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# Health risk evaluation of radon progeny exposure in Nigerian traditional mud houses

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## Abstract

In a study of 56 randomly selected Traditional Mud Houses (TMHs) in Nigeria, the radiation health impacts of radon progeny were evaluated using CR-39 radon detectors within a rainy season. The measured radon concentration ranged from 17 to 174 Bq m$^{-3}$, with an average value of 76 Bq m$^{-3}$ (SD = 36). This was lower than the WHO's recommended reference level of 100 Bq m$^{-3}$. However, 24% of the surveyed houses exceeded this level, indicating potential health risks. The estimated Potential Alpha Energy Concentration (PAEC) due to its progeny ranged from 1.84 to 18.81 mWL with an average value of 8.24 mWL (SD=3.91). The computed annual effective doses yielded an average value of 3.06 ± 1.44 mSv y$^{1}$, which is far less than the recommended reference level of 10 mSv y$^{1}$ by the International Commission on Radiological Protection. The lifetime excess absolute risks varied from 0.4 × 10$^{4}$ to 3.9 × 10$^{4}$, with an average of 1.7 ± 0.8 × 10$^{4}$. Improving the ventilation systems and applying cement plaster and distemper to the building walls and floors were recommended for older TMHs over 50 years old to mitigate radon exposure. This data can inform potential policy measures for indoor radon progeny control in Nigeria.

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## 1. Introduction

Radon, specifically $^{222}$Rn, along with its decay products (progeny or daughters), is an inert, radioactive gas that is undetectable by human sensory organs. It is an indoor pollutant that poses significant radiological health risks, especially at elevated levels due to the release of radiation during decay [1]. Although any level of radiation dose is associated with health risk, regardless of whether it is low or high according to the Linear No-Threshold model (LNT) [2] the magnitude of the risk increases proportionally with the dose received. $^{222}$Rn is widely recognised as a leading risk factor for lung cancer, second only to smoking. The link between radiation exposure from $^{222}$Rn with its progeny and cancer of the lung has been well established [3–6].

$^{222}$Rn seeps into indoor environments as a product of the natural nuclear decay of $^{226}$Ra contained in terrestrial resources such as rocks, soils, water, natural gas, and any products like building materials derived from the Earth's crust. The level of radon in an indoor environment is a function of the local geology, climatic conditions, building characteristics, building materials, dwellers' habits, and ventilation among, other factors.

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As a radioactive gas, $^{222}$Rn in indoor environment disintegrates and releases its short-lived radioisotopes (progeny/daughters). Greater portion of radon exposure is from its progeny/daughters [7]. The daughters are electrically charged with ability to get attached to flying particles (dust) in the indoor air. The daughters make their way into the lung via inhalation of the particles, and get deposited in the lung epithelium. Moreover, as a process that is probabilistic in nature, disintegration may not occur in the indoor air until the radon gas gets into the lungs through inhalation. The decayed radon in the lung discharges its daughter directly on the surface of the respiratory track. Whichever way the radioisotopes get into the lung, the radionuclides decay to emit alpha particles which in turn bombard the cells of the lung and this may lead to cell damage and hence, lung cancer development.

Globally, lung cancer has the highest mortality rate among other cancers. However, it has been established that the mortality rates are higher among Covid-19 patients who also have lung cancer than in the general population [8]. In addition, exposure to radon and its progeny accounts for 5-20 % of lung cancer deaths [9]. In order to reduce the incidences of lung cancer caused by indoor radon inhalation, control techniques for preventing the entrance of radon into buildings under development and remediation action for existing buildings have been recommended by the World Health Organisation [10]. On the basis that there is a 16% rise in the risk of lung cancer per every 100 Bqm$^{-3}$ increase in radon levels at homes, a reference level of 100 Bqm$^{-3}$ of indoor radon for all dwellings has been suggested by WHO [11]. The value is highly conservative when compared with the 300 and 148 Bqm$^{-3}$ [2, 12] reference levels of the International Commission on Radiation Protection (ICRP) and the action level provided by the Environmental Protection Agency (EPA), respectively. Exposure to indoor radon and its progeny is an issue of public concerns, and consequently, growing reports on indoor radon and its progeny measurements have been on the rise for more than four decades in order to assess the levels of population exposures [13–18]. Despite the large quantity of studies conducted and reported in many countries across the globe within the last four decades, data on radon studies is very sparse in Nigeria, and this may be because of inadequate public awareness about the detrimental effects of radon on human health [19]. To substantiate this point with the extent of our knowledge, from the pioneering indoor radon measurement reported in 2010 [20] to the study published in 2019 [21], only nine studies with a total sample size of 404 have been conducted on different occasions. Six out of the nine studies were surveyed in classrooms or school offices (total sample size = 256), and the rest were performed in residential houses/a fertiliser warehouse (total sample size = 148) in Nigeria [19–27].

Ventilation is a critical factor that dictates indoor radon levels, and it in turn depends on the building type, geological location, and building materials. The building types whose indoor air environment is of interest to this research are Traditional Mud Houses (TMH) or mud-built houses in Nigeria because they are usually characterised by certain features that may enhance the accumulation of radon in the indoor environment. Traditional Mud Houses (TMH) are shelters built chiefly from mud, clay, water, and other naturally accessible local materials. As houses built from earthen construction materials, TMHs offer several advantages over houses built of conventional building materials in terms of cost, environmental impact, and thermal comfort. However, TMHs are susceptible to destruction through natural environmental catastrophes if the process of their construction lacks appropriate architectural requirements [28, 29].

According to Mahmood *et al.* [30] more than three billion of the global population live in earthen (mud) buildings, especially among low-income individuals in Africa, Asia, and the Middle West. A considerable portion of Nigerian residents dwell in mud-built houses especially in rural areas and this may not be unconnected with the aforementioned advantages of mud-built houses as against the limitations. Affordability and accessibility are the major factors responsible for the predominance of such houses among low-income earners [30, 31].

The main components of mud as building materials are silt, clay, sand, organic matter, and water, all of which are products of natural origin. As a product of the Earth's crust and because the process of its production does not involve sieving or complex procedures, mud retains its radionuclide contents, including radon, even after being used as building material. Mud can be moulded into bricks and blocks or used directly as building materials. Several studies have established that mud block or brick is one of the building materials with a high level of natural radioactivity [30, 32–35]. TMHs are prevalent in Nigeria and in the study area, most especially in villages, suburbs of urban areas, and on the premises of cities for the provision of essential services. The TMHs are characterised by poorly ventilated bedrooms and living rooms, each of which contained one or two small, hole-like windows. In most of the TMHs, the bedrooms cannot be distinguished from the living rooms in terms of size and usage. Moreover, their floors are not plastered or covered with radon-preventing materials but with mud, hence the floors serve as direct routes through which the generated radon underneath the buildings gains entrance into the indoor environments [17, 30, 33, 36]. The dimensions and orientations of the TMH's windows are atrocious, so the buildup of indoor radon with its daughter may be inevitable. Also, the walls are constructed with either baked mud bricks, unbacked mud bricks, or a combination and are characterised by cracks, which may also assist indoor radon exhalation rates from the materials and encourage the accumulation of radon in homes.

Moreover, the roofs are made of one or more combinations of mat and straw obtained from raffia palm leaves (thatch roofs), and others are roofed with galvanised iron sheets. Figure 1 shows a typical example of TMHs in the study area. Various studies on indoor radon in major TMHs in some countries have been reported [30, 31, 37–41]. Major studies on indoor radon in TMHs from Nigeria have so far not been conducted. In Saudi Arabia, indoor radon levels were studied in various buildings that included traditional mud buildings [42]. The researchers described the TMHs as old, poorly ventilated dwellings. The study revealed that poor ventilation is an important factor imparting effects on radon levels in dwellings, as the poorly ventilated houses investigated presented higher annual effective doses as compared to others. Moreover, the overall findings showed that the level of gas in the investigated area was higher than the world average values, underscoring the need to apply mitigation measures to the area with elevated radon levels and also to extend such a study to other parts of the world that are known to process TMHs, like Nigeria. A comparative study was conducted in India(Degboi and Mashimpur) on anticlines at Winter to assess the levels of radon, thoron, and their progeny in three types of houses: Assam-type, Reinforced Cement Concrete (RCC), and Mud Houses (TMHs) with the aim of assessing associated health for the residents.

The highest concentration levels of the radioisotopes in the studied houses were registered from the TMHs [43]. The observed elevated levels of radioisotopes in the studied TMHs from the two study areas were attributed to the physical characteristics of the structures, including cracks and openings in walls and floors, as well as the materials used in their construction. Nevertheless, findings show that the areas are relatively safe in respect of radon-thoron exposure. Chege *et al.* [44], conducted research at Mrima Hill in Kenya to assess annual effective doses due to thoron and radon exposures in mud dwellings. Although thoron contributed a greater percentage to the annual effective dose due to the abundance of $^{232}$Th in the building materials, the level of radon and its progeny from the TMHs may necessitate mitigation actions to reduce associated health risks from long-term exposure. The study's significance stems from its results that the TMHs from the Mrima Hill region of Kenya have high levels of indoor radon and thoron, the two of which can lead to serious health hazards, most notably an increased risk of lung cancer.

The study further advances scientific understanding of natural radiation exposure and increases public awareness. In addition, it provides legislators with information for improved regulations and building standards. Effective mitigation strategies, enhanced public health, and direction for sustainable development in the region can all result from this research. In Nigeria, an in-situ but not comprehensive study on indoor radon measurement in TMHs was reported by Usikalu *et al.* [45] using active continuous radon monitors (Rad7) for short-term measurement in Nigeria. Even though the study examined radon levels in fifty houses, including twenty mud houses (TMHs), across the three investigated local governments in Ibadan, it revealed that the highest levels of radon were found in the TMHs. The study recommended awareness campaigns and further research to educate residents about the health hazards of radon accumulation, particularly in areas where high levels were recorded. Results of several studies that evaluated radon levels and/or its progeny in TMHs were also published from various part of the world [32, 46–50]. It is worth noting that the data analysed in this research is a subset of the larger dataset obtained in 2016 and presented as a general overview by Aladeniyi *et al.* [51]. This study is particularly focused on TMHs for their peculiarities in properties and the potential impact of radon daughter exposure on the inhabitants residing in the study area.

This study was focused on evaluating the radiological health impacts of radon progeny in some selected TMHs from Nigeria.

Figure 1. A typical mud-built house.

The objectives of the study are:

- to measure radon concentrations in the selected TMHs using passive radon detectors (CR-39); plastic track detector,
- to evaluate the Potential Alpha Energy Concentrations in Working Level (WL),
- to evaluate Exposure Received in Work Level Month (WLM),
- evaluate the Annual Effective Dose (AED) in mSvy$^{-1}$,
- to compute Lifetime Excess of Absolute Risk (LEAR),
- to recommend remedial actions for any area with a possible high level of $^{222}$Rn/progeny, and
- to compare the results with available reference levels. The results will be useful tool for authorities (Policy makers and public health workers etc) saddled with the responsibility of managing indoor radon risk and for epidemiological survey in future.

## 2. Materials and methods

### 2.1. *Study area*

The selected mud houses are located in Ondo, Ekiti, and Osun states in southwestern region of Nigeria. The region lies between latitudes 4° 00′N - 7° 00′N and between longitudes 2° 30′E - 7° 00′E within an equatorial rain forest in Africa. The region is underlaid by a basement complex, and the southern part of the region is underlaid by thick sedimentary rock. The basement complex integrates Precambrian rock units that composed of quartzite, pegmatite, granites, migmatite, and schist/metasediments [52]. While the mean relative humidity of the region falls between 70 and 80% , the mean temperature lies in the range of 28 °C and 30 °C in the south and between 32 °C and 33 °C in the north in every year [53]. The region is composed of two seasons viz the wet (rainy) and dry seasons. The wet season spans from April to November, and the dry season from December to March. Virtually, everywhere mud houses can be found in every town or city in the region, especially among low-income earners such as farmers.

### *2.2. Experimental procedure*

A total of 56 common earthen-floored, baseless mud houses were selected for the study. None of the surveyed houses were two-storey buildings. Passive radon detectors, which are made of conductive plastic diffusion chambers, each of which hosts a CR-39 nuclear track detector (RSKS type, size = 100 $cm^2$, typical sensitivity = 2.0 $tracks.cm^2.kBq^{-1}.h^{-1}.m3$, saturation limit greater than 12000 $kBqhm^{-3}$), supplied by Radosy Ltd. from Portugal, were deployed. A total of 112 of the detectors (CR-39 nuclear track detectors) were opened from the airtight seals, and each of the detectors was installed at ≈ 1.5 m above the floors and 2 m from the walls, windows, and doors to avoid excessive flow of air around them. A total of 66 bedrooms and 46 living rooms from the selected 56 mud houses (unbalanced research design) were used. Two detectors, one for the bedroom and the other for the living room, were installed in a single house according to ISO 11665-4 [54], with the exception of those houses where their bedrooms could not be differentiated from the living rooms or houses built without living rooms. A maximum of two bedrooms were selected in such cases. The geographical locations of the sample points were taken using global positioning system (GPS). Figure 2 shows the geological map of the study locations, along with sample points marked. The installed detectors were left exposed until after six months in the year 2016 within the wet season, when indoor radon concentrations used to attain the highest level [32, 55]. This is because in the wet season, windows and doors are closed for extended periods of time to ward off the cold, as compared to the dry season, when doors and windows are almost constantly kept open. To prevent unwanted exposure of the detection devices, stringent quality assurance procedures were carried out at all stages of the study, that is, prior to the installation of the detectors, during the exposure, and during the counting/analysis of the exposed detectors.

The exposed detectors were harvested, air-tight sealed, and stored in alumininum foil-filled containers to prevent the exposed detectors from being irradiated by background radiation during transit to the laboratory. The packaged exposed detectors were moved to the Laboratory of Natural Radioactivity at the University of Coimbra, Portugal, for etching and analysis. The laboratory is not only internationally certified, but also takes part in regular intercomparison activities with other recognised laboratories to ensure accuracy, and reliability of its results. A total of six detectors, four from the living room and two from the bed rooms were observed lost during detector retrieval.

A 30% solution of NaOH, prepared and heated to a temperature of $90^oC$, was used for etching the exposed detectors over a period of 4 hours. In each process, a water bath was filled with a hydroxide solution, and electrically heated until its temperature attained $90^oC$ in approximately 24 -25 minutes.

The detector films (1-$cm^2$ area) were removed from the plastic chambers and arranged in groups of 12 in detector plastic racks, which were immersed into the hot solution in the bath, and the temperature of the bath was maintained through continuous heating for 4 h. The heating of the bath switched off automatically after the etching process, and the system was allowed to cool for within 20 to 25 minutes. Thereafter, the etched detectors were washed with distillation water, dried, and the tracks on the surfaces of the films were counted using a microscope automatic reader.

Tracks per unit area, $T_{D,}$ (track per $cm^2$) produced in time T were calculated with the background track density subtracted. Track densities were related to radon concentration $C_{Rn}$ ($Bq\ m^{-3}$) using a calibration factor, $K_{Rn}$ (2.48 x $10^{-3}$ Track $cm^{-2}\ h^{-1}/\ Bqm^{-3}$) derived from a certified calibration chamber after exposing radon detectors of the same batch to a standard source in accordance with ISO's procedure.

The radon concentration was estimated using equation (1) [54];

$$\mathrm{C_{Rn}} = \frac{\mathrm{T_D}}{\mathrm{K_{Rn}T}}\ , \tag{1}$$

where T is the time of exposure. Equation (1) generates the basic data from which all relevant indices were calculated. Rewriting equation (1) to become equation (2) ;

$$\mathrm{C_{Rn}} = \frac{N_E - N_B}{\mathrm{A.K_{Rn}.T}}\ , \tag{2}$$

where $N_E$, $N_B$ and A are the number of tracks after exposure, mean number of tracks caused by the background noise and area used for counting the number of etched tracks in $cm^{-2}$ respectively. Let $w = \frac{1}{\mathrm{A.K_{Rn}.T}}$ the standard uncertainty (U) in $C_{Rn}$ is given by ISO standard:

$$U\left(\mathrm{C_{Rn}}\right) = \sqrt{\left(N_E + \frac{N_B}{N}\right).w^2 + (C_{Rn})^2.U_r(w)}\ , \tag{3}$$

where N is the number of detectors used for the background measurement, $U_r$ is relative standard uncertainty which is given by:

$${U_r}^2(w) = {U_r}^2(K_{Rn}) + {U_r}^2(A)\ . \tag{4}$$

The Minimum Detectable Activity (MDA) value of the system is 5 $Bqm^{-3}$. Therefore, the Potential Alpha Energy Concentration (PAEC) in working level (WL) is given by

$$\mathrm{PAEC\ \ (WL)} = \frac{\mathrm{C}_R \times F}{3700}, \tag{5}$$

and Exposure Received (EP) to the daughters of radon is given by:

$$\mathrm{EP\,(WLM)} = \mathrm{PAEC\,(WL)} \times \frac{t}{170} = \left(\frac{\mathrm{C}_R \times F}{3700} \times \frac{t}{170}\right), \tag{6}$$

where $C_R$, F. and t are the concentration of radon in Bq $m^{-3}$, equilibrium factor (0.4) and the time of exposure in h respectively [1].

The annual effective dose (AED) in $mSvy^{-1}$ and the Life Time Excess Risks (LEAR) in number of deaths per 10000 person-years were computed using the obtained values for

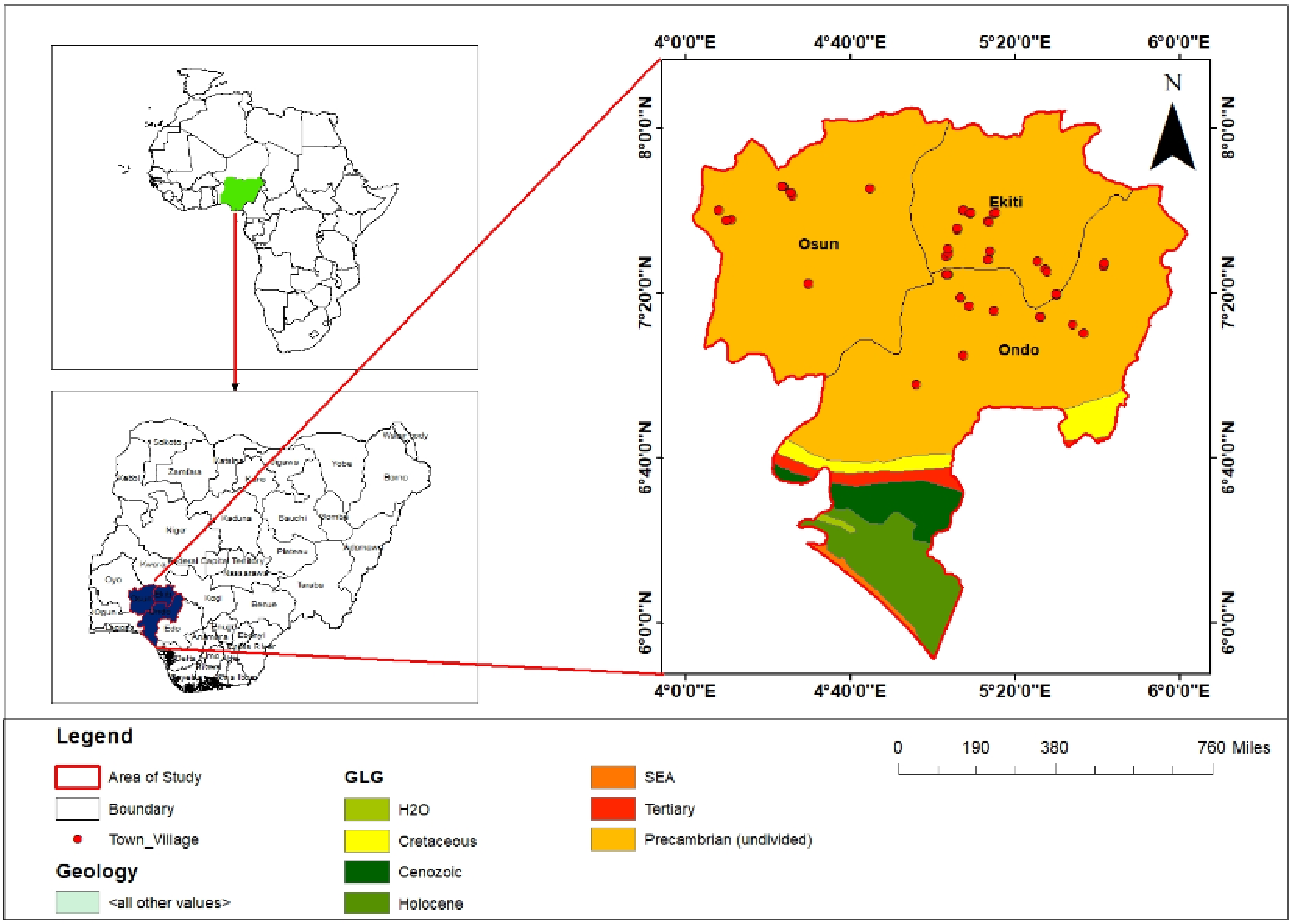

Figure 2. Geological map of the study locations.

Table 1. Descriptive statistics of the measured indoor in bedrooms, living room and the representative values of the houses visited.

| S/N | Bedrooms | Living rooms | House representative values |
|---|---|---|---|
| No | 64 | 40 | 54 |
| Minimum (Bq m$^{-3}$) | 20.0 | 13.0 | 16.5 |
| Maximum (Bq m$^{-3}$) | 176.0 | 194.0 | 173.5 |
| Arithmetic Mean (Bq m$^{-3}$) | 78.7 | 68.0 | 76.0 |
| Standard Deviation (Bq m$^{-3}$) | 37.5 | 40.5 | 36.5 |
| Geometric Mean (Bq m$^{-3}$) | 70.4 | 57.7 | 67.5 |
| GSD (Bq m$^{-3}$) | 1.6 | 1.8 | 1.7 |
| Median (Bq m$^{-3}$) | 71.0 | 55.0 | 66.3 |
| Skewness (Bq m$^{-3}$) | 0.700 | 1.211 | 0.766 |
| Kurtosis (Bq m$^{-3}$) | -0.178 | 1.203 | 0.009 |

PAEL(WL) and EP (WLM) as expressed in equations (5 & 6) with the application of conversion factors 9 mSvWLM$^{-1}$ [2.6 mSv per mJ h m$^{-3}$ ] for the members of the public and 5 × $10^{-4}$ WLM$^{-1}$ [1.4 × $10^{-4}$ per (mJhm$^{-3}$)] respectively as recommended by ICRP, (2010). The indoor occupancy factor of 0.8 in a year, i.e., (24 × 365 × 0.8 ≈ 7000 h y$^{-1}$) was used to compute the EP [1]. The LEAR is associated with chronic exposure situations.

## 3. Results and discussions

The descriptive statistics of the measured radon indoor concentrations for the bedrooms, living rooms, and representative values (mean) of the surveyed houses are presented in Table 1. The difference in the number (64) of bedrooms as opposed to the number (40) of living rooms resulted from the nature of the surveyed houses (some mud houses are without living rooms) and the number of detectors recorded as losses. The skew-

Table 2. Shapiro-Wilk test for test of normality of the data.

| Rooms and Representatives values | Statistic | df | Sig. |
|---|---|---|---|
| Measured Radon Concentration in bedrooms | 0.948 | 64 | 0.009 |
| Measured Radon Concentration in living rooms | 0.893 | 40 | 0.001 |
| Representative values | 0.944 | 54 | 0.014 |
| Ln-Transformed values (Bedrooms) | 0.983 | 64 | 0.530 |
| Ln-Transformed values (Living rooms) | 0.985 | 40 | 0.871 |
| Ln-Transformed values (Representative) | 0.981 | 54 | 0.553 |

df = degree of freedom, sig. = significant.

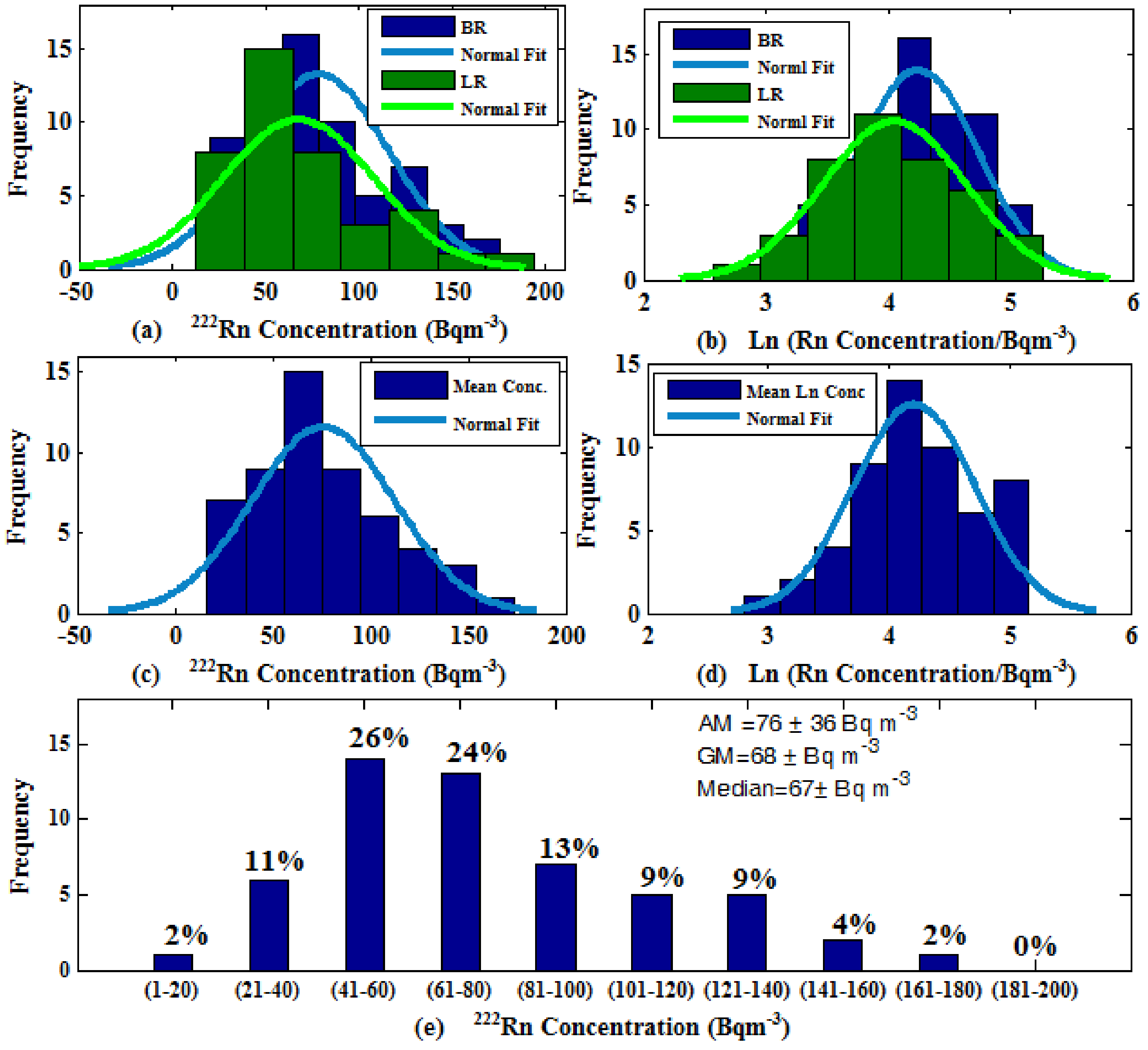

Figure 3. Frequency Distributions (a) Indoor radon Concentration for the Living room (LR) and the Bedroom (BR) (b) Log-Transformed indoor radon Concentration for the rooms, (c) & (d) Mean indoor radon concentration and the log-transformed mean indoor concentration respective and (e) Bar chart.

Table 3. The House Codes, Geographical locations, Average Radon Concentration ($C_{Rn}$) Potential Alpha Energy Concentration (PAEC), Exposure(EP), Annual Effective Doses (AED) and LEAR.

| House Codes | Coordinates | | $C_{Rn}$ (Bqm$^{-3}$) | PAEC (mWL) | EP (WLM) | AED (mSv) | LEAR X ($10^{-4}$) |
|---|---|---|---|---|---|---|---|
| | (N) | (E) | | | | | |
| MH1 | 7$^{0}$30.233’ | 5$^{0}$14.003’ | 98 | 10.59 | 0.44 | 3.96 | 2.20 |
| MH2 | 7$^{0}$28.258’ | 5$^{0}$13.532’ | 27 | 2.92 | 0.12 | 1.08 | 0.60 |
| MH3 | 7$^{0}$28.233’ | 5$^{0}$13.562’ | 57 | 6.16 | 0.25 | 2.25 | 1.25 |
| MH4 | 7$^{0}$30.168’ | 5$^{0}$13.891’ | 140 | 15.14 | 0.62 | 5.58 | 3.10 |
| MH5 | 7$^{0}$39.413’ | 5$^{0}$15.064’ | 52 | 5.62 | 0.23 | 2.07 | 1.15 |
| MH6 | 7$^{0}$37.480’ | 5$^{0}$13.505’ | 27 | 2.92 | 0.12 | 1.08 | 0.60 |
| MH7 | 7$^{0}$37.395’ | 5$^{0}$13.794’ | 52 | 5.62 | 0.23 | 2.07 | 1.15 |
| MH8 | 7$^{0}$39.520’ | 5$^{0}$15.400’ | 51 | 5.51 | 0.23 | 2.07 | 1.15 |
| MH9 | 7$^{0}$29.100’ | 5$^{0}$3.320’ | 132 | 14.27 | 0.59 | 5.31 | 2.95 |
| MH10 | 7$^{0}$29.644’ | 5$^{0}$3.984’ | 61 | 6.59 | 0.27 | 2.43 | 1.35 |
| MH11 | 7$^{0}$30.814’ | 5$^{0}$3.851’ | 103 | 11.14 | 0.46 | 4.14 | 2.30 |
| MH12 | 7$^{0}$35.536’ | 5$^{0}$06.176’ | 152 | 16.43 | 0.68 | 6.12 | 3.40 |
| MH13 | 7$^{0}$35.896’ | 5$^{0}$06.041’ | 95 | 10.27 | 0.42 | 3.78 | 2.10 |
| MH14 | 7$^{0}$40.242’ | 5$^{0}$07.595’ | 109 | 11.78 | 0.49 | 4.41 | 2.45 |
| MH15 | 7$^{0}$40.113’ | 5$^{0}$07.458’ | 174 | 18.81 | 0.77 | 6.93 | 3.85 |
| MH16 | 7$^{0}$39.378’ | 5$^{0}$09.187’ | 131 | 14.16 | 0.58 | 5.22 | 2.90 |
| MH17 | 7$^{0}$39.559’ | 5$^{0}$09.422’ | 134 | 14.49 | 0.60 | 5.40 | 3.00 |
| MH18 | 7$^{0}$19.865’ | 5$^{0}$30.202’ | 77 | 8.32 | 0.34 | 3.06 | 1.70 |
| MH19 | 7$^{0}$19.737’ | 5$^{0}$30.206’ | 81 | 8.76 | 0.36 | 3.24 | 1.80 |
| MH20 | 7$^{0}$19.867’ | 5$^{0}$30.193’ | 79 | 8.54 | 0.35 | 3.15 | 1.75 |
| MH21 | 7$^{0}$19.888’ | 5$^{0}$30.213’ | 104 | 11.24 | 0.46 | 4.14 | 2.30 |
| MH22 | 7$^{0}$25.858’ | 5$^{0}$27.531’ | 62 | 6.70 | 0.28 | 2.52 | 1.40 |
| MH23 | 7$^{0}$25.345’ | 5$^{0}$27.800’ | 60 | 6.49 | 0.27 | 2.43 | 1.35 |
| MH24 | 7$^{0}$27.835’ | 5$^{0}$25.666’ | 61 | 6.59 | 0.27 | 2.43 | 1.35 |
| MH25 | 7$^{0}$15.703’ | 5$^{0}$15.036’ | 17 | 1.84 | 0.08 | 0.72 | 0.40 |
| MH26 | 7$^{0}$19.050’ | 5$^{0}$06.885’ | 69 | 7.46 | 0.31 | 2.79 | 1.55 |
| MH27 | 7$^{0}$19.060’ | 5$^{0}$06.876’ | 34 | 3.68 | 0.15 | 1.35 | 0.75 |
| MH28 | 7$^{0}$10.443’ | 5$^{0}$36.794’ | 81 | 8.76 | 0.36 | 3.24 | 1.80 |
| MH29 | 7$^{0}$12.483’ | 5$^{0}$33.994’ | 31 | 3.35 | 0.14 | 1.26 | 0.70 |
| MH30 | 7$^{0}$14.373’ | 5$^{0}$26.100’ | 62 | 6.70 | 0.28 | 2.52 | 1.40 |
| MH31 | 7$^{0}$14.370’ | 5$^{0}$26.139’ | 56 | 6.05 | 0.25 | 2.25 | 1.25 |
| MH32 | 7$^{0}$14.384’ | 5$^{0}$26.133’ | 53 | 5.73 | 0.24 | 2.16 | 1.20 |
| MH33 | 7$^{0}$24.630’ | 5$^{0}$03.551’ | 41 | 4.43 | 0.18 | 1.62 | 0.90 |
| MH34 | 7$^{0}$24.710’ | 5$^{0}$03.793’ | 65 | 7.03 | 0.29 | 2.61 | 1.45 |
| MH35 | 7$^{0}$24.742’ | 5$^{0}$3.431’ | 130 | 14.05 | 0.58 | 5.22 | 2.90 |
| MH36 | 7$^{0}$24.727’ | 5$^{0}$3.774’ | 67 | 7.24 | 0.30 | 2.70 | 1.50 |
| MH37 | 7$^{0}$24.693’ | 5$^{0}$3.691’ | 92 | 9.95 | 0.41 | 3.69 | 2.05 |
| MH38 | 7$^{0}$16.901’ | 5$^{0}$08.946’ | 32 | 3.46 | 0.14 | 1.26 | 0.70 |
| MH39 | 7$^{0}$26.794’ | 5$^{0}$41.453’ | 58 | 6.27 | 0.26 | 2.34 | 1.30 |
| MH40 | 7$^{0}$26.799’ | 5$^{0}$41.468’ | 56 | 6.05 | 0.25 | 2.25 | 1.25 |
| MH41 | 7$^{0}$27.299’ | 5$^{0}$41.733’ | 154 | 16.65 | 0.69 | 6.21 | 3.45 |
| MH42 | 7$^{0}$27.302’ | 5$^{0}$41.734’ | 66 | 7.14 | 0.29 | 2.61 | 1.45 |
| MH43 | 7$^{0}$40.279’ | 4$^{0}$08.129’ | 42 | 4.54 | 0.19 | 1.71 | 0.95 |
| MH44 | 7$^{0}$37.994’ | 4$^{0}$11.259’ | 47 | 5.08 | 0.21 | 1.89 | 1.05 |
| MH45 | 7$^{0}$37.646’ | 4$^{0}$10.183’ | 32 | 3.46 | 0.14 | 1.26 | 0.70 |
| MH46 | 7$^{0}$46.065’ | 4$^{0}$23.774’ | 71 | 7.68 | 0.32 | 2.88 | 1.60 |
| MH47 | 7$^{0}$46.118’ | 4$^{0}$23.690’ | 74 | 8.00 | 0.33 | 2.97 | 1.65 |
| MH48 | 7$^{0}$46.061’ | 4$^{0}$23.620’ | 86 | 9.30 | 0.38 | 3.42 | 1.90 |
| MH49 | 7$^{0}$46.066’ | 4$^{0}$23.774’ | 79 | 8.54 | 0.35 | 3.15 | 1.75 |
| MH50 | 7$^{0}$46.012’ | 4$^{0}$23.600’ | 102 | 11.03 | 0.45 | 4.05 | 2.25 |
| MH51 | 7$^{0}$46.041’ | 4$^{0}$23.649’ | 51 | 5.51 | 0.23 | 2.07 | 1.15 |
| MH52 | 7$^{0}$44.364’ | 4$^{0}$25.925’ | 115 | 12.43 | 0.51 | 4.59 | 2.55 |
| MH53 | 7$^{0}$43.783’ | 4$^{0}$26.149’ | 93 | 10.05 | 0.41 | 3.69 | 2.05 |
| MH54 | 7$^{0}$44.471’ | 4$^{0}$25.718’ | 43 | 4.65 | 0.19 | 1.71 | 0.95 |
| | | AM | 76 | 8.24 | 0.34 | 3.06 | 1.70 |
| | | SD | 36 | 3.91 | 0.16 | 1.44 | 0.80 |
| | | GM | 68 | 7.34 | 0.30 | 2.72 | 1.51 |

ness, geometric means versus median values (almost equal) for each group (bedrooms, living rooms, and representatives) of the measured radon concentration in Table 1 , the Shapiro-Wilk test for normality in the Table 2 ($P<0.05$), and the visual inspection of the graphs in the Figure 3 (a & c) indicate that the measured indoor radon concentrations do not follow normal distribution but the corresponding log-transformed values are normally distributed, Figure 3 (b & d) and Table 2 ($P > 0.05$). This is in agreement with the outcome of similar studies around the globe [56–58].

According to Mile *et al.* [59] and Lee *et al.* [60], the log-normal distribution nature of indoor radon is attributed to mul-

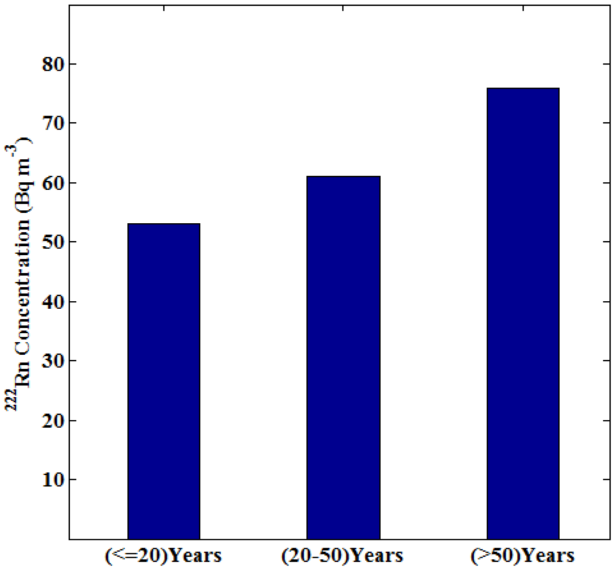

Figure 4. The building age groups.

tiplicative effects of factors independently influencing its concentrations. Such factors are the radium contents in the surrounding soil and rocks, the permeability of the rocks and soil, climatic conditions, the inhabitant's behaviour, and the ventilation system, to mention but a few. The indoor radon representative value for each of the houses was computed by taking the average values of the measured radon concentration from the bedroom and the corresponding concentration from the living rooms, and a similar procedure was applied to calculate the representative value for each house with a pair of readings from the bedroom in houses without living rooms. The representative value of radon concentrations in surveyed houses with single readings due to detector losses was calculated by conducting an Analysis of Covariance (ANCOVA) to compare the means of radon concentration in the rooms. In this case, the room types represented the independent variable with two levels (bedrooms and living rooms), and the log transformed radon concentrations represented the dependent variable, while a confounding factor for radon concentration, that is, the age of the buildings, was controlled for as the covariate.

The outcome of the analysis showed that there was no statistically significant difference between the concentrations of radon based on the room types of the surveyed houses ( $P > 0.05$) and therefore a measured radon concentration in a bedroom was used as a representative (average) radon value in each of the houses with no reading from the living room due to losses [56, 57]. The mean (representatives) indoor radon concentrations of the surveyed houses, 1(2%), 6(11%), 14(26%), 13(24%), 7(13%), 5(9%), 5(9%), 2(4%), and 1(1%) of the surveyed mud houses are in the range of 1-20, 21-40, 41-60, 61-80, 81-100, 101-120,1 21-140,141-160 and 161-180 Bq m$^{-3}$ respectively as shown in Figure 3(e). This variation may not be unconnected to the radium contents of the surrounding soil and rocks (local geology) of the study area, and ventilation [19]. In Table 3, the site locations denoted by MHs, the geographical coordinates, the mean radon values (representatives) for all the surveyed mud houses, the potential alpha energy concentration (PAEC) in WL, the exposure (EP) in WLM, Annual effective Dose in mSv, and the lifetime excess absolute risk (LEAR) are presented. It can be observed that radon concentrations ranged from 17 Bq m$^{-3}$ to 174 Bq m$^{-3}$ with the arithmetic mean 76 Bq m$^{-3}$ (SD = 36) and the geometric mean 68 Bq m$^{-3}$ (GSD = 1.65). The mean values are lower than the reference level (100 Bq m$^{-3}$) recommended by WHO [10], while 13 (24%) and 3 (6%) of the mud houses have radon concentration levels that exceed the WHO's reference level and the USEPA's action level, 148 Bq m$^{-3}$, [12] respectively, whereas none of the radon concentrations in the surveyed houses exceed the reference level (300 Bq m$^{-3}$) suggested by ICRP [2].

The high levels of radon concentration recorded in some of the houses may be accounted for by inadequate ventilation system and the living habits of the inhabitants. The arithmetic mean of radon concentration in this study is 91% higher than the world's average value, 40 Bq m$^{-3}$ [1, 61]. It is also found to be higher than the mean values of 67.7, 69.5, and 7.1 Bq m$^{-3}$ reported for mud houses at Coonoor (Indian), Nilgiri Mountain (India) and the entire Korea, respectively. But the mean value is less than the mean values recorded for mud houses, 114.9 Bq m$^{-3}$ in the city of Lahore and the village of Wagha, Pakistan, 115.17 Bq m$^{-3}$ in the hilly and earthquake prone areas in India; and 152.0 Bq m$^{-3}$ in the Northern Rajasthan of India [15, 30, 47, 62–64]. On the basis of the surveyed building age, the buildings were categorised into new buildings (age <= 20 years), old buildings (age between 20 and 50 years) and very old buildings (age > 50 years) as shown in Figure 4. Results show that the older the building, the higher the indoor radon concentrations.

Inadequate ventilation and high levels of cracks and fissures that characterised the walls and floors of the older buildings could be responsible for the higher radon levels in the older buildings as compared with the new ones [65]. An analysis of variance (ANOVA) was conducted to ascertain whether the new buildings, old buildings, and the very old buildings differ with respect to their indoor radon concentrations. The dependent variables (indoor radon concentration) under the independent variable with the three levels (new buildings, old buildings, and very old buildings) were statistically normal using the Shipro-Wilks test. However, Levene's F test indicated that the data did not meet the assumption of homogeneity of variance ($P = .026$), hence the use of Welch's F test. The results from the analysis of variance (One-Way) show that there is a statistically significant difference among the building groups (new buildings, old buildings, and very old buildings) on the measured indoor radon concentrations, Welch's $F(2, 31.02) = 7.73$, $P < .05$, $\omega^2 = 0.20$. The omega squared ($\omega^2$) shows that 20% of the variability of the dependent variable (indoor radon concentrations) is accounted for by the age of the buildings. Based on the results of this study, it is therefore suggested that mitigation measures such as coating the walls and floors of the old mud buildings with cement plasters or distempers and improving the ventilation systems of the buildings should be put in place in the study

Table 4. Comparison of Annual effectives in this study with other reported findings from Nigeria and around the globe.

| Countries | Predominant building materials & Locations | Devices/ Detectors | Valid sample sizes | Measurement Durations | AED (mSvy$^{-1}$) | Sources |
|---|---|---|---|---|---|---|
| Nigeria | Mud (Residential) | CR-39 | 54 | 6 months | 3.06 ± 1.44 | This study |
| | General building materials (Offices) | CR-39 | 24 | 3months | 1.85 | [20] |
| | General building materials(Offices & classrooms) | CR-39 | 35 | 3months | 0.32 ± 0.20 | [27] |
| | General building materials (School offices) | Pro3 Radon Detector | 10 | 2 days per reading | 0.13 | [25] |
| | General building materials (Residential) | CR-39 | 77 | 6 months | 6.4 | [19] |
| | General building materials(Fertilizer warehouses) | Electret Ion Chamber | 12 | 2-7 days | 0.87 | [23] |
| | General building materials (Residential) | CR-39 | 59 | 5months | 1.0 ± 1.5 | [26] |
| | General building materials(Offices & classrooms) | CR-39 | 25 | 3months | 1.14 | [22] |
| | General building materials (Offices) | CR-39 | 100 | 2months | 4 ± 1 | [21] |
| Other countries | | | | | | |
| Pakistan | Mud (Residential) | CN-85 | 60 | 3months | 2.54 | [30] |
| India | Mud (Residential) | LR-115, Type II | NA | 100days | 1.98 ± 0.22 | [15] |
| India | Mud (Residential) | LR-115 | 42 | 12months | 5.2 | [66] |
| Kenya | Mud (Residential) | CR-39 | 20 | 3 Months | 13.7 | [44] |
| India | Mud (Residential) | LR-115 | | 3 months | 4.9 ± 1.3 | [43] |
| Turkey | Reinforced Concrete (Residential) | CR-39 | 109 | 120 days | 0.9 | [67] |
| Portugal | General building materials (Residential) | CR-39 | 185 | 2months | 15 | [61] |
| Pakistan | General building materials (Residential) | CR-39 | 210 | 3months | 3.49 ± 0.14 | [68] |
| Iran | General building materials (Residential) | CR-39 | 28 | 3months | 1.30 ± 0.65 | [69] |
| India | General building materials (Residential) | LR-115 | 35 | 3months | 0.42 | [70] |
| Saudi Arabia | General building materials (Residential) | CR-39 | 100 | >100 days | 1.51 ± 0.8 | [71] |
| Bulgaria | General building materials (Residential) | CR-39 | 2778 | 12months | 5.2 | [72] |
| Libya | General building materials (Residential) | CR-39 | 50 | 3months | 4.6 | [73] |
| Macedonia | General building materials (Residential) | CR-39 | 437 | 3months | 2.1 | [74] |

area [17].

A post hoc comparison (Games-Howell post hoc) was conducted, was conducted, and the test indicates that mean value for the new buildings (M= 54.0, SD = 9.3) were statistically different from the very old buildings (M= 83.16, SD =35.31), whereas the old buildings (M = 72.5, SD = 41.0) was not significantly different from either of the other groups (new buildings, and very old buildings). The equilibrium factor between radon and its decay products (polonium-218 and polonium-214) can fluctuate due to various variables, such as ventilation and humidity, among others. Since the radon progeny pose a greater percentage of the radon exposure hazard, potential alpha energy concentrations (PAEC) are usually computed to account for their detrimental effects. Table 3 shows the computed PAEC, which varies from 1.84 to 18.81 mWL with a mean value of (8.24 ± 3.91) mWL and a GM value of (7.34 ± 1.65) mW. The mean value is lower than the 29.7 ± 0.8 mWL reported by Shakir *et al.* [48] for four rural districts in northern India, characterised by predominantly mud-built homes. In contrast, Sivakumar [48] found a maximum value of 8.01 mWL in residential mud-built houses during winter at the Nilgiri Mountain Range in South India. Also Table 3 shows estimated EP, and AED values ranged from 0.08 to 0.77 WLM with a mean value of (0.34 ± 0.16) WLM and a GM value of (0.30 ± 1.65) WLM, from 0.72 to 6.93 mSv y$^{-1}$ with a mean value of (3.06 ± 1.44) mSv y$^{-1}$ and a GM value of (2.72 ± 1.65) mSv y$^{-1}$ respectively. The maximum value of AED obtained was found in MH15 and the minimum in MH25. The mean AED value obtained, 3.06 mSv y$^{-1}$, is over 400% higher than the mean values of 0.47 mSv y$^{-1}$ and 0.67 mSv y$^{-1}$ presented by Usikalu *et al.* [45] in their study conducted in Ibadan, Oyo State, Nigeria, and the mean value of 0.67 mSv y$^{-1}$ reported by Chege *et al.* [44] from Mrima, Kenya, in mud dwellings, respectively. This value is over 100% higher than the 2.45 mSv y$^{-1}$ reported by Mahmood *et al.* [30] from Pakistan for their investigated THMs and the 1.98 mSv y$^{-1}$ value recorded by Kant *et al.* [15] in India, respectively.

However, it is 59 %, 75%, and 62% less than the mean values reported from other parts of India [43, 66]. The observed variations may be attributed to factors such as measuring techniques, sample size, period of measurement, and living habits, among others [75]. The estimated annual effective doses, AED for all the investigated mud houses in this study are less than the recommended reference level of 10 mSvy$^{-1}$. Table 4 shows the overall mean annual effective dose being compared with reported values of indoor radon measurements, first from Nigeria and second from other selected countries in the world. Under predominant building materials, the general building materials refer to common building materials such as cement blocks, concrete, gypsum, clay bricks, gravel, granites, cements, and gravel from which buildings are made using two or more combinations of the materials. The life-time excess absolute risks of the population in the study area vary from 0.4 x 10$^{-4}$ to 3.9 x 10$^{-4}$ with a mean value of 1.7 ± 0.8 x 10$^{-4}$ that is, 0.02 % which is far below approximately 4% of the obtained value of lifetime risk of lung cancer resulting from chewing and smoking cigarettes [76].

## 4. Conclusion

Measurements of indoor radon ($^{222}$Rn) levels and its progeny were conducted in some selected houses built of mud in southwestern Nigeria using passive radon detectors, specifically CR-39 detectors. Although 13 (24%) and 3 (6%) of the surveyed houses had radon concentration levels higher than the reference levels of WHO (100 Bq m$^{-3}$) and action level of EPA (148 Bq m$^{-3}$) respectively, the mean values, AM = 76 Bq m$^{-3}$ and GM = 68 Bq m$^{-3}$ were less than the action and reference levels. Building age and inadequate ventilation were observed to have influenced radon concentrations in the surveyed houses, as some buildings have higher radon level than the others. While the observed overall annual effective dose (3.06 mSv y$^{-1}$) is 166% higher than the global mean value of 1.15 mSv y$^{-1}$

[1], the mean value lies within the range of the reference level of 10 mSv $y^{-1}$ recommended by ICRP, (2010). The estimated Potential Alpha Energy Concentration (PAEC) due to its progeny ranged from 1.84 to 18.81 mWL, with an average value of 8.24 mWL (SD=3.91). The mean value of the lifetime excess absolute risks of the population is $1.7 \pm 0.8 \times 10^{-4}$ that is, 0.02 % which is far below 4% of the obtained value of lifetime risk of lung cancer resulting from chewing and smoking cigarettes [68]. It is recommended that the ventilation systems in some of the surveyed buildings be improved, or the use of mud houses with ages greater than 50 should be discouraged.

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