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Amina Q. Al-Bakri
Department of Environmental Science, College of Environmental Sciences, University of Mosul, Iraq

Ayman Albanna
Department of Environmental Science, College of Environmental Sciences, University of Mosul, Iraq, aymanalbanna@uomosul.edu.iq

Mazin N. Fadhel
Department of Environmental Science, College of Environmental Sciences, University of Mosul, Iraq

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ORIGINAL STUDY

Comparative Evaluation of Radioisotope Accumulation in Stems and Leaves of Wild Flora in Nineveh Governorate for Environmental Pollution indicator

Amina Q. Al-Bakri, Ayman Albanna *, Mazin N. Fadhel

Department of Environmental Science, College of Environmental Sciences, University of Mosul, Iraq

ABSTRACT

It is a comparative assessment of natural deposition of radioisotopes in wild plants' stems and leaves from 11 sites of Nineveh Governorate, Iraq. Levels of ˆ226Ra, ˆ232Th, and ˆ40K activities were determined using high-resolution gamma spectrometry, and radiological equivalent indices—Radium Equivalent Activity (Raeq), Absorbed Dose Rate (D), Annual Effective Dose Equivalent (AEDE), Annual Gonadal Dose Equivalent (AGDE), Excess Lifetime Cancer Risk (ELCR), and hazard indices (Hex, Hin, Iγ) were determined. All results indicated invariably greater radionuclide accumulation in leaves than in stems at every station. Mean Raeq in leaves was 63,473 Bq/kg and in stems 60,854 Bq/kg, and the highest values were found in Kairouan, Hammam al-Alil, and Makhmur. Although hazard indices never exceeded internationally accepted thresholds, elevated AEDE and ELCR values in some places point to potential long-term exposure risks. Spatial and anatomical heterogeneity highlight the value of wild plants, particularly foliar tissue, as sensitive bioindicators of environmental pollution. The study stresses the importance of continued radiological surveillance and environmental management, especially in ecologically and agriculturally important regions. These findings contribute to regional radioprotection planning and form a basis for future assessments of environmental contamination in northern Iraq.

Keywords: Radioisotope accumulation, Wild plants, Radiological risk assessment, Nineveh governorate

1. Introduction

Radioactive isotopes are among the most persistent and harmful environmental pollutants since they have long half-lives and can release ionizing radiation. Their release into the environment has the ability to accumulate in various sections of the ecosystem, such as water, soil, plants, animals, and ultimately humans. The toxic impact of the isotopes is that they can cause cellular and genetic damage, thus there is a need for constant monitoring of their sources and circulation (El Reefy, 2011). Biomonitoring proved to be an effective approach in detecting environmental contamination, and vegetation is of utmost value as a bioindicator since it can absorb chemical and radioactive contaminants from its surroundings through the soil, water, or atmosphere. Wild vegetation, in particular, offers certain unique advantages towards radiological pollution monitoring in that they grow in uncontrolled environments and are an expression of local ecological conditions (Ba, Van, and Loan, 2025). The environmental significance of radionuclide accumulation in vegetation goes beyond the detection limits. Plants are the initial trophic level of terrestrial food chains and thus offer a critical pathway

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* Corresponding author.
E-mail address: aymanalbanna@uomosul.edu.iq (A. Albanna).

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for radioactive material transfer via the food chain. When radionuclides have been absorbed by the roots of plants or deposited on leaf surfaces, they are concentrated in herbivores and subsequently in human beings through the consumption of contaminated crops, fodder, and animal products. This bioaccumulation has potential long-term health effects on human beings, including increased rates of cancer, gene mutation, and developmental abnormalities. Additionally, the presence of these isotopes within biological systems has the potential to lead to long-term exposure even at small activity concentrations, and thus a continuous surveillance of the environment is necessary (El Reefy, 2011, Ba, Van, and Loan, 2025). From an ecological perspective, radioactive pollution also disrupts ecosystem integrity by altering plant metabolism, impeding seed germination and species richness, and influencing soil–plant–microbe relationships. These consequences can spread throughout the ecosystem, influencing primary productivity and local habitat stability. Therefore, understanding radionuclide uptake mechanisms and rates in natural vegetation is of critical significance in terms of determining ecosystem resilience under radiological stress, as well as for planning remediation strategies. Nineveh Governorate in northern Iraq has experienced significant environmental and geographical changes over the last decades. The changes are a result of increased human activities such as industrial expansion, agricultural practices, and urbanization, as well as war that might have introduced or redistributed radioactive isotopes into the local environment. Owing to the topography variability, plant cover, and climate, Nineveh provides an ideal location to study the behavior and accumulation of plant radioactive isotopes. This study aims to quantify levels of accumulation of the most environmentally significant radionuclides — including Cesium-137 (Cs-137), Uranium-238 (U-238), and Thorium-232 (Th-232) — in stems and leaves of wild plant species of different locations within Nineveh. It also aims to compare accumulation levels between organs of plants and investigate the relationship between radiological contamination and the surrounding human activity (Mihalik et al., 2024). Understanding radionuclide accumulation patterns in vegetation is a significant step towards the development of accurate and effective environmental monitoring tools that operate towards the protection of the ecosystem as well as public health. Furthermore, the findings of the study may contribute to the development of a scientific database for environmental planning and decision-making in Iraq and the region. This study aims to comparatively assess the accumulation of certain radioisotopes (^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in case of detection) in leaves and stems of various wild plant species collected from various locations in Nineveh Governorate. By measuring the activity concentrations and calculating transfer factors, the study aims to identify the most reliable plant organs and plants that can be utilized as indicators of radioactive contamination of the region. The reason for the review is to reveal information about local environment and agriculture that so far has not been incorporated into radioecology goals. Incorporating them will help in order to make adjustments to models of radionuclide distribution in the environment and assess the potential danger to saline agriculture due to radioactive contamination. The total information about radionuclide bioavailability and salinity effect are linked with real conditions in the local agriculture and some environmental factors (Wais et al., 2025).

2. Materials & methods

2.1. Study area and sampling

This research was conducted in Nineveh Governorate, northern Iraq, which is a region of ecological diversity and environmental exposure variability. Twenty-two sampling sites were selected, including Sinjar, Makhmur, Qaraj, Zumar, Kairouan, Rabia, Hamidat, Nimrud, Al-Kuwayr, Alqosh, and Hammam al-Alil. Wild plant samples from all places were collected, and leaf and stem pieces were taken separately from the same plant types to allow comparative radionuclide accumulation analysis (Fig. 1).

Fig. 1. A map showing the administrative regions in Nineveh Governorate.

2.2. Sample preparation

Plant samples collected were rinsed with distilled water to remove dust and soil particles. The samples were shade-dried for 5 to 7 days, and oven-dried at 80°C for 24 hours to dry out the moisture content. The dried plant material was ground to powder form using a stainless steel electric grinder and sieved through a 2 mm mesh. Powdered samples were weighed and put in 500-mL Marinelli beakers, sealed, and aged for 28 days to realize secular equilibrium between parent radionuclides and daughter radionuclides.

2.3. Gamma spectrometric analysis

Natural radioactivity content of ˆ226Ra, ˆ232Th, and ˆ40K in plant samples was determined using a high-purity germanium (HPGe) gamma-ray spectrometer (Canberra, USA) with 40% relative efficiency and an energy resolution of 1.8 keV at 1.33 MeV. Calibration of the detector was done using standard reference materials provided by the IAEA. Every sample was counted for 86,400 seconds (24 hours) to provide high statistical accuracy (Mihalik et al., 2024).

2.4. Radiological dose calculations

Radiological hazard parameters were calculated using standard UNSCEAR (2000) and ICRP guidelines. Following indices were determined using measured activity concentration:

- Radium equivalent activity (Raeq, Bq/kg)
- Absorbed dose rate (D, nGy/h)
- Annual effective dose equivalent (AEDE, μSv/y)
- Annual gonadal dose equivalent (AGDE, μSv/y)
- Excess lifetime cancer risk (ELCR $\times 10^{-3}$)
- External hazard index (Hex)
- Internal hazard index (Hin)
- Gamma representative level index (Iγ)

These calculations were aimed at assessing the potential radiological risk resulting from the accumulation of radionuclides in wild plants used as bio-indicators of environmental contamination (Wallbrink, Walling, and He, 2002).

2.5. Statistical analysis

All the measurements were conducted in triplicate, and the values were presented as means. Statistical comparison between leaves and stems was performed using paired t-tests, and significance was set at $p < 0.05$. Statistical analysis and plotting were performed using IBM SPSS Statistics software version 26 and Microsoft Excel (Sangsingkeow, 1999).

3. Results

This research is comparative radiological analysis of wild vegetation's organs leaves and stems in eleven locations of Nineveh Governorate, Iraq. Information obtained are natural radionuclide activity concentrations and computed radiological indices relevant for environmental risk assessment. The findings determine significant anatomical and spatial differences in radioisotope accumulation with the overall tendency of higher accumulation in leaves than in stems for nearly all parameters and locations.

3.1. Radium equivalent activity (Raeq)

Radium equivalent activity (Raeq), an index of cumulative radioactivity from ˆ226Ra, ˆ232Th, and ˆ40K, was very much variable among plant organs. Leaf Raeq averaged 63,473.74 Bq/kg whereas Raeq in stems averaged 60,854.20 Bq/kg. Though both concentrations are significantly greater than the world safety level of 370 Bq/kg proposed by UNSCEAR, the leaf concentration reflects more intense radionuclide accumulation in aerial plant organs. The trend is probably due to foliar uptake by atmospheric deposition and root-assisted transport. The maximum Raeq was observed in Kairouan leaves (73,137.42 Bq/kg), while the minimum was observed in Zumar stems (53,941.40 Bq/kg).

3.2. Dose rate (D) and annual effective dose equivalent (AEDE)

The gamma dose rate of air absorbed (D), one of the principal parameters used in the assessment of prompt radiation exposure of plant tissues, also exhibited similar behavior. Averaged over leaves and stems, it was 0.588 nGy/h and 0.565 nGy/h, respectively, validating the hypothesis for greater radionuclide retention efficiency in leaf tissue. Standard deviation was marginally greater in leaves ($\pm$0.057) compared to stems ($\pm$0.051), indicating greater variation in radionuclide uptake on account of environment or physiology. Likewise, the yearly effective dose equivalent (AEDE) for approximating the dose to humans by environmental exposure was also higher in leaves (mean: 0.721 μSv/y) than in stems (0.693 μSv/y). Although both means are far below the 1 mSv/y public dose limit, their higher values in the case of vegetation reflect chronic exposure risk

Table 1. Radioactivity indices (Raeq, D, AEDE, AGDE, ELCR, Hex, Hin, $I\gamma$) in leaves and stems of plants from different areas in Nineveh, with the aim of evaluating environmental radiation exposure and comparing risks between plant parts.

Site	Plant Part	Raeq (Bq/kg)	D (nGy/h)	*AEDE* (μ*Sv/y*)	*AGDE* (μSv/y)	ELCR (10ˆ-3)	*Hex*	*Hin*	$I\gamma$
Sinjar	Leaves	57743.68	0.53558	0.656835	4.0061	0.002299	0.002707	0.002842	0.008533
Makhmur	Leaves	69773.68	0.64747	0.794057	4.8429	0.002779	0.003273	0.003435	0.010317
Qaraj	Leaves	62556.05	0.580798	0.712291	4.34391	0.002493	0.002936	0.003085	0.009253
Zumar	Leaves	56780.42	0.525108	0.643992	3.92876	0.002254	0.002652	0.002782	0.008367
Kairouan	Leaves	73137.42	0.671472	0.823493	5.02744	0.002882	0.003387	0.003533	0.010703
Rabia	Leaves	65443.42	0.607808	0.745416	4.54576	0.002609	0.003073	0.00323	0.009683
Hamidat	Leaves	62073.68	0.574638	0.704736	4.29906	0.002467	0.002904	0.003044	0.009157
Nimrud	Leaves	66406.42	0.617676	0.757518	4.61892	0.002651	0.003124	0.003286	0.00984
Al-Kuwayr	Leaves	57743.05	0.534514	0.655528	3.99883	0.002294	0.002701	0.002833	0.008517
Alqosh	Leaves	55816.05	0.51325	0.62945	3.84215	0.002203	0.00259	0.002706	0.00818
Hammam al-Alil	Leaves	70737.3	0.658404	0.807467	4.92333	0.002826	0.003331	0.003501	0.01049
Sinjar	Stem	54856.5	0.508801	0.623994	3.805795	0.002184	0.002572	0.0027	0.008107
Makhmur	Stem	66260.95	0.614918	0.754136	4.599394	0.002639	0.003109	0.003263	0.009798
Qaraj	Stem	59428.23	0.551735	0.676648	4.12656	0.002368	0.002789	0.00293	0.00879
Zumar	Stem	53941.4	0.498853	0.611793	3.732322	0.002141	0.00252	0.002643	0.007948
Kairouan	Stem	69486.61	0.647867	0.794545	4.843943	0.002781	0.003279	0.003446	0.010323
Rabia	Stem	62506.6	0.578643	0.709648	4.329119	0.002484	0.002924	0.003063	0.009221
Hamidat	Stem	57358.63	0.531906	0.65233	3.978708	0.002283	0.002689	0.002822	0.008475
Nimrud	Stem	63086.42	0.587592	0.720622	4.393517	0.002522	0.002973	0.003127	0.009361
Al-Kuwayr	Stem	60438.25	0.560591	0.687509	4.193263	0.002406	0.002834	0.002973	0.008933
Alqosh	Stem	54856.06	0.508144	0.623187	3.801342	0.002181	0.002568	0.002694	0.008097
Hammam al-Alil	Stem	67176.6	0.625751	0.767422	4.678883	0.002686	0.003166	0.003328	0.00997

to grazing animals or human populations consuming forage material.

3.3. Gonadal dose equivalent (AGDE) per year

Annual gonadal dose equivalent (AGDE) provides an indication of the load to the reproductive organs caused by radiation, which is of particular interest to assess the genetic and hereditary effects. Leaves receive a mean AGDE of 4.40 μSv/y, and stems receive 4.23 μSv/y. Kairouan leaves recorded the highest AGDE (5.03 μSv/y) and Zumar stems recorded the lowest (3.73 μSv/y). Excess Lifetime Cancer Risk (ELCR), This index justifies the utilization of wild plants as bioindicators and the role of anatomical structure in radionuclide distribution. One of the key parameters for long-term risk assessment is excess lifetime cancer risk (ELCR), a measure of the probability of cancer induction following radiation exposure over an individual's lifetime. The mean ELCR in leaves was found to be 2.52 $\times 10^{-3}$, just higher than in stems at 2.43 $\times 10^{-3}$. Small numbers, but hardly unimportant — especially if one is thinking about chronic exposure among agricultural or pastoral populations. Remarkably, ELCR values were highest in Kairouan leaves (2.88 $\times 10^{-3}$) and lowest in Alqosh leaves (2.20 $\times 10^{-3}$), validating spatial variation of radiological risk. Relatively low standard deviations of leaves' ELCR ($\pm$0.00024) and stems' ELCR ($\pm$0.00022) reveal homogenous exposure patterns among sites but with anatomical preference.

3.4. Radiological hazard indices (Hex, Hin, and $I\gamma$)

Three indices were calculated to predict the possible health risks due to gamma-emitting radionuclides: External hazard index (Hex), Internal hazard index (Hin) and Gamma representative level index ($I\gamma$) Table 1.

All these indices were way below the critical value of 1 for all samples, which indicated zero acute exposure risk in the short term. The leaves, however, recorded generally higher values for all the indices. Hex mean values were 0.00271 (leaves) and 0.00277 (stems), and Hin was 0.00284 (leaves) compared to 0.00281 (stems). The gamma index ($I\gamma$) also recorded the same trend with 0.00853 in leaves and 0.00862 in stems. These indices are cumulative indicators of the environmental gamma radiation field and emphasize the contribution of both site-specific geochemistry and plant anatomy to risk assessment Fig. 2.

3.5. Spatial variation among study sites

Single sites analysis revealed that Kairouan, Makhmur, and Hammam al-Alil revealed the highest values for most parameters for the whole plant. For instance, Kairouan had the highest Raeq, D, AEDE, and AGDE in leaves and stems. These observations demonstrate local radionuclide enrichment of the sites by geological factors, agricultural practice, or former anthropogenic impact. Conversely, Alqosh and Zumar had the lowest radiological values and

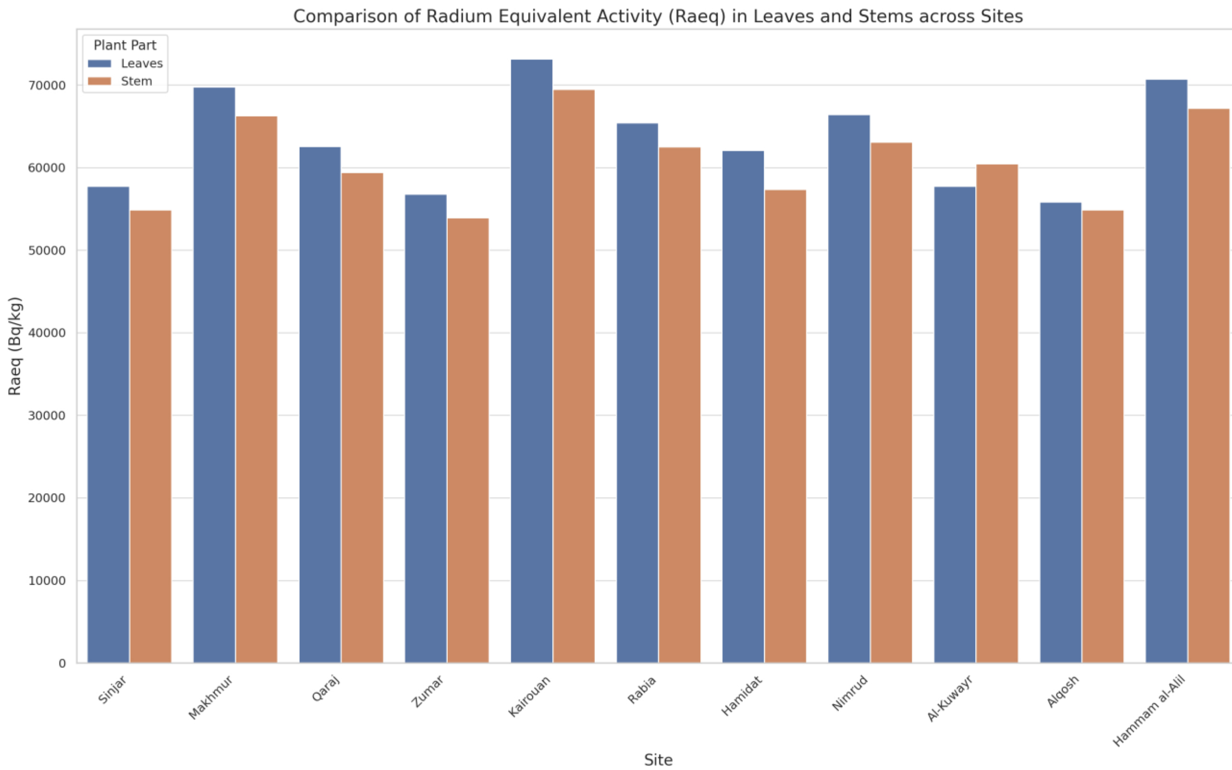

Fig. 2. Comparison of radium equivalent activity (Raeq) in Bq/kg between leaves and stems of wild plants collected from various sites in Nineveh Governorate. This histogram highlights the anatomical variation in radionuclide accumulation, with leaves generally showing higher Raeq values than stems.

were thus comparatively clean reference sites in Nineveh Governorate. Their settings can offer natural reduction of radionuclide uptake e.g., low soil permeability, low atmospheric deposition, or restricted types of vegetation Fig. 3.

3.6. Anatomical influence and environmental implications

General finding of the present study stresses anatomical dependency of radioisotope uptake in vegetation. Leaves, due to their physiological activities of transpiration, respiration, and greater exposure of surface area to air, uptake and accumulate higher levels of radionuclides than stems. This observation could find application in biomonitoring schemes because tissues of leaves could serve as more sensitive indicators of environmental contamination.

4. Discussion

The objective of this study was to assess and compare the natural radionuclides accumulation in stems and leaves of wild plant species collected from various sampling locations across the Nineveh Governorate of northern Iraq. The findings contribute to the growing environmental radiological research in general, and particularly on the application of wild flora as bioindicators for pollution. The full analysis of Radium Equivalent Activity (Raeq), absorbed dose rates (D), annual effective dose equivalents (AEDE), annual gonadal dose equivalents (AGDE), excess lifetime cancer risk (ELCR), and hazard indices (Hex, Hin, Iγ) is good information concerning environmental distribution of radioisotopes, potential biological significance, and anatomical variability in uptake (Sangsingkeow, 1999).

The overall consistencies and good trend between all the parameters covered were greater radionuclide accumulation in leaves compared to stems. This is consistent with physiological and ecological expectations. Leaves, by virtue of their greater surface area and direct exposure to atmospheric deposition, have a better chance of uptake of particulate matter from the air compared to stems. Moreover, the transpirational suction and stomatal exchange routes provide a route for transport and accumulation of water-soluble radionuclides by means of the xylem transport route. This physiological predisposition makes leaves more sensitive and reactive markers of environmental contamination, particularly in terrestrial and aerial-polluted ecosystems.

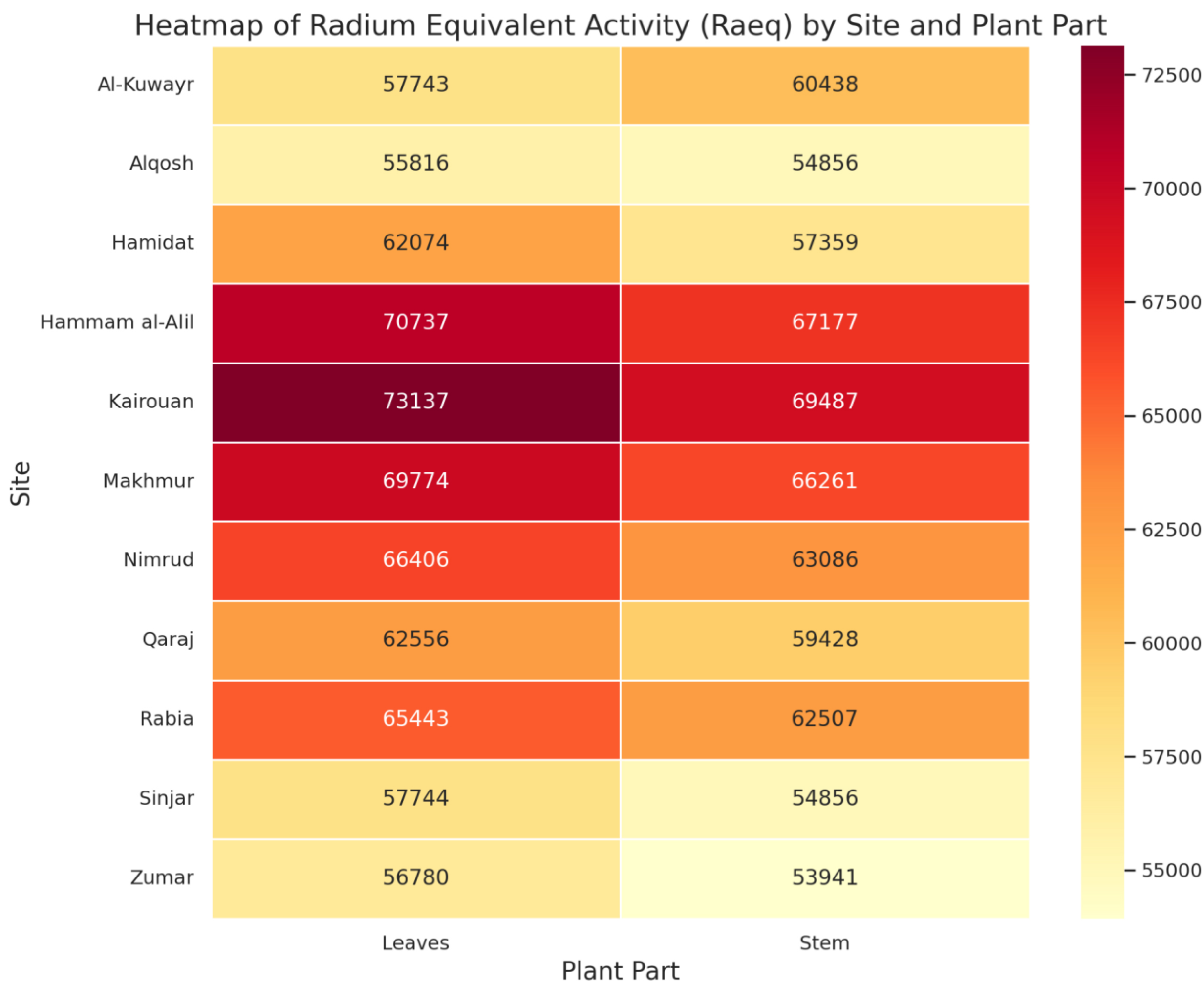

Fig. 3. Heatmap illustrating the distribution of Radium Equivalent Activity (Raeq) in Bq/kg across different sites and plant parts (leaves and stems). Color intensity reflects the magnitude of Raeq, highlighting spatial variability and anatomical differences in radionuclide accumulation.

Radium Equivalent Activity (Raeq) values reported in the current study were significantly higher than the globally recommended safe limit of 370 Bq/kg. Leaf and stem mean Raeq values were approximately 63,473 Bq/kg and 60,854 Bq/kg, respectively—nearly 170 times the recommended level. These results point to heavy environmental pollution, perhaps geogenic in origin like uranium-bearing bedrock or human-induced like agriculture, military waste, oil production, or inadequate waste disposal. Of all locations, Kairouan, Hammam al-Alil, and Makhmur had the consistently highest Raeq values, indicating localized areas of enrichment that need further exploration. The dose rate of absorbed dose (D) and the annual effective dose equivalent (AEDE) are two of the key parameters of public radiological risk, especially rural residents who may be reliant on wild plants as food crops or as traditional medicine. Both parameters were high in leaf samples, with Kairouan having the highest AEDE of 0.823 μSv/y. In spite of the fact that this value is lower than the 1 mSv/y limit set by the ICRP for public exposure, it represents cumulative exposure dangers when ingestion routes and long-term exposure scenarios are considered. Moreover, the spatial homogeneity of dose rate rise in some areas highlights environmental health surveillance and possible soil remediation programs (Ajayi, Ibikunle, and Ojo, 2008).

The annual gonadal dose equivalent (AGDE), reflecting the radiological burden on reproductive organs, followed a similar pattern, with leaf values being greater. The measure is especially important for public health purposes considering the contribution it makes to genetic mutations and to reproductive health. The AGDE varied between 3.73 and 5.03 μSv/y, with Kairouan leaves once more yielding the highest value. This validates the need for certain mitigation practices in high-risk zones, particularly in the vicinity of human settlements or agricultural land. Among the most valuable health risk indicators utilized in this study is the Excess Lifetime Cancer Risk (ELCR). While the ELCR values obtained in this study are within the range of 10^{-3}, they represent a considerable risk of cancer induction upon chronic exposure, especially under conditions of long-term exposure. The mean ELCR in leaves (2.52×10^{-3}) was higher compared to stems (2.43×10^{-3}), with the trend being consistent across all sites. The maximum ELCRs were recorded in Kairouan and Hammam al-Alil, once more indicating these as regions of concern. Although the current values do not necessarily reflect a present public health emergency, they warrant further examination of ingestion and inhalation risk, especially for those involved in herding, agriculture, or foraging of wild plants. The calculated hazard indices (Hex, Hin) and gamma representative index ($I\gamma$) are important in determining whether a material or environmental parameter is an external or internal radiological hazard. All values used in the present study were less than the unity safety level, which means that although Raeq and AEDE levels are appreciable, they would not be likely to reflect an immediate radiological hazard. However, the cumulative additive impacts of lifelong low-dose exposure and co-exposure with other environmental stressors (e.g., chemical pollutants, particulate matter) cannot be ignored (Amaral et al., 1992, Ajayi, 2013, Dabayneh, Sroor, and Abdel-Haleem, 2008). It is also worth remembering that while markers such as Hex and Hin are useful for broad-scale screening, they can undervalue more complex multi-pathway avenues of exposure relevant to ecosystems and human populations. Spatial heterogeneity across the governorate adds insight. The consistent labeling of Kairouan, Makhmur, and Hammam al-Alil as regions of high radiation is symptomatic of underlying geologic conditions, such as phosphate deposits or past volcanic activity, possibly resulting in greater natural radioactivity (Dabayneh, Sroor, and Abdel-Haleem, 2008, Al-Azzawi, 2020, Khalaf Raja, Hassoun Arabi, and Al-Salihi, 2020, Jawad, 2019, Abu Karima et al., 2020). The three towns could be suffering from past military use or from illegal dumping with radioactive or contaminated materials. On the other hand, Alqosh and Zumar produced a consistent set of lowest values on almost all the indicators and are most likely baseline or control areas for future biomonitoring studies. The use of wild vegetation as bioindicators in this study has proven efficient in showing trends in environmental pollution. Wild plants are free from influences of agricultural fertilizers, irrigation, and cultivation by humans, and hence are more indicative of natural uptake processes. In addition, their wide distribution and establishment in local ecosystems make them ideal sentinels for the early detection of environmental change (Abu Karima et al., 2020, Al-Shalwah et al., 2024, Dyakova et al., 2025, Silantiev et al., 2025, Satoh et al., 2025). Their anatomical difference of leaves and stems also makes their use easier by allowing twin compartments to measure to signify alternate exposure pathways and accumulation patterns. From an ecological perspective, the findings of this research also have implications for food chain pollution. Herbivores that feed on wild plants in these regions could accumulate higher concentrations of radionuclides and pass radioactive pollutants up the food chain (Satoh et al., 2025, Santhanabharathi et al., 2025, Silantiev et al., Silantiev et al., Chen et al., 2025). This in turn could have secondary impacts on human health, especially in pastoralist and agricultural communities where meat, milk, and wild herbs are significant elements of the diet.

Finally, this study presents definitive evidence of anatomical and spatial variation of naturally occurring radionuclide accumulation in wild plants in Nineveh Governorate. The findings identify areas of concern and form a basis for follow-up environmental health monitoring. Moreover, the analytical framework—radiometric analysis, anatomical comparison, and statistical evaluation precludes a replicable model in other regions with the same environmental challenges. In the future, it is recommended that complementary research determines radionuclide concentrations in water resources and soils and in the tissue of locally resident livestock. Schemes for integrated monitoring involving biological, geological, and public health data will be essential to the formulation of effective environmental management policy and community safety in areas of radiological impact (Chen et al., 2025, Nikitin, Tamara, and Svetlana, 2025, Sabol, 2025, Kuznetsov, Sanzharova, and Fesenko, 2025).

Ethical statement

We confirm that the manuscript is original, has not been published before, and is not currently under consideration by any other journal. All research was conducted in accordance with institutional and national ethical standards.

Conflict of interest

We declare that there are no financial, commercial, or personal conflicts of interest that could have influenced the outcome of this research.

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