that is crucial for future epidemiological investigations and community-based monitoring initiatives.

Material and methods

Study area description

Dera Ghazi Khan, also referred to D.G. Khan, is situated in Southern Punjab at an elevation of 415 feet on the west bank of the Indus River with coordinates $70^{\circ}38'0''\text{E}$ longitude and $30^{\circ}10'30''\text{N}$ latitude [23]. Geologically, the area features a westward-extending stretch of flat alluvium originating from the Indus River and its tributaries which spans the lower hills [24]. Notably, the area is well known for its distinctive geological settings and abundant mineral reserves. The primary mineral deposits that have been mined for a long time include coal, phosphate rock, common shale, gypsum, iron, silica, silt, and limestone (marble) [21]. Despite a decade-long hiatus in radioactive material extraction, the area's mineral resources continue to be extracted mainly by open-pit excavation methods. Without any in-situ treatment or beneficiation, these materials are transferred to industrial facilities or separation plants. Moreover, the presence of radioactive waste dumping sites and legacy uranium mines in D. G. Khan has raised serious concerns due to their proximity to populated areas and potential environmental impact.

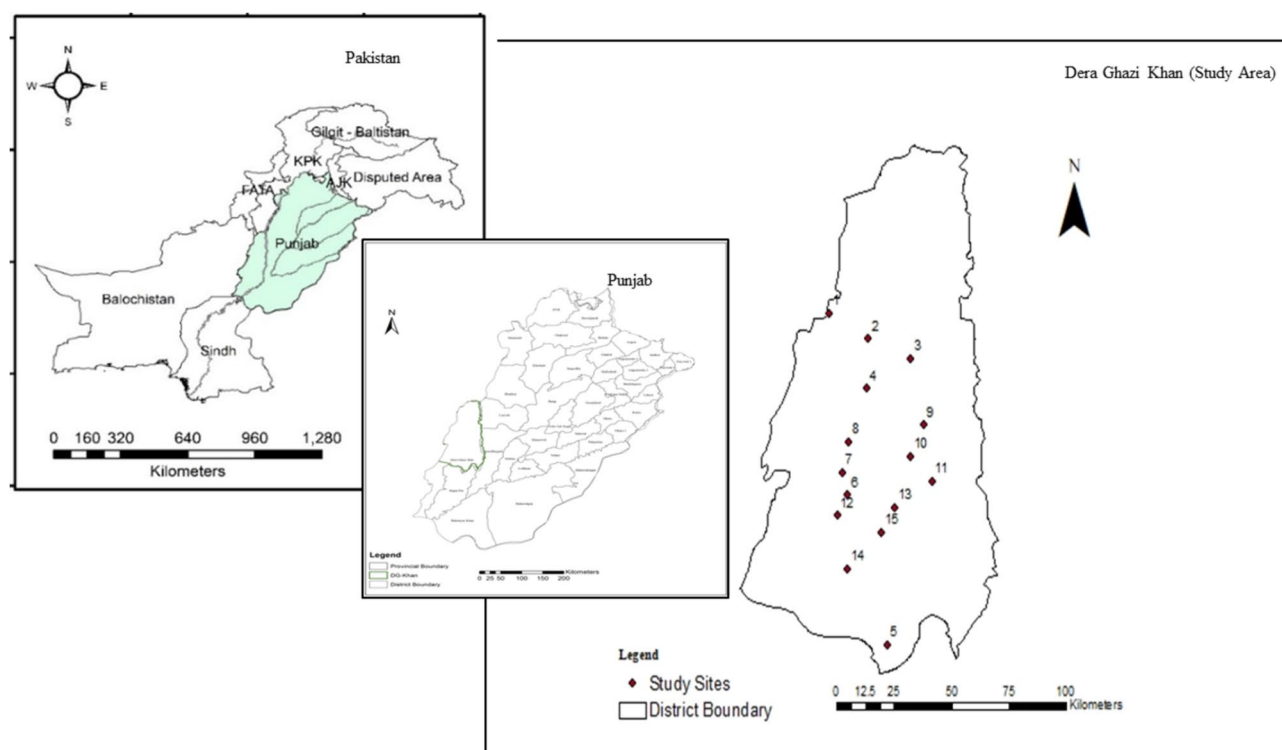


Fig. 1 Map of the current study area, Dera Ghazi Khan

Samples collection and preparation

A total of 15 wheat samples were obtained from locations near to the mining centers and nuclear facilities. The global positioning system (GPS) was used to determine the site coordinates and future traceability of sampling locations (Fig. 1). Sampling points were selected on the basis of accessibility, population density, and wheat availability. Each sample, approximately 2.5 kg, was appropriately preserved in polyethylene bags and tagged for future traceability, following Salih [25]. To make a representative sample from each location, six spots (each measuring 2×2 m) were chosen from each wheat plantation field [26]. To remove dust particles samples were washed with distilled water and weighed. To eliminate organic material, the samples were first allowed to air dry for one to two weeks, followed by a 24-h oven drying process at 105°C and a 48-h ashing in an electric furnace. The ashed wheat samples were weighed, homogenized and packed into cylindrical containers to detect the concentration of gamma emitting radionuclides.

Instrumentation and calibration

To measure the radioactivity concentrations of the samples a high-resolution coaxial high-purity germanium detector (HPGe) type GC 3020, which has a resolution (FWHM) of 2.0 keV at 1332 keV and a relative efficiency of 30% was

used. To minimize the background interference, a cylindrical lead shield (10 cm thick) with a fixed bottom and movable lid was used. The inside lining of the lead shield was made of 3 mm thick copper and 4 mm thick tin to absorb both standard X-rays and any additional photons that may have been generated in the lead. Notably a 100-year-old lead was used to reduce the background radiation, as its activity is significantly lower than the contemporary lead. Using the same technique and configuration as the samples, the background radiation distribution near the detector was determined by measuring an empty sealed beaker. The background measurement time was 65000 s. The background spectra were used to adjust the detected isotope of gamma rays. A dedicated software Genie 2000 version 2.1 (Canberra, USA) was used for spectrum acquisition and analysis. A certified multi-gamma source comprising the radionuclides ^{109}Cd , ^{241}Am , ^{57}Co , ^{139}Ce , ^{137}Cs , ^{60}Co , ^{85}Sr , ^{113}Sn , ^{203}Hg and ^{88}Y were used to calibrate the detector's efficiency. Sample geometry was maintained in accordance with the calibration source's geometry. The IAEA standard reference materials IAEA-375, IAEA-327, RGK-1, and IAEA-373- were used to verify the quality control of the efficiency calibration. control. The activity concentrations of ^{232}Th and ^{226}Ra were calculated using the photo-peaks of their daughter nuclei (^{228}Ac , 911 keV; ^{214}Bi , 609 keV and ^{214}Pb , 351 keV), whereas the activity of ^{40}K and ^{137}Cs was calculated

using the photo-peaks at 662 keV and 1460.8 keV. The uncertainties of the measured values were calculated for quality control and quality assurance. Minimum Detectable Activity (MDA) is the minimum concentration of a radionuclide that can be measured with 95% confidence interval and it was 0.96, 0.62, 1.74 and 0.37 for ^{226}Ra , ^{232}Th , ^{40}K and ^{137}Cs respectively. The MDA values and activity of radionuclides in the sample were measured by following formulas [21, 30].

$$\text{MDA} = \frac{4.66\sqrt{\text{Continuumcounts} - \text{Backgroundcounts}}}{T \times \epsilon \times Y \times V}$$

$$A\left(\frac{\text{Bq}}{\text{Sample}}\right) = \frac{(\text{NetPeakCountsfor samples} - \text{Backgroundcounts})}{(\text{Countingtime} \times \text{Detectionefficiency} \times \text{emissionprobabilityofX-ray})}$$

Statistical analysis

The radioactive content of the wheat samples was measured by using descriptive statistics. The correlations between radionuclides and other variables were determined using correlation analysis. Box plots were employed to illustrate the data's variability and appropriate graphics were used to portray the results of Principal Component Analysis (PCA), which decreased the dimensionality of the data and revealed underlying patterns. R Console 4.3.2 was used for statistical analysis.

Results and discussion

Radiation levels in wheat samples

The activity concentrations of ^{226}Ra , ^{232}Th , and ^{40}K ranged from $\leq \text{MDA}$ to 2.08 ± 0.75 , 0.72 ± 1.81 to 3.55 ± 2.02 and 70.55 ± 14.80 to 213.94 ± 15.62 Bq/kg, with mean values of 1.60, 2.41 and 108.22 Bq/kg, respectively (Table 1). Samples W15, W4, and W8 exhibited the highest values for ^{226}Ra , ^{232}Th , and ^{40}K , whereas samples W12, W8, and W7 demonstrated the lowest activities. Notably, all wheat samples exhibited activity concentrations below the world's average reference limits of 35, 30, and 400 Bq/kg, for ^{226}Ra , ^{232}Th , and ^{40}K respectively [7]. Additionally, ^{137}Cs levels were investigated for all samples. As a long-lived anthropogenic radionuclide, ^{137}Cs poses potential long-term external gamma exposure risks and has the potential to contaminate food chain due to its high mobility [27]. However, ^{137}Cs concentrations were determined to be below the minimum detectable activity ($\leq \text{MDA}$), indicating insignificant contamination. Nonetheless, continuous monitoring is necessary to ensure the ongoing safety and quality of agricultural products in the study area. The non-detection of ^{137}Cs in food samples may be attributed to improved agricultural methods and countermeasures that minimize plant uptake of radio-caesium. These results indicate moderate variability for ^{226}Ra and ^{232}Th , while ^{40}K shows significant variation. This discrepancy is most likely

Table 1 Activity concentration of radionuclides (^{226}Ra , ^{232}Th , ^{40}K and ^{137}Cs Bq/kg) detected in wheat samples

Sample code	A ^{226}Ra (Bq/kg)	A ^{232}Th (Bq/kg)	A ^{40}K (Bq/kg)	A ^{137}Cs (Bq/kg)
W1	1.15 ± 0.82	3.08 ± 1.97	107.34 ± 16.23	$\leq \text{MDA}$
W2	1.27 ± 0.80	2.26 ± 1.92	104.91 ± 15.86	$\leq \text{MDA}$
W3	0.98 ± 0.92	2.18 ± 2.21	86.69 ± 18.18	$\leq \text{MDA}$
W4	1.62 ± 0.84	3.55 ± 2.02	109.88 ± 16.61	$\leq \text{MDA}$
W5	2.48 ± 0.80	2.21 ± 1.87	73.28 ± 15.37	$\leq \text{MDA}$
W6	1.87 ± 0.77	3.21 ± 1.82	70.93 ± 14.88	$\leq \text{MDA}$
W7	2.12 ± 0.76	2.13 ± 1.80	70.55 ± 14.80	$\leq \text{MDA}$
W8	1.61 ± 0.77	0.72 ± 1.81	213.94 ± 15.62	$\leq \text{MDA}$
W9	1.23 ± 0.78	2.93 ± 1.87	116.61 ± 15.49	$\leq \text{MDA}$
W10	1.34 ± 0.76	1.79 ± 1.82	71.31 ± 14.96	$\leq \text{MDA}$
W11	2.26 ± 0.76	3.19 ± 1.81	127.00 ± 15.07	$\leq \text{MDA}$
W12	$\leq \text{MDA}$	1.94 ± 1.97	123.39 ± 16.40	$\leq \text{MDA}$
W13	1.63 ± 0.78	3.26 ± 1.85	158.59 ± 15.53	$\leq \text{MDA}$
W14	1.90 ± 0.78	1.81 ± 1.84	86.50 ± 15.19	$\leq \text{MDA}$
W15	2.08 ± 0.75	3.12 ± 1.78	110.53 ± 14.69	$\leq \text{MDA}$
UNSCEAR	35	30	400	–

caused by agricultural techniques including potassium fertilizers and several environmental conditions that affect ^{40}K absorption from soil to plants. Furthermore, compared to ^{40}K , the larger atomic weights of ^{226}Ra and ^{232}Th cause decreased absorption rates in wheat grain. The findings of current study are consistent with previous global research [15–20].

Radiological risk assessment

Radium equivalent (Ra_{eq})

The Radium equivalent is a single index that indicates the total radiological effects of ^{226}Ra , ^{232}Th , and ^{40}K in a particular environmental media. This standardization makes it easier to understand the entire gamma radiation risk posed by a specific product and helps to determine whether a substance complies with safety standards and regulations. Ra_{eq} was determined by the following formulae.

$$\text{Ra}_{\text{eq}} (\text{Bq/kg}) = A_{\text{Ra}} + 1.43A_{\text{Th}} + 0.077A_{\text{K}} \quad (1)$$

In this equation A_{Ra} , A_{Th} and A_{K} are the specific activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K respectively. For public, maximum permissible limit of radium equivalent is 370 Bq/kg [28]. Ra_{eq} values range from 19.11 to 9.39 Bq/kg, with an average of 13.57 Bq/kg (see Table 2) which is below

the recommended level of 370 Bq/kg set by the Organization for Economic Cooperation and Development (OECD) [29]. Because any substance can be classified as radiotoxic if its Ra_{eq} value exceeds 370 Bq/kg, which corresponds to an average annual dose of 1.05 mSv [7].

Internal hazard index

The internal hazard index (H_{in}) is a measure for evaluating the radiation risk posed by naturally occurring radionuclides. The H_{in} refers to radon and its toxic progenies that can enter the body via inhalation or ingestion. This is explained by the following equation:

$$H_{\text{in}} = \frac{A_{\text{Ra}}}{185} + \frac{A_{\text{Th}}}{259} + \frac{A_{\text{K}}}{4810} \leq 1 \quad (2)$$

For insignificant radiation hazards H_{in} should be less than unity [30, 31]. In the current study H_{in} lacks a specified range but maintains an average value of 0.04 (Table 2) which is less than unity, indicating that the sampled media has a comparatively low degree of internal radiation risk.

Absorbed dose rate (D)

Absorbed dose rate in air is calculated by using specific activity concentrations of ^{40}K , ^{232}Th and ^{226}Ra in wheat samples. Mathematically it can be described as:

$$D (\text{nGy/h}) = (0.4624A_{\text{Ra}} + 0.6044A_{\text{Th}} + 0.0417A_{\text{K}}) \quad (3)$$

where D is absorbed dose rate in air and A_{Ra} , A_{Th} and A_{K} are specific activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K respectively [32]. The D_{air} values ranged from 34.03 to 75.14 $\mu\text{Sv/y}$ with an average value 49.60 $\mu\text{Sv/y}$ (Table 2) which completely adheres to the safety standard described by UNSCEAR [7].

Annual effective dose equivalent (AEDE)

Using the absorbed dose rate, the annual effective dose equivalent was calculated. UNSCEAR recommended using an occupancy of 0.8 (19/24) and a dose conversion factor of 0.7 SvG/y [7]. Consequently, the annual effective dose equivalent ($\mu\text{Sv/y}$) was computed using following formula: (1).

$$\text{AEDE} (\text{Sv/h}) = D (\text{nGy/h}) \times 8760\text{h} \times 0.8 \times 0.7\text{SvG/y} \times 10^{-3} \quad (4)$$

The AEDE ranged from 18.16 to 47.62 $\mu\text{Sv/y}$ with an average value of 26.68 $\mu\text{Sv/y}$ (Table 2). These findings demonstrate that the effective dose equivalent values of the examined wheat samples are less than the world average value of 450 $\mu\text{Sv/y}$ [7]. This implies that the wheat samples

Table 2 Radiological health burden and associated doses with wheat consumption

Sample code	RaEq (Bq/kg)	H _{in}	D _{air}	AEDE	AGDE
S1	13.83	0.04	50.15	25.49	5.20
S2	12.58	0.04	46.31	25.01	5.10
S3	10.77	0.03	39.35	20.60	4.20
S4	15.16	0.05	54.36	27.21	5.55
S5	11.28	0.04	39.91	21.27	4.34
S6	11.92	0.04	41.45	19.69	4.01
S7	10.60	0.03	37.61	19.88	4.05
S8	19.11	0.06	75.14	47.62	9.71
S9	14.40	0.04	52.67	27.52	5.61
S10	9.39	0.03	34.03	18.16	3.70
S11	16.60	0.05	60.18	32.04	6.53
S12	13.14	0.04	49.53	27.79	5.66
S13	18.50	0.05	68.45	37.10	7.56
S14	11.15	0.04	40.60	22.53	4.59
S15	15.06	0.05	54.19	28.25	5.76
Maximum	9.39	0.03	34.03	18.16	3.70
Minimum	19.11	0.06	75.14	47.62	9.71
Mean	13.57	0.04	49.60	26.68	5.44

Table 3 Annual Radiation doses ($\mu\text{Sv/y}$) and excess lifetime cancer risk in adult members of the study area following wheat consumption

Sample	ED	Lungs	Ovaries	Bone Marrow	Testes	Whole Body	Kidney	Liver	ELCR (10^{-3})
W1	199.67	102.23	92.65	110.22	130.99	108.62	99.04	73.48	89.20
W2	171.80	87.96	79.72	94.83	112.70	93.46	85.21	63.22	87.52
W3	151.54	77.59	70.32	83.65	99.41	82.44	75.17	55.77	72.09
W4	219.89	112.58	102.03	121.38	144.25	119.62	109.07	80.92	95.23
W5	150.37	76.99	69.78	83.01	98.65	81.81	74.59	55.34	74.44
W6	176.61	90.43	81.95	97.49	115.86	96.08	87.60	65.00	68.93
W7	143.10	73.27	66.40	78.99	93.88	77.85	70.98	52.66	69.56
W8	218.91	112.08	101.57	120.84	143.61	119.09	108.58	80.56	166.68
W9	203.31	104.10	94.34	112.23	133.38	110.60	100.85	74.82	96.31
W10	128.03	65.56	59.41	70.68	83.99	69.65	63.51	47.12	63.56
W11	227.18	116.32	105.41	125.40	149.03	123.59	112.68	83.60	112.13
W12	174.96	89.58	81.18	96.58	114.78	95.18	86.78	64.39	97.25
W13	252.87	129.47	117.33	139.59	165.89	137.56	125.43	93.06	129.83
W14	145.36	74.42	67.45	80.24	95.36	79.08	72.10	53.49	78.87
W15	209.63	107.33	97.27	115.72	137.52	114.04	103.98	77.15	98.87
MIN	128.04	32.54	29.49	35.08	41.69	34.57	31.52	23.39	63.56
MAX	252.88	85.34	77.34	92.01	109.34	90.68	82.67	61.34	166.68
MEAN	184.89	47.80	43.32	51.54	61.25	50.79	46.31	34.36	93.37

comply with the global documented reference levels for AEDE, demonstrating their radiological safety.

5 Annual gonadal dose equivalent (AGDE)

Gonads play an important part in dosimetry, and ICRP assigns them a weighted value of 0.2 [33]. This higher weighting factor reflects the gonads' susceptibility to radiation and associated risk of mutagenesis. Consequently, the AGDEs arising from the specific activity of ^{226}Ra , ^{232}Th , and ^{40}K were calculated using the following formula [34].

$$\text{AGDE} \left(\frac{\text{mSv}}{\text{y}} \right) = 3.09A_{\text{Ra}} + 4.18A_{\text{Th}} + 0.314A_{\text{K}} \quad (5)$$

The average values of AGDE were found to be 5.44 $\mu\text{Sv/y}$ and ranged from 5.73 to 12.38 $\mu\text{Sv/y}$ (see Table 2) which is below the worldwide average reference value of 300 $\mu\text{Sv/y}$ [7].

Annual effective dose

The annual effective dose (ED) that a person would receive via wheat consumption is calculated by following formula.

$$\text{ED} = A_C \times I_{\text{in}} \times E \quad (6)$$

where as A_C is the activity concentration of radionuclides in wheat, E is the dose conversion factor, ED is the annual effective dose, and I_{in} is the annual wheat intake for adults [35]. According to UNSCEAR the average adult in Pakistan consumes roughly 140 kg of wheat flour yearly [7, 36]. The annual effective dosage ranged between 128.04 and 252.88 $\mu\text{Sv/y}$, with an average of 184.89 $\mu\text{Sv/y}$ (Table 3). These findings indicated that these wheat samples do not pose any substantial health risks in the targeted communities.

Organs/tissues specific effective dose rate

The annual effective dose can be used to determine the amount of radiation levels that enter and accumulate in the various sensitive organs and tissues. The effective dose rate delivered to a certain organ was determined by using the following equation:

$$D_{\text{organ}} \left(\frac{\text{mSv}}{\text{y}} \right) = O \times E_D \times F \quad (7)$$

The ED is an annual effective dose, O is the occupancy factor, which has a value of 0.8, and F is the conversion factor, which represents the organ dose from food consumption. The dedicated conversion factors for specific organs were used to calculate the effective dose rate for different organs and tissues as described by ICRP [37]. The corresponding conversion factors for the lungs, ovaries, bone marrow, testes, whole body, kidney, and liver are 0.64, 0.58, 0.69, 0.82, 0.68, and 0.46 for dosage assessment. The average annual radiation doses measured for various organs were

as follows: the ovaries received 85.79 $\mu\text{Sv/y}$, ranging from 59.41 to 117.33 $\mu\text{Sv/y}$; the lungs averaged 94.66 $\mu\text{Sv/y}$, with a range of 65.56–129.47 $\mu\text{Sv/y}$; bone marrow doses were 102.06 $\mu\text{Sv/y}$, ranged from 70.68 to 139.59 $\mu\text{Sv/y}$; and the testes recorded the highest average dose at 121.29 $\mu\text{Sv/y}$, within a range of 83.99–165.89 $\mu\text{Sv/y}$. The whole-body average dose was calculated at 100.58 $\mu\text{Sv/y}$, ranging from 69.65 to 137.56 $\mu\text{Sv/y}$. Additionally, the kidneys received an average dose of 91.70 $\mu\text{Sv/y}$, with a range of 63.51–125.43 $\mu\text{Sv/y}$, while the liver had the lowest average dose at 68.04 $\mu\text{Sv/y}$, ranging from 47.12 to 93.06 $\mu\text{Sv/y}$ (Table 3). Thus, most organs show safe exposure levels, however increased exposure to the testes results in decreasing resilience to radiation, but the liver showed extraordinary resilience to radiation dose. Organ-specific doses have been found to be safe since the cumulative dosages are lower than those that induce deterministic effects such as acute tissue damage, as well as the danger of long-term stochastic consequences such as cancer.

Excess lifetime cancer risk

The increased cancer risk per unit dose was calculated by analyzing the link between radiation dose and cancer incidence rates between those exposed to varying radiation

levels and those with similar characteristics but not exposed to radiation. The following formula was used to get the ELCR [38]:

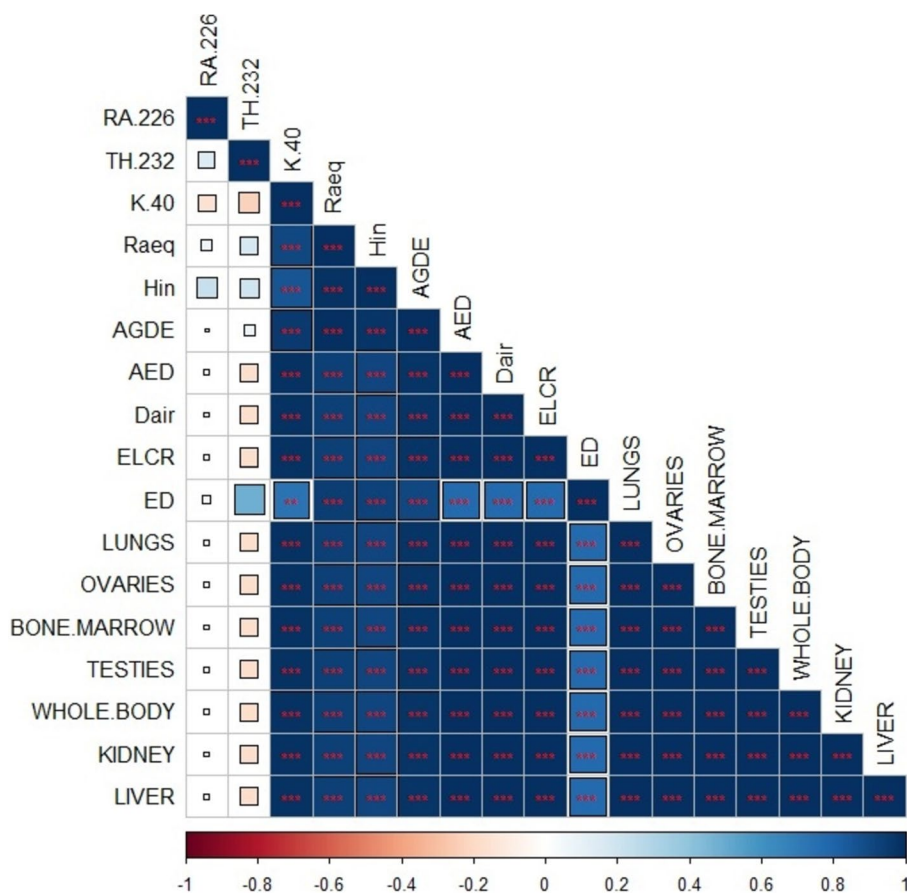
$$\text{ELCR} = \text{AEDR} \times \text{DL} \times \text{RF} \quad (8)$$

where AEDR is the annual effective dose rate, RF is the risk factor, and DL is the life expectancy (70 years). The international commission on radiological protection states that 0.05 is the generally accepted RF value for the public [39]. With a range of 63.56–166.68 (see Table 3), the average ELCR for the wheat samples was around 93.37, which is less than the global average documented reference value [7]. The lower ELCR demonstrates the efficacy of current nuclear safety procedures, legal frameworks, and agricultural practices.

Correlation

The study examined relationships between radionuclides (^{226}Ra , ^{232}Th , and ^{40}K) and their associated health risks by using Pearson correlation analysis (Fig. 2). The results showed that ^{40}K had the most important and largest influence on radiological doses and health hazards, as demonstrated by the strong positive correlation coefficients ($r=0.9$, $p<0.001$). While correlations with AGDE, AED, D_{air} , ELCR, and organ-specific dosages were either close to

Fig. 2 Correlation coefficients among radiological measures



zero or negative, while ^{232}Th had statistically insignificant positive correlation with R_{eq} and H_{in} . Overall, ^{40}K played a crucial role in radiological doses and health risks. ⁴⁰²³²

Box and whisker plot

Radionuclide concentrations and risk assessment are plotted alongside wheat samples from fifteen localities. ^{226}Ra and ^{232}Th have low median values and little variance, but ^{40}K shows a larger median and wider interquartile ranges (IQR), indicating significant variability (Fig. 3). Both H_{in} and R_{eq} have low medians and narrow IQRs, indicating moderate variability. The analysis reveals that AGDE has a low median and narrow IQR for health risk and dose metrics, but AED, D_{air} , and ELCR have higher medians and narrower IQRs. The analysis reveals consistent exposure levels across organ-specific doses for the ovaries, lungs, testes, bone marrow, kidney, whole body, and liver, with low to moderate medians and narrow IQRs.

Principal component analysis

Principal component analysis (PCA) is a powerful statistical technique for reducing the dimensionality of a large data set while retaining much of the variation [40]. To give a summary of the PCA results, the eigenvalues and loadings for the first three principal components (PC1, PC2, and PC3) are presented in Table 4. Factors such as ^{40}K , ELCR, and ED influence the PC1 component, accounting for 90.69% of the variance in the dataset (Fig. 4). PC1 is positively impacted by these parameters, suggesting that it is a good indicator of risk-related metrics and overall radiation exposure. It shows

Table 4 PCA variables

Variables	PC1	PC2	PC3
RA.226	−0.00031	−0.00384	−0.11486
TH.232	−0.00028	−0.036	0.004677
K.40	0.548419	0.358319	0.749872
Raeq	0.04152	−0.02773	−0.05043
Hin	0.000111	−8.5E−05	−0.00045
AGDE	0.170082	−0.04983	−0.09991
AED	0.111392	0.053931	−0.10554
Dair	0.022707	0.010994	−0.02151
ELCR	0.389874	0.188758	−0.36938
ED	0.465186	−0.87238	0.077863
Lungs	0.199615	0.096644	−0.18912
Ovaries	0.180901	0.087584	−0.17139
Bone Marrow	0.21521	0.104195	−0.2039
Testies	0.255757	0.123825	−0.24231
Whole Body	0.212091	0.102685	−0.20094
Kidney	0.193377	0.093624	−0.18321
Liver	0.143473	0.069463	−0.13593

that higher scores are associated with higher radiation exposure and greater health risks in the population. PC2 shows high positive loadings for radiation doses to the ovaries, lungs, and testicles, accounting for 8.97% of the variance. There are negative loadings for both the effective doses and the whole-body doses. PC2 emphasizes the differences in radiation dose to different organs and emphasizes that the exposure to each organ is specific. PC3 explains 0.33% of the variance, suggesting that the kidney and liver have a greater influence on this component than the annual effective

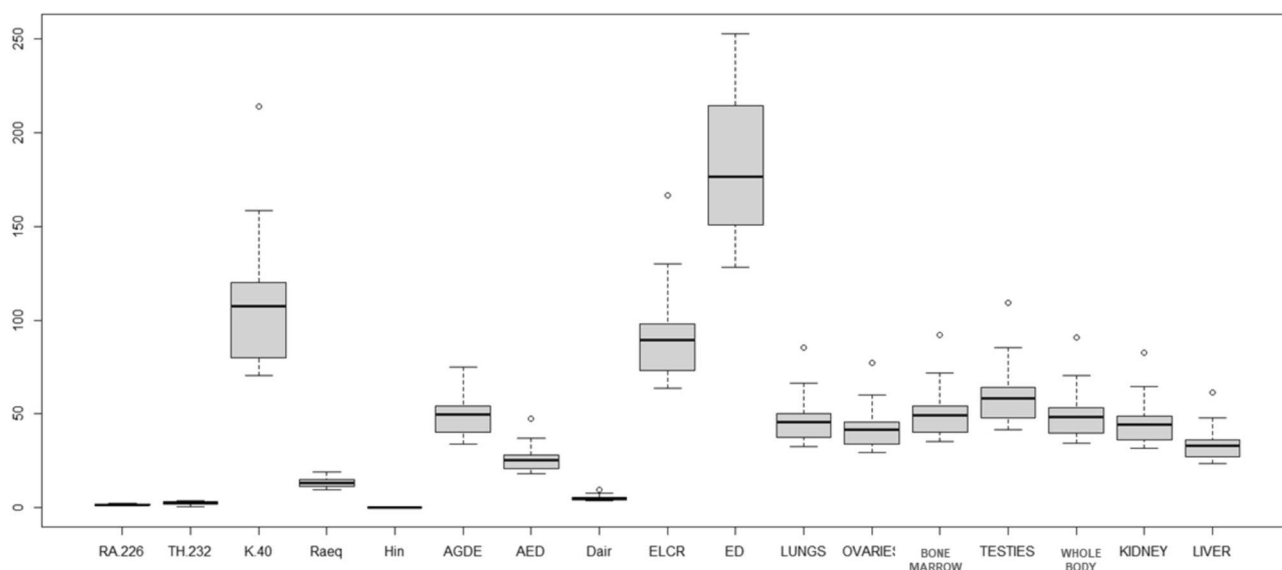


Fig. 3 Box plots of radiological concentrations and associated risks

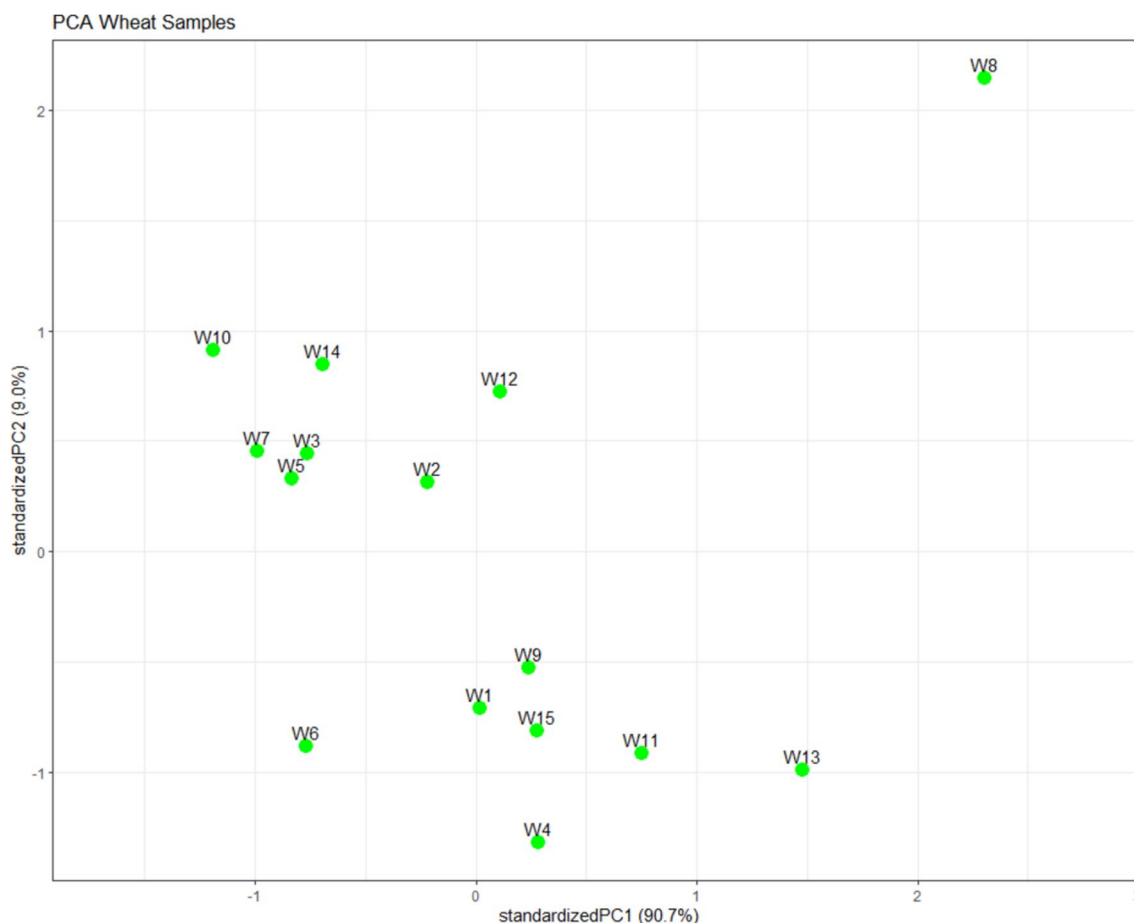


Fig. 4 Visual representation of principal component analysis of radiological health risks and doses of the wheat samples

dosage and bone marrow dose, which have large negative loadings. However, the kidney and liver doses have positive loadings. Information on variations in radiation exposure patterns across several organs is provided by PC3.

Conclusions

To the best of our knowledge, this is the first study to evaluate the radionuclide concentrations in wheat samples and associated radiological health risks in Dera Ghazi Khan. The results demonstrated that average concentrations of the naturally occurring radionuclides (^{226}Ra , ^{232}Th , and ^{40}K) in the wheat samples were found to be lower than the average global reference values. Moreover, radiological hazard indices, like Ra_{eq} , H_{in} , ELCR and radiological doses are found to be within internationally accepted safety limits, implying that wheat consumption from these areas is radiologically safe. Therefore, it is concluded that nuclear facilities in the region are not contributing significantly to radiological contamination in wheat crops.

However, continuous monitoring is recommended to ensure that these safe level are maintained especially as environmental and agricultural conditions evolve. Moreover, additional research is also recommended to investigate other food crops and environmental matrices to provide a more comprehensive risk assessment for the area. This approach will help to ensure safe food production and consumption in the long term.

Acknowledgements The authors are deeply grateful to the Pakistan Institute of Nuclear Science and Technology (PINSTECH), Islamabad, and its Health Physics Division for providing technical facilities. The authors also extend their sincere gratitude to the Researchers Supporting Project Number (RSPD2024R534) at King Saud University, Riyadh, Saudi Arabia, for their valuable support.

Author contributions Sidra Ghias: Conceptualization, Data collection, Methodology, Statistical Analysis, Writing-Original Draft, Formal analysis, Manuscript Submission, Review; Khizar Hayat Satti: Methodology, Review and Supervision; Abdulaziz Al-Anazi: Funding, Review and Format Analysis, Waqas Niaz: Review and Format Analysis; Muhammad Ibrahim: Review and Format Analysis; Abdul Jabbar: Analysis, Methodology, Review, Funding and Supervision, Muhammad Aqeel: Statistical Analysis and Format Analysis.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors state that no known competing financial interest or personal relationship may have had any influence on any of the work disclosed in this study.

References

- Yadav P, Singh B, Garg VK, Mor S, Pulhani V (2017) Bioaccumulation and health risks of heavy metals associated with consumption of rice grains from croplands in Northern India. *Hum Ecol Risk Assess Int J* 23(1):14–27. <https://doi.org/10.1080/10807039.2016.1155949>
- Rattan RK, Datta SP, Chhonkar PK, Suribabu K, Singh AK (2005) Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops, and groundwater—a case study. *Agr Ecosyst Environ* 109(3–4):310–322. <https://doi.org/10.1016/j.agee.2005.02.001>
- Ravi PM, Rout S, Kumar A, Tripathi RM (2014) A review of the studies on environmental transport and speciation analysis of radionuclides in India. *J Radioanal Nucl Chem* 300:169–175. <https://doi.org/10.1007/s10967-013-2929-0>
- Tettey-Larbi L, Darko EO, Schandorf C, Appiah AA (2013) Natural radioactivity levels of some medicinal plants commonly used in Ghana. *Springerplus* 2:1–9. <https://doi.org/10.1186/2193-1801-2-243>
- Pulhani VA, Dafauti S, Hegde AG, Sharma RM, Mishra UC (2005) Uptake and distribution of natural radioactivity in wheat plants from soil. *J Environ Radioact* 79(3):331–346. <https://doi.org/10.1016/j.jenvrad.2004.12.003>
- Jibiri NN, Farai IP, Alausa SK (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 Biophys* 46:53–59. <https://doi.org/10.1007/s00411-007-0105-0>
- United Nations Scientific Committee on the Effects of Atomic Radiation (2000) Sources and Effects of Ionizing Radiation, UNSCEAR 2000 Report, Vol. I: Report to the General Assembly, with Scientific Annexes-Sources. United Nations.
- IARC (2012) Radiation, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans.
- Mohan S, Chopra V (2022) Biological effects of radiation. In: Radiation dosimetry phosphors (pp 485–508). Woodhead Publishing. IARC (2012) Radiation, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans.
- Al-Zoughool M, Krewski D (2009) Health effects of radon: a review of the literature. *Int J Radiat Biol* 85(1):57–69. <https://doi.org/10.1080/09553000802577299>
- Bogutskaya NG, Zuykov MA, Naseka AM, Anderson EB (2011) Normal axial skeleton structure in common roach *Rutilus rutilus* (Actinopterygii: Cyprinidae) and malformations due to radiation contamination in the area of the Mayak (Chelyabinsk Province, Russia) nuclear plant. *J Fish Biol* 79(4):991–1016. <https://doi.org/10.1111/j.1095-8649.2011.03176.x>
- ATSDR (1990) The agency for toxic substances and disease registry: toxicological profile for radon. Public Health Service, U.S. Department of Health and Human Services, Atlanta, Georgia, pp 1–145.
- ATSDR (1999) Toxicological Profile for Uranium. Public Health Service, U.S. Department of Health and Human Services, Atlanta, Georgia, pp 1–462.
- Taskin H, Karavus MELDA, Ay P, Topuzoglu AHMET, Hidiroglu SEYHAN, Karahan G (2009) Radionuclide concentrations in soil and lifetime cancer risk due to gamma radioactivity in Kırklareli. *Turkey J Environ Radioact* 100(1):49–53. <https://doi.org/10.1016/j.jenvrad.2008.09.014>
- Taha TM, Essia HS, Tammam AA (2024) Assessment of the annual effective dose due to intake of natural radionuclides from some food samples. *Assiut Univ J Multidiscipl Sci Res* 53(2):267–275. <https://doi.org/10.21608/aujsmr.2024.26341.1067>
- Kadhim AY, Al-Ghrabi MG, Alsafi HM (2023) Assessment the health risks of radionuclides ^{238}U , ^{232}Th and ^{40}K that influencing on wheat: case study in Al-Qadisiyah, Iraq. In: E3S Web of Conferences (Vol. 405, p. 02021). EDP Sciences. <https://doi.org/10.1051/e3sconf/202340502021>
- Yachiso GT, Chaubey AK, Turi B (2023) Transfer factor of radionuclides from soil to cereal crops around gold mining and evaluation of corresponding radiological hazard levels in Oromia, Ethiopia. *Int J Environ Anal Chem*. <https://doi.org/10.1080/03067319.2023.2257045>
- Sultan DA, Turhan S, Kurnaz A, Hançerlioğulları A, Kamberli AK, Emeksizeoğlu B (2020) Investigation of natural radionuclide and essential metal contents of ancient wheat einkorn (*Triticum monococcum* L.) grown in Turkey. *Radiochimica Acta* 108(12):999–1007. <https://doi.org/10.1515/ract-2020-0753>
- Hussein ZA, Salih NF, Sedeeq SZ (2021) Assessment the natural radioactivity of radionuclides (^{226}Ra , ^{232}Th , ^{40}K , and ^{137}Cs) in wheat grain. *ARO Sci J Koya Univ* 9(1):95–102. <https://doi.org/10.14500/aro.10785>
- Angeleska A, Crceva-Nikolovska R, Dimitrieska-Stojkovikj E, Hajrulai-Musliu Z, Stojanovska-Dimzoska B, Angelovska A (2022) Radionuclide contamination and nutritional evaluation of the wheat mostly used in the Republic of North Macedonia. *Agroknowled J*. <https://doi.org/10.20292/ajss.2022.27379>
- Ghias S, Satti KH, Khan M, Dilband M, Naseem A, Jabbar A, Zafar MI (2021) Health risk assessment of radioactive footprints of the urban soils in the residents of Dera Ghazi Khan, Pakistan. *Chemosphere* 267:129171. <https://doi.org/10.1016/j.chemosphere.2020.129171>
- Malik F, Rafique M (2012) Indoor radon monitoring near an in-situ leach mining site in D G Khan, Pakistan. *J Radiol Protect* 32(4):427. <https://doi.org/10.1088/0952-4746/32/4/427>
- Matiullah MF, Rafique M (2012) Indoor radon monitoring near an in-situ leach mining site in DG Khan, Pakistan. *J Radiol Prot* 32(4):427–437. <https://doi.org/10.1088/0952-4746/32/4/427>
- Gulshan AB, Dasti AA, Sabir H, Atta MI (2012) Indigenous uses of medicinal plants in rural areas of Dera Ghazi Khan, Punjab, Pakistan. *J Agric Biol Sci* 7(9):750–762
- Salih NF, Hussein ZA, Sedeeq SZ (2019) Environmental radioactivity levels in agricultural soil and wheat grains collected from wheat-farming lands of Koya district Kurdistan Region-Iraq. *Radiat Protect Environ* 42(4):128–137
- IAEA (2003) International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, No. 115. IAEA, Vienna.
- Balonov MI, Anspaugh LR, Bouville A, Likhtarev IA (2007) Contribution of internal exposures to the radiological consequences of the Chernobyl accident. *Radiat Prot Dosimetry* 127(1–4):491–496. <https://doi.org/10.1093/rpd/ncm074>
- Ajayi OS (2009) Measurement of activity concentrations of ^{40}K , ^{226}Ra and ^{232}Th for assessment of radiation hazards from soils of the Southwestern region of Nigeria. *Radiat Environ Biophys* 48:323–332. <https://doi.org/10.1007/s00411-009-0225-0>

29. Nuclear Energy Agency (NEA)-OECD (1979) Exposure to Radiation from Natural Radioactivity in Building Materials; Report by NEA Group of Experts. OECD, Paris, France.
30. Gilmore G (2008) Practical gamma-ray spectroscopy. John Wiley & Sons
31. Alzubaidi G, Hamid FB, Abdul Rahman I (2016) Assessment of natural radioactivity levels and radiation hazards in agricultural and virgin soil in the state of Kedah, North of Malaysia. *Sci World J* 2016:6178103. <https://doi.org/10.1155/2016/6178103>
32. Cengiz GB, Oztanriover E (2018) Analysis of natural radioactivity levels in soil samples and dose assessment for Digor District, Kars Turkey. *Caucasian J Sci* 5(1):30–39
33. Al-Jundi J, Salah W, Bawa'aneh MS, Afaneh F (2006) Exposure to radiation from the natural radioactivity in Jordanian building materials. *Radiat Prot Dosimetry* 118(1):93–96. <https://doi.org/10.1093/rpd/nci373>
34. Mohery M, Baz S, Kelany AM, Abdallah AM (2014) Environmental radiation levels in soil and sediment samples collected from floating water from a land runway resulting from heavy rains in the Jeddah region, KSA. *Radiat Phys Chem* 97:16–24. <https://doi.org/10.1016/j.radphyschem.2013.10.003>
35. Ababneh ZQ, Alyassin AM, Aljarrah KM, Ababneh AM (2010) Measurement of natural and artificial radioactivity in powdered milk consumed in Jordan and estimates of the corresponding annual effective dose. *Radiat Prot Dosimetry* 138(3):278–283. <https://doi.org/10.1093/rpd/ncq105>
36. Khan IU, Sun W, Lewis E (2020) Radiological impact on public health from radioactive content in wheat flour available in Pakistani markets. *J Food Prot* 83(2):377–382. <https://doi.org/10.4315/JFP-19-298>
37. ICRP (1996) Age-dependent doses to members of the public from intake of radionuclides. Part 5: Compilation of ingestion and inhalation coefficients. In: ICR Publication 72. Oxford: Pergamon Press.
38. Singh J, Singh H, Singh S, Bajwa BS, Sonkawade RG (2009) Comparative study of natural radioactivity levels in soil samples from the Upper Siwaliks and Punjab, India using gamma-ray spectrometry. *J Environ Radioact* 100(1):94–98. <https://doi.org/10.1016/j.jenvrad.2008.10.002>
39. ICRP (1991) 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60. Ann ICRP 21:1–3
40. Tharwat A (2016) Principal component analysis—a tutorial. *Int J Appl Pattern Recog* 3(3):197–240. <https://doi.org/10.1504/IJAPR.2016.079892>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Sidra Ghias¹  · Khizer Hayat Satti² · Abdulaziz Al-Anazi³ · Waqas Niaz¹ · Muhammad Ibrahim⁴ · Abdul Jabbar² · Muhammad Aqeel⁵

✉ Sidra Ghias
sidraaghias@gmail.com

Khizer Hayat Satti
khizar.pieas@gmail.com

Abdulaziz Al-Anazi
aalanazi15@ksu.edu.sa

Waqas Niaz
waqasjng5628@gmail.com

Muhammad Ibrahim
ibrahim@cuisahiwal.edu.pk

Abdul Jabbar
abduljabbarpk2002@gmail.com

Muhammad Aqeel
muhammadaqeel24@gmail.com

- ¹ Key Laboratory of Marine Chemistry Theory and Technology, Ministry of Education, Ocean University of China, Qingdao 266100, China
- ² Health Physics Division, Pakistan Institute of Nuclear Science and Technology, P.O. Nilore, Islamabad, Pakistan
- ³ Department of Chemical Engineering, College of Engineering, King Saud University, P.O. Box 800, 11421 Riyadh, Saudi Arabia
- ⁴ Department of Biosciences, COMSATS University Islamabad, Sahiwal Campus, Islamabad, Pakistan
- ⁵ Bioinformatics Lab, National Institute for Genomics and Advanced Biotechnology (NIGAB), NARC, Islamabad 45500, Pakistan

Reproduced with permission of copyright owner. Further reproduction
prohibited without permission.