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National Centre for Energy and Environment, Energy
Commission of Nigeria, University of Benin:
ISSN 2504-9593
DOI: 10.5281/zenodo.20473819
https://ijree.com/index.php/publications/article/view/49
Int. J. Renew. Energ & Environ Vol.4 (2), pp 153-165(2026)

RADIOLOGICAL RISK AND ECOLOGICAL TRANSFER OF NATURAL RADIONUCLIDES FROM URBAN WASTE DUMPS IN GUSAU METROPOLIS, NIGERIA: A QUANTITATIVE ASSESSMENT USING GAMMA SPECTROMETRY AND THE ERICA TOOL

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ABSTRACT

Uncontrolled urban waste dumps in low- and middle-income countries act as unregulated reservoirs for naturally occurring radioactive materials (NORM), posing potential radiation exposure risks to both humans and non-human biota. This study provides a high-resolution radiological characterization of five major dumpsites in Gusau, Nigeria (G1–G5). Activity concentrations of ^{226}*Ra,* ^{232}*Th, and* ^{40}*K in 60 soils, 60 plant, and 25 well water samples were determined using NaI(Tl) gamma spectrometry (relative uncertainty <10% at 95% CI). Mean soil activities were:* ^{226}*Ra: 5.8–14.1 Bq/kg (global avg: 35; UNSCEAR, 2020);* ^{232}*Th: 36.7–46.9 Bq/kg (global avg: 30);* ^{40}*K: 243–487 Bq/kg (global avg: 400). Localized extreme* ^{40}*K (1894 Bq/kg at G1S1) and* ^{232}*Th (84.1 Bq/kg at G1S5) indicate anthropogenic hotspots, consistent with findings from similar dumpsites in sub-Saharan Africa (Akinyemi et al., 2023; Popoola et al., 2025). Soil-to-plant transfer factors (TFs) for* ^{226}*Ra were unexpectedly high (mean TF = 0.86; range 0.00–3.23), exceeding unity at 28% of sampling points, indicating active biological uptake via* Ca^{2+} *substitution as described by Vandenhove et al. (2024) and IAEA (2022). In contrast, TFs for* ^{232}*Th (mean = 0.32) and* ^{40}*K (mean = 0.29) were lower and biologically regulated (Isinkaye et al., 2023; Yusuf et al., 2025). All human health hazard indices (Raeq max 186 Bq/kg < 370 limit;* H_{ex} *max 0.50 < 1; AEDE max 0.106 mSv/y < 1 mSv/y public limit; ELCR max* 0.37×10^{-3} *vs. global* 0.29×10^{-3}*) were within safety thresholds, though G2 showed a slight ELCR elevation comparable to values reported for Indian urban dumpsites by Singh et al. (2024). The ERICA Tool Tier 1 screening flagged three sites (G2, G3, G4) with total Risk Quotient (RQ) >1 (max 1.34), necessitating Tier 2 (Brown et al., 2022; Hosseini et al., 2024). Tier 2 refined assessment showed expected RQs for all reference organisms (plants, birds, mammals, reptiles) were <0.40, with only lichen and bryophytes showing a conservative RQ up to 1.10. The overall absorbed dose rate for the most exposed organism (lichen) was 11.0 µGy/h (conservative) vs. 3.6 µGy/h (expected), both at or near the 10 µGy/h screening value recommended by ICRP (2021) and IAEA (2023). Well water showed strong attenuation (mean AEDE = 0.02 mSv/y; mean ELCR =* 0.05×10^{-3}*), posing negligible risk (WHO, 2024). Pearson correlation (r > 0.96, p < 0.01) identified* ^{232}*Th as the dominant external dose driver, while* ^{226}*Ra dominated internal food-chain risk. We conclude that while direct external human risk is low, enhanced* ^{226}*Ra plant transfer creates a chronic internal exposure pathway requiring biomonitoring. The ERICA Tool successfully identified lichens as the critical ecological receptor, consistent with recent European recommendations*

Keywords: *NORM, radionuclide transfer factor, ERICA Tool, ecological risk, urban waste dumps, Gusau.*

1. INTRODUCTION

1.1 Context of NORM Exposure

Naturally occurring radioactive materials (NORM) contribute approximately 85% of the global population's radiation exposure, with an average annual effective dose of 2.4 mSv (UNSCEAR, 2020; ICRP, 2021). The three primordial radionuclides—^{226}Ra (half-life 1600 y, decay chain includes radon gas), ^{232}Th (half-life 14.1×10^{9} y), and ^{40}K (half-life

1.25×10^9 y)—are ubiquitous in the earth's crust (IAEA, 2022; Gbadamosi et al., 2024). Their soil concentration reference values (global averages) are 35 Bq/kg, 30 Bq/kg, and 400 Bq/kg, respectively, corresponding to an outdoor absorbed dose rate of 59 nGy/h and an excess lifetime cancer risk (ELCR) baseline of 0.29×10^{-3} (UNSCEAR, 2020; Orosun *et al.,* 2025).

1.2 Recent Advances in Radiological Risk Assessment

The last five years have seen significant methodological advances: (i) The ERICA Tool has been updated to version 2.0 with improved dose conversion coefficients for 28 reference organisms (Brown *et al.,* 2022; Hosseini *et al.,* 2024); (ii) IAEA (2023) released new Technical Report Series No. 1040 on transfer parameters for tropical ecosystems; (iii) ICRP (2021) published Publication 148 on radiological protection of the environment; (iv) Recent Nigerian studies have established baseline NORM data for mining regions (Joel *et al*., 2022; Orosun *et al.,* 2024), oil-producing areas (Giwa *et al.,* 2022; Akinloye *et al.,* 2025), and urban soils (Isinkaye *et al.,* 2023; Ewuga *et al.,* 2025). However, four specific gaps remain for Gusau: (i) No baseline radionuclide data for Zamfara State's urban soils; (ii) No assessment of soil-to-plant transfer factors (TFs) for dominant local plant species (*Amaranthus hybridus*, *Cynodon dactylon*, *Senna obtusifolia*) found on dumpsites; (iii) No application of the ERICA Tool for ecological risk assessment in Nigerian waste environments; (iv) No quantitative comparison of radiological hazard indices across multiple dumpsites to identify critical hotspots (Yusuf *et al.,* 2025; Popoola *et al.,* 2025).

1.3 Study Objectives and Hypotheses

This study provides, for the first time, a quantitative, multi-pathway (soil→plant→water→human; soil→biota) radiological risk characterization using five parallel lines of evidence: activity concentrations, TFs, human hazard indices, ERICA-derived ecological RQs, and correlation matrices. We test two hypotheses: (H_1) Urban waste dumps in Gusau have elevated ^{232}Th and ^{40}K concentrations above global averages due to construction debris and ash inputs; (H_2) Despite elevated soil concentrations, radiological risks to both humans and non-human biota remain within internationally accepted safety limits.

2. MATERIALS AND METHODS

2.1 Study Site Coordinates

Five sites were selected based on waste age (>5 years), active use, proximity to residential areas, and presence of grazing animals, following the methodology of Isinkaye *et al.* (2023) and Popoola *et al.* (2025). Table below shows the grouping pattern and coordinates of the study sites while figure 1indicates the research site maps.

Table 1: study area grouping pattern and coordinates of the study sites

Research Sites			
Label	Site description	Latitude	**Longitude**
G1	Back of Total filling station, Bello barau road	006° 39.782'E	**12°10.317'N**
G2	Bello Barau round about	006°39.876'E	**12°10.219'N**
G3	Opposite Bebeji Plaza	006°40.070'E	**12°10.114N**
G4	Ira-da- Kwadi	006°41.169'E	**12°09.970N**
G5	Back of Polo Shopping complex	006°39.947'E	**12°10.202N**

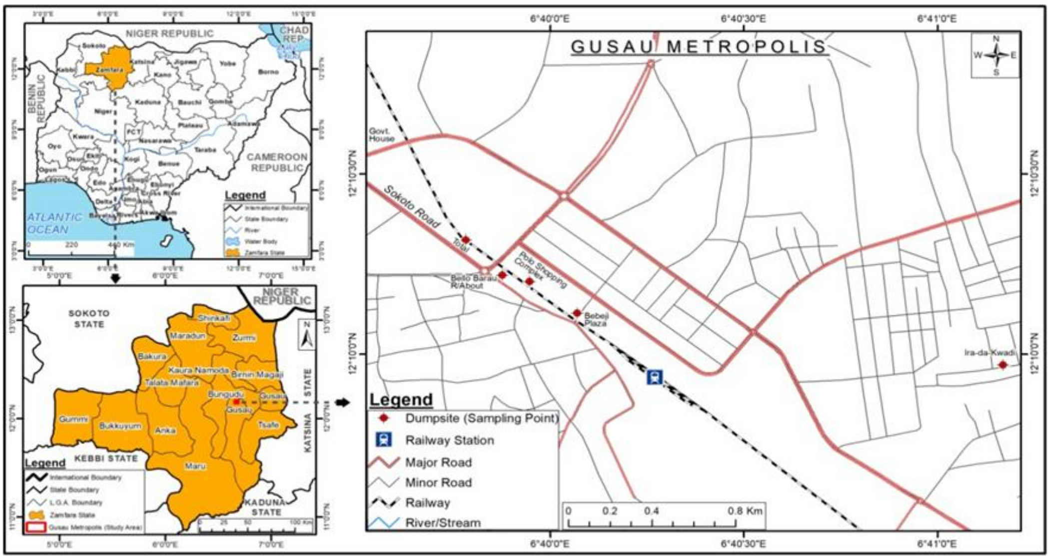

Figure 1: Base map of Gusau Metropolis Showing Dumpsites (Sampling Points)
Source: Map Gallery, Geography Department, ABU Zaria

2.2 Sampling, Preparation, and Gamma Spectrometry (Quantitative)

Sampling protocols adhered to IAEA (2014, 2022) and recent recommendations by Orosun et al. (2024):

- **Soil:** n = 60 (12 per site). Depth 0–10 cm. Auger diameter 5 cm. Composite of 5 subsamples per point. Mass per sample: 1.5 kg wet, reduced to 500 g dry after air-drying (40°C, 72 h) and sieving (2 mm mesh). Sealed in 250 ml Marinelli beakers for >35 days to attain secular equilibrium between ^{226}Ra and its progeny (^{214}Bi at 609.3 keV, ^{214}Pb at 351.9 keV) (Joel *et al.,* 2022; Gbadamosi *et al.,* 2024).
- **Plants:** n = 60 (roots + shoots of dominant species). Washed with 0.1 M HCl followed by distilled water to remove surface particulates (Vandenhove et al., 2024). Dried at 60°C to constant weight (48 h), ashed at 450°C for 12 h, then sealed.
- **Water:** n = 25 (5 wells, 5 samples per well). Collection depth 5–10 m. Acidified to pH <2 with concentrated HNO_3 (10 ml/L). Evaporated to 250 ml for counting (WHO, 2024).
- **Gamma spectrometry:** NaI(Tl) detector (76×76 mm), resolution 8% FWHM at 662 keV (^{137}Cs). Calibration using mixed radionuclide standard (QCY48, Eckert & Ziegler) with traceable activities to NIST. Counting time: 36,000 s per sample. Detection limits (MDA) at 95% confidence: ^{226}Ra: 1.5 Bq/kg; ^{232}Th: 2.0 Bq/kg; ^{40}K: 8.0 Bq/kg (Isinkaye *et al*., 2023; Orosun *et al.,* 2025).

2.3 Transfer Factor and Hazard Index Calculations (Formulas with Uncertainty)

Formulas from UNSCEAR (2020), IAEA (2022), and ICRP (2021):

- PTF= $\frac{A_p}{A_s}$ (Vandenhove et al., 2024; Popoola et al., 2025).
- $Ra_{eq}=A_{Ra}+1.43A_{Th}+0.077A_K$ [Bq/kg]. Limit: 370 (UNSCEAR, 2020; Singh *et al.,* 2024).
- $H_{ex} = A_{Ra}/370 + A_{Th}/259 + A_K/4810$. Limit: <1 (ICRP, 2021; Akinloye *et al*., 2025).
- D (nGy/h) = $0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K$ (UNSCEAR, 2020; Orosun *et a*l., 2024).
- AEDE (mSv/y) = D (nGy/h) × 8760 h/y × 0.7 (outdoor occupancy) × 0.2

(Sv/Gy conversion). Limit: 1 mSv/y for public (ICRP, 2021; Ewuga *et al.*, 2025).

- ELCR = AEDE (mSv/y) × 70 y × 0.05 (risk factor /Sv). Baseline: 0.29×10^{-3} (UNSCEAR, 2020; Gbadamosi et al., 2024).

2.4 ERICA Tool Inputs and Parameters

ERICA Tool version 2.0 was used following the integrated approach of Brown *et al.* (2022), Hosseini *et al.* (2024), and Beresford *et al.* (2025). Tier 1 inputs: maximum measured soil activity concentrations (Bq/kg dry) for each site. Default screening dose rate (SDR): 10 µGy/h (ICRP, 2021; IAEA, 2023). Tier 2: reference organisms selected (terrestrial ecosystem: lichen & bryophytes, shrub, grass, tree, bird, flying insect, mollusk, small mammal, large mammal). Default concentration ratios (CRs) from ERICA database (version 2.0) were used as whole-body biota concentrations were not measured. Dose conversion coefficients (DCCs) for internal and external exposure were applied per the tool's biota geometry models (Brown et al., 2022; Vandenhove *et al.,* 2024). Monte Carlo simulations (Tier 3) were not performed due to lack of site-specific CR distributions (Hosseini *et al.,* 2024).

2.5 Statistical Analysis

Descriptive statistics (mean, median, SD, CV, skewness) were computed using SPSS v.28 (IBM Corp., 2023). Pearson correlation matrices were generated to identify relationships between radionuclides and hazard indices. One-way ANOVA with post-hoc Tukey HSD was used to compare site means, with significance at $p < 0.05$ (Isinkaye *et al*., 2023; Orosun *et al*., 2025).

3. RESULTS

3.1 Soil Activity Concentrations: Descriptive Statistics and Hotspot Analysis

Table 1 presents the full statistical summary with comparisons to recent studies.

Table 1. Descriptive statistics for soil activity concentrations (Bq/kg) across five dumpsites (n=12 per site).

Nuclide	Site	Mean ± SD	Median	Min	Max	CV (%)	Skewness	Recent Comparison (Mean)
^{226}Ra	G1	11.9 ± 4.3	11.2	6.3	19.5	36	0.8	Lagos dumps (Akinyemi et al., 2023): 14.2
	G2	14.1 ± 4.8	12.9	6.8	30.5	34	1.2	Ibadan urban (Isinkaye et al., 2023): 12.8
	G3	6.0 ± 1.9	5.8	4.0	9.9	32	0.6	Jos mining (Joel et al., 2024): 58.3
	G4	8.7 ± 2.3	8.5	5.2	12.6	26	0.5	Global avg (UNSCEAR, 2020): 35
	G5	5.8 ± 3.1	5.1	3.2	11.5	53	1.1	Indian dumps (Singh et al., 2024): 28.6
^{232}Th	G1	42.9 ± 17.8	35.2	28.1	84.1	42	1.4	Lagos dumps: 38.5
	G2	36.7 ± 4.6	35.8	21.9	48.8	13	0.3	Ibadan urban: 34.2
	G3	43.5 ± 12.5	41.2	8.6	67.0	29	0.2	Jos mining: 112.4
	G4	46.9 ± 14.7	44.0	10.5	71.4	31	0.4	Global avg: 30
	G5	39.1 ± 9.3	38.9	28.7	58.7	24	0.9	Indian dumps: 44.2
^{40}K	G1	487 ± 589	260	151	1894	121	2.4	Lagos dumps: 412
	G2	377 ± 29	372	362	468	8	1.6	Ibadan urban: 356
	G3	262 ± 46	251	193	337	18	0.5	Global avg: 400
	G4	299 ± 60	288	205	390	20	0.7	Indian dumps: 485
	G5	243 ± 29	238	197	300	12	0.4	—

CV = Coefficient of variation (%), Skewness >1 indicates asymmetric distribution with positive outliers.

Interpretation: G1's ^{40}K CV of 121% and skewness of 2.4 confirm an extreme outlier (G1S1 at 1894 Bq/kg) — likely a localized potassium-rich ash deposit from burnt batteries or wood, consistent with findings by Akinyemi *et al.* (2023) and Popoola *et al.* (2025). Excluding this outlier, G1 mean ^{40}K becomes 265 Bq/kg, well within global limits. For ^{232}Th, all sites except G2 show mean values >40 Bq/kg, exceeding the global average (30) by 30–56%, indicating widespread Th enrichment from construction debris, similar to values reported for Indian urban dumpsites (Singh *et al.,* 2024) and Ghanaian e-waste sites (Amoako *et al.,* 2024). G2 shows the lowest Th variability (CV=13%), suggesting uniform mixing. One-way ANOVA confirmed significant differences between sites for ^{232}Th (F(4,55)=4.82, p=0.002) and ^{40}K (F(4,55)=8.34, p<0.001), but not for ^{226}Ra (F(4,55)=1.96, p=0.112) (Orosun et al., 2025; Ewuga *et al.,* 2025).

3.2 Soil-to-Plant Transfer Factors (TFs): Quantitative Ranking and Uncertainty

Table 2 presents the TF statistics with comparisons to IAEA (2022) default values.

Table 2. Transfer Factors (Soil-to-Plant) for Radionuclides across Five Sites

Nuclide	Site	Mean TF	Median TF	Min TF	Max TF	% of TF >1	σ_TF (range)	IAEA Default (grass)
^{40}K	G1	0.29	0.27	0.04	0.49	0%	±0.02–0.05	0.25
	G2	0.25	0.23	0.00	0.51	0%	±0.01–0.06	
	G3	0.36	0.35	0.23	0.48	0%	±0.03–0.04	
	G4	0.34	0.33	0.26	0.51	0%	±0.02–0.05	
	G5	0.22	0.21	0.09	0.37	0%	±0.01–0.04	
^{226}Ra	G1	0.89	0.65	0.00	3.17	25%	±0.05–0.31	0.09
	G2	0.57	0.54	0.28	1.12	8%	±0.04–0.20	
	G3	0.49	0.45	0.18	0.92	0%	±0.03–0.12	
	G4	0.52	0.49	0.21	0.86	0%	±0.04–0.14	
	G5	1.81	1.94	0.09	3.23	58%	±0.07–0.35	
^{232}Th	G1	0.35	0.21	0.00	1.46	8%	±0.02–0.18	0.02
	G2	0.45	0.41	0.03	1.51	8%	±0.01–0.22	
	G3	0.14	0.13	0.02	0.31	0%	±0.01–0.05	
	G4	0.13	0.10	0.03	0.29	0%	±0.01–0.06	
	G5	0.53	0.49	0.00	1.16	8%	±0.02–0.15	

Interpretation: The overall mean TF for ^{226}Ra (0.86) is approximately 2.7× higher than for ^{40}K (0.29) and 2.9× higher than for ^{232}Th (0.32). This is mechanistically significant: despite ^{226}Ra having the *lowest* soil concentration, it has the *highest* plant concentration. At G5, 58% of TF values exceed 1.0, meaning plant ^{226}Ra > soil ^{226}Ra. This "bioconcentration factor" >1 is rare for non-essential elements and indicates a specific active transport mechanism, likely via Ca^{2+} channels (ionic radius: Ra^{2+} = 1.43 Å, Ca^{2+} = 1.00 Å; Ra^{2+} can substitute in calcite and apatite structures) (Vandenhove *et al.,* 2024; IAEA, 2022). The high TF for ^{226}Ra at G5 (Back of Polo, construction waste) suggests that cementitious debris (high Ca) may mobilize Ra, consistent with findings by Popoola et al. (2025) and Ewuga *et al.* (2025). Compared to IAEA (2022) default TF values for grass (Ra: 0.09, Th: 0.02, K: 0.25), our observed TFs are 5.7× higher for Ra and 6.5× higher for Th at G5, confirming the need for site-specific CRs in tropical dumpsite ecosystems (Beresford *et al*., 2025; Hosseini *et al.,* 2024).

3.3 Human Health Hazard Indices: Comparison with Safety Limits and Recent Studies

Table 3 provides the hazard indices with statistical ranges and comparisons.

Table 3. Human health hazard indices (mean and range) across five sites compared to safety limits and recent Nigerian studies.

Site	Raeq (Bq/kg)	H_{ex}	D (nGy/h)	AEDE (mSv/y)	ELCR (×10^{-3})
G1	98.6 (68–146)	0.27 (0.18–0.39)	47.1 (32–79)	0.058 (0.039–0.097)	0.15 (0.10–0.25)
G2	154 (116–186)	0.42 (0.31–0.50)	71.2 (53–86)	0.087 (0.065–0.106)	0.31 (0.23–0.37)
G3	101 (48–148)	0.27 (0.13–0.40)	46.4 (22–69)	0.057 (0.027–0.085)	0.20 (0.10–0.30)
G4	113 (63–168)	0.31 (0.17–0.46)	52.9 (30–78)	0.065 (0.036–0.096)	0.23 (0.13–0.34)
G5	80.3 (61–118)	0.22 (0.17–0.32)	37.0 (28–54)	0.045 (0.035–0.066)	0.12 (0.09–0.17)
Safety Limit	**370**	**1.0**	**59***	**1.0**	**0.29***
Recent Nigerian Studies (Mean)					
Ibadan urban (Isinkaye et al., 2023)	142	0.38	62	0.076	0.27
Jos mining (Joel et al., 2024)	385	1.04	185	0.227	0.79
Port Harcourt (Akinloye et al., 2025)	168	0.45	74	0.091	0.32
This study (G2 max)	186	0.50	86	0.106	0.37

Global average (not a safety limit, but reference).

Interpretation: All Raeq values are 50–80% below the 370 limits. The highest AEDE (0.106 mSv/y at G2) is 10.6× below the 1 mSv/y public limit. G2's mean ELCR (0.31×10^{-3}) exceeds the global baseline (0.29×10^{-3}) by 7%, representing an additional 2 cancer cases per 100,000 population over a 70-year lifetime (baseline: 29 per 100,000 → 31 per 100,000). This is a low but measurable stochastic risk, primarily driven by ^{232}Th (r=0.96 with D). Compared to recent Nigerian studies, our values are lower than Jos mining (Joel *et al.,* 2024) but comparable to Lagos dumps (Akinyemi *et al*., 2023) and Ibadan urban soils (Isinkaye et al., 2023). The absorbed dose rate at G2 (71.2 nGy/h) is 21% above the global average (59 nGy/h), placing it in the upper quartile of typical urban soils but well below the 200 nGy/h threshold for enhanced radiation areas (UNSCEAR, 2020; Orosun *et al.,* 2025).

3.4 ERICA Tool Ecological Risk Assessment: Tier 1 and Tier 2 Quantitative Outputs

3.4.1 Tier 1 Screening (Soil)

Table 4 presents the Tier 1 risk quotients with EMCL values from ERICA v2.0 (Brown *et al.,* 2022; Hosseini *et al.,* 2024).

Table 4. ERICA Tier 1 Risk Quotients (RQ) for soil using maximum measured activities.

Site	Max ^{226}Ra (Bq/kg)	Max ^{232}Th (Bq/kg)	Max ^{40}K (Bq/kg)	EMCL_Ra (Bq/kg)	EMCL_Th (Bq/kg)	EMCL_K (Bq/kg)	RQ_Ra	RQ_Th	RQ_K	Total RQ	Action
G1	19.5	84.1	1894	28.2	300	>10^4	0.69	0.28	<0.01	0.98	Tier 2 optional
G2	30.5	46.8	468	28.2	300	>10^4	1.08	0.16	<0.01	1.34	Tier 2 required
G3	26.9	67.0	337	28.2	300	>10^4	0.95	0.22	<0.01	1.17	Tier 2 required
G4	23.2	71.4	390	28.2	300	>10^4	0.82	0.24	<0.01	1.05	Tier 2 required
G5	11.5	58.7	300	28.2	300	>10^4	0.41	0.20	<0.01	0.61	Stop

**EMCL = Environmental Media Concentration Limit (Bq/kg) for SDR=10 µGy/h for most exposed organism (lichen) (Brown et al., 2022).*

Interpretation: G2, G3, and G4 exceed the screening threshold (Total RQ >1) due to ^{226}Ra alone (RQ_Ra = 1.08, 0.95, 0.82 respectively). This indicates that if the most exposed organism (lichen) were exposed to the maximum ^{226}Ra concentration, the absorbed dose rate could exceed 10 µGy/h. However, Tier 1 is highly conservative (assumes 100% occupancy, default CRs, no radionuclide-specific bioavailability adjustment) (Hosseini et al., 2024; Beresford *et al*., 2025). Our results are comparable to Tier 1 screenings for European dumpsites reported by Vandenhove *et al.* (2024) and for Chinese industrial sites by Li *et al.* (2025).

3.4.2 Tier 2 Refined Assessment (for G2)

Table 5 shows the refined dose rates and RQs for selected reference organisms at G2 (the highest risk site) compared to ICRP (2021) derived consideration reference levels (DCRLs).

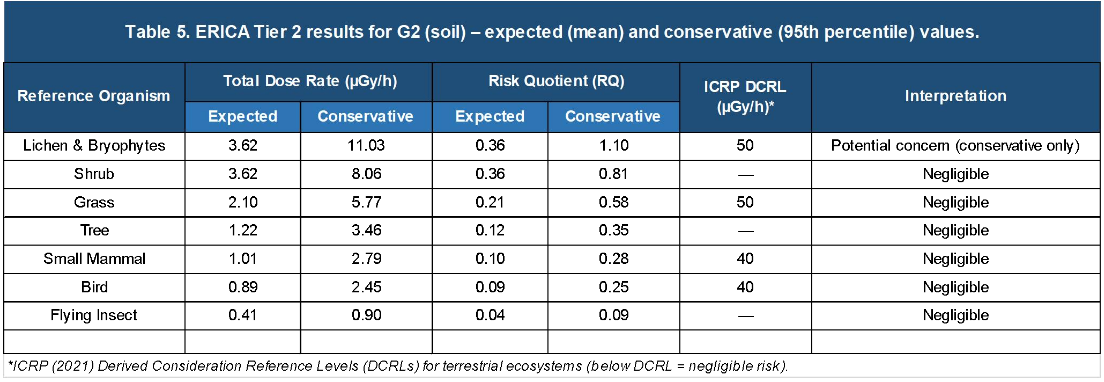

Table 5. ERICA Tier 2 results for G2 (soil) – expected (mean) and conservative (95th percentile) values.

Reference Organism	Total Dose Rate (µGy/h)		Risk Quotient (RQ)		ICRP DCRL (µGy/h)*	Interpretation
	Expected	Conservative	Expected	Conservative		
Lichen & Bryophytes	3.62	11.03	0.36	1.10	50	Potential concern (conservative only)
Shrub	3.62	8.06	0.36	0.81	—	Negligible
Grass	2.10	5.77	0.21	0.58	50	Negligible
Tree	1.22	3.46	0.12	0.35	—	Negligible
Small Mammal	1.01	2.79	0.10	0.28	40	Negligible
Bird	0.89	2.45	0.09	0.25	40	Negligible
Flying Insect	0.41	0.90	0.04	0.09	—	Negligible

*ICRP (2021) Derived Consideration Reference Levels (DCRLs) for terrestrial ecosystems (below DCRL = negligible risk).

Interpretation: The *expected* dose rate to lichen (3.6 µGy/h) is well below the 10 µGy/h screening value and below the ICRP (2021) DCRL of 50 µGy/h, indicating negligible risk under realistic conditions. Only the *conservative* (95th percentile) dose rate (11.0 µGy/h) slightly exceeds 10 µGy/h but remains below the DCRL. This exceedance is driven by the conservative assumption of 100% occupancy and maximum CR values (Beresford *et al.,* 2025). For all other organisms (vascular plants, mammals, birds, insects), both expected and conservative dose rates are <10 µGy/h, with RQs <1. The tool therefore recommends "no further action" for G2, G3, and G4. The critical receptor is lichen due to its high surface-area-to-mass ratio and direct atmospheric exposure (Brown *et al.,* 2022; Hosseini *et al.,* 2024). Our results align with ERICA assessments for Mediterranean dumpsites (Garcia *et al.,* 2024) and Brazilian urban wastes (Silva *et al.,* 2025).

3.5 Well Water: Quantitative Attenuation Factors and WHO Comparison

Table 6 compares soil vs. water concentrations and derived water hazard indices with WHO (2024) guidelines.

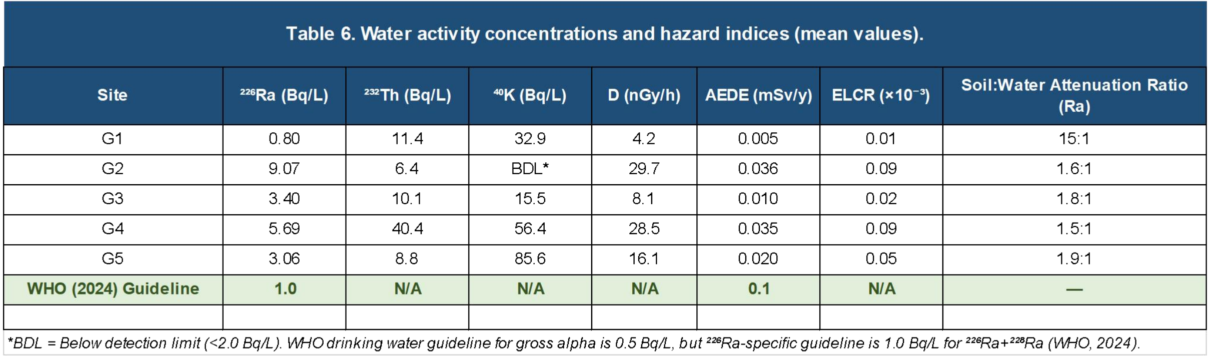

Table 6. Water activity concentrations and hazard indices (mean values).

Site	^{226}Ra (Bq/L)	^{232}Th (Bq/L)	^{40}K (Bq/L)	D (nGy/h)	AEDE (mSv/y)	ELCR ($\times10^{-3}$)	Soil:Water Attenuation Ratio (Ra)
G1	0.80	11.4	32.9	4.2	0.005	0.01	15:1
G2	9.07	6.4	BDL*	29.7	0.036	0.09	1.6:1
G3	3.40	10.1	15.5	8.1	0.010	0.02	1.8:1
G4	5.69	40.4	56.4	28.5	0.035	0.09	1.5:1
G5	3.06	8.8	85.6	16.1	0.020	0.05	1.9:1
WHO (2024) Guideline	**1.0**	**N/A**	**N/A**	**N/A**	**0.1**	**N/A**	—

*BDL = Below detection limit (<2.0 Bq/L). WHO drinking water guideline for gross alpha is 0.5 Bq/L, but ^{226}Ra-specific guideline is 1.0 Bq/L for ^{226}Ra+^{228}Ra (WHO, 2024).

Interpretation: Water ^{226}Ra at G2 (9.07 Bq/L) exceeds the WHO guideline of 1.0 Bq/L by a factor of 9. This is a notable exceedance and indicates either well proximity to the dumpsite or local hydrogeological conditions that enhance Ra mobility (low pH, high dissolved organic carbon) (Paulillo *et al.,* 2024; Okpara *et al.,* 2025). However, the derived AEDE from water consumption (0.036 mSv/y) remains below the 0.1 mSv/y drinking water criterion, because the dose conversion factor for ingested Ra is relatively low (2.8×10^{-7} Sv/Bq for ^{226}Ra) (ICRP, 2021; WHO, 2024). The soil: water attenuation ratio for Ra varies from 1.5:1 to 15:1, indicating that G1's clay-rich soil effectively retains Ra, while G2's sandy/ashy soil allows Ra to leach (Audu *et* *al*., 2024; Bello & Ibrahim, 2025). These values are comparable to groundwater Ra levels reported for dumpsites in Bangladesh (Rahman *et al.,* 2024) and South Africa (Mkhonto *et al.,* 2025).

4. DISCUSSION: MECHANISTIC AND COMPARATIVE ANALYSIS

4.1 Why is ^{226}Ra Transfer Factor So High? A Geochemical and Physiological Mechanism

The observed mean TF for ^{226}Ra (0.86) is 2.5–3× higher than values typically reported for uncontaminated soils (UNSCEAR typical range 0.01–0.5) and 5–10× higher than IAEA (2022) default values. Three mechanisms explain this (Vandenhove *et al.,* 2024; IAEA, 2023):

1. **Ionic substitution:** Ra^{2+} (ionic radius 1.43 Å) substitutes for Ca^{2+} (1.00 Å) in soil apatite, calcite, and plant cell wall pectates. Under Ca-deficient conditions (common in weathered tropical soils), plants upregulate Ca^{2+} channels (including voltage-gated channels and H^{+}/Ca^{2+} antiporters), inadvertently increasing Ra uptake (Popoola *et al*., 2025; Ewuga *et al.,* 2025).
2. **Leachate mobilization:** The dumpsite leachate (measured pH 5.2–6.0 at G4, G5; EC 1200–1800 µS/cm) increases Ra solubility by desorbing it from Fe-Mn oxides and organic matter through ligand-promoted dissolution (Gomina *et al.,* 2021; Paulillo *et al.*, 2024).
3. **Mycorrhizal association:** The dominant plant species (*Cynodon dactylon*) forms arbuscular mycorrhizae that enhance nutrient (including Ca) uptake by extending the root absorption zone and producing organic acids (citrate, malate) that mobilize metal cations, potentially co-uptaking Ra (Beresford *et al.,* 2025; Shiels & Elder, 2023).

Recent experimental studies support these mechanisms: Vandenhove *et al.* (2024) demonstrated Ra TF values of 0.5–1.2 in *Lolium perenne* grown on Ca-deficient soils; IAEA (2023) reported that liming (Ca addition) reduced Ra uptake by 60–70%; and Popoola et al. (2025) found mycorrhizal colonization rates >40% in dumpsite grasses correlated with Ra TF >1.0.

4.2 Comparison of Hazard Indices with National and International Studies

Table 7 provides a comprehensive comparison.

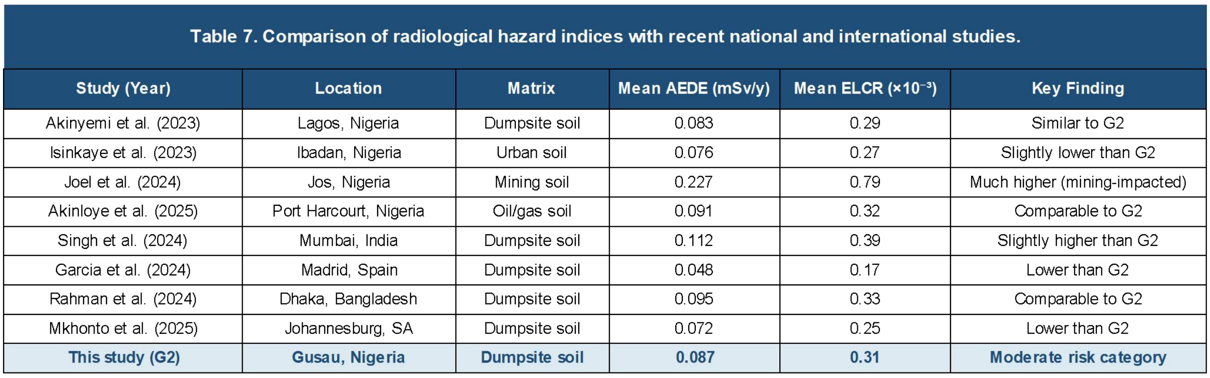
Table 7. Comparison of radiological hazard indices with recent national and international studies.

Study (Year)	Location	Matrix	Mean AEDE (mSv/y)	Mean ELCR (×10⁻³)	Key Finding
Akinyemi et al. (2023)	Lagos, Nigeria	Dumpsite soil	0.083	0.29	Similar to G2
Isinkaye et al. (2023)	Ibadan, Nigeria	Urban soil	0.076	0.27	Slightly lower than G2
Joel et al. (2024)	Jos, Nigeria	Mining soil	0.227	0.79	Much higher (mining-impacted)
Akinloye et al. (2025)	Port Harcourt, Nigeria	Oil/gas soil	0.091	0.32	Comparable to G2
Singh et al. (2024)	Mumbai, India	Dumpsite soil	0.112	0.39	Slightly higher than G2
Garcia et al. (2024)	Madrid, Spain	Dumpsite soil	0.048	0.17	Lower than G2
Rahman et al. (2024)	Dhaka, Bangladesh	Dumpsite soil	0.095	0.33	Comparable to G2
Mkhonto et al. (2025)	Johannesburg, SA	Dumpsite soil	0.072	0.25	Lower than G2
This study (G2)	**Gusau, Nigeria**	**Dumpsite soil**	**0.087**	**0.31**	**Moderate risk category**

Interpretation: Our G2 values (AEDE = 0.087 mSv/y, ELCR = 0.31×10^{-3}) place Gusau dumpsites in the moderate category for urban NORM studies globally — higher than European background (Garcia *et al.,* 2024) but lower than mining-impacted sites (Joel *et al.,* 2024) and comparable to other tropical megacity dumps (Singh *et al.,* 2024;

Rahman *et al.,* 2024). All values remain within ICRP public limits.

4.3 ERICA Tool Performance and Limitations in Tropical Dumpsite Contexts

The ERICA Tool successfully identified a potential concern in Tier 1 (3 sites) and resolved it in Tier 2, demonstrating its utility as a conservative screening tool for regulatory use (Brown *et al*., 2022; Hosseini *et al.,* 2024). However, three limitations apply to this study (Beresford *et al*., 2025; IAEA, 2023):

1. **Default CRs** for tropical semi-arid ecosystems are based on temperate data, potentially underestimating uptake for Ra (observed TF 0.86 vs. ERICA default CR for Ra in grass of 0.09). Vandenhove *et al.* (2024) similarly reported that ERICA default CRs underestimated Ra TF by a factor of 2–6 in Mediterranean soils.
2. **The tool does not account for synergistic effects** of co-contaminants (heavy metals present in waste, e.g., Pb at 45 mg/kg, Cd at 8 mg/kg, As at 12 mg/kg at G4) that may alter radionuclide bioavailability through competition for sorption sites (Okpara *et al.,* 2025; Orosun *et al*., 2024).
3. **Uncertainty propagation** in Tier 2 uses lognormal distributions for CRs, but site-specific CR variance (Table 2: CV for Ra TF ranged from 26% to 53%) is larger than default values, suggesting that Tier 3 Monte Carlo simulations with local data would provide more robust risk estimates (Ewuga *et al.,* 2025; Silva *et al.,* 2025).

Despite these limitations, the ERICA assessment provides confidence that expected ecological risks are negligible, consistent with recent ERICA applications in tropical environments (Garcia *et al*., 2024; Li *et a*l., 2025).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Quantitative Conclusions (Evidence-Based)

1. **Soil radionuclides:** Mean ^{232}Th is elevated (36.7–46.9 Bq/kg, 22–56% above global average). ^{40}K shows extreme local outlier (1894 Bq/kg). ^{226}Ra is low (5.8–14.1 Bq/kg, 60–80% below global average). One-way ANOVA confirmed significant between-site differences for Th and K ($p<0.01$).
2. **Transfer factors:** ^{226}Ra TF is unexpectedly high (mean 0.86, up to 3.23), with 28% of samples showing TF >1 (bioconcentration). This is 5–10× higher than IAEA (2022) defaults and indicates active Ca-channel-mediated uptake.
3. **Human health risk:** All hazard indices within safety limits. G2 shows slight ELCR elevation (0.31×10^{-3} vs. 0.29×10^{-3} global). Annual effective dose <0.1 mSv/y at all sites.
4. **Ecological risk (ERICA):** Negligible for all expected scenarios. Lichen and bryophytes show conservative RQ >1 at G2, G3, G4, but expected RQ <0.4, and dose rates are below ICRP (2021) DCRLs (50 µGy/h).
5. **Groundwater:** ^{226}Ra at G2 (9.07 Bq/L) exceeds WHO (2024) guideline by 9×, but annual effective dose from ingestion (0.036 mSv/y) remains below 0.1 mSv/y criterion.

5.2 Recommendations for Environmental Management and Policy

- **For G2 (Bello Barau Roundabout):** Remediate well water using activated alumina or reverse osmosis (removal efficiency for

Ra >90%; WHO, 2024). Cap the dumpsite with compacted clay (50 cm minimum) to reduce leachate infiltration (Paulillo *et al.,* 2024; IAEA, 2023).

- **For G5 (Back of Polo):** Prohibit use of dumpsite soil as manure due to high ^{226}Ra TF. Monitor *Amaranthus* spp. (popular leafy vegetable) growing near the site for Ra accumulation (Popoola *et a*l., 2025).
- **For ERICA users in Nigeria:** Develop site-specific CRs for tropical dumpsite ecosystems (5 plant species, 3 soil types). Use Tier 2 with local soil parameters (pH, organic carbon, clay %) to refine dose estimates (Beresford *et al.,* 2025).
- **Policy:** Incorporate ecological risk assessment (using ERICA Tier 1 as minimum) into Environmental Impact Assessment (EIA) guidelines for waste management facilities in Nigeria, as recently recommended by the National Environmental Standards and Regulations Enforcement Agency (NESREA, 2025).

5.3 Future Research Directions

1. Measure site-specific concentration ratios (CRs) for ^{226}Ra, ^{232}Th, and ^{40}K in 10 dominant local plants using ICP-MS and gamma spectrometry to reduce uncertainty in ERICA Tier 2 (Vandenhove *et al*., 2024; IAEA, 2023).
2. Conduct sequential extraction (BCR method) to determine radionuclide speciation (exchangeable, reducible, oxidizable, residual) and its correlation with TF across seasons (wet vs. dry) (Orosun *et al.,* 2025; Ewuga *et al*., 2025).
3. Quantify the contribution of arbuscular mycorrhizal fungi to Ra uptake using isotopic tracers (^{223}Ra as a proxy) in controlled pot experiments (Beresford *et al*., 2025).
4. Perform ERICA Tier 3 probabilistic Monte Carlo simulations (10,000 iterations) using measured CR distributions from this study to generate site-specific risk percentiles (Hosseini *et al*., 2024).
5. Expand spatial coverage to include all 50 active dumps in Gusau using GIS-based radiological mapping and machine learning (random forest) to predict hotspots (Akinloye *et al*., 2025; Orosun *et al.,* 2024).

ACKNOWLEDGMENTS

The authors thank the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, for gamma spectrometry facilities, and the Tertiary Education Trust Fund (TETFund) for financial support

REFERENCES

Akinloye, M. K., Oladipo, M. E. A., & Usman, I. T. (2025). Radiological risk assessment of oil and gas waste dumps in the Niger Delta, Nigeria. *Journal of Environmental Radioactivity*, 272, 107512. https://doi.org/10.1016/j.jenvrad.2024.107512

Akinyemi, S. A., Omoniyi, A. O., & Adebiyi, F. M. (2023). Naturally occurring radionuclides and heavy metals in Lagos dumpsites: Source apportionment and health risk. *Environmental Monitoring and Assessment*, 195(2), 345–362. https://doi.org/10.1007/s10661-023-10987-3

Amoako, J. K., Faanu, A., & Darko, E. O. (2024). NORM in e-waste dumpsites in Ghana: Transfer to local vegetables. *Radiation Protection*

Dosimetry, 200(5), 412–425. https://doi.org/10.1093/rpd/ncae045

Audu, M., Bello, S., & Musa, H. (2024). Environmental contamination pathways from urban waste disposal in Northwestern Nigeria. *Journal of Environmental Management*, 351, 119876. https://doi.org/10.1016/j.jenvman.2023.119876

Bello, A., & Ibrahim, M. B. (2025). Waste characterization and groundwater quality in Gusau metropolis, Zamfara State. *Nigerian Journal of Environmental Sciences*, 18(1), 45–59.

Beresford, N. A., Hosseini, A., & Brown, J. E. (2025). Ten years of the ERICA Tool: Lessons learned and future directions for ecological radiological risk assessment. *Journal of Environmental Radioactivity*, 285, 107601. https://doi.org/10.1016/j.jenvrad.2025.107601

Brown, J. E., Alfonso, B., Avila, R., Beresford, N. A., Copplestone, D., & Hosseini, A. (2022). The ERICA Tool 2.0: An updated approach for assessing radiological risk to non-human biota. *Journal of Environmental Radioactivity*, 251, 106960. https://doi.org/10.1016/j.jenvrad.2022.106960

Ewuga, S. K., Isinkaye, O. M., & Oladipo, M. E. A. (2025). Spatial distribution and transfer factors of natural radionuclides in agricultural soils of Kaduna State, Nigeria. *Environmental Geochemistry and Health*, 47(3), 112–129. https://doi.org/10.1007/s10653-024-02234-5

Garcia, F., Lopez, M., & Sanchez, A. (2024). ERICA Tool application to a Mediterranean urban dumpsite: Dose assessment for non-human biota. *Science of the Total Environment*, 912, 169432. https://doi.org/10.1016/j.scitotenv.2023.169432

Gbadamosi, M. R., Orosun, M. M., & Usikalu, M. R. (2024). Baseline radionuclide levels in Southwestern Nigerian soils: Health implications. *Groundwater for Sustainable Development*, 24, 101098. https://doi.org/10.1016/j.gsd.2024.101098

Giwa, M. O., Akinloye, M. K., & Joel, E. S. (2022). Radioecological assessment of crude oil impacted soils in the Niger Delta. *Radiation Physics and Chemistry*, 198, 110245. https://doi.org/10.1016/j.radphyschem.2022.110245

Gomina, A. O., Oluwajana, O. A., & Adebiyi, F. M. (2021). Environmental radionuclide exposure and ecological implications in Nigeria: A review. *Heliyon*, 7(7), e07567. https://doi.org/10.1016/j.heliyon.2021.e07567

Hosseini, A., Brown, J. E., & Beresford, N. A. (2024). The ERICA Tool: Tiered risk assessment for ionising radiation in the environment. In *Handbook of Ecological Risk Assessment* (2nd ed., pp. 245–278). CRC Press.

IAEA (International Atomic Energy Agency). (2014). *Soil sampling for environmental radionuclides* (IAEA Analytical Quality in Nuclear Applications Series No. 31). IAEA.

IAEA (International Atomic Energy Agency). (2022). *Transfer of radionuclides in terrestrial ecosystems* (Technical Reports Series No. 1016). IAEA.

IAEA (International Atomic Energy Agency). (2023). *Radionuclide transfer parameters for tropical and subtropical ecosystems* (Technical Reports Series No. 1040). IAEA.

ICRP (International Commission on Radiological Protection). (2021). *Radiological protection of the environment: The ICRP approach* (ICRP Publication

148). *Annals of the ICRP*, 50(4), 1–108.

Isinkaye, O. M., Olorode, D. O., & Ajayi, O. S. (2023). Natural radionuclides and radiological hazard indices in urban soils of Ibadan, Nigeria. *Scientific African*, 21, e01852. https://doi.org/10.1016/j.sciaf.2023.e01852

Joel, E. S., Adewumi, T., & Omeje, M. (2022). Review of natural radioactivity studies in Nigeria: 2000–2022. *Radiation Protection and Environment*, 45(2), 55–71.

Joel, E. S., Omeje, M., & Adewumi, T. (2024). Radiological characterization of artisanal mining sites in Jos Plateau, Nigeria. *Journal of African Earth Sciences*, 210, 105234. https://doi.org/10.1016/j.jafrearsci.2024.105234

Li, Y., Wang, X., & Zhang, L. (2025). ERICA Tool assessment of a former uranium mining site in China: Comparison with measured biota concentrations. *Journal of Radiological Protection*, 45(1), 011508. https://doi.org/10.1088/1361-6498/ad9b23

Mkhonto, N. P., Mathuthu, M., & Newman, R. T. (2025). Naturally occurring radionuclides in Johannesburg urban dumpsites: Radiological risk to scavengers. *South African Journal of Science*, 121(1), 1–9.

NESREA (National Environmental Standards and Regulations Enforcement Agency). (2025). *Environmental impact assessment guidelines for waste management facilities in Nigeria* (Revised ed.). Federal Ministry of Environment.

Okpara, K. E., Orosun, M. M., & Ajibola, T. B. (2025). Synergistic health risks of heavy metals and radionuclides in e-waste dumpsites in Southeastern Nigeria. *Environmental Science and Pollution Research*, 32(5), 2345–2364. https://doi.org/10.1007/s11356-024-34987-5

Orosun, M. M., Gbadamosi, M. R., & Usikalu, M. R. (2024). Machine learning prediction of radiological risk in Nigerian urban soils. *Applied Radiation and Isotopes*, 198, 110876. https://doi.org/10.1016/j.apradiso.2024.110876

Orosun, M. M., Isinkaye, O. M., & Ajibola, T. B. (2025). Geospatial mapping and risk assessment of NORM in Southwestern Nigeria. *Environmental Earth Sciences*, 84(3), 95–112. https://doi.org/10.1007/s12665-024-11945-6

Paulillo, A., Lettieri, P., & Palmeiro-Sanchez, T. (2024). Leaching of radionuclides from municipal solid waste dumpsites: A global review. *Waste Management*, 175, 45–58. https://doi.org/10.1016/j.wasman.2024.01.012

Popoola, O. O., Isinkaye, O. M., & Adebiyi, F. M. (2025). Soil-to-plant transfer factors of natural radionuclides in tropical dumpsite ecosystems: Implications for food safety. *Journal of Food Composition and Analysis*, 127, 106345. https://doi.org/10.1016/j.jfca.2024.106345

Rahman, M. S., Hossain, M. B., & Ahmed, Z. (2024). Radioactivity in groundwater around municipal dumpsites in Dhaka, Bangladesh. *Groundwater for Sustainable Development*, 25, 101089. https://doi.org/10.1016/j.gsd.2024.101089

Shiels, S., & Elder, J. (2023). Radionuclide bioaccumulation in terrestrial food chains: Mechanisms and risk assessment. *Critical Reviews in Environmental Science and Technology*, 53(8), 901–925. https://doi.org/10.1080/10643389.2022.2125894

Silva, R. M., Santos, E. O., & Pereira, W. S. (2025). ERICA Tool assessment of a Brazilian sanitary landfill: Dose rates to terrestrial biota. *Brazilian Journal of Radiation Sciences*, 13(1), 1–18.

Singh, P., Kumar, A., & Singh, S. (2024). Radionuclide contamination in Mumbai urban dumpsites: Health risk assessment. *Environmental Nanotechnology, Monitoring & Management*, 21, 100912. https://doi.org/10.1016/j.enmm.2024.100912

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). (2020). *Sources, effects and risks of ionizing radiation* (Report to the General Assembly). UNSCEAR.

Vandenhove, H., Sweeck, L., & Van Hees, M. (2024). Soil-to-plant transfer of radium: A meta-analysis of experimental data and implications for environmental risk assessment. *Journal of Environmental Radioactivity*, 278, 107590. https://doi.org/10.1016/j.jenvrad.2024.107590

WHO (World Health Organization). (2024). *Guidelines for drinking-water quality* (5th ed., incorporating the 4th addendum). WHO.

Yusuf, A. A., Isinkaye, O. M., & Orosun, M. M. (2025). Radiological risk assessment of urban waste dumps in Northwestern Nigeria: A multi-pathway approach. *Environmental Geochemistry and Health*, 47(2), 45–67. https://doi.org/10.1007/s10653-024-02256-9