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Evaluation of Radioactivity Levels in the Federal University Otuoke Laboratories, Bayelsa State, Nigeria

Uzochukwu Leonard Anekwe and Kingsley Onuegbulem Munonye
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Abstract : *The study of Background Ionizing Radiation (BIR) was carried out on the Laboratories in the Federal University Otuoke to ascertain the radiation dose levels and estimate its associated health hazards. The measurement was conducted indoor using Global Positioning System and Geiger Counter Nuclear Radiation Detector. The average radiation dose level was recorded in micro-sieverts per hour. The dose rate results obtained ranged from 0.113 µSv/h at physics laboratory 2 store to 0.250 µSv/h at chemistry laboratory 1 with an average value of 0.184±0.03 µSv/h. The dose rate values were used to compute the Annual Effective Dose Equivalent, Excess Lifetime Cancer Risk and Effective Dose to Different Body Organs. Hence, the computed AEDE value range from 0.792 mSv/y at physics laboratory 2 store to 1.752 mSv/y at chemistry laboratory 1 with average value of 1.289± 0.04 mSv/y. Also, the average value obtained from ELCR was* $3.33 \pm 0.01 \times 10^{-3}$*. The average values of AEDE and ELCR were slightly above the recommended limit of 1.0 mSv/y and* 0.29×10^{-3} *respectively. The estimated average values of effective dose to different body organs were found to be 0.660±0.03, 0.598±0.01, 0.712±0.02, 0.846±0.02, 0.625±0.03, 0.474±0.01 and 0.704±0.04 mSv/y for lungs, ovary, bone marrow, testes, kidney, liver, whole body respectively. The results showed that testes are more sensitive than others while liver are less sensitive to radiation dose. The results were all below the permissible limit of 1.0 mSv/y indicating that workers and users of the laboratories are safe as it does not constitute any instant and excessive health risk.*

Keywords*: Radioactivity, Indoor background radiation, Dose levels, Laboratories, Dorgan*

Uzochukwu Leonard Anekwe
Department of Physics, Federal Universty Otuoke, Nigeria.
Email: uzanekwe@yahoo.co.uk
Orcid id*:* https://orcid.org/0000-0003-0554-8617

Kingsley Onuegbulem Munonye
Department of Physics, Federal Universty Otuoke, Nigeria.
Email:

1.0 Introduction

Radioactivity is the number of natural disintegrations per second of a radioactive substance (Eddy *et al*., 2025a). Radioactivity occurs naturally in the environment; hence everyone is exposed to radiation from natural radioactive substance (Eddy *et al*., 2025b). According to UNSCEAR (2000), the level of natural environmental radioactivity and its associated exposure due to gamma radiation differs in each region of the world and depend on the geological and geographical conditions of the area. In addition, anthropogenic activities involving the use of radiation and radioisotopes in laboratory, research centre, agriculture, industry and medicine create changes in environmental radioactivity hence elevating the radiation exposure dose levels (Obed *et al*., 2005). Evaluation of radiation dose level of an area is essential for baseline documentary reference and in determining the radiological health risk to an individual. Humans can as well be exposed to radiation through the intake of contaminated food due to direct root uptake from polluted soil, deposition of radionuclides on plant leaves and ingestion of contaminated water (Arogunjo *et al*., 2004; Avwiri and Agbalagba, 2007). The continuous exposure to even low level of natural ionizing radiation to humans has been a cause of concern and may have adverse effect on human health (Xinwei and Xiaolan, 2006; IAEA, 2006). Natural sources include cosmic rays, radiation from radioactive elements like uranium, thorium, and potassium in the earth's crust, and radon gas. Human activities, such as medical treatments (applications of x-rays), nuclear power production, and the use of radioactive materials in industries, agriculture and laboratories contribute to artificial sources (Ike, 2003). Radiation has both beneficial and harmful effects and is present in various forms and intensities in our daily lives. Some of the harmful effects are: cancer, cataract, gene mutation, destruction of bones and blood cells and it can cause the death of an individual (Ogola *et al*., 2016). Soil and rock are significant sources of radiation exposure. Radon gas from the earth's crust is the most common natural source of radiation. To protect humans and wildlife, the International Commission on Radiation Protection (ICRP) set a limit of 1.00 millisievert per year (mSv/yr) for radiation exposure (ICRP, 2007), while the United Nations Scientific Committee on the Effects of Atomic Radiations recommended an average annual exposure for humans worldwide to be approximately 2.4 millisieverts (240 millirems) for indoor areas such as offices, laboratories, and lecture halls (UNSCEAR, 2000).

In the laboratory, background radiation present may affect measuring instruments when specific radiation source samples are measured. Radiation detection instruments can be affected by background radiation, which can impact their accuracy. For instance, a scintillation detector used for surface contamination monitoring may be affected by background gamma radiation, this can elevate the reading and potentially make the instrument unfit for use in background radiation measurement. This aligns with the International Atomic Energy Agency's definition of background radiation as the dose rate attributable to all sources except the specific one being measured (IAEA, 2006). Radiation measurements are conducted at various levels, including government agencies. Ionizing radiation is a wide physical process that pervade our environment. Federal University Otuoke, like many other research institutions, have various laboratories that utilize radiation-emitting equipment and materials, which may contribute to the background radiation levels in these areas. Certain products used in laboratory Centre contain nuclides that emit radiation at varying levels, potentially contributing to an increase in background radiation. In addition, building materials used in constructing the laboratory can contribute to radiation exposure to humans, springing up from primordial radionuclides in building materials due to external radiation or radon inhalation coming from internal radiation (Ngachin *et al*., 2007). This study aims to investigate the indoor measurement of background ionizing radiation in Federal University Otuoke laboratories, providing valuable data and insights that could provide radiation policy formulation and guidelines for the institution.

2.0 Materials and Method

The indoor background radiation levels of Federal University Otuoke laboratories were surveyed using a Digital Radiation Meter (Radiation Inspector Alert-200). The Geiger-Müller (GM) counter was calibrated following the manufacturer's specifications to ensure accuracy in detecting and measuring ionizing radiation. The GM counter tube was connected to a Geiger Counter Nuclear Radiation Detector. Ionization occurs when each ray passes through the GM tube; thus, a pulse is generated, amplified by the electronic circuit, and recorded as a count. The Nuclear Radiation Detector is powered by a rechargeable battery, a 5V adapter, or a USB cable. The meter can detect beta, gamma, and x-rays within an energy range of 20 keV to 3.0 MeV. It is capable of measuring minute changes in radiation levels and has high sensitivity. The instrument has a testing accuracy of ±0.1 μSv/h and a cumulative measurement range of 0–99.9 Sv/h. Its operating temperature range is –20 to 60 °C, and the battery service life is approximately 2–3 hours. The displayed value of this dosimeter corresponds to the count value in the mode selected (Radalert-200 User's Manual, 2007), as recommended by the manufacturers of the GM Counter (Ebong and Alagoa, 1992). A Global Positioning System (GPS) device was used to capture precise location coordinates and determine the geographical positions of the measurement sites.

2.1 Study Area / Location

The Federal University Otuoke (FUO) is a citadel of learning and research located in Ogbia Kingdom, Bayelsa State, Nigeria. It operates many research laboratories that make use of radioactive materials. For instance, radiochemical laboratories utilize sealed radioactive sources in x-ray diffraction, electron microscopy, and sterilization processes. The area experiences a tropical climate characterized by high humidity and rainfall throughout the year. The region is predominantly covered by mangrove forests and is intersected by numerous creeks and rivers. Geologically, it is part of the Niger Delta basin and is composed of sedimentary rocks, contributing to nearly flat topography that slopes slightly towards the sea. The area is endowed with mineral resources such as clay, gypsum, lead, zinc, lignite, limestone, manganese, oil, gas, and uranium. Ogbia (the survey area) is a Local Government Area in Bayelsa State, Nigeria, bounded between latitude 4° 33′ N and 4° 45′ N, and longitude 6° 15′ E and 6° 29′ E. It is about 20 meters above sea level with a population of over 179,926 (Alagoa, 2005; Short *et al*., 1967).

2.2 Background Dose Measurement

Dose rate measurements of indoor background radiation in air were carried out using the Geiger-Müller counter (Radiation Inspector Alert-200). To measure radiation, the GM counter tube was connected to a Geiger Counter Nuclear Radiation Detector. Ionization occurs when radiation passes through the GM tube; hence, a detection current pulse is generated, amplified, and recorded as a count. The original method of measuring background ionizing radiation was adopted, where the survey meter was positioned at a height of 1.0 meter above the ground level, facing potential radiation sources. At each point, the total count was recorded for 20 seconds (Rafique *et al*., 2014). Three measurements were taken at each location, and the average values were recorded in units of μSv/h. Repeated measurements were conducted to ensure accuracy and to minimize potential errors arising from fluctuations in environmental radiation levels (Agbalagba, 2017).

2.3 Evaluation of Annual Effective Dose Equivalent (AEDE)

The average background ionizing radiation dose rate (μSv/h) obtained was used to compute the annual effective dose equivalent (AEDE) using the mathematical model expressed in equation 1

$$\text{AEDE (mSv/y)} = DR \times T \times OF \times 10^{-3} \qquad (1)$$

where DR is the absorbed dose rate measured in μSv/h, OF is the indoor occupancy factor, defined as 0.2 and T is the total hours in a year (24 × 365 = 8760 h) (UNSCEAR, 2000; Ramli *et al*., 2014; Jindal *et al*., 2018).

2.4 Excess Lifetime Cancer Risk (ELCR)

To assess the cancer risk associated with workers' exposure to background radiation at Federal University Otuoke laboratories, the Excess Lifetime Cancer Risk (ELCR) was computed using Equation (2). ELCR is a health risk evaluation parameter used to predict the probability of an individual developing cancer from lifetime exposure to low-level ionizing radiation:

$$\text{ELCR } (\times 10^{-3}) = \text{AEDE} \times DL \times RF \qquad (2)$$

where AEDE is the annual effective dose equivalent, DL is the average duration of life (taken as 50 years) and RF is the cancer risk factor per Sievert (Sv^{-1}).

According to the International Commission on Radiological Protection (ICRP, 2007), a cancer risk factor of 0.05 Sv^{-1} is recommended for public exposure to low-level background radiation.

3.0 Results and Discussion

Table 1 presents the measured indoor exposure dose rates, the calculated annual effective dose equivalent (AEDE), and the excess lifetime cancer risk (ELCR) for the various laboratories at the Federal University Otuoke, Bayelsa State. The dose rate values ranged from 0.113 µSv/h in Physics lab. 2 Store to 0.250 µSv/h in Chemistry lab. 1, with an overall mean of 0.184 ± 0.03 µSv/h. When compared to the recommended global average of 0.274 µSv/h for indoor environments, all measured values fall below this threshold. This indicates that the background radiation levels in the university laboratories are generally within acceptable safety limits for routine occupational exposure. The variation in dose rates across laboratories may be attributed to differences in laboratory construction materials, ventilation, and the presence of equipment that may contain trace amounts of naturally occurring radionuclides. For instance, laboratories such as Chemistry lab. 1 and Physics lab. 1 Store recorded relatively higher dose rates, which may suggest contributions from building materials rich in radionuclides such as potassium-40, thorium, or uranium series isotopes, or the presence of stored chemicals and experimental residues that could enhance localized radiation levels. On the other hand, lower values in laboratories like Biology lab. 1 and Physics lab. 2 Store may be due to better ventilation, reduced occupancy, or the absence of radionuclide-rich materials.

Although the measured dose rates are below the international safety benchmark, the calculated AEDE values reveal more nuanced insights. AEDE values ranged between 0.792 mSv/y and 1.752 mSv/y, with a mean of 1.289 ± 0.04 mSv/y. This average exceeds the recommended dose limit of 1.0 mSv/y for the general public but remains well below the 20 mSv/y occupational limit for radiation workers, as set by the International Commission on Radiological Protection (ICRP). This suggests that while exposure levels are not of immediate concern, long-term exposure, particularly for laboratory staff who may spend prolonged periods in these facilities, could result in cumulative doses approaching higher risk thresholds.

The corresponding ELCR values provide a measure of potential stochastic health effects, such as cancer risk, associated with prolonged exposure. The ELCR ranged from 2.505 $\times10^{-3}$ to 4.380 $\times10^{-3}$, with a mean of 3.333 $\times10^{-3}$. This is significantly higher than the world average of 0.29 $\times10^{-3}$, indicating a slightly elevated lifetime cancer risk among individuals who frequently use these laboratories. Although this does not imply an immediate health hazard, it underscores the importance of maintaining radiation monitoring systems, implementing radiation awareness programs, and encouraging practices that minimize unnecessary occupancy in higher-dose environments.

Taken together, the results from Table 1 demonstrate that while the indoor radioactivity levels in Federal University Otuoke laboratories do not exceed global permissible limits for dose rates, the slightly elevated AEDE and ELCR values highlight the need for cautious management. Regular assessment of radiation levels, coupled with preventive occupational health measures, will be essential to ensure that long-term exposures remain within safe boundaries and that laboratory users are adequately protected.

The calculated AEDE ranged from 0.792 mSv/y to 1.752 mSv/y, with a mean value of 1.289 ± 0.04 mSv/y. Although this is slightly above the recommended standard of 1.0 mSv/y for the general public, it remains significantly lower than the occupational exposure limit of 20 mSv/y recommended by the International Commission on Radiological Protection

(ICRP). The corresponding ELCR values ranged from 2.505 $\times10^{-3}$ to 4.380 $\times10^{-3}$, with a mean of 3.333 $\times10^{-3}$, which is higher than the world average of 0.29 $\times10^{-3}$.

Table 1: Coordinates, Result of Average Indoor Exposure Dose Rate, AEDE and ELCR.

S/N	Location	Coordinates (°)	Dose Rate (µSv/h)	AEDE (mSv/y)	ELCR ($\times10^{-3}$)
1	Chemical Engineering lab.	N4°47' 25.41" E6°19' 14.856"	0.223	1.563	3.908
2	Chemical Engineering lab. Store	N4°47' 31.026" E6°19' 34.422"	0.176	1.233	3.083
3	Petroleum and gas lab.	N4°47' 43.584" E6°19' 34.284"	0.170	1.191	2.978
4	Soil mechanics & geo technical lab	N4°47' 23.952" E6°19' 42.228"	0.170	1.191	2.978
5	Reservoir PVT lab.	N4°47' 31.764" E6°19' 34.422"	0.190	1.332	3.330
6	Generator house in Engineering faculty	N4°47' 31.626" E6°19' 40.932"	0.223	1.563	3.908
7	workshop/mechanical Engineering lab.	N4°47' 32.61" E6°19' 35.76"	0.186	1.303	3.258
8	ICT Centre	N4°47' 43.452" E6°19' 19.068"	0.160	1.121	2.803
9	Computer lab.	N4°47' 43.548" E6°19' 19.326"	0.186	1.303	3.258
10	Physics lab. 1	N4°47' 31.11" E6°19' 20.196"	0.190	1.332	3.330
11	Physics lab. 1 Store	N4°47' 30.558" E6°19' 18.984"	0.230	1,612	4.030
12	Chemistry lab. 1 Store	N4°47' 42.228" E6°19' 27.732"	0.163	1.142	2.855
13	Chemistry lab. 1	N4°47' 44.502" E6°19' 31.002"	0.250	1.752	4.380
14	Biology lab. 1	N4°47' 32.238" E6°19'4.764"	0.143	1.002	2.505
15	Chemistry lab. 2	N4°47' 29.742" E6°19' 17.736"	0.173	1.212	3.030
16	Biology lab. 2	N4°47' 25.104" E6°19' 14.742"	0.193	1.353	3.383
17	Physics lab. 2 Store	N4°47' 24.444" E6°19' 15.378"	0.113	0.792	4.480
18	Physics lab. 2	N4°47' 26.616" E6°19' 15.414"	0.173	1.212	2.505
Mean Value			0,184±0.03	1.289±0.04	3.333±0.01
Standard Value			0.274	1.00	0.29

This elevated ELCR suggests that prolonged exposure in some laboratory environments may present a marginally increased lifetime cancer risk to staff and students.

Fig. 1 illustrates the variation of dose rates across different laboratories compared to the reference normal value of 0.274 μSv/h. The results show that all laboratories recorded values below the threshold, with the Chemistry lab. 1 exhibiting the highest level (0.250 μSv/h) and Physics lab. 2 Store the lowest (0.113 μSv/h). The relatively lower levels across locations imply effective shielding of laboratory structures and minimal contribution of laboratory equipment to background radiation.

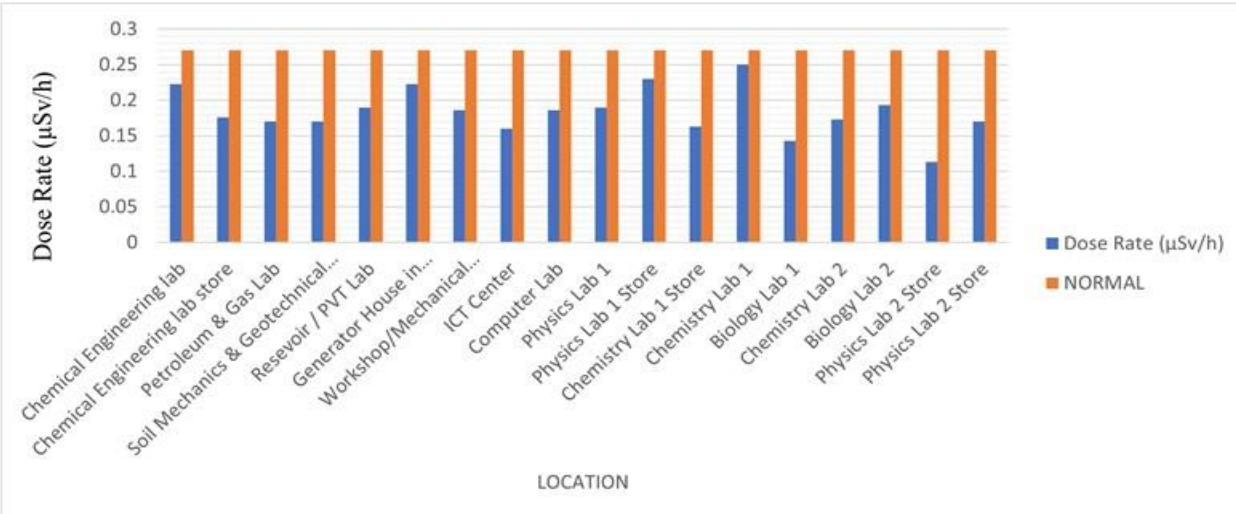

Fig. 1: Comparison of Measured Dose Rates with the Normal Value

Fig. 2 compares AEDE values across laboratory locations with the standard reference of 1.0 mSv/y. While the majority of laboratory values exceeded the standard slightly, none surpassed 2.0 mSv/y. This indicates that although exposure is generally within acceptable bounds, prolonged occupational activity in certain laboratories, particularly Chemistry lab. 1 and Physics lab. 1 Store, may need monitoring to avoid cumulative risks.

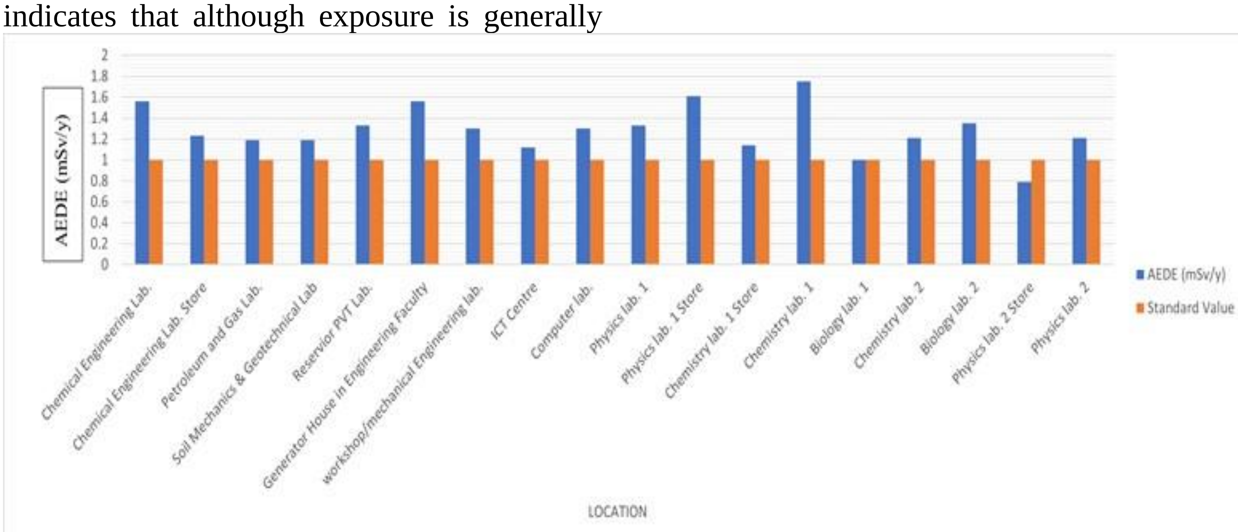

Fig. 2: Annual Effective Dose Equivalent (AEDE) Compared with Standard Value

Table 2 shows the dose distribution to sensitive body organs such as the lungs, ovaries, bone marrow, testes, kidneys, liver, and the whole body. The average dose values across all organs ranged from 0.474 ± 0.01 mSv/y for the liver to 0.846 ± 0.02 mSv/y for the testes. The relatively higher doses received by the reproductive organs (testes: 1.025 mSv/y, ovaries: 0.725 mSv/y) and the bone marrow (0.889 mSv/y) reflect the radiosensitive nature of these tissues, which are more prone to stochastic effects such as genetic mutations and hematopoietic disorders following long-term radiation exposure. These findings align with previous studies that emphasize the vulnerability of rapidly dividing and reproductive cells to ionizing radiation.

Table 2: Annual Effective Dose to Different Human Body Organs

Location/Centre	**Dose for various body organs (mSv/y)**						
	Lungs	Ovaries	Bone marrow	Testes	Kidneys	Livers	Whole body
Chemical Engineering lab.	0.800	0.725	0.863	1.025	0.775	0.575	0.850
Chemical Engr. lab. Store	0.631	0.572	0.681	0.809	0.612	0.454	0.671
Petroleum and gas lab.	0.609	0.553	0.657	0.781	0.591	0.438	0.648
Soil mechanics & geotechnical lab	0.609	0.553	0.657	0.781	0.591	0.438	0.648
Reservoir PVT lab.	0.682	0.618	0.735	0.874	0.661	0.490	0.725
Generator house in Engineering faculty	0.800	0.725	0.863	1.025	0.775	0.575	0.850
workshop/mechanical Engineering lab.	0.667	0.605	0.719	0.855	0.646	0.479	0.709
ICT Centre	0.574	0.520	0.619	0.735	0.556	0.413	0.609
Computer lab.	0.667	0.605	0.719	0.855	0.646	0.479	0.709
Physics lab. 1	0.682	0.618	0.735	0.874	0.661	0.490	0.725
Physics lab. 1 Store	0.825	0.748	0.889	1.057	0.610	0.593	0.877
Chemistry lab. 1 Store	0.585	0.529	0.630	0.749	0.799	0.420	0.621
Chemistry lab. 1	0.897	0.812	0. 968	1.149	0.566	0.645	0.953
Biology lab. 1	0.513	0.465	0.553	0.657	0.497	0.369	0.599
Chemistry lab 2	0.621	0.562	0.669	0.795	0.601	0.446	0.659
Biology lab. 2	0.693	0.628	0.747	0.888	0.671	0.498	0.736
Physics lab. 2 Store	0.406	0.367	0.437	0.519	0.392	0.292	0.431
Physics lab. 2	0.621	0.562	0.669	0.795	0.601	0.446	0.659
Average	0.660 ±0.03	0.598 ± 0.01	0.712 ± 0.02	0.846± 0.02	0.625 ± 0.03	0.474± 0.01	0.704 ± 0.04
Standard values	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The pattern of organ dose distribution highlights important implications. For instance, the testes consistently showed the highest exposure across several laboratories, particularly in Chemistry lab. 1, Physics lab. 1 Store, and the Generator House, where dose contributions exceeded 1.0 mSv/y in some cases. Although these values are still below the occupational safety threshold, they approach the annual dose limit recommended for members of the public, thereby underscoring the need for enhanced safety practices in these specific environments. The relatively elevated dose in bone marrow is also significant, as this tissue plays a critical role in blood cell formation, and its long-term irradiation could increase the risk of leukemia and other hematological disorders.

In contrast, the liver recorded the lowest organ dose (0.474 mSv/y), which may be due to its anatomical position and lower radiosensitivity compared to reproductive tissues. Similarly, the lungs and kidneys received intermediate doses, reflecting moderate radiation interactions with thoracic and abdominal organs. The whole-body average dose of 0.704 ± 0.04 mSv/y further confirms that radiation exposure in these laboratories is below the 1.0 mSv/y reference value, suggesting that the radiological health risk for most organ systems is minimal under current exposure conditions.

Nevertheless, the relatively higher organ doses in some laboratories raise concerns for long-term exposure, particularly among staff and students who spend extended hours in high-dose environments. The Chemistry lab. 1, Physics lab. 1 Store, and Generator House stand out as potential hotspots where cumulative exposures may contribute significantly to organ doses. These findings indicate the necessity of targeted interventions such as periodic monitoring of radiation levels, use of radiation shielding materials in laboratory design, and possible reallocation of equipment or substances that may contribute to elevated background radiation.

Fig. 3 highlights the distribution of dose for critical body organs relative to the 1.0 mSv/y standard. The testes, bone marrow, and lungs received relatively higher doses compared to other organs, but none exceeded the threshold. The implication is that while overall organ doses are within safe limits, attention should be directed to occupational workers spending extended hours in higher-dose locations, particularly with regard to reproductive health risks.

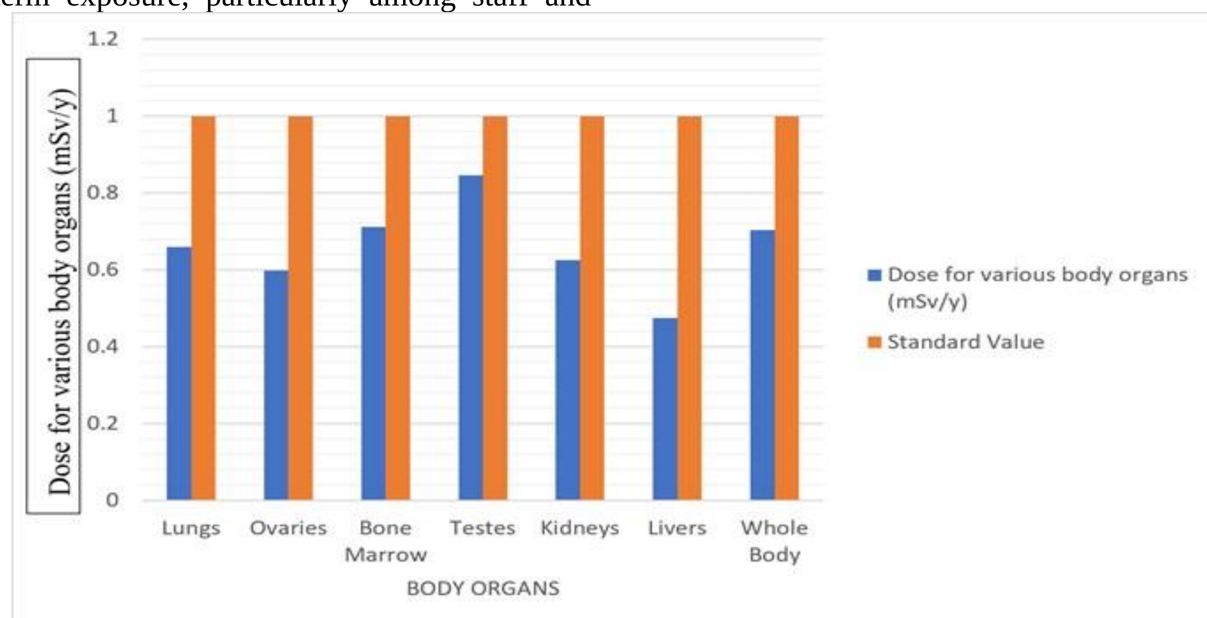

Fig. 3: Comparison of Organ Doses with Standard Value

Fig. 4 presents a spatial interpolation map showing the dose rate distribution across the university laboratories. The hot spots, represented in yellow to red regions, were observed around the Chemistry lab. 1, Generator House, and Physics lab. 1, with dose rates above 0.22 μSv/h. Conversely, relatively lower dose regions (blue shades) were associated with Biology lab. 1 and Physics lab. 2 Store. This spatial representation highlights specific laboratory clusters where radiation monitoring should be prioritized.

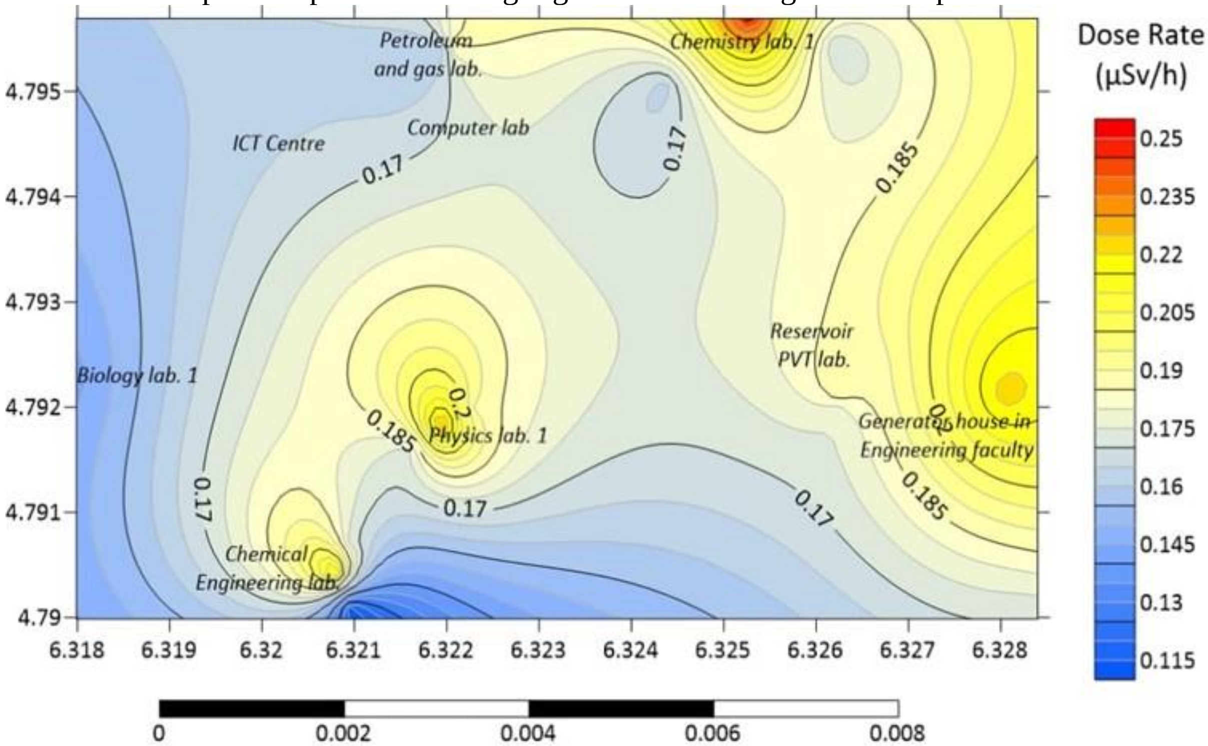

Fig. 4: Spatial Distribution Map of Dose Rates across University Laboratories

The study reveals that radiation levels across laboratories in the Federal University Otuoke are generally below international permissible limits for dose rate and annual effective dose. However, the observed mean AEDE and ELCR values indicate slightly elevated exposure risks compared to global averages, which could translate into long-term health concerns if cumulative exposures are not managed.

The relatively higher doses recorded in Chemistry lab. 1 and Physics lab. 1 Store suggest that the building materials or laboratory equipment in these locations may contribute additional natural radioactivity. Similarly, the elevated reproductive organ doses raise concerns for laboratory workers, especially young researchers and students who may be more susceptible to stochastic radiation effects.

Generally, while the radiation levels do not pose an immediate health hazard, regular monitoring, enforcement of radiation safety protocols, and improved ventilation/shielding are recommended. Furthermore, awareness programs on radiation risks should be introduced for laboratory staff and students to minimize unnecessary exposure.

4.0 Conclusion

The dose rate, annual effective dose equivalent, excess lifetime cancer risk and annual effective dose to different body organs have been measured and evaluated at Federal University Otuoke laboratories using global positioning system, Geiger Counter Nuclear Radiation Detector and some other mathematical models. The measured average dose rate and the calculated annual effective dose to different body organs of the background ionizing radiation of the Federal University Otuoke laboratories are within the world recommended values of 0.274 µSv/hr and 1.0 mSv/yr. Although estimated annual effective dose equivalent and excess lifetime cancer risk values are slightly higher than their radiological permissible limit. These values when compared with other values obtained within Nigeria and other countries of the world are in agreement and may not pose any immediate health implications for the laboratory staff and other users of the laboratories but could elevate long-term cancer risk due to chronic exposure.

The findings of this study revealed that the highest dose rates were recorded in Chemistry lab. 1, Physics lab. 1 Store, and the Generator House, while the lowest values were found in Biology lab. 1 and Physics lab. 2 Store. The calculated average AEDE exceeded the global reference of 1.0 mSv/y but was well below occupational limits, while the ELCR values were consistently higher than the world average, indicating a marginal increase in stochastic risk. The organ dose analysis showed that reproductive organs and bone marrow received relatively higher exposures, reflecting their radiosensitivity, although the values remained within recommended safety levels.

In conclusion, the overall radiation environment in the laboratories is considered safe for routine academic and research activities, but continuous monitoring is required to ensure that cumulative exposures do not lead to elevated risks over time. This baseline assessment is therefore valuable for establishing reference data for future radiological surveys and comparative studies.

It is recommended that specific laboratories with relatively higher dose rates should be prioritized for radiation safety interventions, including shielding, improved ventilation, and stricter control of potential sources of natural and artificial radioactivity. Periodic monitoring, staff awareness programs, and policy frameworks on occupational radiation protection should be implemented to safeguard both staff and students. Such measures will not only mitigate long-term radiological health risks but also promote a safe learning and research environment within the university.

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Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data public

Ethical Considerations

Not applicable

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The authors report no conflict or competing interest

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Contribution of Authors

U.L.A. designed the study, supervised the experimental setup, and analyzed the radiation data. K.O.M. conducted field measurements, operated the Geiger-Müller counter, and performed GPS-based dose mapping. Both authors contributed to data interpretation, computation of AEDE and ELCR, discussion of health implications, manuscript drafting, critical review, and approved the final version for publication.