

Assessment of Natural Radionuclides, Soil-to-Plant Transfer and Radiological Significance of a Municipal Waste Dumpsite in Kaura Namoda, Zamfara State, Nigeria

Hassan Isah¹, Bilyaminu Usman², and Bashar Yahaya³

Departments of Physics, College of Education, Maru, Zamfara State, Nigeria

*Corresponding Author's Email: mahmud9790@gmail.com

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ABSTRACT

This study investigated the occurrence of natural radionuclides in soil and vegetation at a municipal waste dumpsite in Kaura Namoda, Zamfara State, Nigeria, with emphasis on soil-to-plant transfer and radiological significance. Soil and corresponding plant samples collected from six sampling locations were analysed for ^{40}K , ^{226}Ra , and ^{232}Th using NaI(Tl) gamma-ray spectrometry. Soil-to-plant transfer factors (TFs) were determined from the activity concentrations in paired soil and plant samples. The absorbed dose rate (D_{air}), annual effective dose equivalent (AEDE), radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), and excess lifetime cancer risk (ELCR) were also evaluated. Mean soil activity concentrations were 237.46, 51.01, and 159.03 Bqkg⁻¹ for ^{40}K , ^{226}Ra , and ^{232}Th , respectively, while corresponding mean plant activities were 216.54, 37.48, and 82.97 Bqkg⁻¹, respectively. The mean TFs were 1.80 for ^{40}K , 0.79 for ^{226}Ra , and 0.80 for ^{232}Th , indicating comparatively greater transfer of ^{40}K into vegetation. Mean D_{air} , AEDE, Ra_{eq} , H_{ex} , and ELCR were 131.61 nGyh⁻¹, 0.16 mSv y⁻¹, 295.28 Bqkg⁻¹, 0.80, and 0.42×10^{-3} , respectively. KRN 01 recorded the highest radiological values, including a D_{air} of 278.68 nGyh⁻¹, a Ra_{eq} of 625.13 Bqkg⁻¹, an H_{ex} of 1.69, and an ELCR of 0.89×10^{-3} . Although the site-wide mean Ra_{eq} and H_{ex} were below their conventional reference levels, the elevated values at KRN 01 demonstrate considerable spatial variability within the dumpsite. The findings confirm measurable transfer of natural radionuclides from soil to vegetation and provide baseline information for continued environmental monitoring and prudent management of agricultural activities within and around the dumpsite.

Keywords: natural radionuclides; ^{40}K ; ^{226}Ra ; ^{232}Th ; soil-to-plant transfer; radiological indices; municipal waste; Kaura Namoda.

1.0 INTRODUCTION

Naturally occurring radionuclides are present in rocks, soils and other environmental media and contribute to terrestrial radiation exposure. Of particular environmental importance are ^{40}K and radionuclides associated with the ^{238}U and ^{232}Th decay series. Their occurrence in soil is controlled by geological source materials, mineral composition, weathering, soil characteristics and other site-specific processes. Waste disposal sites can add another layer of spatial complexity because materials originating from domestic, agricultural, commercial and other human activities are accumulated at the same location over time (UNSCEAR, 2024).

The soil–vegetation interface is important in environmental radioactivity studies because radionuclides present in soil can become available for plant uptake and subsequently enter terrestrial food pathways (Ali *et al.*, 2024). The soil-to-plant transfer factor (TF) is consequently useful for describing the relative movement of a radionuclide from soil into plant tissue and for assessing differences in radionuclide

availability and uptake. Transfer is not governed by soil activity alone; soil properties, chemical form, nutrient behaviour, plant species and local environmental conditions can all affect uptake (Adegbulugbe *et al.*, 2024). In particular, ^{40}K may show comparatively high plant transfer because potassium is an essential nutrient required for normal plant growth (Orosun *et al.*, 2022; Oladele *et al.*, 2023; Chetty & Ilori, 2024).

The radiological condition of a soil environment can be examined through several complementary indicators. Absorbed dose rate provides an estimate of external gamma radiation in air, while AEDE converts the dose rate into an annual exposure estimate. Ra_{eq} combines the contributions of ^{226}Ra , ^{232}Th and ^{40}K into a common radiological measure and H_{ex} provides an assessment of external radiation hazard. ELCR is used to express the estimated additional lifetime cancer risk associated with long-term exposure. Together, these parameters allow radionuclide measurements to be interpreted from both environmental and radiological perspectives (Eke *et al.*, 2024).

For comparison, UNSCEAR (2024) reports worldwide population-weighted average soil activity concentrations of approximately 512 Bqkg⁻¹ for ⁴⁰K, 33 Bqkg⁻¹ for ²²⁶Ra and 42 Bqkg⁻¹ for ²³²Th, with an average outdoor terrestrial absorbed dose rate of about 49 nGy h⁻¹. Local departures from these values are expected because terrestrial radioactivity is strongly influenced by geology and environmental setting.

Studies conducted in Nigeria have demonstrated substantial spatial and crop-to-crop variation in natural radionuclide concentrations and soil-to-plant transfer. Laniyan and Adewumi (2021) documented variations in radionuclide-related radiological characteristics around mining environments, while Oladele *et al.* (2023) and Chetty and Ilori (2024) reported marked differences in transfer behaviour among crops and locations. Such findings indicate the value of site-specific investigations that combine radionuclide concentration measurements with plant uptake and radiological indices.

Despite these studies, information that simultaneously addresses natural radionuclide occurrence, soil-to-plant transfer and radiological significance at municipal waste dumpsites in northwestern Nigeria remains limited. The present study therefore examines the Kaura Namoda municipal waste dumpsite in Zamfara State. Specifically, the study determines the activity concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th in soil and plant samples, evaluates their soil-to-plant transfer factors, and assesses selected radiological indices. The results are intended to contribute baseline information for environmental

monitoring and radiation-protection planning around municipal waste disposal areas.

1.1 Aim and Objectives

The study was designed to assess natural radionuclides, their transfer from soil to vegetation and the associated radiological significance of the Kaura Namoda municipal waste dumpsite.

The specific objectives were to:

1. determine the activity concentrations of ⁴⁰K, ²²⁶Ra and ²³²Th in soil and plant samples;
2. calculate the soil-to-plant transfer factors of the investigated radionuclides; and
3. evaluate the radiological indices associated with the measured soil activity concentrations.

2.0 MATERIALS AND METHODS

2.1 Study Area

The investigation was carried out at a municipal waste dumpsite in Kaura Namoda, Zamfara State, northwestern Nigeria. The dumpsite is situated within an environment characterized by human settlement, agricultural activity and the disposal of municipal wastes. The simultaneous presence of accumulated waste, soil and vegetation makes the location suitable for examining environmental radionuclide occurrence and possible soil-to-plant movement. Table 2.1 indicates the coordinates of the study areas taken during fieldwork exercises. Coordinates were recorded in the field using a Garmin 72H handheld GPS receiver with ±3m accuracy. Six sampling points were established within the dumpsite, and corresponding soil and plant samples were collected from each location.

Table 2.1: Geographical coordinates of the six (6) Sampling Points in Kaura Namoda.

S/No	Sampling Code	Latitude(N)	Longitude (E)
1	KRN 01	12°35`20.41``	06°35`39.77``
2	KRN 02	12°35`20.37``	06°35`39.70``
3	KRN 03	12°35`20.36``	06°35`39.68``
4	KRN 04	12°35`20.36``	06°35`39.82``
5	KRN 05	12°35`20.61``	06°35`39.56``
6	KRN 06	12°35`20.63``	06°35`39.79``

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2.2 Sample Collection and Preparation

Soil and corresponding plant samples were obtained from selected sampling points within the dumpsite. Each sample was appropriately labeled and transported to the laboratory for preparation and analysis. The soil samples

were air-dried, homogenized and sieved to obtain a relatively uniform material for measurement. Plant samples were washed with distilled water to remove adhering soil and other external materials before being oven-dried and homogenized. The prepared samples

were transferred into suitable sealed containers and stored until secular equilibrium was attained prior to gamma-ray measurement.

2.3 Gamma Spectrometric Analysis

The activity concentrations of ^{40}K , ^{226}Ra and ^{232}Th in the prepared samples were evaluated by gamma-ray spectrometry using a NaI(Tl) scintillation detector. A

$$C = \frac{N}{\epsilon \cdot I_\gamma \cdot t \cdot m}$$

Where, N = net count rate, ϵ = detector efficiency, I_γ = gamma emission probability, t = counting time, and m = sample mass.

2.4 Soil-to-Plant Transfer Factor

$$\text{TF} = \frac{C_{\text{plant}}}{C_{\text{soil}}}$$

Where: C_{plant} = radionuclide activity concentration in plant tissue (Bq kg^{-1} dry weight);

C_{soil} = radionuclide activity concentration in soil (Bq kg^{-1} dry weight).

2.5 Radiological Hazard Indices

Radiological assessment was based on the absorbed dose rate (D_{air}), annual effective dose equivalent (AEDE), radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), and excess lifetime cancer risk (ELCR).

$$D = 0.462C_{\text{Ra}} + 0.604C_{\text{Th}} + 0.0417C_{\text{K}}$$

2.5.2 Annual Effective Dose Equivalent

AEDE was derived from the absorbed dose rate using the adopted occupancy factor, annual exposure time, and $AEDE = D \times 8760 \times 0.7 \times 10^{-6}$

Where: D = absorbed dose rate in air (nGy h^{-1}), 8760 = number of hours in a year, 0.7 Sv Gy^{-1} = conversion coefficient from absorbed dose in air to effective dose, and 10^{-6} = conversion from nGy to mSv. This model assumes continuous outdoor exposure and is widely applied in environmental radiological assessments to evaluate human radiation risk (Eke *et al.*, 2024).

$$Ra_{\text{eq}} = C_{\text{Ra}} + 1.43C_{\text{Th}} + 0.077C_{\text{K}}$$

2.5.4 External Hazard Index

The external hazard index, H_{ex} , was calculated to assess the potential external gamma-radiation hazard associated

$$H_{\text{ex}} = \frac{Ra_{\text{eq}}}{370}$$

This index ensures that radiation exposure from natural radionuclides remains within safe limits for human health, with values less than unity indicating negligible external radiation hazard (UNSCEAR, 2000).

2.5.5 Excess Lifetime Cancer Risk

$$ELCR = AEDE \times DL \times RF$$

lead shielding arrangement was employed to minimize background radiation, while detector calibration was performed using appropriate standard reference materials. The activity concentration (C) of each radionuclide was subsequently determined from the measured gamma-ray spectra using the expression reported by Eke *et al.* (2024):

$$(2.1)$$

For each radionuclide, the soil-to-plant transfer factor was obtained from the ratio of its activity concentration in plant tissue to the activity concentration measured in the corresponding soil sample (Adegbulugbe *et al.*, 2024):

$$(2.2)$$

These parameters provide different but related measures of the possible radiological significance of the measured soil activities.

2.5.1 Absorbed Dose Rate

The absorbed dose rate in air, D_{air} , was estimated from the measured soil activities using the standard conversion coefficients for ^{40}K , ^{226}Ra , and ^{232}Th . It represents the contribution of terrestrial radionuclides to external gamma exposure and is expressed in nGy h^{-1} .

$$(2.3)$$

dose-conversion coefficient. The resulting value represents an estimated annual effective exposure and is expressed in mSv y^{-1} .

$$(2.4)$$

2.5.3 Radium Equivalent Activity

Ra_{eq} was used to express the combined gamma contribution of ^{226}Ra , ^{232}Th , and ^{40}K as a single equivalent activity concentration. The commonly applied reference level is 370 Bq kg^{-1} .

$$(2.5)$$

with the soil. A value of $H_{\text{ex}} \leq 1$ is conventionally regarded as corresponding to an acceptable external hazard level.

$$(2.6)$$

ELCR was used as an estimate of the additional lifetime cancer risk associated with prolonged radiation exposure under the assumptions adopted in the calculation. It should be interpreted as a model-based risk estimate rather than evidence of observed cancer incidence.

$$(2.7)$$

Where: *AEDE* = annual effective dose equivalent (mSv y^{-1}), *DL* = duration of life (70 years), and *RF* = risk factor (0.05 Sv^{-1}).

3.0 RESULTS AND DISCUSSION

3.1 Activity Concentrations of Radionuclides in Soil

The mean soil activity concentrations measured at the Kaura Namoda dumpsite were $237.46 \text{ Bq kg}^{-1}$ for ^{40}K , 51.01 Bq kg^{-1} for ^{226}Ra , and $159.03 \text{ Bq kg}^{-1}$ for ^{232}Th . Among the three radionuclides, ^{232}Th showed the highest mean activity. The mean ^{40}K value was lower than the worldwide population-weighted soil average reported by UNSCEAR (2024), whereas the mean activities of ^{226}Ra

and ^{232}Th were higher than the corresponding worldwide averages.

^{232}Th exhibited the highest mean soil activity ($159.03 \text{ Bq kg}^{-1}$), approximately 3.1 times the measured ^{226}Ra concentration. This value also exceeded the worldwide population-weighted soil average reported by UNSCEAR. The elevated ^{232}Th may reflect contributions from the local geological environment and heterogeneous materials accumulated within the dumpsite. However, the spatial variability observed among the KRN locations suggests that geological sources alone may not explain the distribution, emphasizing the influence of local waste composition and soil characteristics. The detailed activity concentrations are presented in Table 3.1.

Table 3.1 Activity Concentrations of Natural Radionuclides in Soil

Activity concentrations of Radionuclides in Soil			
Sample ID	K- 40(Bq/Kg)	Ra-226 (Bq/Kg)	Th- 232(Bq/Kg)
KRN 01	738.62 ± 33.87	39.79 ± 10.8	369.56 ± 64.08
KRN 02	51.19 ± 11.72	47.43 ± 14.31	118.08 ± 28.08
KRN 03	275.3 ± 63.42	73.42 ± 11.27	70.95 ± 9.12
KRN 04	220.58 ± 50.44	40.12 ± 8.91	252.98 ± 62.26
KRN 05	111.14 ± 25.4	71.02 ± 13.96	67.32 ± 7.5
KRN 06	27.86 ± 6.41	34.27 ± 9.82	69.31 ± 8.78
Mean	237.45 ± 88.54	51.01 ± 11.51	158.03 ± 29.97
Maximum	738.62	73.42	369.56
Min.	27.86	34.27	67.32

3.2 Radionuclide Concentrations in Plant Samples

The mean plant ^{40}K activity concentration was $216.54 \text{ Bq kg}^{-1}$. The presence of ^{40}K in vegetation is expected because potassium is an essential nutrient and is actively regulated by plants. The measured plant concentrations of ^{226}Ra and ^{232}Th were generally lower than their corresponding soil concentrations, although the magnitude varied among sampling locations.

The difference between soil and plant activities demonstrates that the concentration of a radionuclide in

soil is not, by itself, a sufficient predictor of its concentration in vegetation. Uptake can be modified by radionuclide mobility, soil characteristics, nutrient interactions, and plant-specific physiological processes. Comparable variability in soil-to-crop transfer has been reported in Nigerian studies (Oladele *et al.*, 2023; Chetty & Ilori, 2024). The detailed activity concentrations are presented in Table 3.2.

Table 3.2 Activity Concentrations of Natural Radionuclides in Plant

Activity concentrations of Radionuclides in Plant			
Sample ID	K- 40(Bq/Kg)	Ra-226 (Bq/Kg)	Th- 232(Bq/Kg)
KRNP 1	160.45 ± 3.45	39.96 ± 2.28	79.08 ± 5.57
KRNP 2	124.4 ± 2.62	42.93 ± 7.37	39.86 ± 1.7
KRNP 3	362.42 ± 5.8	31.7 ± 2.57	144.94 ± 1.81
KRNP 4	431.56 ± 5.06	40.62 ± 2.83	116.12 ± 1.77
KRNP 5.	117.29 ± 2.54	40.98 ± 4.51	53.11 ± 2.26
KRNP 6.	106.11 ± 2.8	28.71 ± 3.67	64.72 ± 2.11
Mean	217.04 ± 3.71	37.48 ± 3.87	82.97 ± 2.54
Maximum	431.56	42.93	144.94
Min.	106.11	28.71	39.86

3.3 Soil-to-Plant Transfer Factors

The mean TFs were 1.80 for ^{40}K , 0.79 for ^{226}Ra , and 0.80 for ^{232}Th . Maximum values were 3.81, 1.01, and 2.04, respectively. Thus, ^{40}K showed the greatest average soil-to-plant transfer among the radionuclides investigated. The comparatively high ^{40}K TF is consistent with the

biological role of potassium in plants. Potassium is actively absorbed to support essential physiological processes, and this can result in greater plant uptake than would be expected for non-essential elements. Oladele *et al.* (2023) likewise reported relatively high ^{40}K transfer in crops from southwestern Nigeria.

Table 3.3. Soil-to-plant transfer factors

Transfer Factors			
Sample ID	TF (^{40}K)	TF (^{226}Ra)	TF (^{232}Th)
KRNP 1	0.22	1	0.21
KRNP 2	2.43	0.91	0.34
KRNP 3	1.32	0.43	2.04
KRNP 4	1.96	1.01	0.46
KRNP 5.	1.06	0.58	0.79
KRNP 6.	3.81	0.84	0.93
Mean	1.8	0.79	0.8
Maximum	3.81	1.01	2.04
Min.	0.22	0.43	0.21

To illustrate the distributions of transfer factor, a graphical representation is shown in figure 3.1

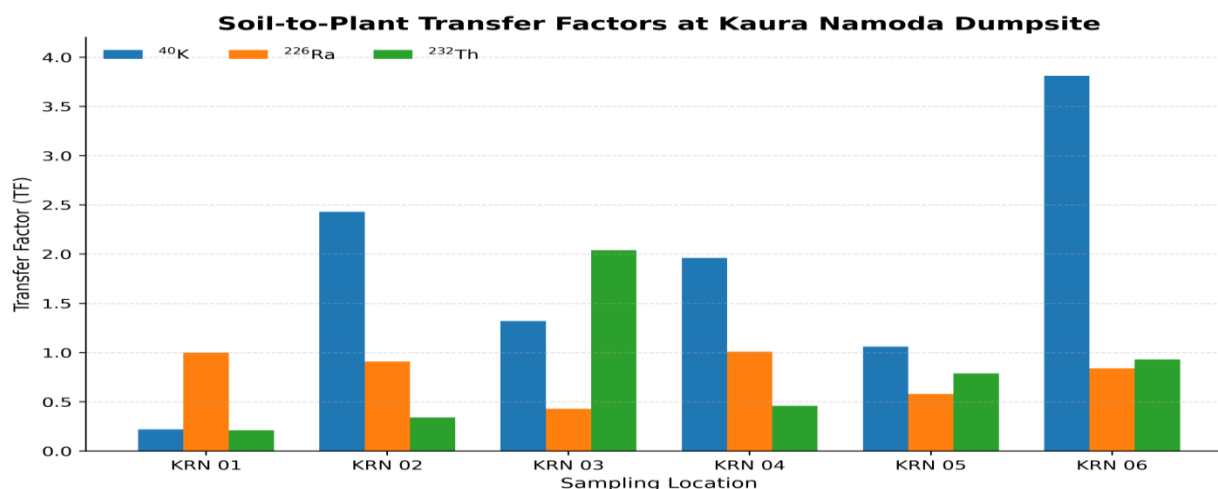


Figure 3.1. Soil-to-plant transfer factors at the Kaura Namoda dumpsite

The bar chart indicates considerable variation in soil-to-plant transfer factors (TFs) among the six sampling locations. ^{40}K showed the highest transfer overall, particularly at KRN 06 (TF $\approx$ 3.81), indicating relatively greater plant uptake of potassium. ^{226}Ra exhibited comparatively lower and more consistent transfer, with values ranging from about 0.43 to 1.01. In contrast, ^{232}Th displayed marked spatial variation, with a notably high TF of approximately 2.04 at KRN 03. Overall, the pattern suggests that radionuclide transfer from soil to plants

varies by location and radionuclide, likely reflecting differences in soil properties and plant uptake behaviour.

3.4 Radiological Assessment**3.4.1 Absorbed Dose Rate**

The absorbed dose rate ranged from 60.04 to 278.68 nGy h^{-1} , with a mean of 131.61 nGy h^{-1} . The mean was approximately 2.7 times the UNSCEAR (2024) worldwide population-weighted outdoor terrestrial average of 49 nGy h^{-1} . The comparatively high dose rate

is consistent with the elevated ^{232}Th concentration and the contribution of ^{40}K at the site (Table 3.4).

Table 3.4. Radiological indices across the sampling locations

Radiological Indices Values					
Sample ID	Dair(nGy/h)	AEDE (mSv/y)	Raeq (Bq/K)	Hex	ELCR 10^{-3}
KRN 01	278.68	0.34	625.13	1.69	0.89
KRN 02	97.38	0.12	220.24	0.59	0.31
KRN 03	89.46	0.11	196.07	0.53	0.29
KRN 04	184.83	0.23	418.86	1.13	0.59
KRN 05	79.25	0.1	175.84	0.47	0.25
KRN 06	60.04	0.07	135.53	0.37	0.19
Mean	131.61	0.16	295.28	0.8	0.42
Max	278.68	0.34	625.13	1.69	0.89
Min.	60.04	0.07	135.53	0.37	0.19

KRN 01 recorded the maximum dose rate of $278.68 \text{ nGy h}^{-1}$, indicating that the radiological condition was not spatially uniform across the dumpsite. To illustrate the distributions of radiological indices, a graphical representation is shown in **Figure 3.2**.

Figure 3.2. Variation of the major radiological indices across the six sampling locations (KRN 01–KRN 06) in

the Kaura Namoda dumpsite. The indices considered include absorbed dose rate (D_{air}), annual effective dose equivalent (AEDE), radium equivalent activity (R_{eq}), external hazard index (H_{ex}), and excess lifetime cancer risk (ELCR). The figure provides a clear visual comparison of the radiological characteristics of the different sampling locations.

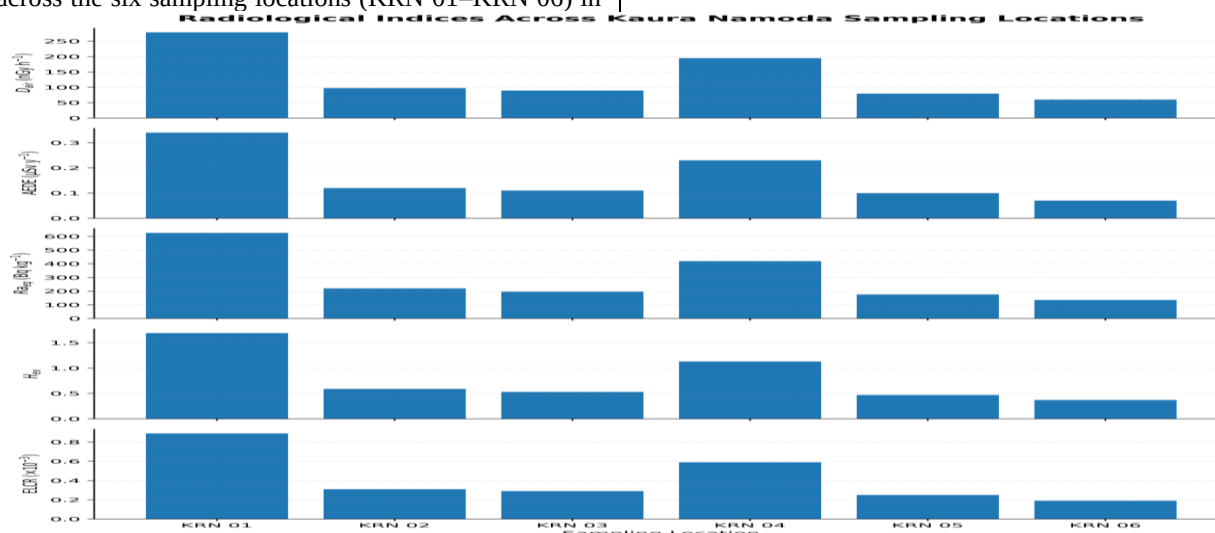


Figure 3.2. Radiological indices across Kaura Namoda sampling locations

The figure shows considerable spatial variation in the radiological indices across the sampling locations. KRN 01 records the highest values for all the indices, followed by KRN 04, whereas KRN 06 generally records the lowest values. The relatively high values at KRN 01 correspond to its higher radionuclide activity

concentrations, particularly those contributing to the overall radium equivalent and absorbed dose. The variation among the locations may be attributed to differences in the composition and distribution of radionuclide-bearing materials within the dumpsite. Overall, the results indicate that radiological

characteristics are not uniform across the study area, with KRN 01 showing the greatest radiological contribution among the investigated locations.

3.4.2 Annual Effective Dose Equivalent

The mean AEDE was 0.16 mSvy^{-1} , compared with the worldwide outdoor terrestrial value of approximately 0.06 mSvy^{-1} reported by UNSCEAR (2024). The higher value is consistent with the measured absorbed dose rate. Because AEDE is derived from the dose rate using assumed exposure parameters, it should be interpreted as an estimated exposure indicator rather than a direct measurement of individual dose.

3.4.3 Radium Equivalent Activity

The mean Ra_{eq} was 295.28 Bqkg^{-1} , while the highest location, KRN 01, reached 625.13 Bqkg^{-1} . The site mean was below the commonly used reference level of 370 Bqkg^{-1} , but the KRN 01 value exceeded it. This contrast demonstrates the importance of reporting both the overall site mean and individual sampling-point values when evaluating heterogeneous environments.

3.4.4 External Hazard Index

The mean H_{ex} was 0.80, whereas KRN 01 had a value of 1.69. The site-wide mean was below the conventional criterion of unity, but the value recorded at KRN 01 exceeded that criterion. This indicates that a small part of the investigated area may contribute disproportionately to the overall external gamma-radiation hazard.

3.4.5 Excess Lifetime Cancer Risk

The mean ELCR was 0.42×10^{-3} and increased to 0.89×10^{-3} at KRN 01. The higher value at KRN 01 is consistent with its elevated absorbed dose rate and Ra_{eq} . ELCR should, however, be treated as a calculated risk estimate based on assumed exposure conditions and should not be interpreted as a direct prediction of cancer occurrence among people using the site.

3.5 Integrated Assessment

The combined results show that the Kaura Namoda dumpsite exhibits measurable natural radionuclide activity, appreciable soil-to-plant transfer, and spatially variable radiological characteristics. The relatively elevated mean ^{232}Th activity is reflected in the dose-related indices, while ^{40}K displays the strongest average transfer into vegetation.

An important finding is that soil activity and plant uptake do not necessarily show identical spatial patterns. This is expected because transfer depends on radionuclide availability, soil properties, and plant uptake mechanisms in addition to the total radionuclide concentration in soil. Consequently, radiological assessment of waste-disposal

environments benefits from considering both the environmental reservoir in soil and the biological transfer pathway.

The environmental pathway represented by the present measurements can be summarized as:

soil radionuclide activity → radionuclide availability → plant uptake → soil-to-plant transfer → possible exposure pathway

This integrated interpretation is particularly relevant where vegetation grows on or close to waste-disposal areas. Recent Nigerian research also identifies soil-to-plant transfer as an important component of evaluating radionuclide movement into crops (Adebayo *et al.*, 2026).

4.0 CONCLUSION

The study demonstrated the occurrence of ^{40}K , ^{226}Ra , and ^{232}Th in soil at the Kaura Namoda municipal waste dumpsite and confirmed measurable transfer of natural radionuclides from soil into vegetation. Mean soil activities were 237.46 , 51.01 , and 159.03 Bqkg^{-1} for ^{40}K , ^{226}Ra , and ^{232}Th , respectively. The mean TFs were 1.80 for ^{40}K , 0.79 for ^{226}Ra , and 0.80 for ^{232}Th , with ^{40}K showing the strongest average transfer.

The mean absorbed dose rate of $131.61 \text{ nGy h}^{-1}$ was above the UNSCEAR worldwide outdoor terrestrial average. Mean Ra_{eq} , H_{ex} , and ELCR were $295.28 \text{ Bq kg}^{-1}$, 0.80, and 0.42×10^{-3} , respectively. Although the site-wide mean Ra_{eq} and H_{ex} were below their conventional reference levels, KRN 01 displayed substantially higher values, particularly Ra_{eq} of 625.13 Bqkg^{-1} and H_{ex} of 1.69.

Overall, the results indicate spatially heterogeneous radiological conditions at the dumpsite. The findings provide useful baseline information for environmental monitoring and demonstrate why assessment of radionuclide transfer to vegetation should accompany soil-based radiological evaluation.

5.0 RECOMMENDATIONS

Based on the findings, the following recommendations are proposed:

- Periodic radiological monitoring should be maintained at the dumpsite, with priority given to locations exhibiting comparatively elevated indices such as KRN 01.
- Cultivation of food crops directly within or immediately adjacent to areas with elevated radionuclide activities should be carefully managed.
- Municipal waste collection, segregation, and disposal practices should be improved to minimise uncontrolled accumulation and mixing of waste materials.

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- iv. Further investigations should examine additional plant species, different soil depths, and seasonal changes to clarify the controls on radionuclide mobility and uptake.

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1. Where agricultural use occurs, future work should evaluate additional exposure pathways, particularly ingestion through locally cultivated food crops.

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