PRINT ISSN 1119-8362
Electronic ISSN 2659-1499

Full-text Available Online at
https://www.ajol.info/index.php/jasem
https://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 29 (3) 831-840 Mar. 2025

Effect of Chronic Exposure to Low-Level Radon Gas from Tertiary Institutions Workplaces in Western Nigeria

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ABSTRACT: The carcinogenic effect of exposure to radon on human health is a concern globally. Hence, the objective of this paper was to assess the effect of chronic exposure to low-level radon gas from tertiary institutions workplaces in Western Nigeria using dosimetric and Monte Carlo simulation (MCS). Data obtained show that 84.09% of 132 workplaces investigated are within 100 Bqm^{-3} (0.01 WL) action level recommended for indoor radon. The average values obtained for the estimation of excess lifetime cancer risk at each studied institution ranged from 0.28% to 0.50% for the dosimetric method and 0.32% to 0.58% for the probabilistic method. The sensitivity analysis revealed that annual occupational exposure to radon decay products is the highest contributor to the risk estimate, followed by the mean life time duration, while the risk factor contributes least. Thus, chronic exposure to low-level indoor radon can lead to lung cancer, most especially for a non-smoker, at a certain stage in life if adequate precautionary measures are not taken to reduce the concentration of indoor radon. Hence, the use of air conditions should be minimized at the workplaces by cultivating a healthy life style of allowing sufficient diffusion of indoor radon-induced air with outdoor air.

DOI: https://dx.doi.org/10.4314/jasem.v29i3.19

Cite this Article as: ONI, E. A; AYANLOLA, P. S; AREMU, A. A; OLADAPO, O. O; LAWAL. M. K (2025) Effect of Chronic Exposure to Low-Level Radon Gas from Tertiary Institutions Workplaces in Western Nigeria. *J. Appl. Sci. Environ. Manage.* 29 (3) 831-840

Dates: Received: 21 February 2025; Revised: 10 March 2025; Accepted: 18 March 2025; Published: 31 March 2025

Keywords: Low-level radon-222; workplaces; chronic exposure; cancer risk; dosimetric; Monte Carlo simulation

In ensuring healthy life style and promote well-being for all, the fight against hazardous contaminants in different environmental matrices has been taken serious globally, an activity that conform to goal 3 of the Sustainable Development Goals (SDGs). However, the ability of human to alter its immediate environment has led to the disruption of the earth's constituents thereby bringing naturally occurring radioactive materials (NORMs) in close proximity to humans (UNSCEAR, 2000). These actions have been continually exposing humans to ionizing radiation (IR), even at low-level (UNSCEAR, 2000; WHO, 2009; ICRP, 2014). Findings revealed that 98% of the radiation dose received by humans emanate from natural sources while the remaining 2% result from artificial sources. Out of this 98%, 52% of the exposure results from radon gas (UNSCEAR, 2000). Humans are exposed to IR in various ways, and the presence of radon in workplaces is one of them. Workplaces can be either below ground or above ground surface. The below ground workplaces are mining sites, radon spas, subways and show caves (Steinhausler, 1988; Stellungnahme, 1997; UNSCEAR, 2000). Aboveground workplaces include

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schools, offices, shops, and factories (UNSCEAR, 2000). In Nigeria, the government, both at the state and federal level, and several organizations and dignitaries have established public and private tertiary institutions to ensure formal education of its citizen, an action that align with goal 4 of the SDGs. The establishment of the tertiary institutions also led to infrastructure development and job opportunities, while the well-being of the workers is not neglected. However, radiologically, it has been established that high levels of radon exist in dwellings, but it is only relatively recently that attention has been paid to low-level exposure in workplaces other than mines (UNSCEAR, 1988; 2000; Goraczko *et al.,* 2003; Fridman *et al.,* 2016; Dobrzynski and Zarys, 2017; Burgio *et al.,* 2018; Haryes, 2022). Radon-222 (^{222}Rn) is a radioactive and noble gas that cannot be sensed, the gas can propagate into the indoor atmosphere by advection and diffusion from soil, building materials, and emanation from water (UNSCEAR, 1988; 2000) and concentrate in enclosed spaces or poorly ventilated and badly designed dwellings or workplaces.

Thus, inhalation is the principal route of radon exposure of humans (USECEAR, 2008; WHO, 2009) and the gas deposit non-homogeneously and irradiate the respiratory tract (NCRP, 1984; NRC, 1988; ICRP, 1993; UNSCEAR, 1993; 2000). A chronic exposure to low-level radon gas can leads to lung cancer, with the symptoms appearing years later (EPA, 2003; WHO, 2009). The continuous research on radon made World Health Organization (WHO) reports radon as a human carcinogen through the specialized cancer research agency with no minimum acceptable dosage threshold (IARC, 1988; WHO, 2009) with other organization making studies on radon a top priority. However, efforts to reduce the number of lung cancers related to radon exposures have so far only been successful in the developed countries (WHO, 2009) with developing countries, Nigeria inclusive, lacking behind. Hence, there is a need to continually intimate the general public on danger of radon as the public health awareness is yet to have an impact (Pacheco-Torgal, 2012). In the last two decades, studies have been conducted on radon levels both locally and internationally with special focus in workplaces (Gooding *et al.,* 1992; Yu *et al.,* 1997; Virk *et al.,* 2000; Oikawa *et al.,* 2006; Rahman *et al.,* 2006; Kubiak *et al.,* 2023). In Nigeria, a radon concentration ranging from 157 to 495 Bqm^{-3} was reported and found to be within ICRP reference level (Obed *et al.,* 2010). In another study, it was revealed that there is a possible health risk with buildings having direct contact with the basement and poorly ventilated than those that has easy access to natural ventilation (Usikalu *et al.,* 2020). In addition, it was observed that 21.4% of the values obtained for another studied locations were greater than 100 Bqm^{-3} recommended by WHO (Oni *et al.,* 2022). Another similar studied concluded that the level of radon in the studied locations was influenced by the geographical features and age of the buildings (Aremu *et al.,* 2023).

In all the aforementioned studies, emphasizes was laid on quantifying the radon concentrations while few of the studies uses mathematical model to assess the effect of exposure to radon. However, risk estimates of the chronic exposures to radon at low-levels are required to address the potential biological implications on human health, and to also refine the estimates of the risk in workplaces (EPA, 1992). Recently, the use of probabilistic approaches has been incorporated into research to further understand the harmful risks of exposure to contaminant in different environmental matrices (Shahrbabki *et al.,* 2018; Karami *et al.,* 2019; Orosun *et al.,* 2020a; Omeje *et al.,* 2022). Hence, the objective of this paper was to assess the effect of chronic exposure to low-level radon gas from tertiary institutions workplaces in Western Nigeria

MATERIALS AND METHODS

Study Location: Southwestern Nigeria boosts over fifty (50) tertiary institutions comprising both the federal, states and private institutions. Out of which eleven (11) institutions (Figure 1), spreading across the geographical features of the six states were randomly selected based on the permission received to carry out the study and one hundred and thirty-two workplaces were studied.

Quantification of Radon Concentration: The radon concentration was assessed for seven (7) days at each of the study location using Electret Ion Chambers (EIC) system (Rad Elec Inc., USA). The operational details of the device and its application in measuring radon concentration have earlier been described elsewhere (Kotrappa *et al.,* 1990; Kotrappa, 2008; Kotrappa and Steck, 2010; Aremu *et al.,* 2023; Lawal *et al.,* 2023). The concentration of radon gas (C_{Rn}) in air was calculated using Equation 1.

$$C_{Rn}\ (\mathrm{Bq}m^{-3}) = \frac{V_d \times E_p}{C_f} \quad (1)$$

where V_d represent the drop in voltage between the final and initial electret readings, Ep represent the exposure period (7 days) and C_f represent the calibration factor of the detector.

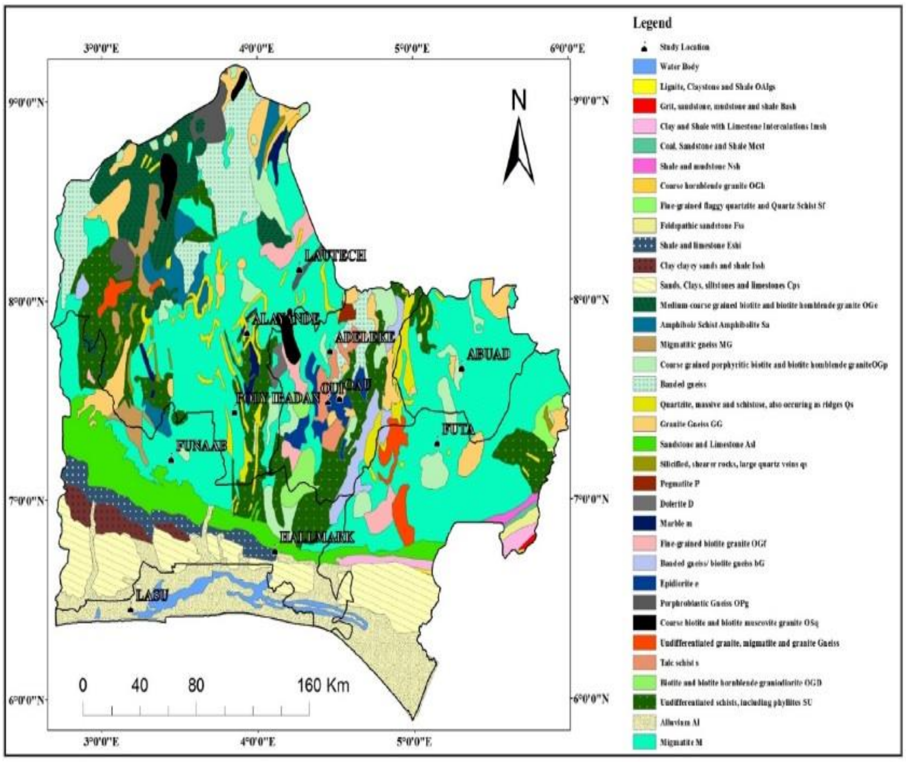

Fig.1: Map showing the study locations.

The concentration later converted to working levels (WL) using Equation 2 since exposure to radon is due mainly to the inhalation of RDPs.

$$WL = \frac{C_{Rn} \times 0.027 \times ER}{100} \quad (2)$$

where C_{Rn} remain as defined by Equation 1 but converted to pCiL^{-1}, with 1 Bqm^{-3} equivalent to 0.027 pCiL^{-1} and *ER* is the radon equilibrium ratio taken to be 0.5 (NRC, 1988; 1999; UNSCEAR, 2000; 2019).

Quantification of Radiological Indices

Annual occupational exposure to RDPs: The cumulative exposure to RDPs is measured in working level month (WLM) expressed by Equation 3:

$$WLM = WL \times 170 \quad (3)$$

Hence, the annual occupational exposure (AOE) to RDPs, typical given in working level months per year (WLMy^{-1}) was obtained by Equation 4.

$$AOE\ (WLMy^{-1}) = \frac{WL \times T}{170} \quad (4)$$

Where T (1920 hy^{-1}) is the annual working hour (IARC, 1988; NRC, 1999).

Annual effective dose due to indoor radon (D_{ef}*):* The present study adopted the ICRP recommendation to estimate D_{ef} using Equation 5.

$$D_{ef}\ (\text{mSv}y^{-1}) = C_{Rn} \times D \times T \quad (5)$$

Where C_{Rn} and T remain as earlier defined, E_f is the indoor equilibrium factor (0.4), and D is the dose conversion factor, 9×10^{-6} mSv/Bqhm^{-3} (UNSCEAR, 2000; 2006; 2019) while 6.7 nSv/Bqhm^{-3} (10 mSv/WLM) was recommended by ICRP Publication 137 (ICRP, 2017). O_f is the occupancy factor, 0.23 (2000/8760).

Annual equivalent dose (D_{eq}*) for lung:* The effective dose quantifies the radiation to the body taking into account the sensitivity of internal organs. However, since Rn-222 is majorly alpha (α) emitting radionuclide, the effective doses from the inhalation of radon isotopes are due largely to the equivalent doses received by the lungs. The dose deposited to lung tissue was estimated using Equation 6.

$$D_{eq}\ (\text{mSv}y^{-1}) = D_{ef} \times R_{wf} \times T_{wf} \quad (6)$$

Where, R_{wf} is the radiation weighting factor, 20 for α particles; T_{wf} is tissue weighing factor, 0.12 for lung (ICRP, 2003).

Excess lifetime cancer risk: The ELCR is the probability that an individual exposure to carcinogenic agent could result in cancer (Freni, 1987; Vaeth and Pierce, 1990; ICRP, 2007). The ELCR due to exposure to RDPs was calculated using Equation 7.

$$ELCR = AOE \times DL \times RF \quad (7)$$

where AOE remain as earlier define in Equation 4, DL represents the mean life time duration (assuming seventy years (70) as the life expectancy of an average Nigerian). RF is the risk coefficient factor, based on Publication 115 of ICRP reviewing the epidemiological data of radon-induced lung cancers, focusing on low levels of exposure and exposure rates in mines, the RF value was 5.0 x 10^{-4} WLM^{-1} (ICRP, 2010).

Lung cancer cases per million people per year (LCC): Lung cancer risk is defined as the excess deaths per million persons per year (My^{-1}) due to lung cancer per unit exposure to radon and its short-lived daughters. It was estimated using Equation 8.

$$LCC = 18 \times 10^{-6} \times D_{eq} \quad (8)$$

Where 18 x 10^{-6} is the risk factor for lung cancer induction in mSv^{-1} (Hashim and Nayif, 2019; Azhdarpoor *et al.,* 2021).

Monte Carlo Estimation of Cancer Risk: The uncertainty in measured radon concentration, rate at which radon gas is inhaled in indoor air per day by the exposed individual at the workplaces, working hours, the mean life time, and radon equilibrium factor are all sources of uncertainty that makes the evaluation of risk assessment somewhat complicated based on the dosimetric approach (EPA, 1992). Thus, the estimation of the cancer risk using the model presented in Equation (7) can either underestimate or overestimates the actual cancer risk (Augustsson and Berger 2014; Orosun *et al.,* 2020a). In view of this, the present study use probabilistic approach by means of the Monte Carlo simulation (MCS) to further predict the risks associated with occupational exposure to RDPs. Monte Carlo simulation is a powerful computational algorithm-based technique that simulate random processes. The algorithm is used to model the probability of different outcomes in a process that cannot be easily predicted due to the intervention of random variables, understand the impact of risk and uncertainty. In addition, this technique has been incorporated into the field of radiation physics to model the behaviour of particles and their interactions with matters. Thus, rather than using one-point value in estimating the cancer risk as presented by the model in Equation (7), the MCS used iterative values based on the input parameter of the model (AOE (min, max and mean values), DL and RF) to repeatedly calculate and predict the cancer risk by interchanging the arrays of values and lastly obtain the result with different assurance levels (1% to 99%). In this present study, the MCS was carried out using Oracle Crystal Ball (version 11.1.3.0.0), a spreadsheet-based application for risk assessment. The simulation was run for 10000 number of iterations. The output of the simulation generates the probability and cumulative probability for the risk analysis and contribution to variance for the sensitivity analysis.

RESULTS AND DISCUSSION

Radon Concentration: Table 1 presents the descriptive summary of the values obtained for the radon concentrations from all the workplaces assessed at each of the study location. The measured radon concentration varies between 7.68 Bqm^{-3} (TI6) and 219.03 Bqm^{-3} (TI3). The distribution of radon is moderately symmetric as evident by the values obtained for the skewness and kurtosis statistics. The estimated coefficient of variability (CV) ranges between 30% and 60%. According to the levels and classification of coefficient of variation, four (4) of the studied locations exhibit moderately distributed indoor radon concentration while the remaining 7 locations exhibit high variability (Isinkaye, 2018; Orosun *et al.,* 2020a; 2020b).

Table 1: Summary of the measured radon concentrations (Bqm^{-3})

Statistics	TI1	TI2	TI3	TI4	TI5	TI6	TI7	TI8	TI9	TI10	TI11
Min	24.22	27.26	35.82	39.31	10.18	7.68	22.40	33.09	27.68	21.61	31.09
Max	112.90	106.03	219.03	136.14	137.56	89.37	145.60	114.18	177.11	146.78	111.61
Mean	51.18	67.10	89.95	85.76	78.77	50.62	64.76	69.07	79.71	75.39	67.46
SD	30.43	24.16	50.62	25.57	46.91	26.32	35.35	27.53	47.01	42.38	26.70
S	1.55	-0.16	1.59	0.24	-0.12	0.16	1.15	0.20	0.92	0.26	0.34
K	1.28	-1.12	3.08	0.69	-1.81	-1.19	1.23	-1.47	-0.10	-1.34	-1.40
CV (%)	59	36	56	30	60	52	55	40	59	56	40

TI1 – ADELEKE; TI2 – OUI; TI3 – OAU; TI4 – ABUAD; TI5 – FUTA; TI6 – HALLMARK; TI7 – FUNAAB; TI8 – LASU; TI9 – LAUTECH; TI10 – POLYIBADAN; TI11 – ALAYANDE; *SD - standard deviation, S – Skewness, K – Kurtosis, CV - coefficient of variation*

The variation recorded can be attributed to the geological differences of the Precambrian base complex on which each tertiary institution was cited and this is in agreement with the results obtained in other related studies (Esan *et al.,* 2020; Oni *et al.,* 2022; Aremu *et al.,* 2023). In addition, it was reported that variation in radon concentrations is shaped by how the workplaces in question is being used, the geographical features on which the buildings where constructed and the influence of external conditions (Kubiak and Basinka, 2023).

Generally, the mean radon concentration is in the order: TI3 > TI4 > TI9 > TI5 >TI10 > TI8 > TI11 > TI2 > TI7 > TI1 > TI6. The highest mean radon concentration was recorded in TI3 with a value of 89.95 Bqm^{-3} located in Osun State while the lowest value was recorded at TI6 (Ogun State) with a value of 50.62 Bqm^{-3}. A comparison of the range of results obtained in this present study to those of other related studies in Nigeria is presented in Table 2. It was observed that the value obtained is within the ranges of values reported.

Table 2: Comparison of the results obtained related studies with present study

Authors	**Results (Bqm^{-3})**
Obed *et al.,* 2010	157 – 495
Okeji *et al.,* 2013	2.50 – 21.30
Afolabi *et al.,* 2013	0 – 196.0
Usikalu *et al.,* 2020	6.62 – 614.52
Present study	7.68 – 219.03

Table 3: Recommended action for exposure to low-level radon concentration (NRC, 1988).

Exposure	Action needed
≤ 0.01 WL	No action is needed
0.01 < WL ≤ 0.05	Remedial action may be suggested
WL > 0.05	Remedial action is needed

Furthermore, the findings showed that 111 workplaces representing 84.09% of the total offices are within the advisory level legally enforce 0.01 WL (100 Bqm^{-3}) in any 8 h period of exposure to RDPs at workplace (WHO, 2009) and United Kingdom respectively (NRC, 1999), 20 offices representing 15.15% are within the 0.02 WL (148 Bqm^{-3}) advisory level by the USEPA, with 1 office (0.76%) having 0.03 WL. In addition, based on the results obtained for the WL, 131 occupants of those offices are exposed to less than 0.24 WLMy^{-1} RDPs as revealed by the mean results for the annual occupational exposure (AOE) to RDPs. Thus, comparing the range of values obtained for exposure to RDPs with the classification in Table 3, it was observed that there is need to take remedial action to minimize the occupational exposure to radon in the assessed workplaces.

Radiological hazard indices: Table 4 shows the results obtained for estimated radiological indices in view of the exposure RDPs. The results obtained for the radon concentration translated to the values obtained for the annual effective dose (D_{ef}) due to exposure radon (0.10 mSvy^{-1} – 2.94 mSvy^{-1}) and annual equivalent dose (D_{eq}) to lungs (0.25 mSvy^{-1} – 7.04 mSvy^{-1}). Although the ICRP recommend 300 Bqm^{-3} as the upper level for exposures to radon in dwellings and workplaces, cumulating to an effective dose limit of 4 mSvy^{-1} for occupational exposure (ICRP, 2014), the results obtained showed that the minimum, maximum and mean values of the annual effective dose for all the 132 offices is less than the upper limit recommended by the ICRP.

However, the probability that an exposure to RDPs could result in cancer ranges from 0.04% to 1.22%. This is evident by the fact that for an average radon concentration of 0.01 WL (100 Bqm^{-3}), the lifetime risk of lung cancer for non-smokers is 0.5% (ICRP, 2010). Thus, the chance that an individual that occupies these offices will develop cancer at a certain stage in life as the risk of cancer increases with increasing radon exposure (UNSCEAR, 2000; ICRP, 2010)· This was further corroborated by the results obtained for the lung cancer cases (LCC), revealing that in the offices of the assessed tertiary institutions, between 4.45 and 126.79 per million persons per year may experience lung cancer cases. This however falls below 170 – 230 per million person's reference level of the ICRP (1993).

Monte Carlo Simulation: Figures 2a and b presents the samples of the pictorial view of the risk assessment (in terms of probability and cumulative probability) and sensitivity analysis (contribution to variance in pie chart) of the probabilistic assessment of cancer risk using MCS approached for all the tertiary institutions. Presented in Table 5 is the 5%, 50% (mean) and 95% assurance level of the simulation for the probabilistic assessment of the cancer risk from the exposure to indoor radon from the workplaces of the assessed institutions using MCS. On the average, the result of the MCS risk (0.32% to 0.58%) conforms to the dosimetric risk value (0.28% to 0.50%) presented in Table 5. The sensitivity analysis presented by the pie chart in Figure 2, reveal how the estimate of the input values in mathematical model (Equation 7) impacts the risk assessment. The sensitivity analysis revealed that each of the input parameters contributed differently to the simulated ELCR and this justify the role played by the age (mean lifetime duration), risk factor and annual occupation exposure to RDPs on the cancer risk assessment. Based on the contribution of variation reported by the sensitivity analysis, it was observed that the highest contributor to the risk estimate is the AOE, followed by the mean life time duration (DL), while the risk factor contributes least.

Table 4: Descriptive summary of the estimated radiological indices.

Location	Statistics	WL	AOE ($WLMy^{-1}$)	Def ($mSvy^{-1}$)	Deq ($mSvy^{-1}$)	ELCR (%)	LCC (My^{-1})
TI1	Min	0.003	0.038	0.325	0.779	0.135	14.023
	Max	0.015	0.179	1.513	3.631	0.628	65.355
	Mean	0.007	0.085	0.719	1.726	0.285	31.067
TI2	Min	0.004	0.043	0.365	0.877	0.152	15.783
	Max	0.014	0.168	1.421	3.410	0.589	61.381
	Mean	0.009	0.106	0.898	2.156	0.373	38.805
TI3	Min	0.005	0.057	0.480	1.152	0.199	20.737
	Max	0.030	0.348	2.935	7.044	1.218	126.789
	Mean	0.013	0.155	1.310	2.905	0.502	52.292
TI4	Min	0.005	0.062	0.527	1.264	0.219	22.757
	Max	0.018	0.216	1.824	4.378	0.757	78.811
	Mean	0.012	0.137	1.153	2.767	0.477	49.808
TI5	Min	0.001	0.016	0.136	0.327	0.057	5.891
	Max	0.019	0.218	1.843	4.424	0.765	79.630
	Mean	0.011	0.124	1.046	2.511	0.438	45.194
TI6	Min	0.001	0.012	0.103	0.247	0.043	4.448
	Max	0.012	0.142	1.198	2.874	0.497	51.735
	Mean	0.007	0.080	0.674	1.618	0.281	29.130
TI7	Min	0.003	0.036	0.300	0.720	0.125	12.967
	Max	0.020	0.231	1.951	4.682	0.809	84.285
	Mean	0.009	0.107	0.905	2.171	0.360	39.079
TI8	Min	0.004	0.053	0.443	1.064	0.184	19.156
	Max	0.015	0.181	1.530	3.672	0.635	66.096
	Mean	0.009	0.111	0.934	2.242	0.384	40.360
TI9	Min	0.004	0.044	0.371	0.890	0.154	16.023
	Max	0.024	0.281	2.373	5.696	0.985	102.524
	Mean	0.011	0.127	1.111	2.668	0.443	48.017
TI10	Min	0.003	0.034	0.290	0.695	0.120	12.507
	Max	0.020	0.233	1.967	4.720	0.816	84.969
	Mean	0.010	0.122	1.027	2.465	0.419	44.372
TI11	Min	0.004	0.049	0.417	1.000	0.173	17.998
	Max	0.015	0.177	1.496	3.589	0.620	64.608
	Mean	0.009	0.108	0.904	2.187	0.375	39.372

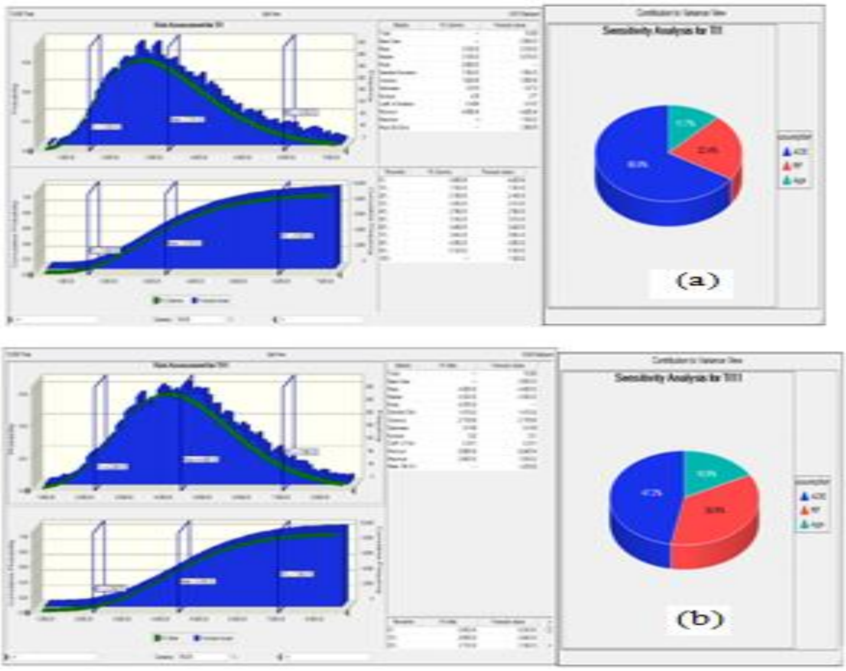

Fig.2: Sample of the cumulative probability and sensitivity analysis plot of the risks from exposure to RDPs (a) T11 (b) T111

Table 5: Assurance level of the Monte Carlo simulation

Percentile	TI1	TI2	TI3	TI4	TI5	TI6	TI7	TI8	TI9	TI10	TI11
5%	0.152	0.201	0.239	0.242	0.193	0.112	0.189	0.222	0.221	0.206	0.224
Mean	0.331	0.420	0.582	0.479	0.497	0.315	0.428	0.443	0.523	0.504	0.445
95%	0.593	0.679	1.12	0.794	0.845	0.536	0.753	0.705	0.935	0.849	0.705

It is pertinent to mention that, the retirement age for non-academic and academic staff in Nigeria tertiary institution is 65 and 70 years respectively, cumulating to between 30 - 35 years of works. Thus, the cumulative exposure to low-concentration of radon and its progeny at the workplace for such working years (long period) can manifest into lung cancer, and with the symptoms appearing years later evening after leaving the place of work (EPA, 203; WHO, 2009). Although the occupancy rate is lower compare to that of the dwellings, however, the results obtained revealed that there is need for proper monitoring of radon levels in workplaces. This is because; a lifetime of exposure to radon at 100 Bqm^{-3} increases the risk of lung cancer by 0.1% for non-smokers, and 2% for smokers (ICRP, 2010). In addition, findings revealed that radon and its decay products have been found to be responsible for 40 – 50% of total lifetime exposure of a person to health problems (UNSCEAR, 2000) and that 3 – 14% of all lung cancers in a country result from exposure to radon gases, depending on the average radon level and the smoking prevalence in a country (WHO, 2009). Thus, the long-time effect of chronic exposure to low-level radon concentration is dangerous as high and low doses of radiation cause significant health effects, with health effects for low doses likely to occur in subsequent decades and generations (Burgio *et al*., 2018).

Conclusion: Based on the analyses carried out and going by the WHO recommendation of communicating the risk associated with radon to different audiences and recommending appropriate action of reducing radon concentration. Hence, recommendation to reduce radon exposure in workplaces include: (1) the use of air conditions should be minimized by cultivating a healthy life style of allowing sufficient diffusion of indoor radon-induced air with outdoor air (2) similar studies in other tertiary institutions located in different parts of the country should be carried out so as to intimate the workers about how safe they are at the place of work (3) the workers and general public should be enlightened and educated on the health implications of exposure to radon (4) as being practice in the developed countries, a national radon policy should be set to focus on identifying geographical areas where the workers and general public are most at risk from exposure to radon.

Declaration of conflict of interest: The authors declare no conflict of interest in this work.

Data Availability Statement: Data are available upon request from the first author or corresponding author or any of the other authors.

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