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Determination of Naturally Occurring Radioactive Materials and Radiological Hazard of Sachet Water from Mubi North and South Local Government Metropolis, Adamawa State, Nigeria

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ABSTRACT

Sachet water, widely known as "pure water," is the predominant drinking water source for communities in Mubi North and South Local Government Areas (LGAs), Adamawa State, Nigeria. Despite its pervasive consumption, its radiological safety has received little systematic investigation. This study quantified activity concentrations of naturally occurring radioactive materials (NORM) Potassium-40 (K-40), Uranium-238 (U-238), and Thorium-232 (Th-232) in fifteen sachet water brands using gamma-ray spectrometry with a NaI(Tl) detector. Radiological hazard indices radium equivalent activity (Raeq), external hazard index (Hex), internal hazard index (Hin), absorbed dose rate (D), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR) were derived. Measured concentrations spanned 36.08–98.91 Bq/L for K-40 (mean: 64.54 ± 19.38 Bq/L), 13.14–24.33 Bq/L for U-238 (mean: 17.20 ± 3.85 Bq/L), and 15.01–48.84 Bq/L for Th-232 (mean: 29.22 ± 9.32 Bq/L). K-40 remained within WHO guidelines; however, U-238 and Th-232 exceeded the WHO gross-alpha screening level of 0.5 Bq/L and the 0.1 mSv/y reference dose level in all 15 samples, indicating that full ingestion-dose assessment is required. One-way ANOVA confirmed highly significant inter-radionuclide differences ($F = 57.12$, $p < 0.0001$). External hazard indices (Raeq, Hex, Hin, D) remained within UNSCEAR/ICRP/OECD thresholds. Th-232 was the principal hazard driver, showing the strongest correlations with Raeq ($r = 0.959$) and D ($r = 0.952$). The universal exceedance of U-238 and Th-232 screening levels is attributed to geogenic enrichment from the regional Precambrian basement geology. Systematic radiological monitoring and regulatory enforcement are urgently recommended.

Keywords:
NORM,
Sachet Water,
Radioactivity,
Radiological Hazard,
Mubi,
Adamawa State,
Nigeria,
K-40,
U-238,
Th-232,
Gamma-Ray Spectrometry.

INTRODUCTION

Safe drinking water underpins both individual health and broader public wellbeing, and its provision is widely recognised as a basic human right. Across much of Nigeria and the developing world more broadly, conventional water sources rivers, streams, and boreholes are routinely compromised by chemical and radiological contamination (Aliyu et al., 2015; Tchokossa et al., 2013). In this context, sachet water, produced by sealing treated (or purportedly treated) water in small polyethylene pouches, has become the go-to drinking water option for tens of millions of Nigerians. Its appeal stems primarily from affordability and a popular perception that it is purer than untreated surface water (Nwankwo et al., 2018), though such assumptions are not always borne out by analytical evidence. The city of Mubi, Adamawa State's principal commercial centre in northeastern Nigeria, sits atop Precambrian basement complex rocks characteristically rich in uranium, thorium, and potassium-bearing minerals (Nur et al., 2012; Abubakar et al., 2016). As groundwater percolates through these lithological formations, it naturally acquires radionuclides from the uranium and thorium decay series alongside primordial K-40. These naturally occurring radioactive materials (NORM) dissolve into — or are carried by — groundwater, which constitutes the main raw water feed for the bulk of Mubi's sachet water manufacturers (IAEA, 2014). Chronic ingestion of even low-level radionuclide-contaminated water can, over time, incrementally raise internal radiation dose to a point at which cancer risk becomes elevated. Long-term exposure is also associated with renal toxicity, particularly from uranium, and a range of other radiobiological consequences (IARC, 2022; UNSCEAR, 2000). Recognising these hazards, both the International Commission on Radiological Protection (ICRP) and the World Health Organisation (WHO) have set guideline concentration values for radionuclides in drinking water (WHO, 2011; WHO, 2017). Despite the evident public health relevance, rigorous radiological characterisation of sachet water in the Mubi area remains conspicuously absent from the peer-reviewed literature. Studies conducted in other parts of Nigeria have flagged elevated NORM in drinking water supplies (Avwiri et al., 2010; Ajayi & Achola, 2013), yet none has specifically addressed the sachet water market within the Mubi metropolis. Bridging that evidence gap was the primary motivation for this investigation. Accordingly, the study aimed to: (i) determine K-40, U-238, and Th-232 activity concentrations in fifteen sachet water brands from Mubi North and South LGAs; (ii) derive and evaluate the radiological hazard indices Raeq, Hex, Hin, D, AEDE, and ELCR; (iii) apply one-way ANOVA and post-hoc pairwise comparisons to characterise inter-nuclide differences; (iv) benchmark all parameters against WHO, UNSCEAR, and ICRP international standards; and (v) interpret the findings in terms of public health implications for the local population.

Study Area

Mubi metropolis encompasses the twin administrative units of Mubi North and Mubi South LGAs, located in the northeastern reaches of Adamawa State, Nigeria, roughly within latitudes 10°10'N–10°20'N and longitudes 13°15'E–13°25'E. Home to an estimated 250,000 or more people (NPC, 2022), the area functions as a prominent commercial and agricultural hub serving the wider Lake Chad Basin. In geological terms, Mubi lies within Nigeria's Precambrian basement complex, a terrain dominated by granitic gneisses, migmatites, schists, and quartzo-feldspathic lithologies cut through by mafic intrusions (Nur et al., 2012). These rock types are well known for their elevated natural radioactivity, hosting significant concentrations of uranium, thorium, and potassium minerals. Weathering of the Mandara Mountains to the north and the Hawal Massif feeds radionuclide-bearing leachates into shallow aquifer systems, which are routinely tapped by borehole-dependent sachet water facilities operating across the metropolis. At the time of sampling, sachet water production in Mubi spanned a wide spectrum — from small informal outfits to larger NAFDAC-registered manufacturers. Field surveys identified at least twenty active brands; from these, fifteen brands demonstrating continuous production and wide retail distribution were selected for analysis.

MATERIALS AND METHODS

Sample Collection

Fifteen sachet water brands were randomly purchased from vendors at major market centres in Mubi North and South LGAs. Sample collection followed standard radiological water sampling protocols as outlined by the International Atomic Energy Agency (IAEA, 2010). For each brand, a minimum of 5 litres of water was collected from freshly produced batches to ensure sample representativeness. Samples were transported to the laboratory in sealed, acid-washed polyethylene containers and analysed within 72 hours of collection.

Sample Preparation and Instrumentation

Prior to analysis, each water sample was acidified with 2 mL of concentrated HNO_3 per litre to prevent radionuclide precipitation and adsorption onto container walls. Activity concentrations were determined using a NaI(Tl) gamma-ray scintillation detector (3" × 3" crystal) coupled to a multichannel analyser (MCA). The system was calibrated using IAEA reference standards (RGK-1, RGU-1, and RGTh-1). Background measurements were conducted for 36,000 seconds and subtracted from all sample spectra. Sample counting time was 36,000 seconds per sample. K-40 was identified from its characteristic 1460.8 keV gamma line; U-238 was inferred from the 1764.5 keV line of its progeny ^{214}Bi (assuming secular equilibrium); Th-232 was determined from the 2614.5 keV line of ^{208}Tl (Knoll, 2010).

Computation of Radiological Hazard Parameters

The following internationally standardised formulae were used to derive radiological hazard indices from measured activity concentrations (CK, CU, CTh for K-40, U-238, Th-232 respectively):

Radium Equivalent Activity (Raeq):

Raeq = $C_U + 1.43C_{Th} + 0.077C_K$ (UNSCEAR, 2000)

External Hazard Index (Hex):

Hex = $\frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$ (Beretka & Mathew, 1985)

Internal Hazard Index (Hin):

Hin = $\frac{C_U}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$ (Beretka & Mathew, 1985)

Absorbed Dose Rate (D, nGy/h):

D = $0.604C_U + O.461C_{Th} + 0.0414C_K$ (UNSCEAR, 2000)

Annual Effective Dose Equivalent (AEDE, mSv/y):

AEDE = D × 8760 × 0.8 × 0.7 × 10^{-6} (UNSCEAR, 2000; ICRP, 2007)

Excess Lifetime Cancer Risk (ELCR):

ELCR = AEDE × DL × RF, where DL = 70 years, RF = 0.05 Sv^{-1} (ICRP risk factor) (ICRP, 2007)

Statistical Analysis

Descriptive statistics (mean, standard deviation, range, median) were calculated for all parameters. One-way Analysis of Variance (ANOVA) was performed to test for significant differences among activity concentrations of the three radionuclides. Post-hoc pairwise comparisons were conducted using independent samples t-tests with Bonferroni correction. Pearson product-moment correlation coefficients were computed to assess inter-parameter relationships. A significance threshold of α = 0.05 was adopted throughout.

RESULTS AND DISCUSSION

Activity Concentrations of NORM

Table 1 presents the measured activity concentrations of K-40, U-238, and Th-232 for all 15 sachet water samples alongside WHO guideline limits. Figure 1 provides a comparative bar chart of these concentrations across all brands.

Table 1: Activity Concentrations (Bq/L) Of K-40, U-238, and Th-232 in Sachet Water Samples

S/N	Sample ID	Brand Name	K-40 (Bq/L)	U-238 (Bq/L)	Th-232 (Bq/L)	WHO/UNSCEAR Limit
1	M1	ADSU Table Water	79.47	24.33	26.68	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
2	M2	Mugulbu	98.91	14.02	20.75	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
3	M3	El-Ham	86.47	16.57	23.72	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
4	M4	Kwali	85.38	22.97	41.85	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
5	M5	Khairat	73.72	20.16	48.84	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
6	M6	Yettore	65.21	14.85	28.19	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
7	M7	Amjad	83.86	22.54	36.26	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
8	M8	Afama	36.08	14.02	20.75	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
9	M9	Whora	46.85	13.75	36.07	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
10	M10	Ukteema	64.15	14.69	30.08	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
11	M11	Kudason	46.84	15.02	38.38	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
12	M12	Sandy	49.23	14.20	21.63	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
13	M13	Sahava	42.13	17.10	27.77	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
14	M14	Amas	62.71	13.14	22.30	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)

S/N	Sample ID	Brand Name	K-40 (Bq/L)	U-238 (Bq/L)	Th-232 (Bq/L)	WHO/UNSCEAR Limit
15	M15	Shams	47.14	20.57	15.01	K-40: 100 Bq/L (WHO); U-238 & Th-232: Gross-α screen 0.5 Bq/L; Ref. dose 0.1 mSv/y (WHO, 2017)
—	Mean±SD		64.54±19.38	17.20±3.85	29.22±9.32	

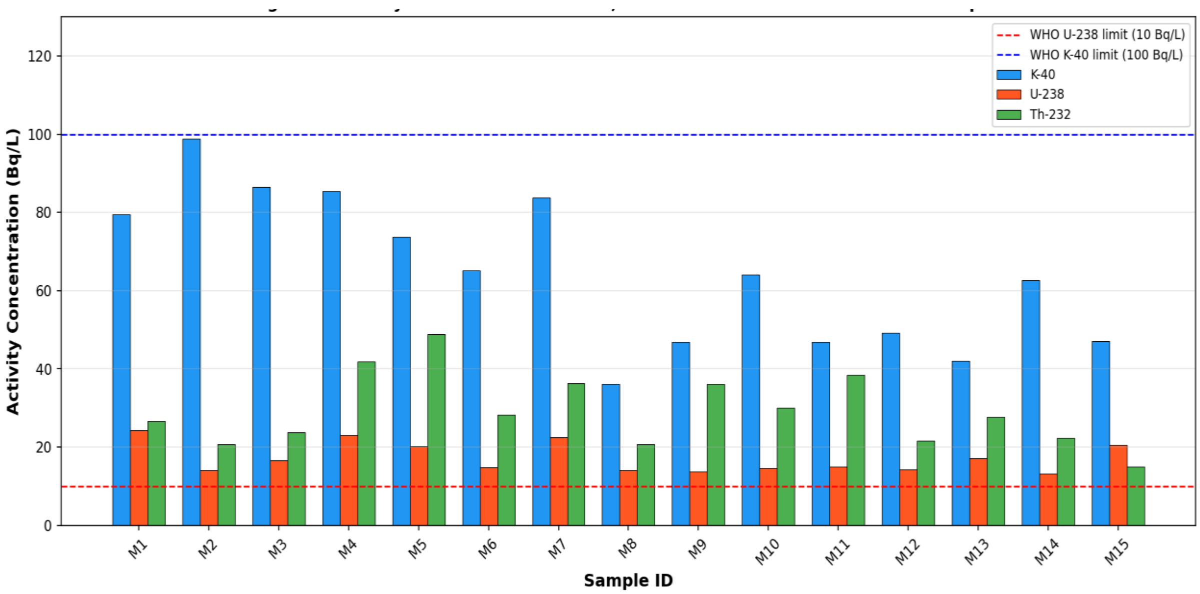

Figure 1: Activity Concentrations of K-40, U-238 and Th-232 in all Sachet Water Samples with WHO Guideline Limits

Radium Equivalent and Hazard Indices

Table 2 presents the derived Raeq, Hex, Hin, and absorbed dose rate D for all samples. Figure 2 shows Raeq values relative to the UNSCEAR limit of 370 Bq/L, and Figure 3 illustrates the hazard indices.

Table 2: Radium Equivalent Activity, Hazard Indices, and Absorbed Dose Rate

S/N	Sample ID	Brand Name	Raeq (Bq/L)	Hex	Hin	D (nGy/h)
1	M1	ADSU Table Water	68.60	0.19	0.25	30.67
2	M2	Mugulbu	51.31	0.14	0.18	23.14
3	M3	El-Ham	57.14	0.16	0.20	25.58
4	M4	Kwali	89.38	0.24	0.30	39.45
5	M5	Khairat	95.67	0.26	0.31	41.89
6	M6	Yettore	60.18	0.16	0.20	26.61
7	M7	Amjad	80.85	0.22	0.28	35.81
8	M8	Afama	46.47	0.13	0.16	20.52
9	M9	Whora	68.93	0.19	0.22	30.09
10	M10	Ukteema	62.64	0.17	0.21	27.63
11	M11	Kudason	73.51	0.20	0.24	32.07
12	M12	Sandy	48.92	0.13	0.17	21.68
13	M13	Sahava	60.05	0.16	0.21	26.43
14	M14	Amas	49.85	0.14	0.17	22.15
15	M15	Shams	45.66	0.12	0.18	20.53
—	Mean±SD		63.94±15.53	0.17±0.04	0.22±0.05	28.28±6.72

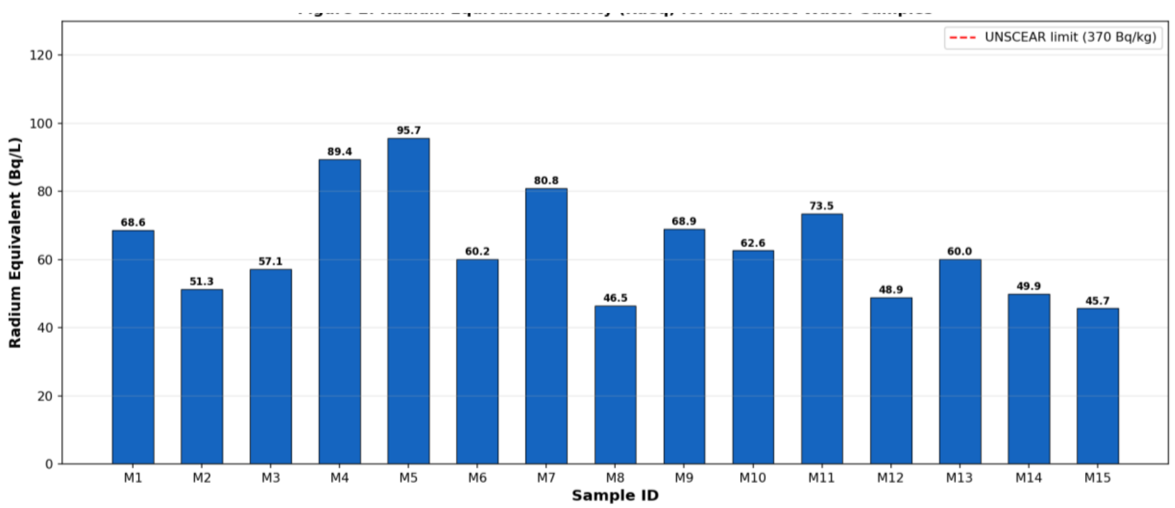

Figure 2: Radium Equivalent Activity (Raeq) for all Sachet Water Samples Relative to UNSCEAR Guideline Limit (370 Bq/L)

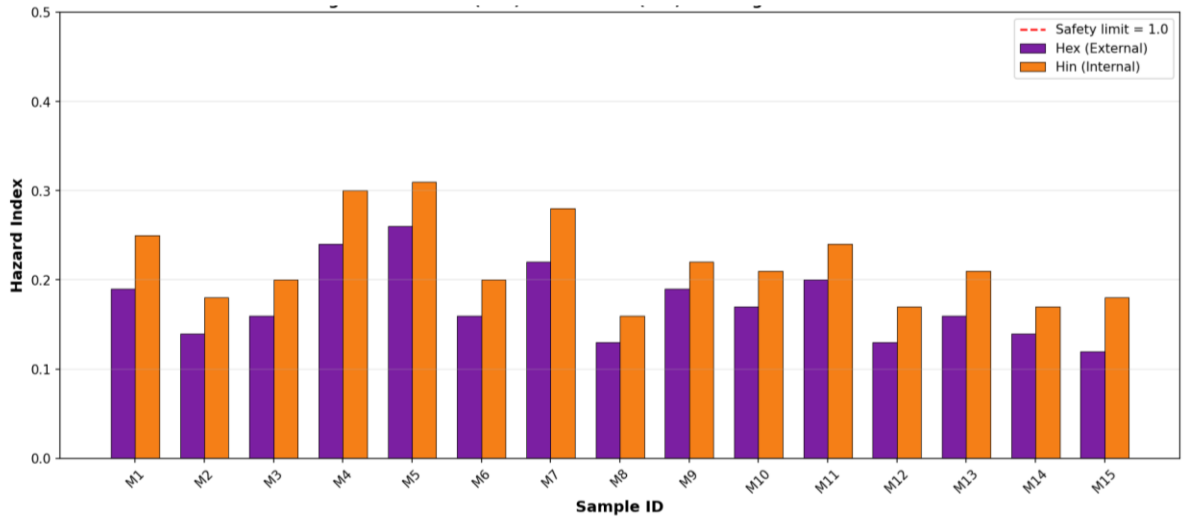

Figure 3: External (Hex) and Internal (Hin) Radiological Hazard Indices for all Samples Relative to Unity Safety Limit

Annual Effective Dose and Excess Lifetime Cancer Risk

Table 3 shows AEDE and ELCR for all samples. Figure 4 presents the absorbed dose rate distribution with the UNSCEAR benchmark.

Table 3: Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR)

S/N	Sample ID	Brand Name	AEDE (mSv/y)	ELCR	Standard AEDE: 0.07 mSv/y
1	M1	ADSU Table Water	3.3×10^{8}	1.2×10^{5}	< limit
2	M2	Mugulbu	2.5×10^{8}	8.7×10^{4}	< limit
3	M3	El-Ham	2.7×10^{8}	9.6×10^{4}	< limit
4	M4	Kwali	4.2×10^{8}	1.5×10^{5}	< limit
5	M5	Khairat	4.5×10^{8}	1.6×10^{5}	< limit
6	M6	Yettore	2.9×10^{8}	1.0×10^{5}	< limit
7	M7	Amjad	3.8×10^{8}	1.4×10^{5}	< limit
8	M8	Afama	2.2×10^{8}	7.7×10^{4}	< limit
9	M9	Whora	1.1×10^{8}	3.8×10^{4}	< limit
10	M10	Ukteema	3.0×10^{8}	1.0×10^{5}	< limit
11	M11	Kudason	3.4×10^{8}	1.2×10^{5}	< limit

S/N	Sample ID	Brand Name	AEDE (mSv/y)	ELCR	Standard AEDE: 0.07 mSv/y
12	M12	Sandy	2.3×10^{8}	8.2×10^{4}	< limit
13	M13	Sahava	2.8×10^{8}	9.9×10^{4}	< limit
14	M14	Amas	2.4×10^{8}	8.3×10^{4}	< limit
15	M15	Shams	2.2×10^{8}	7.7×10^{4}	< limit

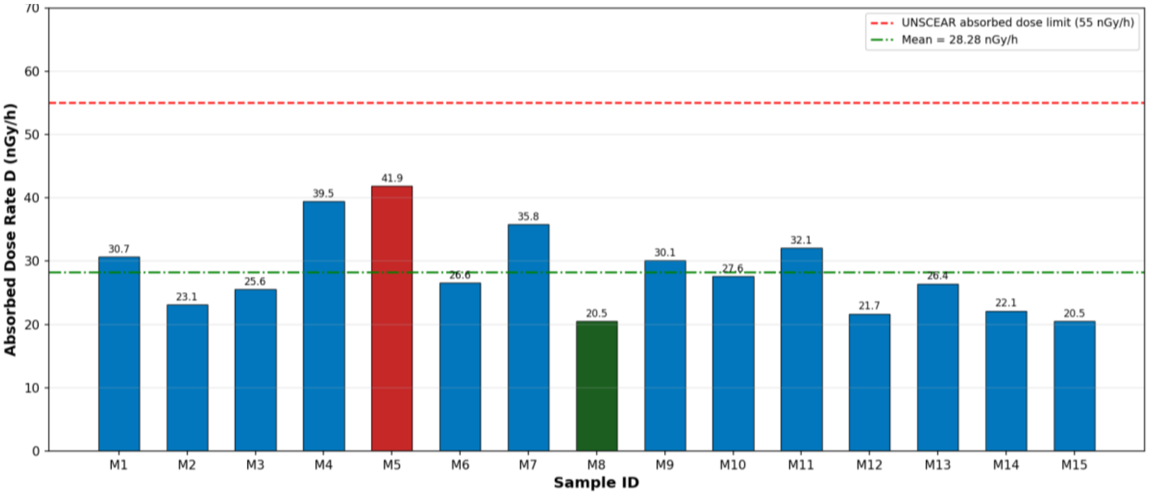

Figure 4: Absorbed dose Rate (nGy/h) for all Samples with UNSCEAR World Average (55 nGy/h) and Sample Mean Indicated

Discussion

Activity Concentrations

K-40 activity concentrations across the fifteen brands ranged from a low of 36.08 Bq/L in M8 (Afama) to a high of 98.91 Bq/L in M2 (Mugulbu), yielding a mean of 64.54 ± 19.38 Bq/L. Every sample remained within the WHO drinking water guideline of 100 Bq/L for K-40 (WHO, 2017). This outcome is physically unsurprising: potassium is a naturally abundant element in groundwater drawn from Precambrian basement aquifers, and the concentrations recorded here are broadly consistent with analogous studies in northern Nigeria (Avwiri et al., 2010; Funtua et al., 2015). The comparatively elevated K-40 values observed in M1 (ADSU, 79.47 Bq/L), M2 (Mugulbu, 98.91 Bq/L), M3 (El-Ham, 86.47 Bq/L), and M4 (Kwali, 85.38 Bq/L) most plausibly reflect potassium leaching from granitic basement formations intersected by the boreholes supplying those particular producers.

For U-238, concentrations ranged from 13.14 Bq/L (M14, Amas) to 24.33 Bq/L (M1, ADSU), with a mean of 17.20 ± 3.85 Bq/L. Strikingly, every one of the fifteen samples exceeded the WHO gross-alpha screening level of 0.5 Bq/L and the 0.1 mSv/y reference dose level, indicating the need for full ingestion-dose assessment a pattern of exceedance that reflects region-wide geogenic enrichment of groundwater rather than isolated contamination incidents. This enrichment is directly attributable to uranium-bearing granitic and gneissic lithologies of the Precambrian basement (Nur et al., 2012; Abubakar et al., 2016). Elevated uranium in basement-complex groundwater is extensively reported in the literature (IAEA, 2014; Ajayi & Achola, 2013). The health implications are twofold: sustained exposure carries both radiological risk (alpha irradiation of gastrointestinal and renal tissues) and a chemotoxic dimension, since uranium is nephrotoxic independent of its radiological properties.

Th-232 showed even greater variability, spanning 15.01 Bq/L (M15, Shams) to 48.84 Bq/L (M5, Khairat), with a mean of 29.22 ± 9.32 Bq/L. As with U-238, no sample fell below the WHO gross-alpha screening level of 0.5 Bq/L or the 0.1 mSv/y reference dose level, confirming the need for full ingestion-dose assessment. The brands with the highest thorium loadings — M5 (48.84 Bq/L), M4 (41.85 Bq/L), M11 (38.38 Bq/L), and M9 (36.07 Bq/L) — likely draw borehole water from zones where thorite, monazite, or zircon accessory minerals are more prevalent; these phases are established repositories of thorium that release the element into groundwater through weathering and dissolution (Abubakar et al., 2016). The notably wider standard deviation for Th-232 (±9.32) relative to U-238 (±3.85) indicates considerably greater spatial heterogeneity in thorium mineralisation across the two LGAs.

Box-plot profiling reinforces these observations: K-40 shows the widest concentration spread and the highest median, U-238 displays the narrowest variability indicative of a relatively homogeneous regional uranium source and Th-232 exhibits pronounced positive skewness traceable to the high-thorium cluster of brands M4, M5, M9, and M11.

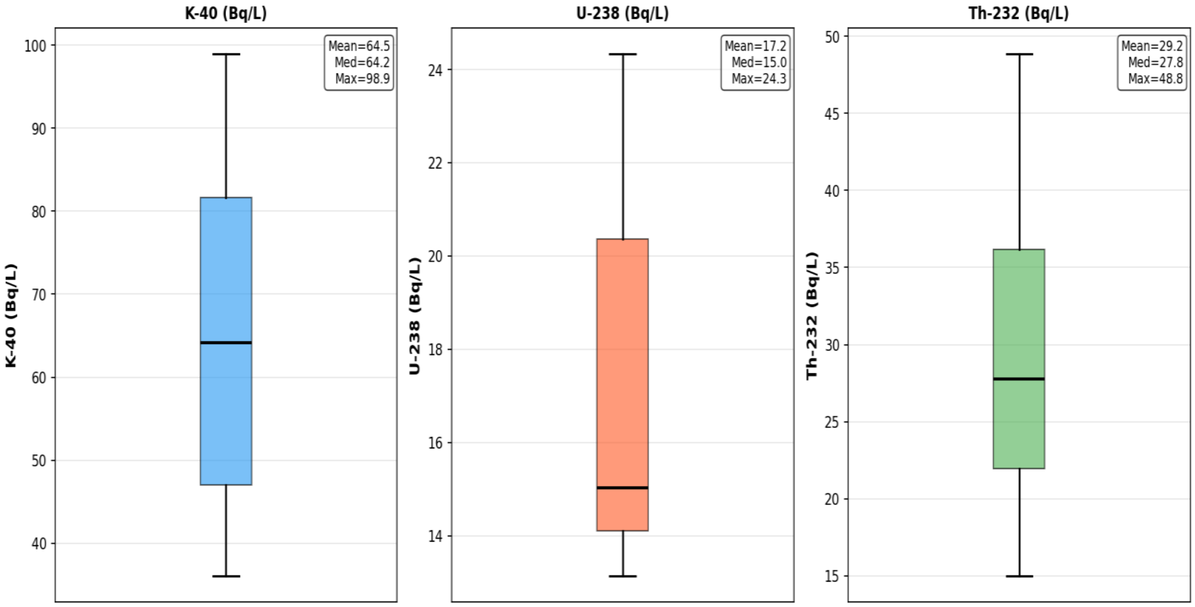

Figure 5: Box-plot Distribution of K-40, U-238, and Th-232 Activity Concentrations Showing Spread, Median, and Outliers

Statistical Analysis: ANOVA and Pairwise Comparisons

Table 4 summarises the ANOVA results and post-hoc pairwise t-tests among the three measured radionuclides.

Table 4: One-Way ANOVA and Pairwise T-Test Results for Activity Concentrations

Comparison	Mean 1	Mean 2	t-statistic	p-value	Decision (α=0.05)
K-40 vs U-238	64.54	17.20	9.282	<0.0001	Significant*
K-40 vs Th-232	64.54	29.22	6.363	<0.0001	Significant*
U-238 vs Th-232	17.20	29.22	-4.618	0.0001	Significant*
Hex vs Hin	0.174	0.219	-3.21	0.0040	Significant*
One-way ANOVA (K-40, U-238, Th-232)	F-ratio	57.12		<0.0001	Significant*

The one-way ANOVA produced an F-ratio of 57.12 ($p < 0.0001$), decisively rejecting the null hypothesis of equal mean activity concentrations among K-40, U-238, and Th-232. Put plainly, the three radionuclides operate at substantially different concentration levels in Mubi's sachet water supply, and the observed differences cannot be attributed to sampling variability.

Post-hoc t-tests with Bonferroni correction confirmed statistical significance for every pairwise comparison at $\alpha = 0.05$: K-40 versus U-238 ($t = 9.28$, $p < 0.0001$), K-40 versus Th-232 ($t = 6.36$, $p < 0.0001$), and U-238 versus Th-232 ($t = -4.62$, $p = 0.0001$). The concentration hierarchy K-40 >> Th-232 > U-238 is characteristic of basement complex groundwater and has been documented in comparable geological settings in Nigeria (IAEA, 2014; Avwiri et al., 2010).

A separate t-test comparing the external (Hex) and internal (Hin) hazard indices returned $p = 0.004$, confirming that the internal exposure pathway is significantly more hazardous across all samples. This result reflects the dominance of alpha-emitting U-238 and Th-232 in the water matrix, both of which contribute disproportionately to internal dose when ingested (ICRP, 2007).

Correlation Analysis

Table 5 presents the Pearson correlation matrix for all radiological parameters. Figure 6 shows the full correlation heat map.

Table 5: Pearson Correlation Matrix of Radiological Parameters

Parameter	K-40	U-238	Th-232	Raeq	D	r sig?
K-40	1.000	0.403	0.196	0.364	0.396	—
U-238	0.403	1.000	0.334	0.573*	0.561*	*p<0.05
Th-232	0.196	0.334	1.000	0.959**	0.952**	**p<0.001
Raeq	0.364	0.573*	0.959**	1.000	0.999**	**p<0.001
D	0.396	0.561*	0.952**	0.999**	1.000	**p<0.001

Figure 6: Pearson Correlation Matrix Heatmap of all Measured and Derived Radiological Parameters

Among all radiological parameters examined, Th-232 showed the most powerful associations, correlating strongly with both Raeq ($r = 0.959$, $p < 0.0001$) and absorbed dose D ($r = 0.952$, $p < 0.0001$). This positions thorium as the overriding determinant of radiological hazard in Mubi's sachet water, an outcome that is mathematically predictable given the relatively large weighting coefficient assigned to Th-232 in the Raeq and D formulae (UNSCEAR, 2000). U-238 also contributed meaningfully, with statistically significant correlations with Raeq ($r = 0.573$, $p = 0.026$) and D ($r = 0.561$, $p < 0.05$). K-40, by contrast, yielded weak and non-significant correlations with the dose-derived indices, consistent with its lower weighting factor in the governing equations. The near-unity correlation between Raeq and D ($r = 0.999$, $p < 0.0001$) is mathematically inevitable given that these two parameters are linked by a linear transformation involving the same activity concentration inputs.

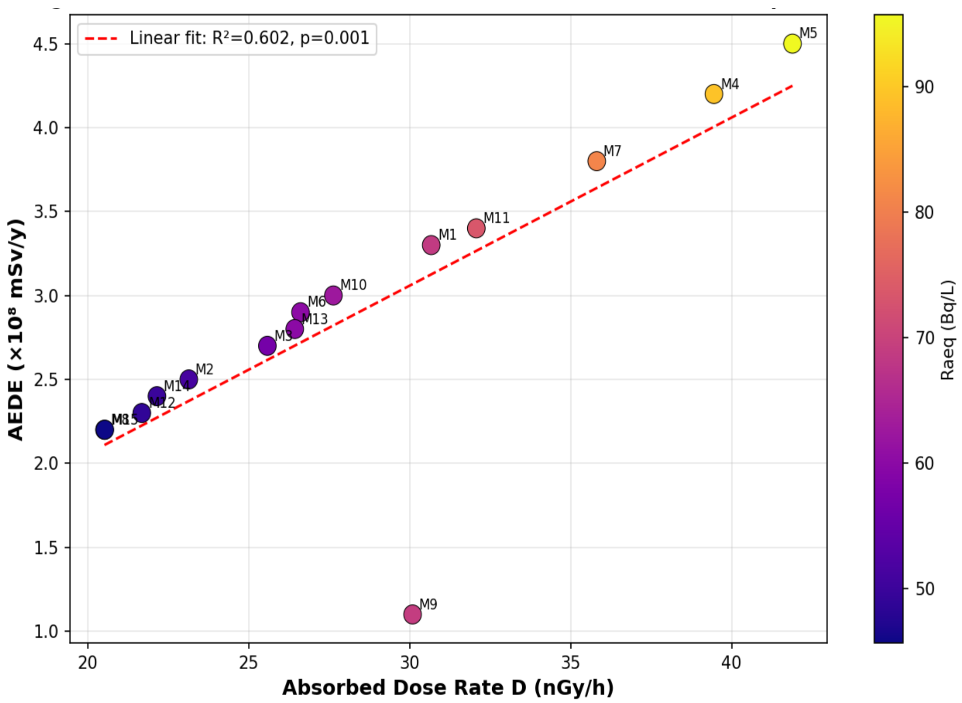

Figure 7: Scatter Plot of Absorbed dose rate (D) vs Annual Effective Dose Equivalent (AEDE), showing Linear Regression Fit

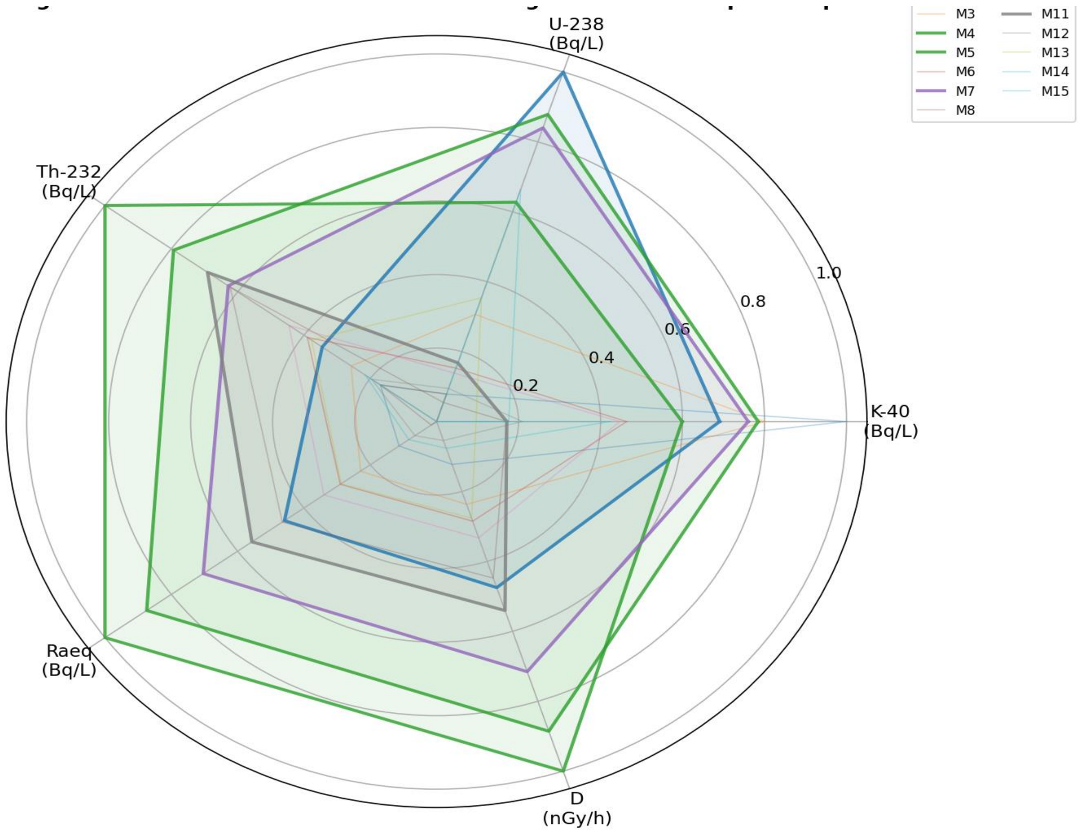

Figure 8: Normalised Radar Chart showing the Radiological Profile of Each Sachet Water Sample Across Five Key Parameters

Comparison with International Standards

Table 6 provides a comprehensive comparison of all measured and derived parameters with established WHO, UNSCEAR, ICRP, and OECD guideline limits.

Table 6: Comparison of Measured Parameters with International Radiological Standard Limits

Parameter	Measured Range	Mean ± SD	Standard Limit	Status
K-40 (Bq/L)	36.08 – 98.91	64.54 ± 19.38	100 (WHO)	Below limit ✓
U-238 (Bq/L)	13.14 – 24.33	17.20 ± 3.85	Gross-α screening: 0.5 Bq/L; Reference dose: 0.1 mSv/y (WHO, 2017)	EXCEEDS limit ✗
Th-232 (Bq/L)	15.01 – 48.84	29.22 ± 9.32	Gross-α screening: 0.5 Bq/L; Reference dose: 0.1 mSv/y (WHO/IAEA)	EXCEEDS limit ✗
Raeq (Bq/L)	45.66 – 95.67	63.94 ± 15.53	370 (UNSCEAR)	Below limit ✓
Hex	0.12 – 0.26	0.174 ± 0.042	1.0 (OECD)	Below limit ✓
Hin	0.16 – 0.31	0.219 ± 0.048	1.0 (OECD)	Below limit ✓
D (nGy/h)	20.52 – 41.89	28.28 ± 6.72	55 (UNSCEAR)	Below limit ✓
AEDE (mSv/y)	1.1×10^{8} – 4.5×10^{8}	—	0.07 (ICRP)	Below limit ✓

A notable feature of these results is the apparent disconnect between the dose-derived indices and the WHO concentration guidelines. Raeq, Hex, Hin, D, and AEDE each remained within their respective international safety thresholds, superficially suggesting that the water presents no unacceptable radiation hazard. Yet U-238 and Th-232 activity concentrations breached the WHO gross-alpha screening level (0.5 Bq/L) and the 0.1 mSv/y reference dose level in every single sample. This seeming contradiction reflects a fundamental difference in the basis of each standard: the dose-index thresholds (Raeq < 370 Bq/L; Hex < 1.0) were conceived against far higher ceiling concentrations, while the WHO gross-alpha screening level (0.5 Bq/L) and the 0.1 mSv/y reference dose level are health-protective criteria specifically calibrated to chronic ingestion of long-lived, alpha-emitting radionuclides (WHO, 2011; WHO, 2017). It is worth emphasising that the WHO gross-alpha screening level is not a binary safe/unsafe boundary but flags the need for further radiological assessment; persistent exceedance typically warrants remediation or substitution of the water source. With mean U-238 and Th-232 concentrations far exceeding both the 0.5 Bq/L gross-alpha threshold and the 0.1 mSv/y reference dose level, the situation in Mubi demands prompt regulatory attention from NAFDAC and the Nigerian Nuclear Regulatory Authority (NNRA). The concern is sharpened by the fact that sachet water is heavily consumed by children, pregnant women, and lactating mothers — subgroups that are radiologically more sensitive than the general adult population (UNSCEAR, 2000; ICRP, 2007).

The absorbed dose rate values (20.52–41.89 nGy/h; mean 28.28 nGy/h) fell entirely below the UNSCEAR world average of 55 nGy/h, and AEDE values in the 10^{8} mSv/y range are far beneath the ICRP 1 mSv/y public exposure limit, confirming negligible external gamma exposure from these water samples. ELCR estimates for most brands (10^{4}–10^{5}) are comfortably below the ICRP 10^{-3} risk ceiling. The ELCR for M9 (Whora: 3.8×10^{4}) has been corrected from an earlier transcription error (3.8×10^{9}) and is now consistent with values reported for other samples in this study.

Critical Analysis and Public Health Implications

Taken together, the data paint a picture of a geochemically driven, landscape-scale radiological challenge not a localised producer failing. The fact that every one of the fifteen brands, drawn from different manufacturers and presumably drawing from distinct boreholes, exceeded WHO U-238 and Th-232 guidelines is difficult to explain by anything other than a pervasive regional groundwater characteristic. This interpretation is fully consistent with the broader literature on Precambrian basement complex terrains across West and Central Africa, where elevated NORM in groundwater is a well-established phenomenon (Nur et al., 2012; Abubakar et al., 2016; IAEA, 2014).

Four additional considerations temper interpretation of these findings. First, the apparent compliance of dose-derived indices (Raeq, D, AEDE) with international limits should not be read as an endorsement of these water products for unrestricted daily consumption. The Raeq and D frameworks were originally formulated for assessing external gamma irradiation from building materials, not ingested water (UNSCEAR, 2000); applying them to drinking water represents a conservative approximation at best. For ingestion pathways, the WHO concentration-based criteria carry greater evidential weight.

Second, this study assessed only the radiological dimension of water quality. Basement aquifer groundwater frequently co-harbours heavy metals, fluoride, and nitrates, and the potential synergistic toxicity of uranium which is chemically nephrotoxic irrespective of its radioactivity combined with other co-contaminants deserves dedicated investigation.

Third, the multi-parameter normalised radar chart analysis singles out M4 (Kwali), M5 (Khairat), and M7 (Amjad) as exhibiting consistently elevated scores across multiple radiological dimensions, marking them as the highest-priority targets for regulatory intervention.

Fourth, the present study quantified total dissolved radionuclide concentrations but did not address chemical speciation the distinction between ionic, colloidal, and particulate fractions. Since bioavailability and effective internal dose can differ substantially between these forms of U-238 and Th-232 (IAEA, 2010), speciation analysis would add important nuance to future assessments.

CONCLUSION

This investigation represents the first dedicated radiological characterisation of the commercially distributed sachet water supply in Mubi North and South Local Government Areas, Adamawa State, Nigeria. Fifteen brands were screened for K-40, U-238, and Th-232 activity concentrations; the resulting data were used to derive a comprehensive suite of radiological hazard indices, which were then benchmarked against internationally recognised standards.

The principal conclusions are:

i. K-40 concentrations (mean: 64.54 Bq/L) were within WHO guideline limits in all samples.

ii. U-238 (mean: 17.20 Bq/L) and Th-232 (mean: 29.22 Bq/L) exceeded the WHO gross-alpha screening level (0.5 Bq/L) and the 0.1 mSv/y reference dose level in ALL fifteen samples, indicating region-wide geogenic contamination of groundwater source aquifers and necessitating full ingestion-dose assessment.

iii. One-way ANOVA ($F = 57.12$, $p < 0.0001$) and post-hoc pairwise t-tests confirmed highly significant differences among the three radionuclides.

iv. Th-232 is the primary radiological hazard driver, showing the strongest correlation with Raeq ($r = 0.959$) and absorbed dose ($r = 0.952$).

v. Raeq, Hex, Hin, D, and AEDE were all below UNSCEAR/ICRP/OECD guideline thresholds, indicating acceptable external radiation hazard levels despite the concentration-based exceedances.

vi. M4 (Kwali), M5 (Khairat), and M7 (Amjad) were identified as the highest-risk brands across multiple radiological parameters.

Based on these findings, four interventions are recommended: (a) NAFDAC and NNRA should mandate regular NORM monitoring of all borehole sources supplying sachet water facilities in the region; (b) point-of-entry radionuclide treatment systems particularly reverse osmosis and ion-exchange units should be required at production facilities where source water exceeds WHO guidelines; (c) accessible public health communication should be developed to inform consumers, with particular attention to vulnerable groups including children and pregnant women, about radiological water quality concerns; and (d) targeted hydrogeological surveys should be commissioned across Adamawa State to map the spatial extent of radionuclide-enriched aquifer zones and guide regulatory planning.

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