GPH-International Journal of Applied Science
(Online ISSN 3050-9653)
Volume 09 | Issue 07 | 2026
Published by: Global Publication House
DOI: https://doi.org/10.5281/zenodo.22251118
Available online at: www.gphjournal.org
Journal homepage: https://gphjournal.org/index.php/as/index

RESRAD-BUILD SIMULATION OF INDOOR RADIATION EXPOSURE PATHWAYS IN NIGERIAN RESIDENTIAL BUILDINGS

SINEBE, Hope Anita[1*], AKPOLILE, Anita Franklin[2], ENAROSEHA, O.E Omamoke[3], AGBAJOR, Godwin Kparobo[4]
Department of Physics, Delta State University
*Corresponding Author: Hsinebe@gmail.com

Abstract

Indoor radiation exposure from naturally occurring radioactive materials (NORMs) in building materials poses potential long-term health risks, yet comprehensive pathway-specific dose assessments using advanced computational tools remain limited in Nigeria. This study evaluated activity concentrations and simulated indoor exposure pathways for 72 building material samples collected from Northern Delta State, Nigeria. Gamma spectrometry measured ^{40}K, ^{238}U, and ^{232}Th at 94.00 ± 15.52, 11.57 ± 2.32, and 9.05 ± 1.43 Bq/kg, respectively were all below UNSCEAR global averages. A RESRAD-BUILD model (implemented in Python) simulated a typical Nigerian residential room with 5.0 m × 4.0 m × 3.0 m dimensions, 0.15 m wall thickness, 0.5 h^{-1} air exchange rate, and 80 % indoor occupancy. The mean annual effective dose (AED) from all pathways was 0.0875 ± 0.0126 mSv/y, well below the ICRP public dose limit of 1 mSv/y. External gamma exposure was the dominant pathway, contributing 82.9 % of the total dose, followed by ingestion (17.1 %) and inhalation (0.04 %). Simulated doses agreed closely with empirical estimates (mean difference 3.1 %). Materials from South Africa and Italy showed the highest radionuclide concentrations while Chinese and local Nigerian materials showed the lowest. These results demonstrate that RESRAD-BUILD simulation provides a reliable, pathway-resolved assessment of indoor radiation exposure, and that external gamma radiation from building materials is the primary concern in typical Nigerian residential buildings.

Keywords:

RESRAD-BUILD; Indoor Radiation Exposure; Building Materials; NORMs.

1. Introduction

Natural radioactivity occurs widely in the environment as a result of the existence of natural radioactive isotopes in the Earth's crust [1,2]. Building materials that are derived from natural substances (clay, sand, granite, limestone, and concrete) contain significant amounts of radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) [3]. By being utilized during construction processes, these materials represent potentially hazardous sources of radiation exposure within the interiors, where people spend about 80% of their lives [4].

Indoor exposures to radioactive substances through building materials take place in three major ways: (i) exposure to external gamma radiation emitted by radionuclides present in the walls, floors, and ceiling; (ii) inhalation of radioactive noble gas ^{222}Rn and its daughters, mostly applicable for those materials that contain uranium; and (iii) consumption of radioactive dust particles [5]. While the exposure to exterior gamma rays usually accounts for the major portion of the total received dose, inhalation exposure represents particular concerns related to radon accumulation indoors and associated risks of damaging the lungs and developing cancer [6].

The building industry in Nigeria is characterized by a high use of indigenous materials that have rather variable properties in relation to their radiation hazards depending on geologic composition and manufacturing technology [7]. Various studies previously identified excessive levels of radioactivity in different building materials in Nigeria, granite, [8]. ceramic tiles, [9], cement products, [10], however, the majority of recent studies was concerned only with measurement of the activities of radionuclides without further consideration of dose exposure pathways.

The computer software called RESRAD-BUILD developed at Argonne National Laboratory allows for assessing radiation doses through simulation of the contamination transfer, air exchange, and dose accumulation [11]. The above method proved to be efficient in many countries around the world while estimating the safety of building materials [12,13,14], nevertheless, it is currently underused in Nigeria.

This study aims to: (1) determine the activity concentrations of ^{40}K, ^{238}U, and ^{232}Th in some commonly utilized building materials from Northern Delta State, Nigeria; (2) calculate the indoor radiation exposure pathways using the RESRAD-BUILD model for estimation of relative contribution of external, inhalation, and ingestion pathways in the overall annual effective dose.

2. Materials and Method

2.1 Study Area and Sample Collection

This research was carried out in the northern part of Delta State, Nigeria (latitude 5°30′00″N – 6°30′00″N; longitude 5°00′00″E – 6°30′00″E). It occupies an area of the Niger Delta basin, and it contains Benin Formation geology with dominantly continental sands and gravels along with some layers of clay [15].

A total of 72 samples of building material was obtained from various markets, wholesaler stores, and constructions sites in nine Local Government Areas. These samples belong to thirteen material types (sand, cement, granite, paint, tiles, wood, stone, ceiling, PVC, roofing, POP additives/mixtures), and they have been sourced from nine different geographic regions (Local, Nigerian, Indian, Italian, Chinese, South African, Benin City, Foreign, Unknown). A total weight of approximately 2 kg of each sample has been gathered following the guidelines of the [16].

2.2 Sample Preparation and Gamma Spectrometry

Samples were ground, sieved (2 mm), oven-dried at 110 °C for 24 hours, and sealed in Marinelli beakers for 28 days to achieve secular equilibrium [17]. Activity levels of 40K, 238U, and

232Th were measured using a NaI(Tl) gamma-ray spectrometer, providing input datasets for the Python-based RESRAD-BUILD simulation framework.

Calibration employed IAEA reference materials (RGU-1, RGTh-1, RGK-1). Counting time was 36,000 seconds per sample. Activity concentrations were calculated using detector efficiency, net count rate, and gamma emission probability [18]. These values served as input datasets for the computational simulation framework. Activity concentrations were calculated using:

$$\varepsilon(E)=\frac{CPS(E)}{A\times P\gamma(E)} \tag{2.1}$$

where $\varepsilon(E)$ represents the detector efficiency at energy E, CPS(E) is the net count rate at energy E in counts per second, A is the activity of the standard in Becquerels, and γ(E) is the gamma emission probability at energy [18].

Python-Based RESRAD-BUILD Simulation Framework

The RESRAD-BUILD algorithm was implemented in Python 3.9 [19] to simulate indoor radiation exposure. The model represented a typical Nigerian residential room (5.0 m × 4.0 m × 3.0 m, wall thickness 0.15 m, air exchange rate 0.5 h^{-1}, occupancy 80 %; [20]. Three pathways were modelled:

External exposure from gamma radiation: External gamma exposure using dose conversion factors [4].

$$D_{ext}=\sum_i C_i\times DCF_i\times T\times F_{occ} \tag{2.2}$$

where C_i is the activity concentration of radionuclide i (Bq/kg), DCF_i are dose conversion factors 0.462 for ^{238}U series, 0.604 for ^{232}Th series, 0.0417 for ^{40}K [4], T = 8760 h (hours per year), and F_{occ} = 0.8 (indoor occupancy fraction).

Inhalation exposure from radon progeny was modeled using a single-compartment mass balance: Inhalation of radon progeny via a single-compartment mass balance with emanation coefficients [21].

$$C_{Rn}=\frac{E\times A}{\lambda\times V} \tag{2.3}$$

where C_{Rn} is indoor radon concentration (Bq/m^3), E is radon emanation rate from building materials (Bq/m^2·h), A is total surface area of walls, floor, and ceiling (m^2), λ is radon decay constant (0.007 h^{-1}), and V is room volume (m^3). The emanation rate was estimated from ^{226}Ra activity using an emanation coefficient of 0.2 (typical for building materials). The inhalation dose was then calculated using a dose conversion factor of 0.01 mSv per year per Bq/m^3 [21].

Ingestion of contaminated dust using ingestion rates and dose conversion factors values for ^{238}U, ^{232}Th, and ^{40}K [11,21].

The total annual effective dose was calculated by summing contributions across pathways.

$$D_{total} = D_{ext} + D_{inh} + D_{ing} \quad (2.4)$$

2.4 Empirical Dose Estimation for Comparison

For validation, empirical absorbed dose rates were calculated using formulas based on measured activity concentrations [4]. Annual effective doses were derived using identical room geometry and occupancy assumptions, enabling direct comparison with the Python-based RESRAD-BUILD outputs.

$$D = 0.462 \times C_U + 0.604 \times C_{Th} + 0.0417 \times C_K \quad (2.5)$$

where C_U, C_{Th}, and C_K are activity concentrations (Bq/kg) of ^{238}U, ^{232}Th, and ^{40}K, respectively. The empirical annual effective dose (AED_{emp}) was then derived as:

$$AED_{emp} = D \times 8760 \times 0.7 \times 0.8 \times 10^{-6} \quad (2.6)$$

2.5 Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum, maximum) were computed for radionuclide concentrations and simulated dose components. Pearson correlation analysis was performed to evaluate relationships between radionuclide activity and external gamma dose. All analyses were conducted using Python 3.9 with SciPy and NumPy libraries.

3. Results

3.1 Activity Concentrations of Natural Radionuclides

The measured activity concentrations of 40K, 238U, and 232Th across 72 building material samples were 94.00 ± 15.52, 11.57 ± 2.32, and 9.05 ± 1.43 Bq/kg, respectively. All values were below UNSCEAR global averages [4], confirming relatively low natural radioactivity in the Niger Delta region compared to other Nigerian areas [7,10]. These empirical measurements provided the input datasets for the Python-based RESRAD-BUILD simulation framework.

Table 1. Descriptive Statistics of Radionuclide Activity Concentrations (N = 72)

Parameter	Mean	Std. Dev.	Min	Max	CV (%)
^{40}K (Bq/kg)	94.00	15.52	64.27	130.65	16.51
^{238}U (Bq/kg)	11.57	2.32	7.39	20.31	20.03
^{232}Th (Bq/kg)	9.05	1.43	6.15	11.86	15.83

Figures 1-3 presents changes in activity concentration levels according to material types. In the case of ^{40}K activity concentration, roof material had the highest value of 112.71 Bq/kg, followed by POP additives (102.06 Bq/kg) and tiles (101.76 Bq/kg). Cement and sand were recorded with the lowest values (86.16 and 89.02 Bq/kg, respectively). In the case of ^{238}U, the highest activity concentration level was recorded in POP additives (13.23 Bq/kg) and PVC (13.18 Bq/kg); while cement recorded the lowest activity concentration level (10.50 Bq/kg). ^{232}Th, however, had the highest concentration levels recorded in PVC (11.48 Bq/kg) and POP additives (10.72 Bq/kg) while wood was lowest (8.47 Bq/kg). ANOVA indicated significant differences among material groups for all three radionuclides ($p < 0.01$).

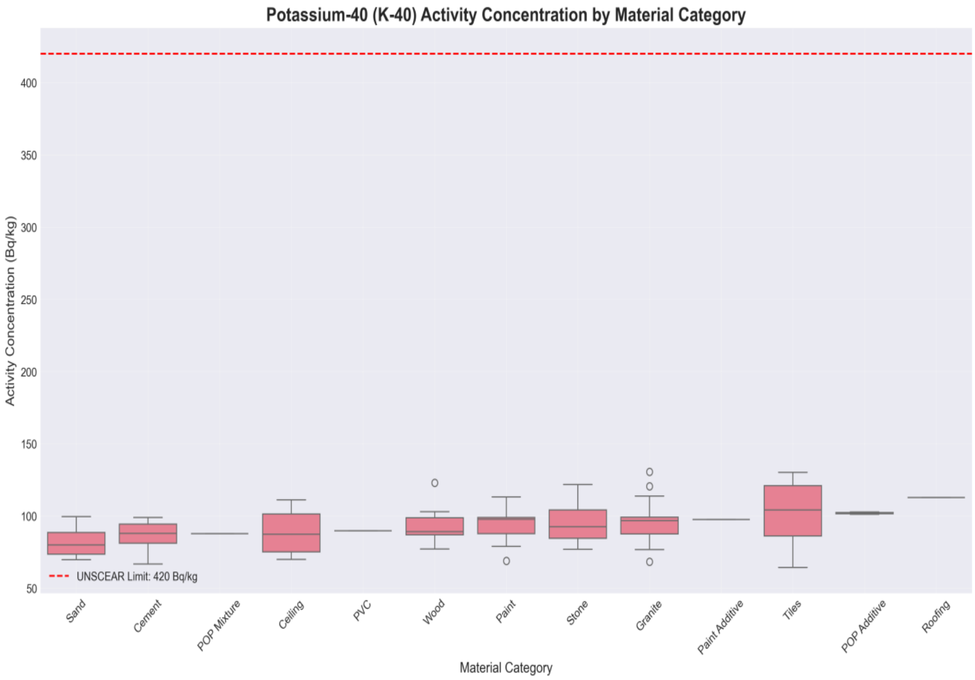

Figure 1. Pottasium-40 Activity Concentration by Material Category

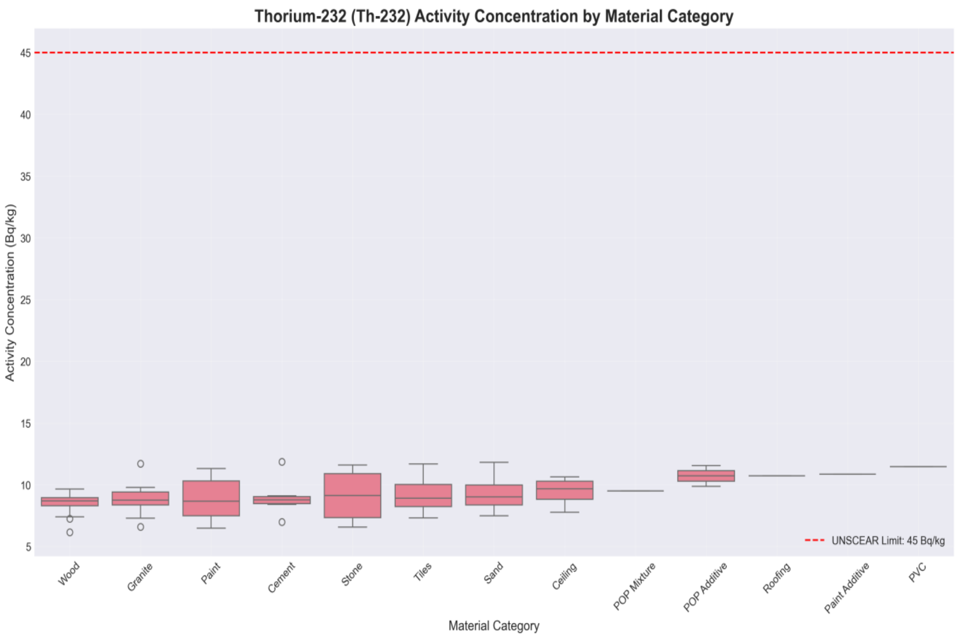

Figure 2. Thorium-232 Activity Concentration by Material Category

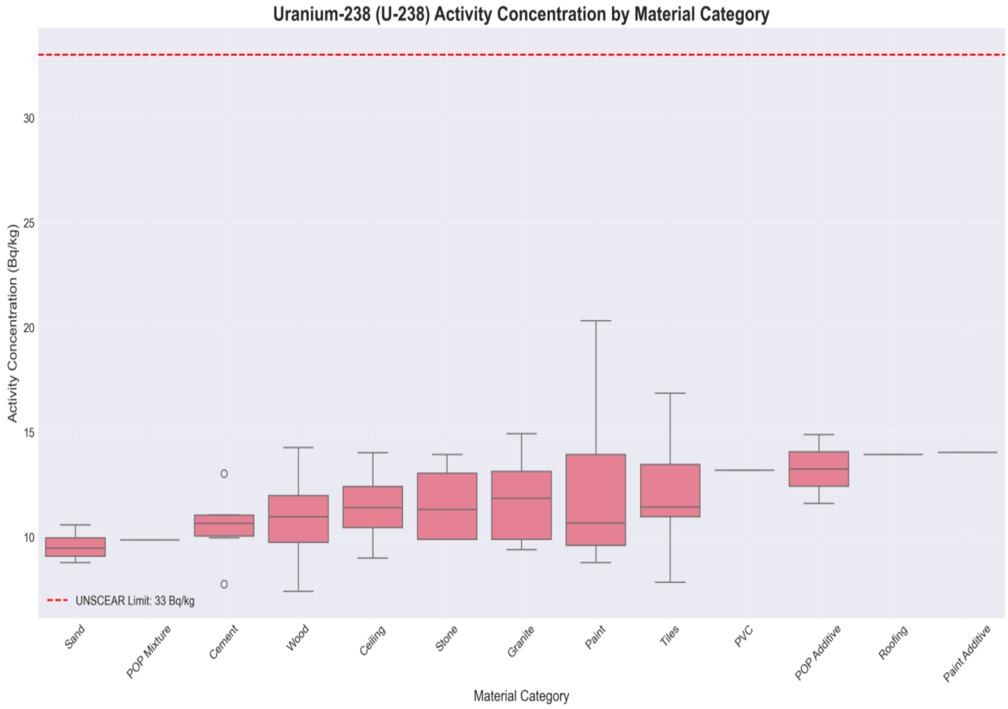

Figure 3. Uranium-238 Activity Concentration by Material Category

In addition, the origin-based variations were highly evident as shown in Table 2. South African sources contained the highest levels of ^{238}U (15.63 Bq/kg) and ^{232}Th (10.93 Bq/kg). Italian sources showed higher levels of ^{40}K (103.08 Bq/kg) and ^{238}U (13.08 Bq/kg). Chinese materials consistently showed the lowest readings for all three radionuclides.

Table 2: Summary of Activity Concentrations by Material Origin

Origin	N	^{40}K (Mean ± SD)	^{238}U (Mean ± SD)	^{232}Th (Mean ± SD)
Benin City	1	97.64	14.03	10.85
South Africa	1	120.18	15.63	10.93
Foreign	1	78.81	11.04	8.89
Italian	5	103.08 ± 14.34	13.08 ± 1.43	9.34 ± 1.48
Indian	9	88.64 ±13.07	11.49 ±1.92	8.49 ±1.07
Nigeria	26	97.07 ± 16.16	11.79 ± 2.95	9.14 ± 1.56
Local	22	89.82 ± 12.07	11.04 ± 1.87	8.96 ± 1.45
China	4	88.42 ± 30.06	10.62 ± 1.91	8.61 ± 1.44
Unknown	3	98.74 ±14.33	11.28 ±2.40	9.25 ±1.61

Overall	72	94.00 ± 15.52	11.57 ± 2.32	9.05 ± 1.43

3.2 RESRAD-BUILD Simulation Outputs

The computational model generated pathway-resolved annual effective doses ranging from 0.0634 to 0.1241 mSv/y, with a mean of 0.0875 ± 0.0126 mSv/y. All simulated doses were well below the ICRP public dose limit of 1 mSv/y [6]. The pathway contributions were consistent across material categories:

Table 3. RESRAD-BUILD Simulated Doses by Exposure Pathway

Pathway	Mean (mSv/y)	Std. Dev.	Minimum	Maximum	Contribution (%)
External gamma	0.0725	0.0105	0.0526	0.1016	82.9
Inhalation	3.64×10^{-5}	1.24×10^{-5}	1.42×10^{-5}	1.07×10^{-4}	0.04
Ingestion	0.0150	0.0022	0.0099	0.0224	17.1
Total	0.0875	0.0126	0.0634	0.1241	100

External gamma exposure: 82.9 % of total dose.

Ingestion of dust: 17.1 %.

Inhalation of radon progeny: 0.04 %.

Validation Against Empirical Estimates

Comparison between simulated doses and empirical UNSCEAR-based calculations showed excellent agreement, with a mean difference of 3.1 % and correlation coefficient r = 0.999. This validates the algorithmic accuracy of the Python-based RESRAD-BUILD framework, confirming its reliability for environmental exposure modelling.

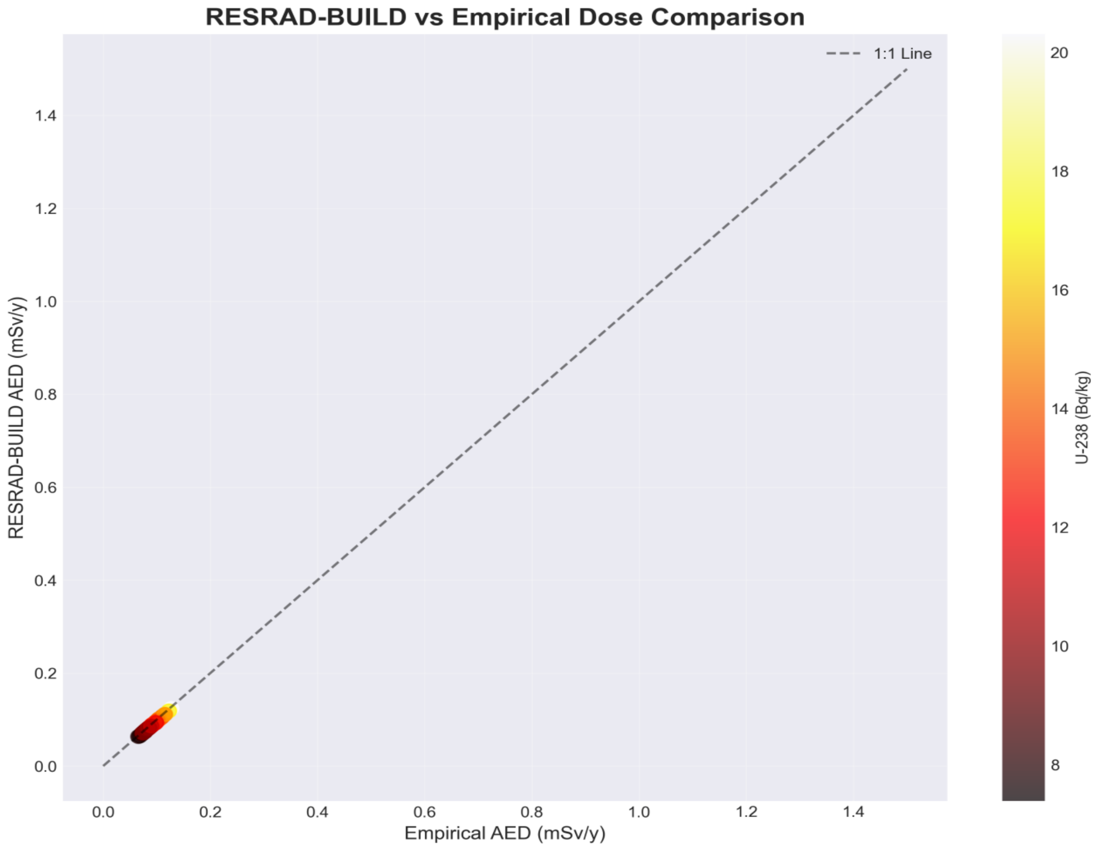

Figure 4. Comparison of RESRAD-BUILD total simulated dose vs. empirical dose estimate. The red dashed line indicates perfect agreement (1:1 line).

3.3 Pathway Contributions by Material Category

Roofing, paint additives, and tiles produced the highest total simulated doses, while cement and wood produced the lowest. Despite these variations, the proportional pathway contributions remained stable (external gamma ~83 %, ingestion ~17 %, inhalation <0.05 %), indicating that room geometry and occupancy assumptions in the computational model drive pathway distribution more than material type.

Table 4. Pathway Contributions for Selected Material Categories

Category	N	External (mSv/y)	Inhalation (mSv/y)	Ingestion (mSv/y)	Total (mSv/y)
Roofing	1	0.0891	3.98×10^{-5}	0.0189	0.1080
Paint additive	1	0.0865	3.85×10^{-5}	0.0184	0.1049
Tiles	8	0.0782 ± 0.0150	3.71×10^{-5} ± 0.62	0.0167 ± 0.0032	0.0949 ± 0.0182

Granite	17	0.0748 ± 0.0090	$3.60 \times 10^{-5} \pm 0.48$	0.0155 ± 0.0019	0.0903 ± 0.0109
Cement	7	0.0704 ± 0.0088	$3.45 \times 10^{-5} \pm 0.41$	0.0147 ± 0.0019	0.0851 ± 0.0107
Wood	13	0.0712 ± 0.0081	$3.48 \times 10^{-5} \pm 0.39$	0.0149 ± 0.0017	0.0861 ± 0.0098

3.4 Correlation Analysis

Pearson correlation analysis revealed strong positive relationships between radionuclide concentrations and external gamma dose: 238U ($r = 0.93$, $p < 0.01$), 232Th ($r = 0.82$, $p < 0.01$), and 40K ($r = 0.64$, $p < 0.01$). These correlations reflect the dose conversion factors embedded in the computational framework [4], further validating the model's ability to capture dose-response relationships.

Table 5. Pearson Correlation Matrix

Parameter	^{40}K	^{238}U	^{232}Th	External dose
^{40}K	1.00	0.48**	0.24*	0.64**
^{238}U	0.48**	1.00	0.68**	0.93**
^{232}Th	0.24*	0.68**	1.00	0.82**
External dose	0.64**	0.93**	0.82**	1.00

*Note: **$p < 0.01$, $p < 0.05$

4. Discussion

The Python-based RESRAD-BUILD simulation developed in this study demonstrates the effectiveness of computational modelling for pathway-resolved radiation dose assessment. By integrating measured activity concentrations of 40K, 238U, and 232Th with realistic room geometry and occupancy parameters, the framework produced results that closely matched empirical UNSCEAR estimates, with a mean difference of only 3.1 %. This agreement validates the computational reliability of the Python implementation and confirms its suitability as a reproducible modelling tool [11,22]. The measured activity concentrations (40K: 94 Bq/kg, 238U: 11.6 Bq/kg, 232Th: 9.1 Bq/kg) were lower than global averages [4] and significantly lower than values reported in other Nigerian regions [7,10]. These differences reflect geological variation, with the Niger Delta's sedimentary sands and clays typically exhibiting lower natural radioactivity than crystalline basement rocks [15,22,23,24]. While reassuring from a public health perspective, the observed variability across material categories and origins underscores the need for computational frameworks that can flexibly incorporate diverse datasets and generate pathway-specific risk estimates. The simulation confirmed that external gamma radiation is the dominant pathway (82.9 %), consistent with previous RESRAD-BUILD applications [11,13,25]. Inhalation contributed negligibly (0.04 %), reflecting the predominance of surface materials with low radon emanation rates [26,27,28]. Ingestion accounted for 17.1 %, highlighting the importance of considering dust exposure, particularly for children. These pathway-resolved insights illustrate the strength of computational modelling: unlike empirical formulas, the Python-based RESRAD-BUILD framework provides detailed breakdowns that inform targeted mitigation strategies. Beyond radiation safety, the computational approach demonstrates broader applicability. By leveraging open-source tools such as Python, the framework can be adapted to other domains requiring environmental exposure modelling, including air quality, chemical contamination, and smart building design. This positions the study not only as a contribution to radiation physics but also as an example of how computer applications can advance environmental risk assessment through reproducible, scalable, and adaptable simulation.

5. Conclusion

This study demonstrates that a Python-based implementation of the RESRAD-BUILD framework provides a reliable and efficient computational tool for simulating indoor radiation exposure pathways in Nigerian residential buildings. By integrating measured activity concentrations of 40K, 238U, and 232Th with realistic room geometry, air exchange, and occupancy parameters, the model produced pathway resolved dose estimates that closely matched empirical calculations, with a mean difference of only 3.1 %.The results confirm that external gamma radiation is the dominant pathway, while ingestion and inhalation contribute smaller fractions. Importantly, the computational approach reframes radiation exposure assessment as a simulation problem, enabling reproducible, adaptable, and scalable evaluations. This highlights the broader potential of Python-driven frameworks for environmental risk modelling, where complex exposure scenarios can be quantified with precision and transparency. Beyond radiation safety, the methodology underscores the value of computational modelling in public health protection and environmental engineering. By leveraging open-source tools such as Python, researchers and regulators can extend this framework to other domains such as air quality, chemical exposure, and smart building design thereby advancing the role of computer applications in environmental safety and risk assessment.

References

1. Ershov BG. Natural radioactivity of the crust as an important factor of the chemical evolution of the early Earth. Precambrian Res. 2024; 406:107400.

2. Agbajor GK, Enaroseha OO, Osia-Aibangbee D, Akpolile AF, Umukoro AB. Ingestion exposure of natural radionuclide and toxic heavy metallic origin in samples of local staple food. Nuclear Analysis. 2025;4(3):100182.

3. Marengo M, Martin CJ, Rubow S, Sera T, Amador Z, Torres L. Radiation safety and accidental radiation exposures in nuclear medicine. Semin Nucl Med. 2022;52(2):94-113.

4. United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. Report to the General Assembly. New York: United Nations; 2000.

5. Asere AM, Owolabi TO, Alafe BDBD, Alabi OP, Alimi MB. Assessment of excess gamma dose exposure level in typical Nigerian commercial building materials distribution outlets. J Niger Soc Phys Sci. 2021:216-223.

6. International Commission on Radiological Protection. The 2007 recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann ICRP. 2007;37(2-4).

7. Aladeniyi K, Arogunjo AM, Pereira AJSC, Khandaker MU, Bradley DA, Sulieman A. Evaluation of radiometric standards of major building materials used in dwellings of South-Western Nigeria. Radiat Phys Chem. 2021; 178:109021.

8. Maxwell O, Adewoyin OO, Joel ES, Ehi-Eromosele CO, Akinwumi SA, Usikalu MR, et al. Radiation exposure to dwellers due to naturally occurring radionuclides found in selected commercial building materials sold in Nigeria. J Radiat Res Appl Sci. 2018;11(3):225-31.

9. Joel ES, Maxwell O, Adewoyin OO, Ehi-Eromosele CO, Embong Z, Oyawoye F. Assessment of natural radioactivity in various commercial tiles used for building purposes in Nigeria. MethodsX. 2018; 5:8-19.

10. Garba NN, Rabi'u N, Aliyu ASA, Kankara UM, Vatsa AM, Isma'ila A, et al. Evaluation of radiological risk associated with local building materials commonly used in Northwestern Nigeria. Heliyon. 2023;9(5).

11. Yu C, Cheng JJ, Gnanapragasam E, Kamboj S, LePoire D, Wang C. User's manual for RESRAD-BUILD code V.4: Vol. 1, methodology and models used in RESRAD-BUILD code. Argonne (IL): Argonne National Laboratory; 2022. Report No.: ANL/EVS-21/17-Vol.1.

12. Abdullahi S, Ismail AF, Yasir MS. Radioactive investigation of Malaysia's building materials containing NORM and potential radiological risks analysis using RESRAD-BUILD computer code. Int J Environ Anal Chem. 2022;102(9):2000-12.

13. Alhamdi WA, Jarjes AH, Mohammed Ahmed S. Comparative dose assessment of natural radioactivity in building materials: empirical equation versus RESRAD-BUILD computer code. J Radiat Res Appl Sci. 2025;18(1):101224.

14. Dao NQ, Ba VN, Mai PTX, Loan TTH. Assessment of radiological doses of raw building materials and CEN room model using RESRAD-BUILD. Ann Nucl Energy. 2024; 202:110459.

15. Short KC, Stäuble AJ. Outline of geology of Niger Delta. AAPG Bull. 1967;51(5):761-79.

16. International Atomic Energy Agency. Soil sampling for environmental contaminants. Vienna: IAEA; 2004. IAEA-TECDOC-1415.

17. Mokobia CE, Tchokossa P, Olomo JB, Balogun FA. An assessment of the natural radioactivity content of some liquid paints available in Nigeria. Niger J Phys. 2003; 15:14-16.

18. Gilmore GR. Practical gamma-ray spectrometry. Warrington (UK): Gordon R. Gilmore Nuclear Training Services Ltd; 2008.

19. Akpojotor G, Ehwerhemuepha L. An overview of the Python African Computational Science and Engineering Tour Project [Internet]. Invited talk presented at: PyCon US 2012; 2012 Mar 7-15; Santa Clara (CA), USA. Available from: http://pyvideo.org/video/738/25-an-overview-of-the-python-african-computation

20. Olarinoye IO, Kolo MT, Shittu HO, Anumah AS. Estimation of indoor gamma radiation dose rate from concrete blocks constructed from tin mine tailings. J Build Eng. 2023; 66:105934.

21. International Commission on Radiological Protection. Human respiratory tract model for radiological protection. ICRP Publication 66. Ann ICRP. 1994;24(1-3).

22. Akpolile AF. Levels of concentration of radionuclides and radiological detriments in soil, mosses and lichen samples from Ekakpamre, Nigeria. FUW Trends Sci Technol J. 2021;6(2):523-7.

23. Akpolile AF. Radiological survey of some popular beaches in Abraka Town, Ethiope East Local Government Area, Delta State, Nigeria. Chem Afr. 2024;7(2):969-76.

24. Osiga-Aibangbee D, Enaroseha OO, Agbajor GK. Potential health risk assessment of sediment and water in some Niger Delta areas of Nigeria. Nuclear Analysis. 2025 Mar 1;4(1):100159.

25. Akpolile AF, Omoriwhovo JO, Eki EC. Cross-influence of natural radioactivity and nuclear waste management in oil-rich regions: a case study of Ekakpamre community in Delta State, Nigeria. Nuclear Analysis. 2026:100238.

26. Osiga-Aibangbee D, Enaroseha OO, Agbajor GK. Potential health risk assessment of sediment and water in some Niger Delta areas of Nigeria. Nuclear Analysis. 2025;4(1):100159.

27. Sinebe, HA., Mokobia C., Akpolile F. Assessment of the level of radionuclide in drinking water in selected schools in the northern part of Delta State, Nigeria. Niger J Sci Environ. 2022;20(2):34-47.

28. Sinebe HA, Okonkwo JE, Erhonyota TA, Okpaidi O. Assessment of natural radioactivity hazard in water sample in some parts of Delta State, Nigeria. J Pure Appl Sci (Sci Forum). 2026;26(3). Available from: https://atbuscienceforum.com.ng/index.php/jpas/article/view/305