

## Assessment of Radiological Doses Associated with Natural Radionuclides in Soil From Al-Marj Region—Libya

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تقييم الجرعات الإشعاعية المرتبطة بالنويدات المشعة الطبيعية في تربة منطقة المرج – ليبيا

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Received: 14-02-2026	Accepted: 01-04-2026	Published: 10-04-2026
		
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### Abstract

Background: Naturally occurring radionuclides are the primary contributors to ionizing radiation exposure in the human environment. Monitoring their levels in soil is essential for assessing radiological baselines and ensuring public health safety, particularly in agricultural and residential regions. Objectives: This study aims to investigate the specific activity levels of  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  in soil samples collected from the Al-Marj region of Libya and to evaluate potential radiological hazards and health risks associated with these radionuclides. Methods: Ten representative soil samples were collected from various farms at a depth of 0–20 cm using a stainless steel auger. The samples were analyzed using NaI(Tl) gamma-ray spectroscopy to determine activity concentrations. Radiological indices, including absorbed dose rates, annual effective dose equivalents (AEDE), and excess lifetime cancer risk (ELCR), were calculated to assess the radiation profile. Results: The mean activity concentrations were 44.00, 43.62, and 140.62 Bq/kg for  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$ , respectively. While indoor and outdoor absorbed dose rates exceeded global limits in most samples, the AEDE remained within the safety thresholds established by UNSCEAR and ICRP. Notably, the indoor ELCR was higher than the world average ( $1.16 \times 10^{-3}$ ), indicating a need for further environmental monitoring. Conclusion: Although the elevated ELCR suggests a potential long-term risk, the effective doses to specific organs were well below permissible limits. Consequently, the Al-Marj region is generally considered radiologically safe for the public. These findings provide a crucial reference for future radiological impact assessments in the area.

**Keywords:** Annual effective dose; Excess life cancer risk; NaI(Tl)gamma spectrometer, Organ dose, Radiological dose.

### الملخص

الخلفية: تُعد النويدات المشعة الطبيعية المصدر الرئيسي للتعرض للإشعاع المؤين في البيئة البشرية. ويُعد رصد مستوياتها في التربة أمرًا ضروريًا لتقييم الخلفية الإشعاعية وضمان السلامة الصحية العامة، خاصةً في المناطق الزراعية والسكنية.

الأهداف: تهدف هذه الدراسة إلى التحقق من مستويات النشاط النوعي للنظائر المشعة  $^{238}\text{U}$  و  $^{232}\text{Th}$  و  $^{40}\text{K}$  في عينات التربة المجمعّة من منطقة المرج في ليبيا، وتقييم المخاطر الإشعاعية والصحية المحتملة المرتبطة بهذه النويدات المشعة.

المنهجية: جُمعت عشر عينات تربة ممثلة من مزارع مختلفة وعلى عمق يتراوح بين 0-20 سم باستخدام مثقاب من الفولاذ المقاوم للصدأ. وتم تحليل العينات باستخدام مطياف أشعة جاما المعتمدة على كاشف NaI(Tl) لتحديد تراكيز النشاط الإشعاعي. كما حُسبت المؤشرات الإشعاعية، بما في ذلك معدلات الجرعة الممتصة، والجرعة الفعالة السنوية المكافئة (AEDE)، وخطر الإصابة بالسرطان مدى الحياة الزائد (ELCR)، وذلك لتقييم الوضع الإشعاعي للمنطقة.

النتائج: بلغ متوسط تراكيز النشاط الإشعاعي لكل من  $^{238}\text{U}$  و  $^{232}\text{Th}$  و  $^{40}\text{K}$  نحو 44.00 و 43.62 و 140.62 بيكريل/كجم على التوالي. وبينما تجاوزت معدلات الجرعة الممتصة الداخلية والخارجية الحدود العالمية في معظم العينات، بقيت الجرعة الفعالة السنوية المكافئة ضمن حدود الأمان المعتمدة من قبل UNSCEAR و ICRP. ومن اللافت أن قيمة خطر الإصابة بالسرطان مدى الحياة في البيئات الداخلية كانت أعلى من المتوسط العالمي ( $1.16 \times 10^{-3}$ )، مما يشير إلى الحاجة إلى مزيد من المراقبة البيئية.

الاستنتاج: على الرغم من أن ارتفاع قيمة خطر الإصابة بالسرطان مدى الحياة قد يشير إلى احتمال وجود مخاطر طويلة الأمد، فإن الجرعات الفعالة الواصلة إلى الأعضاء المختلفة كانت أقل بكثير من الحدود المسموح بها. وبناءً على ذلك، يمكن اعتبار منطقة المرج آمنة إشعاعياً بصورة عامة بالنسبة للسكان. وتوفر هذه النتائج مرجعاً مهماً للدراسات المستقبلية المتعلقة بتقييم التأثيرات الإشعاعية في المنطقة.

**الكلمات المفتاحية:** الجرعة الفعالة السنوية، خطر الإصابة بالسرطان مدى الحياة، مطياف جاما NaI(Tl)، جرعة الأعضاء، الجرعة الإشعاعية.

## 1. INTRODUCTION

The main external source of irradiation to the human body is the naturally occurring radiation, which contributes to the background dose, emanating from both cosmic radiation and terrestrial radioisotopes integrated into various geological structures (Arogunjo et al., 2009). These sources contribute to both external and internal exposure specially of gamma radiation, primarily through the inhalation gas  $^{222}\text{Rn}$  and its short-lived products. Such radioactive exposure poses significant health risks, most notably the induction of lung tissue damage and an increased probability of on cogenesis (Tzortzis et al., 2004). Furthermore, anthropogenic activities including phosphate fertilizer application, charcoal combustion, and mineral extraction can technologically enhance these natural concentrations, thereby altering the radiological profile of a given region (Amal S. Nasr, 2024; Essa et al., 2021). Terrestrial radionuclides, specifically the primordial decay series of Uranium  $^{238}\text{U}$  and Thorium  $^{232}\text{Th}$  along with the non-series radionuclide Potassium  $^{40}\text{K}$ , have been intrinsic components of the Earth's crust since its formation (Augustine Kolapo Ademola et al., 2014). The environmental distribution of these elements is a direct reflection

of local geological formations and geochemical processes (Kurnaza et al., 2007). Soil, as a naturally radioactive medium, serves as a primary source of public radiation exposure and a vehicle for radionuclide transfer into the human body (El-Taher A. and Al-Zahrani J. H., 2014; Onjefu et al. 2021). Consequently, estimating absorbed gamma dose rates is a fundamental aspect of environmental health physics, especially given the high spatial variability of these doses (Rohit Mehra et al., 2010; Noor Adil Mohammed and Sameera Ahmed Ebrahiem, 2020). In Libya, several radiological assessments have been conducted across different geographical regions to establish a national baseline for natural radioactivity. For instance, studies in the western region, specifically in Zliten, reported activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  that generally fall within international recommended limits (Muna M. Aoneas, 2024). Similarly, investigations in the southern regions like Wadi Al-Shatti and Zawiya highlighted the radiation hazard indicators in the two cities, it has been noted that the values are within the safe and recommended limits for most soil samples (Mustafa Sahoub, 2024; Lolo Alqaidhi, Saleh Alashrah and Khalda Osman, 2025). In the eastern sector, research spanning from Ajdabiya to Qaminis indicated localized elevations in  $^{226}\text{Ra}$  levels, often attributed to the geochemical nature of the coastal belt (Saeid Y. Elorfi et al., 2025). Despite these efforts, the Al-Marj region, characterized by its unique plateau topography and intensive agricultural activities, lacks detailed radiological mapping. This study fills this gap by quantifying the specific activity concentrations of  $^{238}\text{U}$ ,  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  in Al-Marj soil. Furthermore, it evaluates the associated radiological hazard indices to establish a baseline database, serving as an essential reference for environmental monitoring and public health safety in the region.

## 2. METHOD

### Study Area

The study was conducted in the Al-Marj region, northeastern Libya. The area is characterized by a semi-humid climate with an average annual rainfall of 382 mm. Geologically, the soil is immature and rich in calcium carbonate ( $\text{CaCO}_3$ ). Due to the expansion of irrigated agriculture and the inherent soil characteristics, the region has seen an intensive application of chemical fertilizers and pesticides. These anthropogenic activities, combined with local human impact, have necessitated an assessment of the radiological profile of the agricultural lands.



**Fig. 1** Location map of samples.

### Sample Collection and Preparation

Ten representative soil samples were collected from various farms in the Al-Marj region. The samples were extracted from a depth of 0–20 cm using a stainless steel auger. The collected samples were transferred to the Advanced Nuclear Physics Laboratory at Omar Al-Mukhtar University. The soil was ground, passed through a 2 mm mesh sieve, and dried in an oven at 100°C for two hours to remove moisture. To ensure homogeneity, the dried samples were weighed and sealed in cylindrical containers. These containers were stored for four weeks to achieve secular radioactive equilibrium between the long-lived primordial radionuclides  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and their respective daughter products.

### Gamma Spectrometry Analysis

The activity concentrations were determined using a gamma spectrometry system equipped with a NaI(Tl) scintillation detector (Model PM-9266B, Serial No. WA00012638). The detector features a "1.5 × 1.5" crystal with an energy resolution of 12.6% at the 661.7 keV line of  $^{137}\text{Cs}$ . To reduce natural background radiation, the detector was encased in a 15 mm thick lead shield, as shown in Figure 2.



**Fig. 2** Show the gamma spectrometry system used in the measurement.

Energy calibration was performed using standard point sources, including  $^{137}\text{Cs}$  (661.7 keV),  $^{22}\text{Na}$  (511 and 1274 keV), and  $^{60}\text{Co}$  (1173.2 and 1332.5 keV). Each sample was counted for 7200 seconds. The activity concentration of  $^{226}\text{Ra}$  was evaluated via the 186.2 keV line (with appropriate corrections) and the daughter products of the  $^{238}\text{U}$  series, specifically  $^{214}\text{Pb}$  (295.2 and 351.9 keV) and  $^{214}\text{Bi}$  (609.3, 1120.3, and 1764.5 keV). The  $^{232}\text{Th}$  concentration was evaluated through the gamma lines of  $^{228}\text{Ac}$  (911.2 and 968.9 keV) and  $^{212}\text{Pb}$  (238.6 keV). The activity of  $^{40}\text{K}$  was directly measured using its characteristic photopeak energy at 1460.8 keV.

### 3. Calculation

#### Specific Activity

The specific activity  $A$  of a radionuclide, measured in a unit (Bq/kg), can be expressed using the equation (Abdulkadir Shiekh Al-Aydarou et al., 2022; Jemila Mussa Al et al., 2022):

$$A = \frac{N}{I\gamma \varepsilon M T} \quad (1)$$

Where  $N$  is the count per sec,  $I\gamma$  is probability of emission of a gamma from the peak energy,  $\varepsilon$  is the absolute efficiency determined by the calibration,  $T$  is the measurement time in seconds, and  $M$  is the sample weight in (kg).

#### Absorbed Dose Rate

The indoor absorbed dose rate  $D$  (nGy/h) of the natural radionuclides  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  can be calculated from equation (European Commission (EC), 1999):

$$D_{\text{in}} = 0.92 A_{\text{U}} + 1.1 A_{\text{Th}} + 0.081 A_{\text{K}} \quad (2)$$

The outdoor absorbed dose rate in air at 1 meter above the surface of the ground due to the natural radionuclides  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and  $^{40}\text{K}$  was estimated using formula given as (UNSCEAR, 2008):

$$D_{\text{out}} = 0.462 A_{\text{U}} + 0.604 A_{\text{Th}} + 0.041 A_{\text{K}} \quad (3)$$

#### Annual Effective Dose Equivalent

The Annual Effective Dose Equivalent (AEDE), measured in (mSv/yr), assesses the probability of stochastic and deterministic effects in exposed individuals. This value was determined using the following mathematical expressions (UNSCEAR, 1993):

$$AEDE_{(\text{Indoor})} = D_{\text{in}} \times 8760 \text{ h} \times 0.8 \times 0.7 \times 10^{-6} \quad (4)$$

$$AEDE_{(\text{Outdoor})} = D_{\text{out}} \times 8760 \text{ h} \times 0.2 \times 0.7 \times 10^{-6} \quad (5)$$

To convert the absorbed dose rate in air  $D$  in (nGy/h) to the effective dose rate in (mSv/y)

from the factor (0.7 Sv/Gy). The outdoor occupancy factor is 0.2 and an indoor occupancy factor is 0.8. The recommended value of the total annual effective dose equivalent (indoors and outdoors) should be less than 1 mSv/y [20].

### Excess Lifetime Cancer Risk

This parameter indicates the lifetime risk of developing cancer at a specific contact level. The following formula has been used to determine the ELCR (ImehJameset al. 2020):

$$\text{ELCR} = \text{AEDE} \times \text{DL} \times \text{RF} \quad (6)$$

Where DL is the average duration of life (about 70 years) and RF is the fatal cancer risk per Sievert. According to ICRP 106 (RF = 0.05 mSv<sup>-1</sup>) for the public. The indoor and outdoor ELCR determined using the following equations (ICRP, 2012):

$$\text{ELCR}_{\text{indoor}} = \text{AEDE}_{\text{indoor}} \times \text{DL} \times \text{RF} \quad (7)$$

$$\text{ELCR}_{\text{outdoor}} = \text{AEDE}_{\text{outdoor}} \times \text{DL} \times \text{RF} \quad (8)$$

The quantification of radiation dose intake to diverse body organs and tissues estimates according to the effective dose to organs (D<sub>organ</sub>) (mSv/y). D<sub>organ</sub> can be estimated using the following equation (Darwish et al., 2015):

$$D_{\text{org(indoor)}} = O \times \text{AEDE}_{\text{(Indoor)}} \times F \quad (9)$$

D<sub>organ</sub> for the indoor and outdoor calculated using the following formulas

$$D_{\text{org(Outdoor)}} = O \times \text{AEDE}_{\text{(Outdoor)}} \times F \quad (10)$$

The occupancy factor **O** of indoor and outdoor were 0.2 and 0.8 respectively. **F** represents the conversion coefficient utilized to derive the organ dose from air dose. The value of **F** as given by ICRP 1996 (ICRP,1996) for whole body lungs, ovaries, bone marrow, testes, liver, and kidney are 0.68, 0.64, 0.58, 0.69, 0.82, 0.46 and 0.62, respectively ( Ugbede F. O. and Benson I. D., 2018).

### 3. ETHIC APPROVAL

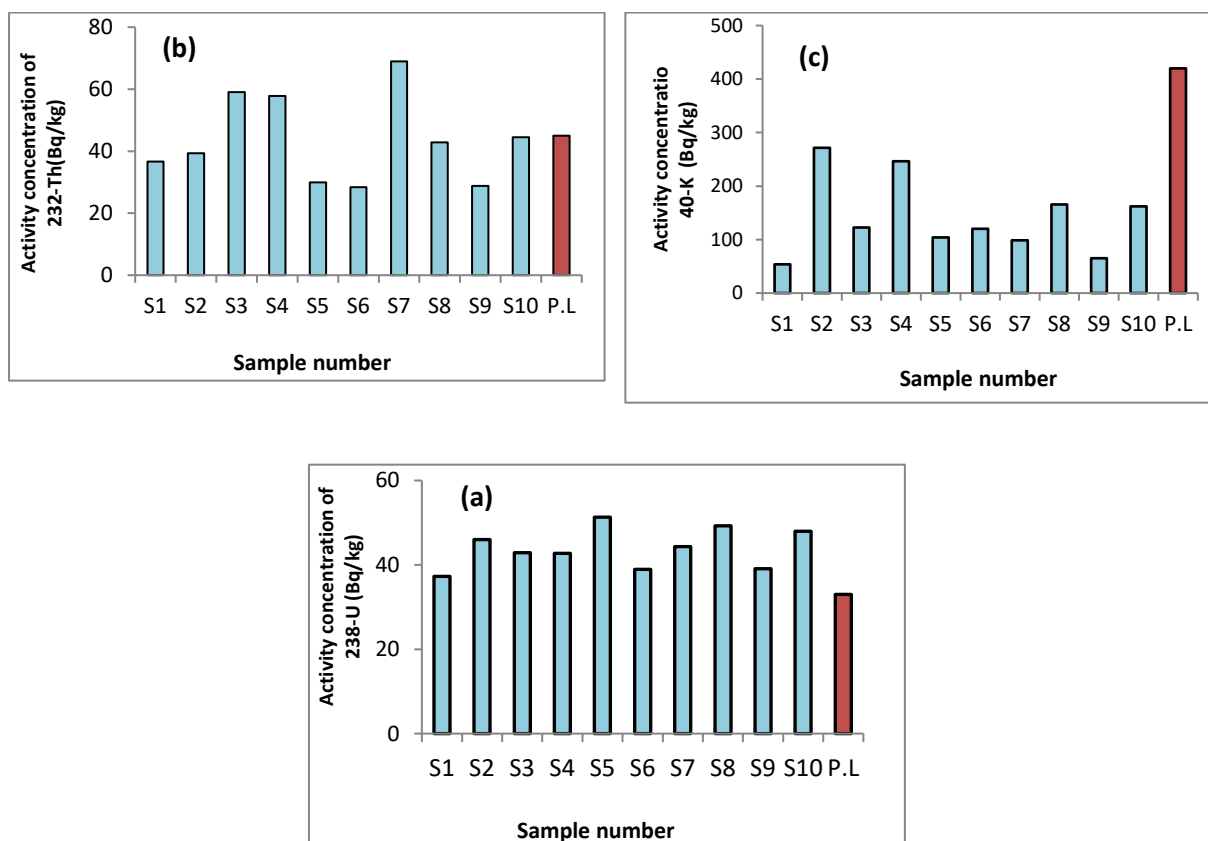
Ethical approval and informed consent were obtained from the participating farmers prior to sample collection on their farms.

### 4. RESULT

#### Radionuclide Specific Activity

The specific activity concentrations of <sup>238</sup>U, <sup>232</sup>Th, and <sup>40</sup>K in the soil samples from Al-Marj are illustrated in Figure 3. The radiological analysis indicates a significant elevation in <sup>238</sup>U activity, with most samples exceeding the global average value 33 Bq/kg. This enrichment is not merely a geological coincidence but is highly correlated with the intensive use of

phosphate-based fertilizers in Al-Marj's agricultural plains. Phosphate rocks are naturally enriched with uranium, and long-term application leads to its accumulation in the topsoil. In contrast,  $^{232}\text{Th}$  levels remained generally within the world recommended value 45 Bq/kg, suggesting that the thorium content is primarily governed by the natural weathering of the local red clay soil rather than anthropogenic activities.  $^{40}\text{K}$  levels, while below the 420 Bq/kg recommended value, still contribute significantly to the total gamma dose, reflecting the potassium-rich nature of clay minerals in the region (UNSCEAR, 2010).



**Fig. 3.** The specific activity concentrations of radionuclides in soil are: (a)  $^{238}\text{U}$ , (b)  $^{232}\text{Th}$ , and (c)  $^{40}\text{K}$ .

The estimated radiological dose parameters for the analyzed soil samples are detailed in Table 1.

### Indoor and Outdoor Absorbed Dose Rates

The absorbed dose rates reached their peak values indoors at  $D_{\text{in}} = 124.58$  nGy/h and outdoors at  $D_{\text{out}} = 68.80$  nGy/h (Sample S7). The results demonstrated that  $D_{\text{in}}$  exceeded the UNSCEAR permissible limit of 84 nGy/h across the majority of the analyzed soil samples (UNSCEAR, 2000). Similarly, most  $D_{\text{out}}$  values were higher than the recommended global baseline of 55 nGy/h (UNSCEAR, 2010). These findings indicate a potential elevation in radiological exposure for the local population due to the cumulative effect of these low-dose rates.

**Table .1.** The estimated radiological dose of soil the analyzed soil samples

Dose parameters		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	P.L
<b>(a)</b>	<b>Dose</b>											
	<b>D<sub>In</sub> (nGy/h)</b>	78.98	107.51	114.34	122.90	88.55	76.8	124.58	105.93	72.86	106.24	84
	<b>D<sub>Out</sub> (nGy/h)</b>	42.50	57.32	62.68	67.13	46.20	40.6	68.80	56.56	38.52	56.93	55
	<b>AEDE<sub>In</sub>(mSv/y)</b>	0.39	0.53	0.56	0.60	0.43	0.38	0.61	0.52	0.36	0.52	1
	<b>AEDE<sub>Out</sub> (mSv/y)</b>	0.05	0.07	0.08	0.08	0.06	0.05	0.08	0.07	0.05	0.07	0.07
	<b>ELCR<sub>Indoor</sub> ×10<sup>-3</sup></b>	1.28	1.74	1.85	1.99	1.43	1.24	2.01	1.71	1.18	1.72	1.16
	<b>ELCR<sub>Outdoor</sub> ×10<sup>-3</sup></b>	0.17	0.23	0.25	0.27	0.19	0.16	0.27	0.23	0.16	0.23	0.29
<b>(b)</b>	<b>Dorgan (mSv/y)</b>											
	<b>Whole body<sub>indoor</sub></b>	0.26	0.36	0.38	0.41	0.29	0.26	0.42	0.35	0.24	0.35	0.68
	<b>Whole body<sub>outdoor</sub></b>	0.03	0.05	0.05	0.05	0.04	0.03	0.06	0.05	0.03	0.05	0.68
	<b>Lungs<sub>indoor</sub></b>	0.25	0.34	0.36	0.39	0.28	0.24	0.39	0.33	0.23	0.33	0.64
	<b>Lung<sub>Soutdoor</sub></b>	0.03	0.04	0.05	0.05	0.04	0.03	0.05	0.04	0.03	0.04	0.64
	<b>Ovaries<sub>indoor</sub></b>	0.33	0.22	0.31	0.32	0.35	0.25	0.22	0.35	0.30	0.21	0.58
	<b>Ovaries<sub>outdoor</sub></b>	0.03	0.04	0.04	0.05	0.03	0.03	0.05	0.04	0.03	0.04	0.58
	<b>Bone marrow<sub>indoor</sub></b>	0.27	0.36	0.39	0.42	0.30	0.26	0.42	0.36	0.25	0.36	0.69
	<b>Bone marrow<sub>outdoor</sub></b>	0.04	0.05	0.05	0.06	0.04	0.03	0.06	0.05	0.03	0.05	0.69
	<b>Testes<sub>indoor</sub></b>	0.32	0.43	0.46	0.49	0.36	0.31	0.50	0.42	0.29	0.43	0.82
	<b>Testes<sub>outdoor</sub></b>	0.04	0.06	0.06	0.07	0.05	0.04	0.07	0.06	0.04	0.06	0.82
	<b>Kidney<sub>indoor</sub></b>	0.24	0.33	0.35	0.37	0.27	0.23	0.38	0.32	0.22	0.32	0.62
	<b>Kidney<sub>outdoor</sub></b>	0.03	0.04	0.05	0.05	0.03	0.03	0.05	0.04	0.03	0.04	0.62
	<b>Liver<sub>indoor</sub></b>	0.18	0.24	0.26	0.28	0.20	0.17	0.28	0.25	0.16	0.24	0.46
	<b>Liver<sub>outdoor</sub></b>	0.02	0.03	0.03	0.04	0.03	0.02	0.04	0.03	0.02	0.03	0.46

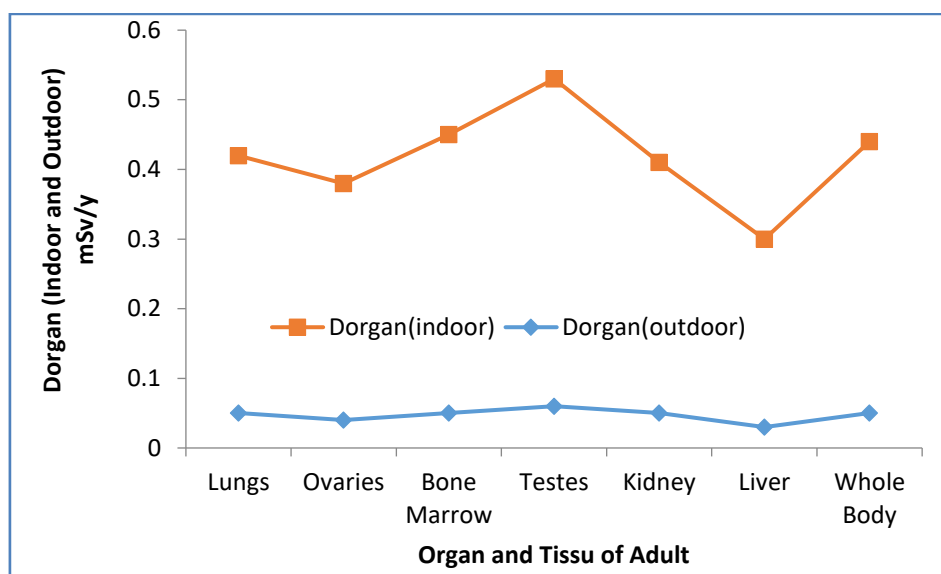
### Annual Effective Dose Equivalent (AEDE)

The assessment of cumulative exposure through the Annual Effective Dose Equivalent (AEDE) confirms that both indoor and outdoor mean values remain within safety thresholds. The calculated mean AEDE<sub>in</sub> of 0.49 mSv/y is safely below the public dose limit of 1 mSv/y. Furthermore, the AEDE<sub>out</sub> values ranged from 0.05 to 0.08 mSv/y. Although localized values at certain sampling points (S3, S4, and S7) marginally exceeded the world average reference value of 0.07 mSv/y, the overall calculated mean 0.066 mSv/y remains compliant with international radiological safety criteria.

### Indoor and Outdoor Excess Lifetime Cancer Risk (ELCR)

The calculated mean of ELCR<sub>in</sub> significantly exceeds the worldwide recommended value of  $1.62 \times 10^{-3}$ , with sample S7 exhibiting the highest risk at  $2.01 \times 10^{-3}$ . This elevated risk is primarily driven by the ingestion and inhalation of decay products from the <sup>238</sup>U series. Conversely, all reported ELCR<sub>out</sub> values remained strictly the global safety limit of  $0.29 \times 10^{-3}$  (UNSCEAR, 2010). On the other hand, the annual effective doses to specific organs (D<sub>organ</sub>)

were consistently higher for indoor exposure than outdoor. Among the assessed organs, the liver received the lowest dose (ranging from 0.16 to 0.28 mSv/y indoors), while the testes received the highest dose (up to 0.50 mSv/y indoors), reflecting the varying tissue weighting factors of different human tissues, as shown in Fig. 4. Notably, sample S7 consistently exhibited the highest  $D_{organ}$  values across all categories. These results emphasize the critical importance of continuous radiological monitoring in agriculturally active regions like Al-Marj to ensure that ingestion and inhalation pathways do not pose long-term health risks.



**Fig. 4** Comparison of estimated annual effective doses across different human organs under indoor and outdoor exposure scenarios.

**Table .2** Comparison of specific activity levels with other national studies in Libya.

REGION	$^{238}\text{U}$ (BQ/KG)	$^{232}\text{Th}$ (BQ/KG)	$^{40}\text{K}$ (BQ/KG)	ELCR $\times 10^{-3}$
AL-MARJ (PRESENT STUDY)	> 33	< 45	< 420	>1.62
ZLITEN	22.1	12.2	294.3	0.85
WADI AL-SHATTI	27.3	40.8	210.5	1.10
AJDABIYA	35.5	32.7	184.5	1,45
WORLD AVERAGE	33	45	420	1.62

## 5. DISCUSSION

The radiological assessment of soil samples from the Al-Marj region reveals a distinct enrichment of  $^{238}\text{U}$  relative to the world average limit, a phenomenon primarily attributed to the anthropogenic accumulation of uranium through the intensive application of phosphate-based fertilizers in agricultural plains. Conversely, the levels of  $^{232}\text{Th}$  and  $^{40}\text{K}$  align more closely with natural processes, reflecting the weathering of local red clay minerals rather than external chemical inputs.

While the indoor and outdoor absorbed dose rates  $D_{in}$  and  $D_{out}$  frequently exceeded the UNSCEAR permissible limits, the calculated annual effective dose equivalent (AEDE) remains safely below the world recommended limit for most values, indicating that current ambient radiation levels do not pose an immediate regulatory threat for most values. However, the significantly elevated indoor excess lifetime cancer risk  $ELCR_{in}$ , which surpasses the world recommended value, highlights a potential long-term health concern driven by the inhalation and ingestion of  $^{238}U$  decay products. This risk is further underscored by the variable organ-specific doses, which were notably higher in sensitive tissues such as the testes compared to the liver, suggesting that continuous radiological monitoring is essential to mitigate the cumulative effects of low-dose exposure in this agriculturally active region.

## 6. CONCLUSION

this investigation demonstrates that intensive agro-chemical practices in the Al-Marj region have driven a localized, anthropogenic enrichment of soil  $^{238}U$  above global limit, while  $^{232}Th$  and  $^{40}K$  levels remain governed by natural pedogenic weathering of local clays. Although ambient absorbed dose rates exceed standard safety thresholds, they do not present an immediate acute public health hazard, as the cumulative annual effective doses remain strictly within safe regulatory limits. on the other hand, the pronounced elevation of the indoor Excess Lifetime Cancer Risk signals a significant long-term health concern. These results underscore a critical requirement for rigorous environmental surveillance and optimized fertilizer management to mitigate long-term, cumulative low-dose radiation impacts on the local population.

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**Compliance with ethical standards***Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

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