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Evaluating Radioactivity Levels and Determining Risk Indicators in Plant Samples in Kirkuk- Iraq

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ABSTRACT

This study aims to assess the natural radioactivity of radioactive isotopes (Ra^{226}, $Th^{232}$and K^{40}) in plant samples using a high-purity germanium (HpGe) gamma-ray spectrometer. Fifteen plant samples, equally distributed among vegetables, legumes, and grains, were collected from local markets in Kirkuk, Iraq. The radioactivity of radionuclides was analyzed, and relevant radiation risk indicators were calculated. Results showed that the specific activity of Ra^{226} ranged from (0.46 to 50.04 $Bq.kg^{-1}$) while the specific activity of Th^{232} ranged from below detection limits (B.D.L. to 25.42 $Bq.kg^{-1}$). For K^{40}, the specific activity ranged from (90.35 to 587.60 $Bq.kg^{-1}$). Radiation risk indicators were calculated, with radium equivalent (Ra_{eq}) values ranging from (7.946 to 118.772 $Bq.kg^{-1}$). The gamma level index (I_{γ}) ranged from (0.067 to 0.876), while the external hazard coefficient (H_{ex}) ranged from (0.021 to 0.320), and the internal hazard coefficient (H_{in}) ranged from (0.022 to 0.456). The absorbed dose rate in air (D) was estimated to range from (4.268 to 63.728 $nGy.h^{-1}$). Annual external and internal effective doses were calculated, with maximum values of (0.078 and 0.312 $mSv.y^{-1}$), respectively, and minimum values of (0.001 and 0.020 $mSv.y^{-1}$), respectively. Variation in radiation risk indicator values was observed, with some within internationally permissible limits, while others exceeded these limits, particularly in vegetable samples. This variation is attributed to the potential use of irrigation water with high radioactive content, which may pose a potential risk to living organisms that depend on these plants for food.

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1. INTRODUCTION

Most developing countries rely on the agricultural sector as a primary driver of economic growth. Significant efforts have been made to ensure sustainable food security, as providing adequate food contributes to reducing food-related problems, thereby enhancing population health and work capacity, and consequently driving economic growth[1]. Natural radioactivity is primarily attributed to radionuclides such as (Ra^{226}, $Th^{232}$and K^{40}) and their isotopes present in soil, air, and water. The study of these radionuclide concentrations is of great importance in monitoring environmental radioactivity[2]. Governments worldwide have paid great attention to studying the environmental effects resulting from radioactive pollution caused by some complex industries, which leads to environmental imbalance and harm to plants and living organisms, which constitute a main source of human food [3]. Studies indicate high radioactivity in plant leaves, due to their role in photosynthesis and dependence on elements present in the soil. Consequently, soil contaminated with radioactive nuclides loses its ability to support high-quality crop growth and is considered degraded. The spread of contaminants in plants depends on several factors, including the concentration of contaminants in soil and water, air movement, and rainfall amount. Soil is considered the primary element in containing toxic metals and controlling their movement within the plant [4].

Radionuclides are transferred to humans through the food chain, either through direct consumption of plants or by consuming products from animals that feed on these plants. The levels of radionuclides that humans receive from food range from a few tens to several hundreds of Becquerel's per kilogram of food [5]. Most individuals receive about 180 Bq of potassium K40, which is an essential element in plants. The human body contains about 0.14 kg of natural K40, making it the main source of natural radioactivity in the human body, whose potential effects cannot be ignored [6]. High concentrations of radionuclides and heavy elements in vegetables and crops have negative effects on human health and other living organisms. Their accumulation in the human body may lead to certain diseases, including lung cancer[7].

2. STUDY OBJECTIVE

The natural radioactivity of (Ra^{226}, $Th^{232}$and K^{40}) was measured for samples (vegetables, legumes, and grains) using a high-purity germanium detector (HpGe). Additionally, risk indicators were analyzed in plant samples obtained from local markets in Kirkuk governorate. The importance of this study stems from the fact that radiation poses a risk to living organisms and humans, and its widespread presence in plants, water, and soil. Numerous studies have been conducted to measure the natural radioactivity of radionuclides and evaluate risk indicators in various countries around the world, including Turkey [8], Egypt [9], Ghana[10], India[11], Nigeria [12], Serbia[13], and Iraq [14]. The results of these studies are summarized in Table (3).

3. MATERIALS AND METHODS

3.1. SAMPLE SOURCES

Fifteen (15) plant samples were collected from local markets, equally distributed among vegetables, legumes, and grains (5 per category). Samples were selected based on their diverse origins (Iraqi and Turkish). Additionally, leafy vegetables were obtained from local grocery stores, cultivated using surface water and well water.

3.2. SAMPLE DETAILS AND PREPARATION

Plants were chosen for the study due to their significance as primary food sources for humans and other living organisms. Vegetable samples underwent thorough cleaning using tap water to remove adherent impurities, including sand, insects, and dirt. Samples were stored in labeled polyethylene bags for accurate identification. The average wet weight of samples was approximately 800 grams. Samples were air-dried for six weeks, followed by thermal drying in an oven at 100°C for one hour to reach a constant weight [15]. Subsequently, samples were ground using a laboratory mill and passed through a 1 mm diameter sieve to ensure homogeneity. Dried and ground samples were weighed using a precision balance and stored in sealed polyethylene containers, with 500 grams per sample. Samples were left for 30 days to achieve radioactive equilibrium between radium and thorium isotopes (Ra^{226}, Th^{232}) [16].

3.3. CHARACTERISTICS OF THE High-PRUTIY GERMANIUM DETECTOR (HPGE)

A High-Purity Germanium (HpGe) detector was used to measure radioactivity in prepared samples placed in front of the pre-calibrated detector crystal. The crystal is hermetically sealed by a 10 cm thick lead shield and a movable cover with a 62.2 mm diameter. Detector calibration is performed weekly to ensure stability as part of quality assurance procedures. The adopted detector crystal is a high-purity semiconductor (germanium) type GC4020 from Canberra, USA. This detector has an efficiency of 40% and can separate closely spaced gamma-ray lines with a resolution of 2.0 kev at 1.33 MeV. It operates with a bias voltage of +13000 volts and an operating voltage of +22000 volts [17]. The detector is unstable at room temperature, and the crystal may be damaged due to induced noise. Therefore, the detector is cooled to 77 K during operation using liquid nitrogen contained in a Dewar flask. The cooling unit is a 75000SL model. This detector converts the energy of incident radiation into electrical pulses through the interaction of gamma rays with the highly sensitive detector material, generating carriers that deflect and accumulate at the electrodes via the field. The acquisition time for each sample placed on the detector front is 7200 seconds, with a dead time of 0.06-0.23%. Genie 2000 software (CANBERRA) was used to analyze the resulting spectra [18]. The detector was calibrated weekly as part of quality assurance procedures to maintain measurement accuracy.

4. THEORETICAL ASPECT

The specific radioactivity of the radionuclides (Ra^{226}, $Th^{232}$and K^{40}) is calculated based on the method of exposure to external radiation, where the radioactivity is calculated according to the following equation:

$$A_C\left(\frac{Bq}{Kg}\right)=\frac{C_{net}}{\varepsilon(E_{\gamma})\times I_{\gamma}\times m} \quad (1)$$

Where I_{γ} represents the emission probability, C_{net} represents the net peak of the positive number, m is the mass of each sample in kg, and ε (E_{γ}) is the absolute energy efficiency of the detector [19].

Radon Equivalent Activity (Ra_{eq}) is widely used as an indicator of radiation hazard, as it includes those categories specific to the eyes of competitors with different concentrations of (Ra^{226}, $Th^{232}$and K^{40}) and is calculated according to the following ratios:

$$Ra_{eq}(Bq/kg) = A_{Ra} + 1.43A_{Th} + 0.077A_{K} \quad (2)$$

Where A_{Ra}, A_{Th} are the specific activity (Ra^{226}, Th^{232}, K^{40}) in units of $Bq.kg^{-1}$, respectively [20].
The absorbed dose rate (D) in the air at a height of 1m above the ground can be calculated through the following equation:

$$D(nGy/h) = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_{K} \quad (3)$$

Cosmic rays in the open air are absorbed, so the absorbed dose rate in the air and at sea level is about (30 $nGy.h^{-1}$). The average specific activity (Ra^{226}, $Th^{232}$and K^{40}) was used in units of $Bq.Kg^{-1}$ in the plant samples, and the conversion factor was applied. (0.7 $svG.y^{-1}$) used by UNSCAR [21].
The external hazard index (H_{ex}) determined for all samples analyzed depends on the rate of radiation dose absorbed by the body, the amount of energy, the size of the radioactive source, and the distance separating the source from the body through the following equation: [22].

$$H_{ex} = \left(\frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810}\right) \leq 1 \quad (4)$$

The internal risk index (H_{in}) appears when radioactive substances enter the body of a living organism when inhaling and swallowing contaminated food materials, as the deposition of a quantity of them in human bones causes what is called bone abscess. The internal risk index is calculated from the following relationship:

$$H_{in} = \left(\frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810}\right) < 1 \quad (5)$$

This index must be less than one in the human body in order for it to be safe [23].
Gamma level coefficient (I_γ) The danger index for gamma rays that are associated with natural radionuclides in plant samples is calculated based on the radiation danger index through the following relationship:

$$I_\gamma = \left(\frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_{K}}{1500}\right) \quad (6)$$

Average Annual Effective Dose Equivalent (AEDE), where the conversion factor of the absorbed dose (D) in the air must be taken into account, which is the equivalent of the dose expelled by [24].

$$AEDE_{out}(mSv/yr) = D(nGy/h) \times 0.7\ (Sv/Gy) \times 0.2 \times 8760\ (h/y) \times 10^{-6} \quad (7)$$

$$AEDE_{in}(mSv/yr) = D(nGy/h) \times 0.7\ (Sv/Gy) \times\ 0.8 \times\ 8760\ (h/y) \times 10^{-6} \quad (8)$$

Where (0.7 $SvG.y^{-1}$) is the conversion factor from the dose absorbed in the air to the dose to which adults are exposed (0.2) is the external dose equivalent, where (8760) is the number of hours per year and the corresponding value worldwide for the external ($AEDE_{out}$) and internal dose. ($AEDE_{in}$) are respectively, where the value of (AEDE) is (0.08 mSv) all over the world (O.E.C.D ,1979). The X-ray spectrum of plant samples (vegetables, legumes, grains) was analyzed using a high-purity germanium (HpGe) detector, and the results are taken directly from the computer using the (Gene2000) program.

5. RESULTS AND DSICUSSION

The results presented in Table (1) show the effective concentrations of radioactive nuclides (Ra^{226}, Th^{232} and K^{40}) in plant samples, calculated using Equation (1) after the system was pre-calibrated using standard elements. The efficiency for each element was determined through the efficiency curve.

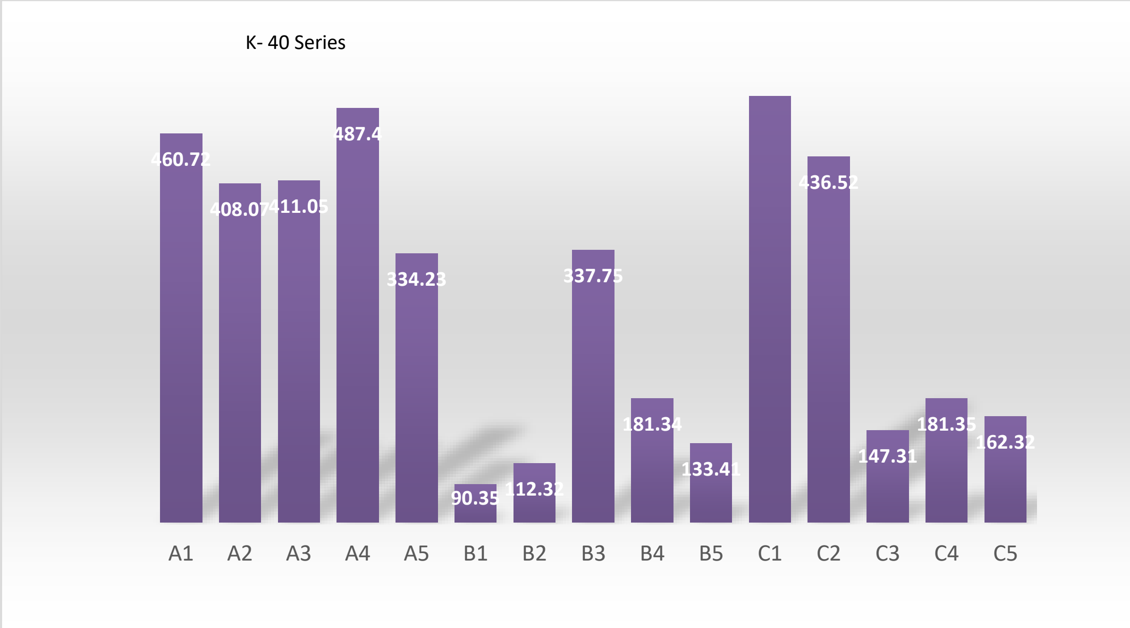
Table (2) illustrates the radiological hazard parameters measured using Equations (2) to (8), with these results compared to globally permitted levels [25]. Figures (1) to (3) demonstrate the variation in natural radioactivity values for the radioactive nuclides (Ra^{226}, $Th^{232}$and K^{40}) obtained.

Table (1) shows the specific activity concentrations of (Ra^{226}, Th^{232}, K^{40}).

Sample Type	Sample Name	Sample Code	Ra^{226} (Bq.Kg^{-1})	Th^{232} (Bq.Kg^{-1})	K^{40} (Bq.Kg^{-1})
Vegetables	Celery	A1	44.04 ± 3.2	25.42 ± 1.9	460.72 ± 3.2
	Cress	A2	41.32 ± 1.5	21.27 ± 2.1	408.07 ± 2.5
	Basil	A3	39.31 ± 2.3	22.92 ± 3.2	411.05 ± 2.3
	Swiss Chard	A4	50.04 ± 0.9	21.82 ± 1.8	487.40 ± 2.5
	Spinach	A5	43.12 ± 2.1	22.28 ± 2.3	334.23 ± 2.7
	Low Value		39.31 ± 2.3	21.27 ± 2.1	334.23 ± 2.7
	Highest Value		50.04 ± 0.9	25.42 ± 1.9	487.40 ± 2.5
	Average		43.56 ± 2	22.74 ± 2.26	420.29 ± 2.64
Average Global Values [25]			35	45	412
Cereals	Wheat	B1	0.46 ± 0.14	0.37 ± 0.15	90.35 ± 1.95
	Barley	B2	2.12 ± 0.81	0.51 ± 0.12	112.32 ± 2.31
	Rice	B3	2.32 ± 0.29	B.D.L	337.75 ± 5.11
	Sesame	B4	5.37 ± 0.31	3.45 ± 0.11	181.34 ± 7.32
	Maize	B5	1.52 ± 0.03	1.98 ± 0.21	133.41 ± 1.91
	Low Value		0.46 ± 0.14	B.D.L	90.35 ± 1.95
	Highest Value		5.37 ± 0.31	3.45 ± 0.11	181.34 ± 7.32
	Average		2.35 ± 0.31	1.26 ± 0.11	171.03 ± 3.72
Average Global Values [25]			40	40	500
Legumes	Beans	C1	3.11 ± 1.6	3.85 ± 1.8	587.60 ± 6.54
	Peas	C2	2.31 ± 1.5	5.68 ± 1.7	436.52 ± 5.31
	Hummus	C3	5.83 ± 0.5	3.50 ± 0.73	147.31 ± 4.02
	Cowpeas	C4	7.25 ± 0.2	2.32 ± 0.41	181.35 ± 7.51
	Vicia Faba	C5	5.02 ± 0.7	6.20 ± 0.52	162.32 ± 3.36
	Low Value		3.11 ± 1.6	2.32 ± 0.41	147.31 ± 4.02
	Highest Value		7.25 ± 0.2	6.20 ± 0.52	587.60 ± 6.54
	Average		4.70 ± 1.3	4.31 ± 1.03	303.02 ± 5.34
Average Global Values [25]			40	40	500
Sample Type	Sample Name	Sample Code	Ra^{226} (Bq Kg^{-1})	Th^{232}(Bq Kg^{-1})	K^{40}(Bq Kg^{-1})
Vegetables	Celery	A1	44.04 ± 3.2	25.42 ± 1.9	460.72 ± 3.2
	Cress	A2	41.32 ± 1.5	21.27 ± 2.1	408.07 ± 2.5
	Basil	A3	39.31 ± 2.3	22.92 ± 3.2	411.05 ± 2.3
	Swiss Chard	A4	50.04 ± 0.9	21.82 ± 1.8	487.40 ± 2.5
	Spinach	A5	43.12 ± 2.1	22.28 ± 2.3	334.23 ± 2.7
	Low Value		39.31 ± 2.3	21.27 ± 2.1	334.23 ± 2.7
	Highest Value		50.04 ± 0.9	25.42 ± 1.9	487.40 ± 2.5
	Average		43.56 ± 2	22.74 ± 2.26	420.29 ± 2.64
Average Global Values [25]			35	45	412
Cereals	Wheat	B1	0.46 ± 0.14	0.37 ± 0.15	90.35 ± 1.95
	Barley	B2	2.12 ± 0.81	0.51 ± 0.12	112.32 ± 2.31
	Rice	B3	2.32 ± 0.29	B.D.L	337.75 ± 5.11
	Sesame	B4	5.37 ± 0.31	3.45 ± 0.11	181.34 ± 7.32
	Maize	B5	1.52 ± 0.03	1.98 ± 0.21	133.41 ± 1.91
	Low Value		0.46 ± 0.14	B.D.L	90.35 ± 1.95
	Highest Value		5.37 ± 0.31	3.45 ± 0.11	181.34 ± 7.32
	Average		2.35 ± 0.31	1.26 ± 0.11	171.03 ± 3.72
Average Global Values [25]			40	40	500
Legumes	Beans	C1	3.11 ± 1.6	3.85 ± 1.8	587.60 ± 6.54
	Peas	C2	2.31 ± 1.5	5.68 ± 1.7	436.52 ± 5.31
	Hummus	C3	5.83 ± 0.5	3.50 ± 0.73	147.31 ± 4.02
	Cowpeas	C4	7.25 ± 0.2	2.32 ± 0.41	181.35 ± 7.51
	Vicia Faba	C5	5.02 ± 0.7	6.20 ± 0.52	162.32 ± 3.36
	Low Value		3.11 ± 1.6	2.32 ± 0.41	147.31 ± 4.02
	Highest Value		7.25 ± 0.2	6.20 ± 0.52	587.60 ± 6.54
	Average		4.70 ± 1.3	4.31 ± 1.03	303.02 ± 5.34
Average Global Values [25]			40	40	500

Figure (1) includes Figures (a, b, c) show a comparison of the specific radioactivity of Ra^{226} in the samples (vegetables, grains, legumes) studied

Figure (2) includes Figures (a, b, c) show a comparison of the specific radioactivity of Th^{232} in the samples (vegetables, grains, legumes) studied.



Figures (3) show a comparison of the specific radioactivity of K^{40} in the samples (vegetables, grains, legumes) studied.

Table (2) shows the values of the radiation hazard coefficients for the absorbed dose in the air (D), the radium equivalent concentration (Ra_{eq}), the external hazard factor (H_{ex}), the internal hazard factor (H_{in}), the effective concentration factor similar to the gamma level (I_{γ}), and the annual external effective dose ($AEDE_{out}$). and internal ($AEDE_{in}$).

Table (2): Radiation hazard coefficients

Sample Code	Ra_{eq} ($Bq.kg^{-1}$)	D ($nGy.h^{-1}$)	H_{ex}	H_{in}	I_{γ}	$AEDE_{out}$ ($mSv.y^{-1}$)	$AEDE_{in}$ ($mSv.y^{-1}$)
A1	115.866	54.912	0.312	0.431	0.854	0.067	**0.269**
A2	103.157	54.820	0.278	0.390	0.760	0.067	**0.268**
A3	103.736	54.727	0.280	0.386	0.765	0.067	**0.268**
A4	118.772	63.728	0.320	0.456	0.876	0.078	**0.312**
A5	100.716	53.439	0.272	0.388	0.733	0.065	**0.262**
Average	108.449	56.325	0.292	4.10	0.797	0.068	**0.276**
B1	7.946	4.268	0.021	0.022	0.067	0.005	**0.020**
B2	11.497	6.272	0.031	0.036	0.081	0.007	**0.030**
B3	28.326	15.485	0.076	0.082	0.240	0.018	**0.075**
B4	24.266	12.889	0.065	0.080	0.191	0.015	**0.063**
B5	14.624	7.677	0.039	0.043	0.118	0.009	**0.037**
Average	17.331	9.318	0.046	0.052	0.139	0.010	**0.045**
C1	53.860	28.706	0.145	0.153	0.450	0.035	**0.140**
C2	44.044	23.028	0.118	0.125	0.363	0.028	**0.112**
C3	22.177	11.778	0.059	0.075	0.172	0.014	**0.057**
C4	24.531	13.342	0.066	0.085	0.192	0.016	**0.065**
C5	26.384	13.545	0.071	0.084	0.203	0.016	**0.066**
Average	34.199	18.079	0.091	0.104	0.276	0.021	**0.088**
Average Global Values [25]	370	55	≤1	≤1	≤1	0.7	**0.42**

The results of the spectral analysis of natural radioactivity in plant samples collected from local markets, comprising 15 samples with five samples each of vegetables, grains, and legumes, revealed varying concentrations as shown in Figures (1-3). Table (1) displays the specific activity and mean values for (Ra^{226}, $Th^{232}$and K^{40}). The highest specific activity of Ra^{226} in vegetables was found in sample (A4) at (50.04 $Bq.Kg^{-1}$), which exceeds globally permitted levels, possibly due to the use of sewage water for irrigation. The lowest value was in sample (A3) at (39.31 $Bq.Kg^{-1}$), with a mean of (43.56 $Bq.Kg^{-1}$). For grains, the highest Ra^{226} value was in sample (B4) at (5.37 $Bq.Kg^{-1}$) and the lowest in (B1) at (0.46 $Bq.Kg^{-1}$), with a mean of (2.35 $Bq.Kg^{-1}$). In legumes, the highest Ra^{226} value was (7.25 $Bq.Kg^{-1}$) in sample (C4) and the lowest (3.11 $Bq.Kg^{-1}$) in sample (C1), with a mean of (4.70 $Bq.Kg^{-1}$).

These results align with those obtained in Serbia [13], and are within globally permitted levels. The specific activity of Th^{232} in vegetables was highest in sample (A1) at (25.42 $Bq.Kg^{-1}$) and lowest in sample (A4) at (21.27 $Bq.Kg^{-1}$), with a mean of (22.74 $Bq.Kg^{-1}$). In grains, the highest Th^{232} value was in sample (B4) at (3.45 $Bq.Kg^{-1}$) and the lowest in (B3) at (B.D.L Bq.Kg-1), with a mean of (1.26 $Bq.Kg^{-1}$). For legumes, the highest Th^{232} value was (6.20 $Bq.Kg^{-1}$) in sample (C5) and the lowest (2.32 $Bq.Kg^{-1}$) in sample (C4), with a mean of (4.31 $Bq.Kg^{-1}$). These results are consistent with those obtained in Nigeria [12]. and within globally permitted levels. The specific activity of K^{40} in vegetables was highest in sample (A4) at (487.40 $Bq.Kg^{-1}$) and lowest in sample (A5) at (334.23 $Bq.Kg^{-1}$), with a mean of (420.29 $Bq.Kg^{-1}$). In grains, the highest K^{40} value was in sample (B4) at (181.34 $Bq.Kg^{-1}$) and the lowest in (B1) at (90.35 $Bq.Kg^{-1}$), with a mean of (171.03 $Bq.Kg^{-1}$). For legumes, the highest K^{40} value was (587.60 $Bq.Kg^{-1}$) in sample (C1) and the lowest (147.31 $Bq.Kg^{-1}$) in sample (C3), with a mean of (303.02 $Bq.Kg^{-1}$).

These results align with those obtained in Turkey [8]. and are within globally permitted levels. Regarding hazard indices, the highest radium equivalent activity (Ra_{eq}) was in sample (A4) at (118.772 $Bq.Kg^{-1}$) and the lowest in sample (B1) at (7.946 $Bq.Kg^{-1}$).

The gamma level index (I_{γ}) was highest in sample (A4) at (0.876) and lowest in sample (B1) at (0.067). The external hazard index (H_{ex}) was highest at (0.320) in (A4) and lowest at (0.021) in (B4). The internal hazard index (H_{in}) was highest at (0.456) in (A4) and lowest at (0.022) in (B4). The absorbed dose rate D in air was highest at (63.728) in (A4) and lowest at (4.268) in (B1). The annual effective dose equivalent outdoor and indoor were highest at (0.078, 0.312 $mSv.y^{-1}$) respectively in sample (A4) and lowest at (0.001, 0.020 $mSv.y^{-1}$) respectively in sample (B1). The hazard index values varied, with some within internationally permitted limits and others exceeding these limits, particularly in vegetable samples.

6. CONCLUSIONS

An analysis of specific radioactivity values and hazard indices in the studied samples was conducted. The results revealed a significant variation in distribution. Some values were within globally permissible limits, while others exceeded these limits, particularly in vegetable samples. This variation can be attributed to several factors, primarily the quality of water used for irrigation, which may contain high proportions of radioactive contaminants, and the impact of adjacent industrial activities on soil and plants. These findings raise concerns about potential health effects on living organisms that rely on these plants for food, including the possibility of increased cancer risk with continuous consumption.

Table (3) shows a comparison of the levels of natural radioactivity in the studied plant samples with those found in other countries.

Country	Ra^{226}	Th232	K^{40}	Source
Türkiye	25.82	B.D.L	491.62	**[8]**
Egypt	10.2	7.9	200	**[9]**
Ghana	20 - 47	42 -71	566 – 1093	**[10]**
India	15 – 84	3.02 – 17.6	145 – 354	**[11]**
Nigeria	14,7 – 16.2	7.0 – 11.4	67.70	**[12]**
Serbia	0.6 – 8.2	1.7 – 15.1	126 – 1243	**[13]**
Iraq	0.20 – 1.45	0.11 – 0.48	68.07 - 1355	**[14]**
Our Stusy	0.46 - 5.37	B.D.L - 3.45	90.35 - 81.34	

7. RECOMMENDATIONS

Based on the derived results, we recommend Expanding the scope of the study to include a larger and more diverse range of plant samples, using advanced and varied analytical techniques to improve the accuracy and reliability of the results. Conducting long-term studies to track changes in radioactivity levels over time, as well as assessing potential health effects in humans and other living organisms consuming these plants, and developing strategies to reduce radioactive contamination in areas where levels exceed permissible limits. These recommendations are necessary given the importance of plants as a major source of food for humans and other organisms, and the potential impact of long-term exposure. the long-term impact of radiation on public health.

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