Risk Assessment of Gamma Emission from Natural Radioactivity in Soil to Human Body Organs in Oil Palm Processing Mills Environment, Delta State, Nigeria

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ABSTRACT

Soil samples collected from communities with palm-oil processing facilities were assessed for activity concentrations of natural radionuclides to ascertain whether the industrial operations have elevated the activity concentrations of the naturally occurring radioactive materials and to examine if the human body organs radiosensitivity to the soil gamma radioactive emissions is within acceptable safety limits set by international regulatory professional bodies. Soil samples collected for the study were measured by gamma ray spectrometry using Thallium activated sodium iodide (NaI[TI]) detector. The mean activity concentration of ^{238}U, ^{232}Th and ^{40}K for the soil samples was respectively 38.35±2.44Bq/kg, 31.00±2.52Bq/kg and 525.37±2.92Bq/kg indicating that ^{238}U and ^{40}K are above the world average reference mean of 33Bq/kg for ^{238}U and 420Bq/kg for ^{40}K. ^{232}Th values were lower than the world average reference mean of 45Bq/kg. Values of absorbed dose rates in soils at Ute-Ogbeje and Mbiri were higher than the permissible safety standard of 59ηGy/h. The mean values of radiological hazard index parameters are all below the international permissible safety standards. The sensitivity of radiation from soil radionuclides to body organs like liver, kidneys, lungs, testes and ovaries were all below the international permissible safety standards of 1.0mSv/y, but the radio-sensitivity showed a decreasing order: Testes > Lungs > Kidneys > ovaries > Liver indicating that testes have the highest radiation sensitivity while the liver have the lowest, therefore no radiological health risk from soil gamma exposure. However, the high values of ^{238}U, ^{40}K, absorbed dose rates and outdoor annual effective dose equivalent for some communities indicates a statistically elevated cancer probability and increased radon potential for the inhabitants. Engineering soil control, groundwater treatment and food safety, and medical surveillance oversight are recommended to address the high outdoor effective dose on community dwellers.

Keywords: Fly Ash, Hazard Indices, Palm-oil Processing Mill Effluent, Radio-sensitivity to Body Organs, Soil Gamma Radioactive Emissions

INTRODUCTION

Naturally occurring radioactive materials (NORMs) such as ^{238}U, ^{232}Th and their decay products, along with ^{40}K, are present everywhere in the Earth crust in different geological settings like soil and rocks, and are largely determined by the type of parent rock as well as its geological history (UNSCEAR, 2000; Seow et. al., 2024). Clay-rich sediments like shales and mudstones in sedimentary rocks or formations often show higher radioactivity contents compared to carbonates (limestones) and sandstones that have low radioactivity (Kapanadze et. al, 2021). Geological materials are therefore the major contributor to natural radioactivity and their accumulation and distribution depends on the abundance of certain minerals (Kapanadze et. al, 2021; Uyanik et. al, 2022; Ofomola et. al, 2023). Cosmic, terrestrial, human activities, ingested food and building materials are the various sources of natural radiation on earth (Shahbazi-Gahrouei et. al, 2013). Radionuclides move through the environmental media such as air, soil, water, consumer products, and the food chain. When they are released into the environment due to their unstable nuclei, they produce ionizing radiations that strike significantly cells of living organisms and get the cells injured which ultimately leads to cancer where extremely high doses can cause death (Ajibade et. al, 2022). Thus, ingestion, inhalation and dermal exposure to radiation from these radionuclides have negative consequences. Radionuclides also pose serious potential health risk during agricultural activities and industrial operations due to the external gamma radiation they emit thereby exposing the human body of workers and nearby residents in such environments to varying sensitivity of different organs to radiation-induced health challenges (Ogungbemi et. al., 2023; Lawal et. al., 2026). Samat and Evans (2011) and Ajibade et. al (2022) reported that ^{238}U accumulate in human lungs and kidneys, ^{232}Th accumulate in human lungs, liver and skeleton tissues while ^{40}K accumulate in the muscles.

The Niger-delta region is a great hub and nerve centre of agro-industrial activities like palm oil processing and production which is an industry that involves significant soil disturbance during cultivation and processing (Anyaoha and Zhang, 2023). These palm oil production mills that are extensively distributed across the region are potential point sources of environmental contamination via discharge of palm oil mill effluent (POME) and the accumulation of processing by-products (Akinloye et. al, 2015; Omeje et. al, 2018). While previous investigations in the Niger Delta have assessed the physico-chemical alterations of soils receiving POME (Tambe et. al., 2024), as well as the radiological assessments of POME contaminated soil with primary focus on external hazard indices and annual effective doses of the whole body (IAEA, 2003; Agbalagba and Esi, 2023; Fasanmi and Isinkaye, 2026), specific considerations was not given to the differential sensitivity of various body organs to gamma exposure. Radiation sensitivity to organ-specific (distinct human body organs) exposure is a very critical issue from the standpoint of radiological protection that needs to be addressed. This is because epidemiological evidence have shown that certain tissues such as the bone marrow, colon, lungs, heart, kidneys, liver, testes, ovaries, and stomach have a greater susceptibility to radiation-induced carcinogenesis (Okeyode et. al., 2025). Besides, deposition of these radionuclides in the organs of the human body can lead to weakening the immune system, including various types of diseases and increase in mortality rate (Adeleye et. al, 2020; Ajibade et. al, 2022). Ionizing radiations from radionuclides can cause somatic and genetic effects that tend to damage radiosensitive organs in the body, and can even lead to death (Ajayi et. al., 1995; Ajibade et. al., 2022). This study was therefore aimed at assessing the soil gamma radiation sensitivity to human body organs in palm oil processing mills environment and its possible radiological effects on the residents in and around the investigated area in the Western Niger-Delta region of Nigeria. The findings will serve as baseline data for informed regulatory decision-making geared at contributing to the development of targeted radiological protection strategies for workers and residents in palm oil processing communities.

Study Area

The communities of Owere-Olobor, Otolokpo, Ute-Ogbeje, Igbodo, Mbiri and Ekuoma are located in Ika North-East Local Government Area (headquarter at Owa-Oyibu) of Delta State, Nigeria with coordinates of Latitudes 5^{o}55’ and 6^{o}15’ N and Longitudes 6^{0} 05’ and 6^{o}25’ E (Fig. 1). The area is situated within the humid tropical rain forest zone of Southern Nigeria and experiences heavy rainfall and high temperatures that is typical of low lying areas in Southern Nigeria (Ojeh and Orhiunu, 2021). The area also falls within a belt that is historically known for extensive oil palm plantations (Ojeh and Orhiunu, 2021), hence making it relevant to carry out the radiological assessment of its soils.

Geologically, the area is underlain by a sedimentary formation that lies on the Benin Formation (Fig. 2) which is often referred to as the coastal plain sands (Qp) associated with the tertiary period of the Miocene-Recent epoch and consists mainly of coarse to fine-grained sands, sandstones and gravels with occasional intercalations of thin clay lenses (Olobaniyi et. al., 2007). The formation is massively composed of highly porous, fresh water bearing sands and gravels constituting one of the most prolific aquifers in the Southern Nigeria, and functioning as a water table aquifer showing characteristics of unconfined and semi-confined conditions (Etim et. al., 2013; Ofomala et. al., 2017). However, Akpobore and Efobo (2014) and Irunkwor et. al. (2022) adduced that aquifer systems in this region is characterized with high transmissivity values and contains fresh water of generally good quality though vulnerable to surface contaminants due to the sandy overburden. Thus, the hydrogeological settings of the area implies that any contaminants including naturally occurring radionuclides leached from the soil would have the potential to migrate vertically and impact the shallow groundwater systems that many communities depend upon.

The geologic history of Ika North-East Local Government Area (LGA) is therefore tied closely to the sedimentary cycles of the Niger Delta with underlying formation typically unconsolidated and exhibiting high porosity and permeability that allows for significant infiltration of rainfall, leading to the development of a deep and extensive freshwater lens, and having significant implications for both groundwater storage and the geochemical behavior of natural radionuclides. Moreover, the spatial extent and coordinates of Ika North-East LGA of Delta State significantly influence its climatic conditions and economic activities which include extensive large-scale palm-oil plantations and production making the radiological assessment of soils in the region highly necessary (Ojeh and Orhiunu, 2021).

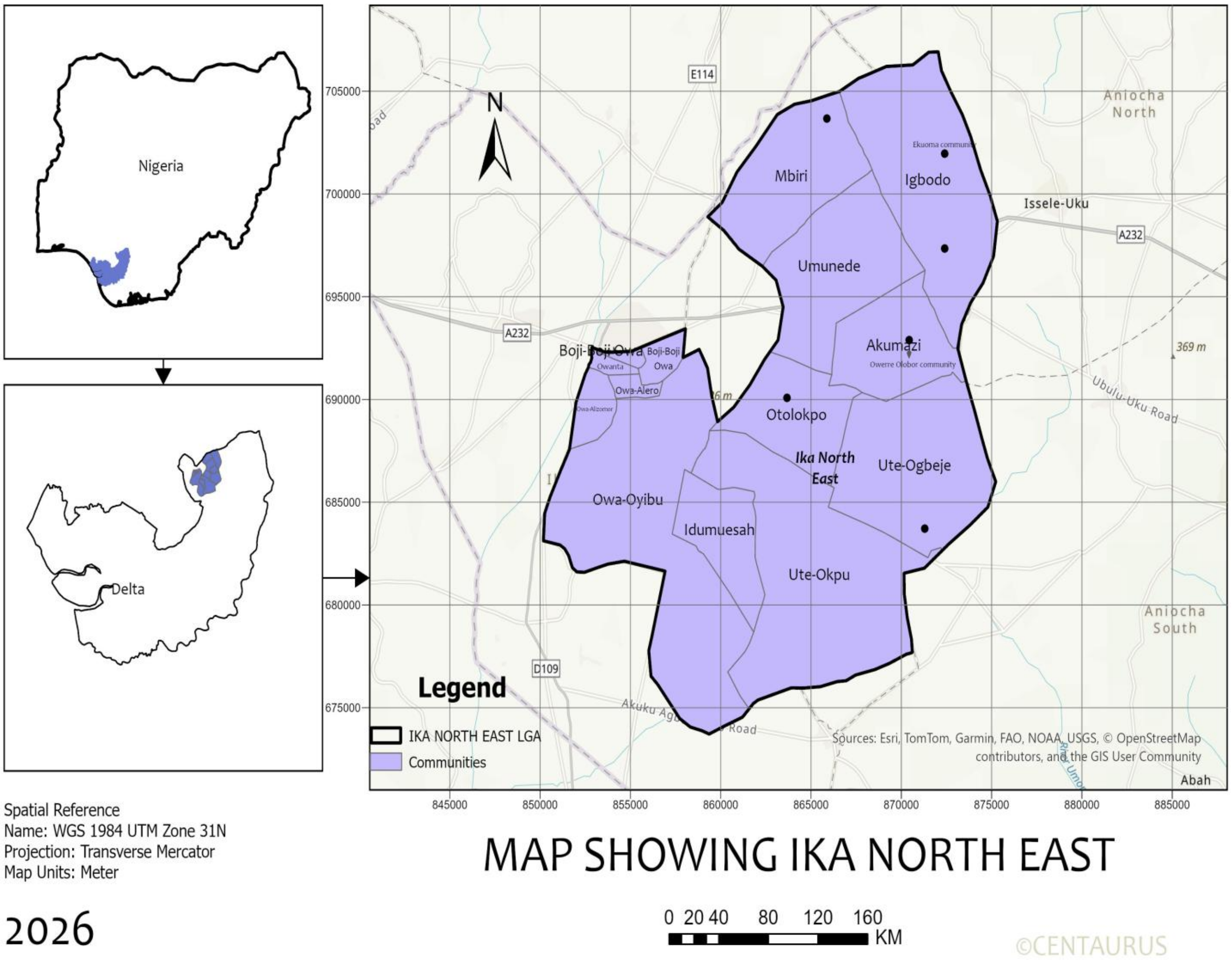

Figure 1: Map of Delta State Showing Ika North-East Local Government Area

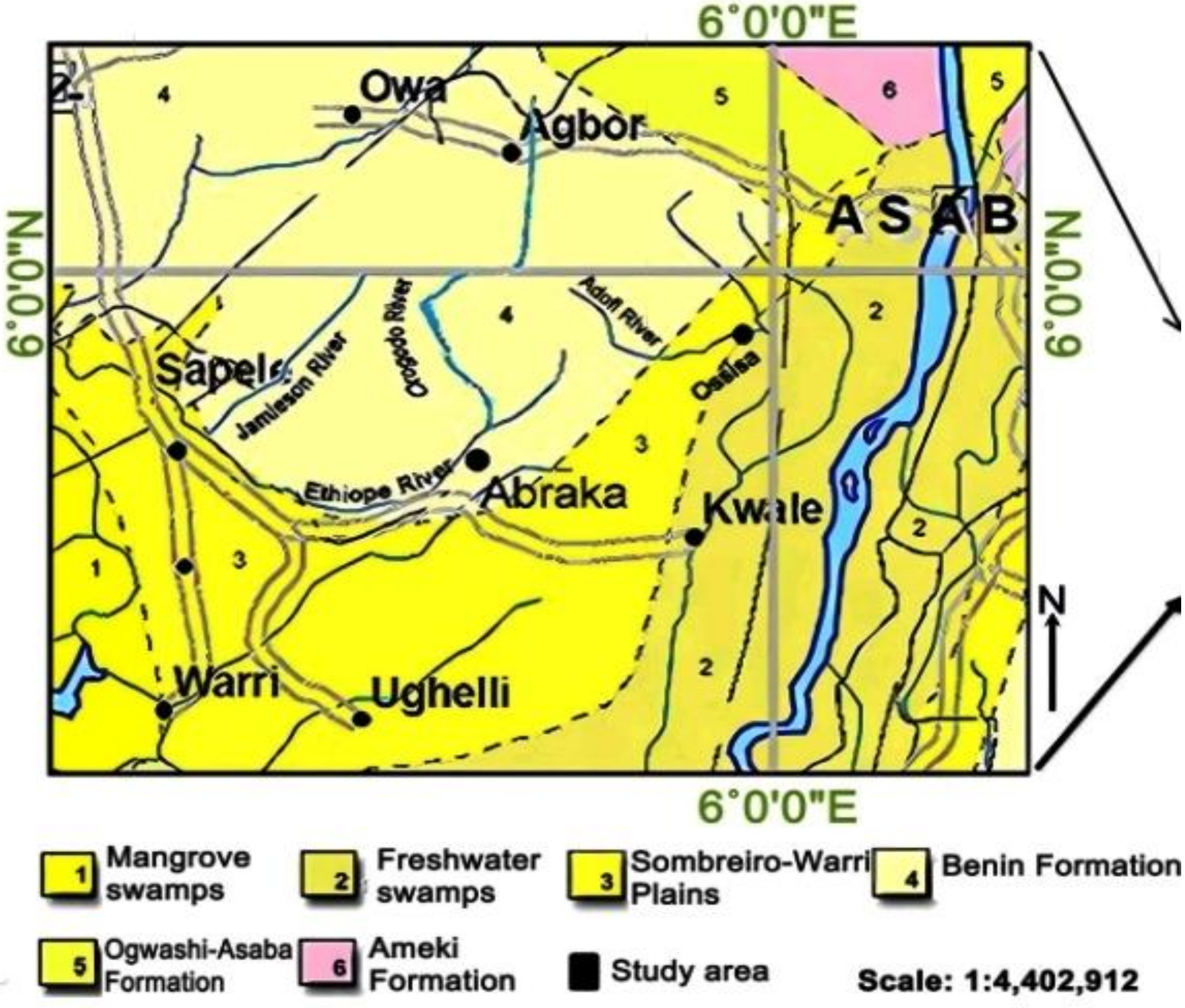

Figure 2: Geological Map of Western Niger Delta Showing the Geologic Formation of communities within Owa Metropolis (Adapted from Irwin and Oghenevwede (2014); Chinyem and Ovwamuedo (2024)).

MATERIALS AND METHODS

Data Acquisition

The study employed purposive and stratified sampling methods, and samples were collected according to international established experience by ASTM (1983), ASTM (1986), and IAEA (2004).

Research Design and Soil Sample Collection

The sites were split into sampling areas and were divided into cells of 50metres by 50metres grids. Each grid block was assigned a unique number and specific sampling locations or grid points where samples were collected were chosen randomly using a sample random number generator (e.g. choosing from N identical cards) to ensure randomization or unbiased selection within defined boundaries of the study area. Six (6) cores were drilled in zigzag pattern within each cell to a depth of 20cm to ensure adequate representation of the soil profile since Avwiri and Agbalagba (2014) defined radioactivity in soil as the average activity concentration in the top 20cm which is an accepted international compromise arising from alternate measures that are often based on deposition per unit area assuming atmospheric fallout. Six (6) soil samples were therefore collected from the cores using a stainless steel soil hand auger and a spatula that has been thoroughly cleaned with acid and washed with detergent, then rinsed with distilled water before being used to drill to the required 20cm depth. The six (6) soil samples collected from the different points were mixed thoroughly to give a composite sample. The essence of the mixing was to ensure that a homogenous sample that is representative of the soil of the sampled area was obtained. The samples were stored in a clean aluminium foil, enclosed in a black polyethene bag to prevent them from atmospheric humidity and were properly labeled in-situ.

Sample Preparation

The collected samples were taken to the laboratory where stones and organic materials were removed then oven-dried at a temperature of about 105°C for several hours to remove excess moisture content. The dried samples were grinded into fine grains of <2mm grain size and then sieved through a 150µm mesh to remove any debris and to homogenize the clay and mineral particles present. Subsequently, about 100 - 500g (0.1 - 0.5kg) of the representative portions of the grinded samples were weighed into a clean, dry Marinelli beaker and were sealed with an adhesive tape then left for 28 days to attain secular equilibrium between the long-lived parent radionuclide and their short-lived daughter radionuclides and were thereafter placed in the detector for a pre-set time to obtain spectrums for counting. The acquired spectrums from the counting were analyzed with software in order to obtain energies that correspond to the different radionuclides present in the sample.

Calibration of NaI(TI) Detector

The Thallium activated Canberra sodium iodide [NaI(TI)] detector at the National Institute of Radiation Protection and Research (NIRPR), University of Ibadan, Nigeria was calibrated with the IAEA certified mixed multi gamma ray (MGS6M315) standard sources of ^{155}Eu, ^{133}Cs and ^{60}Co to determine energy and efficiency for the gamma spectroscopy. Genie 2000 software was utilized to generate a 36,000 seconds background spectrum at 600V with annual calibrations that is aimed at ensuring accuracy for measuring natural radionuclides such as uranium (U), thorium (Th0 and potassium-40 (^{40}K) in environmental samples. IAEA-sediment-315 traceable standards was used to determine detector efficiency while energy calibration peaks of 1460keV for K, 1764.5keV Bi for uranium (U) and 2614.5keV Ti for thorium (Th) were considered for the radionuclide samples counting. The efficiency calibration is done annually using the IAEA certified material to create a calibration curve and to convert the net peak area to radioactivity concentration in Bq/kg.

Sample Analysis (Counting)

The radiometric isotopes of the collected soil samples were determined with a 76mm x 76mm Thallium activated Canberra sodium iodide [NaI(TI)] detector at the National Institute of Radiation Protection and Research (NIRPR), University of Ibadan, Nigeria. Each of the samples was counted for 10 hours (36000 seconds) in the NaI[TI] detector which was coupled to a Genie 2000 multichannel analyzer (MCA) through a preamplifier and was adequately shielded by Lead (Pb) to reduce the background radiation by about 95%. The NaI[TI] has an energy resolution of 8% at 0.662MeV (^{137}Cs). Energy values upon which measurements of ^{238}U, ^{232}Th series and ^{40}K activities of the radionuclides in the soil samples were to be based were initially determined. The analysis was done for four (4) weeks in order to identify the activity concentration of each radionuclide and their progenies in the soil samples. The activities of ^{238}U was determined from the average activities of its progenies at gamma energy of 1.760MeV while that of ^{232}Th was determined from the activities of its progenies at gamma energy of 2.615MeV and the activity concentration of ^{40}K was determined with only its gamma energy of 1.460MeV. The activity of the respective radionuclides in the samples was calculated after subtracting decay corrections. The background spectra measured under the same conditions for both the standard and sample measurements were used to correct the calculated sample activity concentrations.

The specific activity concentrations of the counted radionuclides in the soil samples were estimated with the relationship adopted by Jibiril and Ajao (2005), Jibiril and Bankole (2006) and Irunkwor et. al (2022):

$$AC_{sp}\,(\mathrm{Bq/kg}) = \frac{C_n}{\varepsilon P_\gamma M_s t} \quad \text{.. .. ..} \quad 1$$

Where: AC_{sp} is the activity concentration of radionuclide in the soil samples in Bq/kg; C_n is the count rate under each photo peak due to each radionuclide; ε is the detector efficiency for the specific gamma-ray energy; P_γ is the absolute transition probability of the specific gamma-ray; M_s is the mass of the soil sample (kg); and t is the counting time in seconds (s).

Statistical Analysis

The Statistical Package for Social Science (SPSS-27) computer software was used to analyze the data. Statistical parameters such as mean, minimum and maximum were used for the data analysis. Thus, data values in this study are reported as: means ± SD (standard deviation) and $p<0.05$ for all comparisons. Statistical graphical visualization charts were used to present data for clearer understanding and interpretations

Evaluation of Hazard Indices and Sensitivity to Body Organs

The radiological health status of inhabitants in the study area was evaluated using the following hazard indices and dose parameters to body organs:

Absorbed Dose Rate (D): The absorbed gamma dose rate measures the radiation or energy deposited in the air emitted from the soil at 1.0m above the ground surface in respect of the uniform distribution of radionuclides in the study area. This was computed by applying the formula given by IAEA (2003):

$$D\ (\eta Gy/h) = 0.462A_u + 0.604A_{Th} + 0.0417A_k \quad \ldots \quad 2$$

Where A_u, A_{Th} and A_k are respectively the activity concentration of ^{238}U, ^{232}Th and ^{40}K in Bq/kg.

Annual Effective Dose Equivalent (AEDE): The AEDE measures the stochastic and deterministic risks of the effects of the radiations from radionuclides in the soil on the irradiated individuals living in an area. This study examines two (2) scenarios of exposures viz:

(a) Outdoor annual effective dose equivalent ($AEDE_{(Outdoor)}$) which refers to the total effective dose equivalent that an individual would receive strictly from being outdoors in one (1) year due to ionizing radiation sources present in the outdoor environment from terrestrial gamma radiation emitted from naturally occurring radionuclides present in the soil and rocks.

(b) Indoor annual effective dose equivalent ($AEDE_{(indoor)}$) which refers to the total effective equivalent dose that an individual would receive in one (1) year from radiation sources present in the indoor environment such as radiations emitted from radionuclides that are naturally present in building materials like concrete, brick, stone and gypsum. An individual can also be exposed to radiation indoor through inhalation of radioactive gases such as ^{222}Rn that emanates from the soil beneath the building and from building materials. Another source is when the short-lived solid decay products of radon and thoron get attached to aerosol particles in the air and are inhaled; they are then deposited in the lungs delivering a significant radiation dose to the bronchial epithelium.

Arising from these enumerated effects of annual effective dose equivalent on irradiated individuals, the outdoor and indoor AEDE was computed using the relation by UNSCEAR (2000) and Zubair (2020):

$$AEDE\ (mSv/y) = D \times T \times OF \times C \quad \ldots \quad 3$$

$$AEDE_{(Outdoor)}\ (mSv/y) = D \times 8760 \times 0.2 \times 0.7\times10^{-6} \quad \ldots \quad 4$$

$$AEDE_{(Indoor)}\ (mSv/y) = D \times 8760 \times 0.8 \times 0.7\times10^{-6} \quad \ldots \quad 5$$

Where D is the absorbed dose rate in air, T is the average time an individual is exposed to radiation from radionuclides in one (1) year (i.e. 24 hours per day x 365 days = 8760hours/year), OF is the occupancy factor which is taken as 0.2 for outdoor and 0.8 for indoor, and C is the dose conversion factor which is taken as 0.7Sv/Gy.

Excess Lifetime Cancer Risk (ELCR): This is used to estimate the probability of contracting cancer or to estimate the likelihood that a fatal cancer will occur in an individual or in a population due to exposure to a specific amount of ionizing radiation from radionuclides above and beyond the baseline (natural) incidence of cancer (UNSCEAR, 2000; ICRP, 2012). The word “excess” particularly applies to the additional risk attributed solely to the radiation exposure (ICRP, 2012). The Excess lifetime cancer risk in this study was computed applying the relation (ICRP, 2012):

$$ELCR = AEDE \times DL \times RF \qquad 6$$

Where AEDE is the annual effective dose equivalent, DL is the average duration of life of an individual or members of the public which was estimated to be 70 years for Nigeria by ICRP (2012) and Eke et. al. (2022), and RF is the risk factor or the fatal cancer risk per sievert which was given by ICRP (2012) as 0.05.

However, in this study ELCR was computed for indoor individuals only since UNSCEAR (2000, 2008) assumed that most persons spend more time indoors (that is 19 hours per day) than outdoors (5 hours per day) making indoor dwellers more exposed to radiations (and being irradiated 19 hours in every 24 hours).

Internal Hazard Index (H_{in}): The internal hazard index is used to examine the potential risk from internal radiation caused by ingestion or inhalation of radionuclides. It particularly measures the hazards caused to humans or individuals when they inhale radon gas released from soil or building materials thus causing lung cancer when inhaled and deposited in the epithelium of the lungs. The internal hazard index therefore helps to limit the activity concentration of ^{226}Ra in a material such that the emitted radon gas does not accumulate to dangerous levels in a confined room (OECD/NEA, 1979). The internal hazard index was computed using the relation (OECD, 1979):

$$\mathbf{H_{in}} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \qquad 7$$

Where A_{Ra}, A_{Th} and A_k are respectively the activity concentration of ^{226}Ra (^{238}U), ^{232}Th and ^{40}K

External Hazard Index (H_{ex}): The external hazard index is designed to examine the external gamma radiation dose rate inside a structure so as to ensure that the gamma radiation dose rate does not exceed a defined safety limit (EC, 1999). The H_{ex} value must be less than unity (1) for the material to be classified as acceptable (OECD/NEA, 1979). The external hazard index for this study was computed with the relation (EC, 1979):

$$\mathbf{H_{ex}} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \qquad 8$$

Where A_{Ra}, A_{Th} and A_k are respectively the activity concentration of ^{226}Ra (^{238}U), ^{232}Th and ^{40}K

Activity Utilization Index (AUI): The activity utilization index measures the hazards or risks of external gamma radiation when an individual is standing next to or is being surrounded by the material such as living in a house made of brick or standing on a highly radioactive soil (IAEA, 2004). The activity utilization index is therefore a regulatory decision index that is used to decide whether a particular material can be utilized in a product (such as building material) or it must be treated as radioactive waste (IAEA, 2004). The reference international body (IAEA, 2004) further stated that for a material to be considered suitable for unconditional release or utilization, AUI must be less than 2. The AUI of soil in this study was computed with this relation (IAEA, 2004; Zubair, 2020):

$$\mathbf{AUI} = \frac{A_U}{150} + \frac{A_{Th}}{100} + \frac{A_k}{1500} \leq 2 \qquad 9$$

Where A_U, A_{Th} and A_k are respectively the activity concentration of ^{238}U (^{226}Ra), ^{232}Th and ^{40}K

Dose to Body Organ (D_{Organ}): According to ICRP (2007), IAEA (2022) and USNRC (2024) the radiation dose from a radionuclide to body organ is the rate at which a particular tissue or organ in the body absorbs ionizing radiation energy from radionuclides per unit mass in a particular tissue or organ of the human body resulting in biological risk and damage to the tissue or organ if above a certain threshold. The rate at which an individual body organ is irradiated depends on the radiation field the individual finds himself, the type of radiation and the shielding properties of the body itself. $D(_{Organ})$ was computed with the relation (El-Gamal et. al, 2007; Darwish et. al, 2015):

$D(_{Organ})$ (mSv/y) = AEDE x DL x RF 10

Where AEDE is the annual effective dose equivalent, DL is the average duration of life of an individual or members of the public which was estimated to be 70 years for Nigeria by ICRP (2012) and Eke et. al. (2022), and RF is the risk factor or the fatal cancer risk per sievert which was given by ICRP (2012) as 0.05.

RESULTS AND DISCUSSION

Activity Concentration of Radionuclides in the Communities Soils

The specific radioactivity values and their associated radiological health hazard indices as well as the radiation dose to body organs are presented in Table 1. The activity concentration of uranium-238 ranged from 36.20±2.06 to 39.25±3.70Bq/kg with a mean value of 38.35±2.44Bq/kg. The activity concentration of Thorium-232 ranged from 26.43±3.41 to 34.10±3.52Bq/kg with a mean value of 31.00±2.52Bq/kg while that of Potassium-40 ranged from 496.51±3.18 to 558.45±2.21Bq/kg with a mean value of 525.37±2.92Bq/kg. It was observed that the activity concentration of ^{238}U and ^{40}K in the soils of the six (6) communities are higher than the international acceptable standard of 33Bq/kg and 420Bq/kg respectively. The high values of ^{238}U in the soils implies a potential for the decay of ^{238}U into its Radium-226 and Radon-222 progeny and potentially leading to radon gas accumulation and consequently indoor radon gas inhalation which may significantly increases the chances of the inhabitants of the area to contract lung cancer disease- a serious health risk (UNSCEAR, 2000; ICRP, 2012). Moreover, the elevated concentrations of ^{238}U and ^{40}K could also be attributed to the wastes/sludge discharge from the palm oil processing mills into the surrounding soils as well as the phosphate fertilizers that were applied to the soil to enhance good yield of the palm oil plant plantations since studies by Akinloye et. al(2015) noted that phosphorus fertilizers derived from phosphate rocks contains very high concentrations of ^{238}U and ^{232}Th series. The high values of ^{238}U and ^{40}K also indicates that the discharged wastes/sludge and smoke arising from burning of the fibre, shell and empty fruit bunches (husks) from the palm oil and palm kernel oil facilities during production lead to the redistribution and elevation of the naturally occurring radioactive materials (NORMs) in the surrounding soils in the 6 communities. This finding agrees with the works of Akinloye et. al (2015) and Omeje et. al (2018) on their conclusion that the elevated concentrations of ^{226}Ra and ^{40}K in the soil samples collected in the environment of palm oil processing mills was attributed to the emitted smoke or fly ash as well as the long-term solid wastes and waste water (which is also referred to as palm oil mill effluent {POME}) that are discharged into disposal sites or used as soil conditioners or manure for farming, leading to incremental increases in the natural background radiation levels of the recipient media. Nevertheless, the activity concentrations of ^{232}Th in the sampled soil of the 6 communities were found to be lower than the international permissible limit of 45Bq/kg.

Table 1: Activity Concentration of Natural Radionuclides in the Community Soil Samples and the associated Radiation Hazard Indices and Dose Parameters

Communities	**Specific Activity (Bqkg^{-1})**			**Radiological Hazard Indices**							**Dose Rates to Body Organs (Indoor) (mSv/y)**				
				D (ηGy/h)	AEDE		ELCR (Indoor) (mSv/y)	H_{ex}	H_{in}	AUI					
	^{238}U	^{232}Th	^{40}K		Indoor (mSv/y)	Outdoor (mSv/y)					Liver	kidney	Lungs	Testes	Ovaries
Owere-Olobor	38.65±1.45	26.43±3.41	496.67±3.55	54.53	0.27	0.067	0.945	0.31	0.41	0.85	0.34	0.47	0.48	0.62	0.44
Otolokpo	37.82±1.52	30.25±2.10	543.42±3.22	58.40	0.29	0.072	1.015	0.33	0.43	0.92	0.37	0.50	0.52	0.66	0.47
Ute-Ogbeje	39.23±3.20	32.85±2.68	530.71±3.62	60.09	0.29	0.074	1.015	0.39	0.45	0.94	0.37	0.50	0.52	0.66	0.47
Igbodo	36.20±2.06	34.10±3.52	496.51±3.18	58.03	0.28	0.071	-0.98	0.33	0.43	0.91	0.36	0.49	0.50	0.64	0.45
Mbiri	39.25±3.70	33.64±1.60	558.45±2.21	61.74	0.30	0.076	1.05	0.35	0.46	0.97	0.39	0.52	0.54	0.69	0.49
Ekuoma	38.93±2.72	28.75±1.80	526.44±1.72	57.30	0.28	0.070	0.98	0.32	0.43	0.89	0.36	0.49	0.50	0.64	0.45
Average	**38.35±2.44**	**31.00±2.52**	**525.37±2.92**	**58.35**	**0.29**	**0.07**	**0.99**	**0.34**	**0.44**	**0.91**	**0.37**	**0.50**	**0.51**	**0.65**	**0.46**
International Permissible Standards UNSCEAR (2008), ICRP (2021), WHO (2009)	**33**	**45**	**420**	**59**	**0.41**	**0.07**	**0.29**	**≤1.0**	**≤1.0**	**≤2.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Evaluation of the Radiological Hazard Indices

(i) The outdoor values of the absorbed dose rates (D) in air varied from 54.53 to 61.74ηGy/h with mean value of 58.35ηGy/h (Table 1). The values of absorbed dose rates at Ute-Ogbeje and Mbiri communities are higher than the global reference value for normal background radiation for soil which is 59ηGy/h (UNSCEAR, 2008). These higher values above the 59ηGy/h benchmark helped to identify Ute-Ogbeje and Mbiri as communities with elevated radiation implying higher gamma radiation in the environment and a high potential long-term health risk for people living in those communities to contract cancer since the area is used for both farming and housing (Robinson and Gbaraton, 2023). Again, using the soil for building houses might lead to increase in external exposure of the individuals to high radon burden in their dwellings (Esi et. al, 2024). The high values of absorbed dose rates above the international recommended benchmark also serve as a warning signal to further investigate and monitor the environment strictly (Anekwe and Onoja, 2020; Abdulkareem et. al, 2024).

(ii) The indoor and outdoor annual effective dose equivalent (AEDE) values varied respectively from (0.27 to 0.30mSv/y) with mean value of 0.29mSv/y and from (0.067 to 0.076mSv/y) with a mean value of 0.07mSv/y (Table 1). These values are observed lower than the recommended safety benchmark of 1.0mSv/y (ICRP, 2012), yet the risk of radiation doses from the soil on the individuals residing in these communities is considered acceptably high in accordance with the ICRP (2012) Linear No-Threshold (LNT) model which was adopted by the World Health Organization (WHO) and assumes there is no threshold dose below which there is absolutely no risk of cancer since this risk increases in a linear fashion with the dose. The values of indoor AEDE in this study is lower than the 0.936mSv/y, 0.63mSv/y and 0.617mSv/y values recorded respectively by Anekwe and Onoja (2020), Mokobia et. al. (2020) and Xu et. al. (2024).

(iii) The indoor values of excess lifetime cancer risk (ELCR) ranged from 0.945 to 1.05mSv/y with an average value of 0.99mSv/y. The ELCR was evaluated for indoor occupants since from the standpoint of environmental radiological protection, indoor environments exhibit higher radiation levels than outdoor settings due to reduced ventilation and contributions from building materials (such as bricks, concrete, soil) and the assumption that individuals spend more time (19 hours per day) indoors and therefore are more irradiated (UNSCEAR, 2000). From Table 1 and Fig.3, the indoor values of ELCR in the soil of the six sampled communities are much higher than the international safety limit of 0.29mSv/y which implies that the probability of the individuals living in the six communities developing cancer over a lifetime exposure level of radiations emanating from the radionuclides in the soil is high enough to cause death (UNSCEAR, 2008; ICRP, 2012).

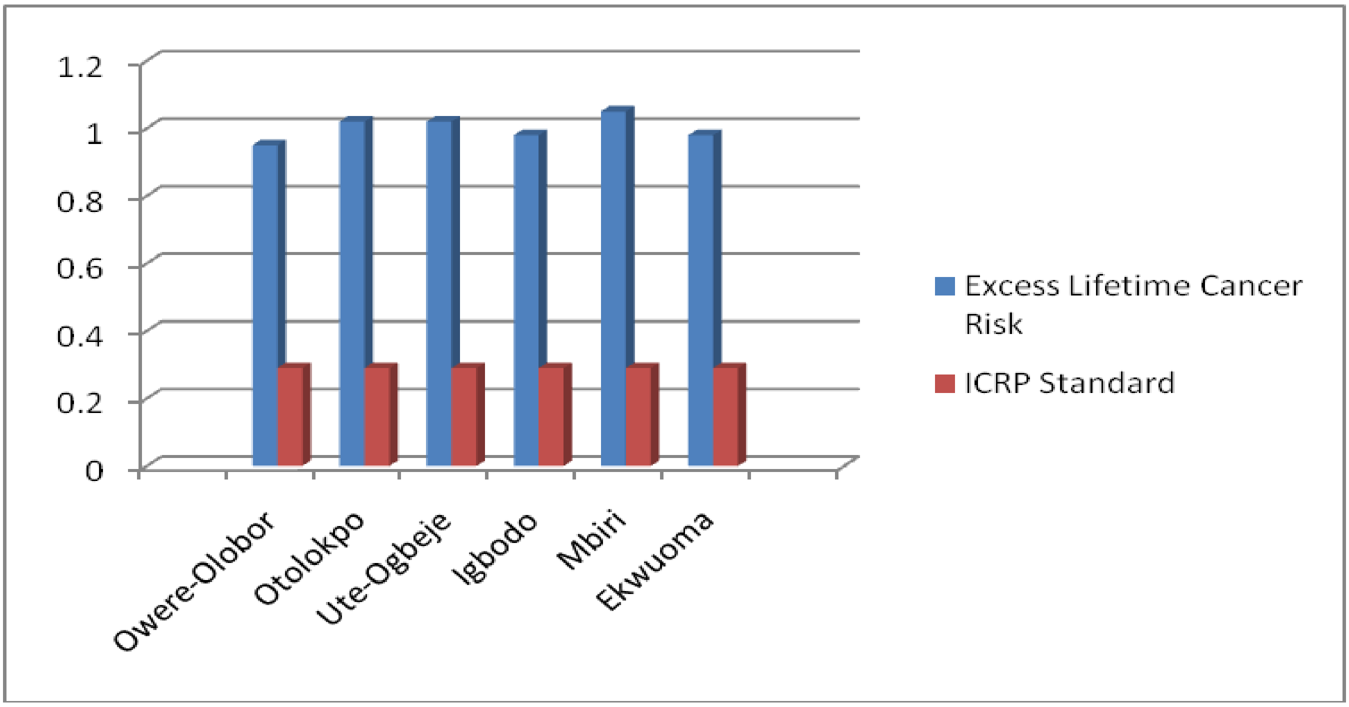

Figure 3: Excess Lifetime Cancer Risk in Soil Samples of the Study Area

(iii) The values of the internal hazard index varied from 0.41 to 0.46 with a mean of 0.44 which are lower than the acceptable safety limit of ≤1. Again, the values of the external hazard index varied from 0.31 to 0.39 with an average of 0.34. These values are below the standard of ≤ 1 in all the six communities. These low values of external and internal hazard indices of soil below the acceptable safety limit implies that the soil is radiologically safe for use in construction and human habitation since there is no radiological health risk from the soil gamma radiation exposure (Rao, 2018; Kabore et al, 2022; Muya et. al, 2024). The soil is therefore in full compliance with international safety standards for public exposure.

(iv) The activity utilization index (AUI) was used to assess the risk from external gamma radiation emitted directly from the soil or a material such as building or brick. It therefore measures the radiation hazard caused to either a person who is standing next to a material or a person that is surrounded by the material, for instance if the person is standing on contaminated soil or living in a house made of brick from the soil (Veiga et. al., 2006; UNSCEAR, 2000). The activity utilization index was quantified in this study as presented in Table 1 and Fig. 4 and the values varied from 0.85 to 0.97 with a mean value of 0.91. These AUI values are well below the average worldwide reference value of 2 (UNSCEAR, 2000; UNSCEAR, 2008; Darwish et. al., 2015; Eke et. al., 2024). Soil samples from Owere Olobor, Otolokpo, Ute-Ogbeje, Igbodo, Mbiri and Ekwuoma therefore pose no significant radiological health hazard to the people living in the communities. The AUI soil values for this study are higher than the one obtained by Sivakumar et. al (2014) and Eke et. al. (2024), but lower than those obtained by Manigandan and Shekar (2014), Dizman et. al (2016) and Joel et. al (2019).

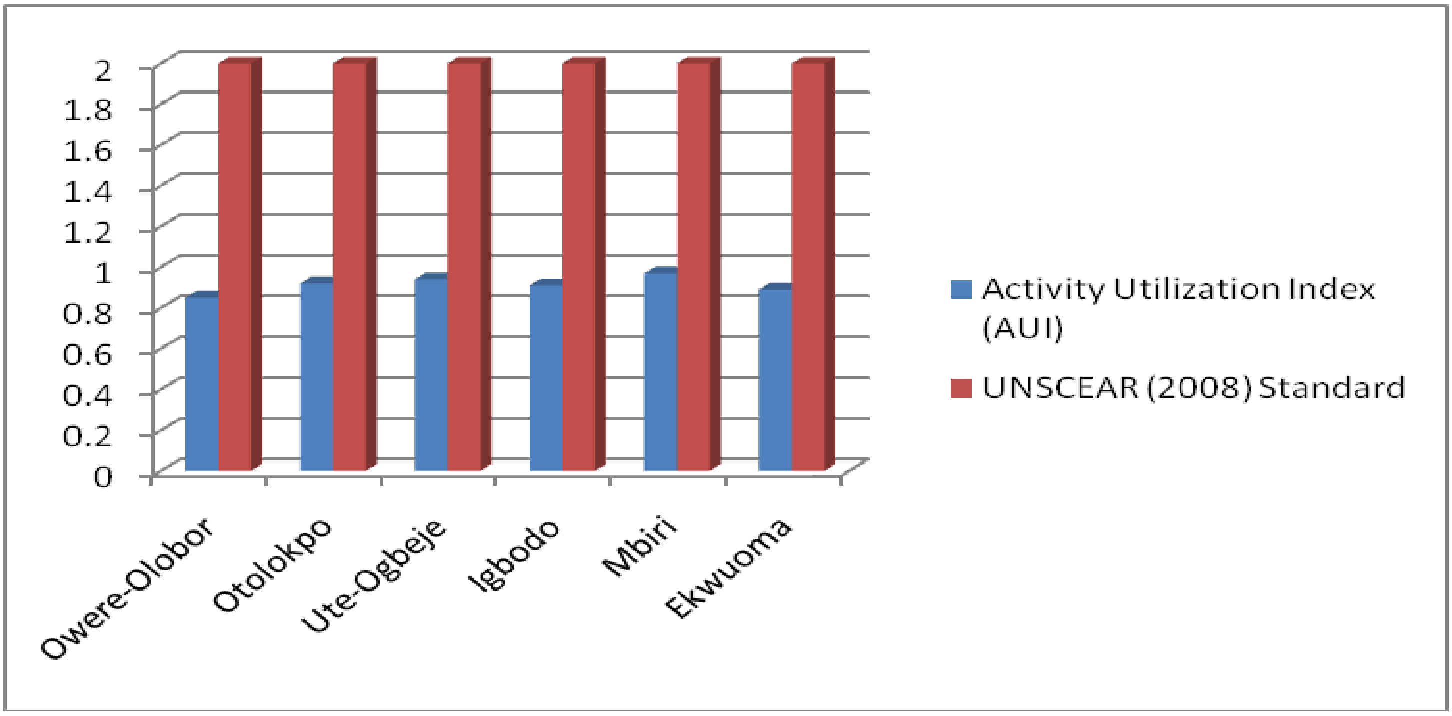

Figure 4: Activity Utilization Index in Soil Samples of the Study Area

Evaluation of Radiation Sensitivity to Body Organs

The value of radiation dose to body organ such as liver, kidney, lungs, testes and ovaries ranged respectively from (0.34 to 0.39), (0.47 to 0.52), (0.48 to 0.54), (0.62 to 0.69), and (0.44 to 0.49) with mean values of 0.37, 0.50, 0.51, 0.65, and 0.46 (Table 1). These values are lower than the set limit of 1.0mSv/y implying no radiological health risk from soil gamma exposure to body organs and that the radionuclides in soil is in full compliance with international safety standards for public exposure. However, it is expected that individuals staying indoors always will have a much higher radiation exposure dose to human body organs than outdoors due to the number of time spent indoors and therefore they will be exposed to radiation from materials used in the construction of buildings as well as indoor inhalation of radon gas which is a known human carcinogen in homes, that has lead to individuals contracting lung cancer and ultimately resulting to an estimated 21,000 lung cancer deaths annually in the United States of America (USA) (USEPA, 2003). From Table 1 and Fig. 5 we observe that the dose to body organs decreases in the following order: Testes > Lungs > Kidneys > ovaries > Liver indicating that testes have the highest radiation sensitivity while the livers have the lowest.

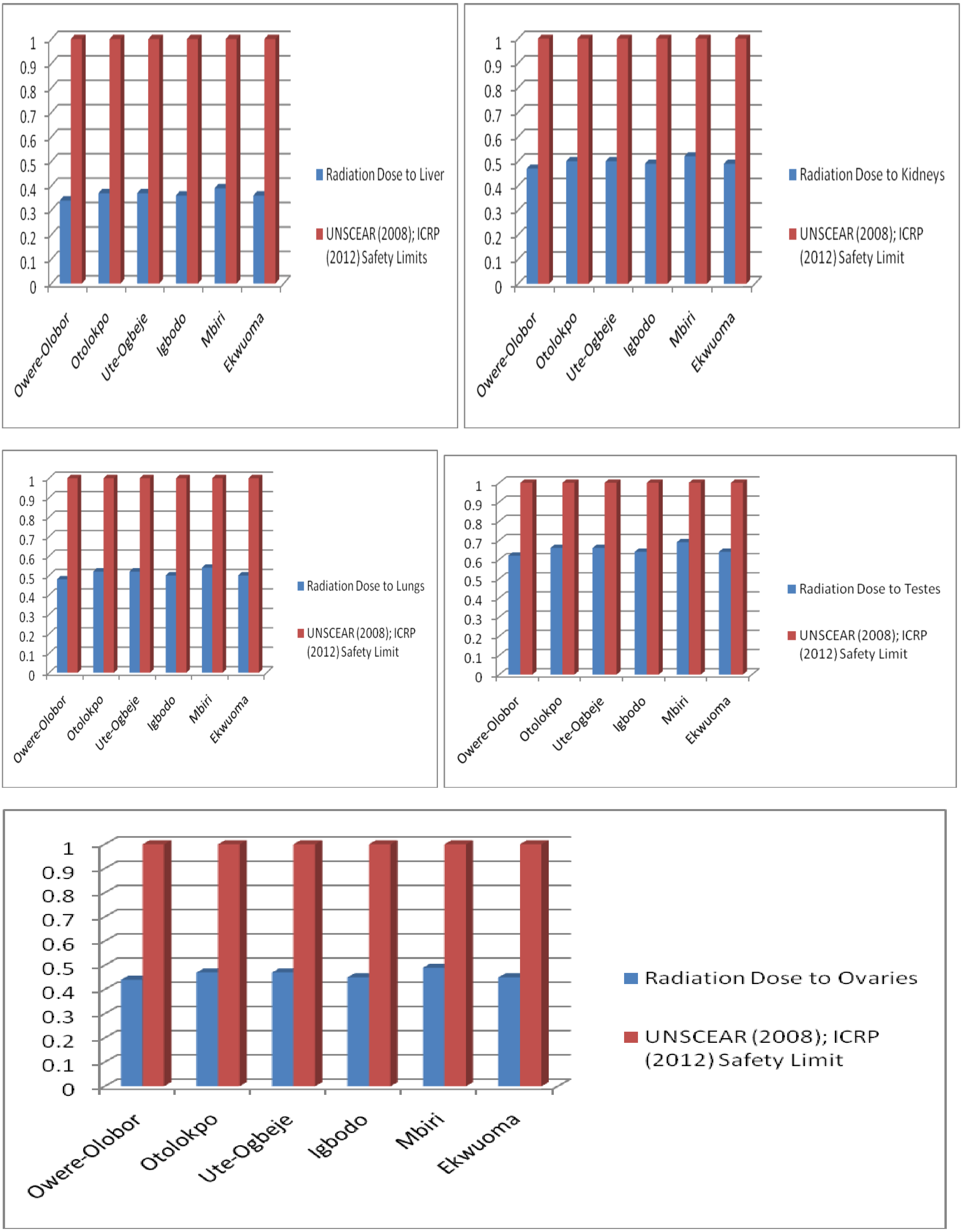

Figure 5: Radiation Dose Rates to Body Organs in the Study Area

This finding agrees with the studies of Darwish et. al (2015) that recorded highest radiation sensitivity for testes and lowest for ovaries. Conversely, the result of organ sensitivity to soil radioactivity in this study is higher than the 0.533mSv/y recorded for Testes for indoor dwellers in the works by Esi et. al. (2024).

However, based on the organ-specific dose rates ranging from 0.37 to 0.65mSv/y below the ICRP recommended acceptable standard of 1.0mSv/y, and considering the cumulative lifelong exposure specific to each organ system, the potential long-term and epidemiological effects as well as the actual health outcomes of individuals living in the investigated communities can be summarized as follows:

(i) The liver as a radiosensitive organ due to its high regenerative capacity and metabolic activity, chronic low-dose exposure (0.37mSv/y) would carry with it a theoretical risk of hepatocellular injury over decades. Long-term effects include subtle DNA damage in hepatocytes, although liver cirrhosis or radiation-induced hepatitis is unlikely at this dose rate. The long-term stochastic risk which is considered as the primary long-term risk is hepatocellular carcinoma (i.e radiation-induced carcinogenesis) and would remain very low at this dose (ICRP, 2007);

(ii) The kidneys are considered moderately radiosensitive organ and chronic exposure to radiation from gamma radiations in the soil radionuclides could theoretically contribute to a gradual decline in glomerular filtration rate (GFR) over a lifetime (ICRP, 2007; ICRP, 2012). However, the dose recorded in this study (0.50mSv/y) is below the threshold associated with radiation nephropathy, but the stochastic risks include renal cell carcinoma.

(iii) Due to the large surface area of the epithelial tissues, lungs are classified among the more radiosensitive organs in the human body. If exposure is combined with irritants like particulate matter from the palm oil processing, long-term effects of this 0.51mSv/y dose would result in a very low incremental risk of pulmonary fibrosis and chronic inflammation (Olafisoye et. al., 2022; ICRP, 2007). It could also result to contracting cancer of the lungs over time by the inhabitants of the investigated communities if the gamma emissions are accompanied by inhalation of radionuclides (such as radon progeny) from the soil;

(iv) The testes are highly radiosensitive due to the fast or brisk division of spermatogonia. Long-term effects at this dose rate (0.65mSv/y) are unlikely to cause sterility, but chronic exposure could lead to subtle cumulative reductions in sperm count or temporarily having oligospermia over decades (ICRP, 2007); and

(v) Ovaries like the testes are highly radiosensitive, but less radiosensitive than the testes as regards sterility (ICRP, 2007; 2012). Long-term effects of gamma emissions from natural radioactivity in the investigated community soils on the ovaries of the inhabitants include a potential for earlier depletion of the ovarian follicle pool over a lifetime and this might slightly advance the menopause age of those living within and around the communities. Stochastic risks include heritable effects and ovarian cancer (ICRP, 2007), though the absolute risk remains very low.

Epidemiological surveillance would not likely detect a statistically significant increase in cancers of the lung, liver or kidney in the population surrounding the oil palm processing mills, because it may not be solely attributable to the gamma emissions from soil since the annual doses are comparable to or slightly above typical global background radiation of about 2.4mSv/y. Therefore any observed health trends would be likely cofounded by other occupational or environmental exposures associated with palm oil milling (such as diesel exhaust, particulate matter, heat stress) rather than directly being linked to the gamma radiation.

Applying the ICRP (2007) risk coefficient of approximately 5% per sievert (Sv) for stochastic projection of cancer risk in the general population of the investigated area, the lifetime excess cancer risk for an individual exposed to the highest organ dose (testes: 0.65mSv/y) over 70 years would be in the order of 0.02-0.03% above baseline. Epidemiologically, this level of risk is undetectable in a population of moderate size provided exposure conditions remain stable and no additional exposure pathways like ingestion or inhalation of radioactive dust are present.

CONCLUSION

The activity concentrations of ^{238}U and ^{40}K measured for the soil samples in this study were respectively higher than the average world values of 33Bq/kg and 420Bq/kg (UNSCEAR, 2008), whereas that of ^{232}Th was found lower than the 45Bq/kg permissible world average value. The indoor annual effective dose equivalent, the external hazard index, the internal hazard index, the absorbed dose rates in some of the communities (Owere-Olobor, Otolokpo, Igbodo and Ekwuoma), and the activity utilization index were all lower than the global recommended mean values set by international bodies like UNSCEAR, ICRP and IAEA. The mean excess lifetime cancer risk (ELCR) evaluated for indoor dwellers and the absorbed dose rates at Ute-Ogbeje and Mbiri recorded high radiological values above the international permissible safety limits indicating a very a high probability of indoor inhabitants to contracting cancer when exposed to the radiation from radionuclides in the soil hence posing a significant risk factor. However, the high values of ^{238}U, ^{40}K, absorbed dose rates (>59ηGy/h), and outdoor annual effective dose equivalent (AEDE) (>0.07mSv/y) obtained in this study for the affected communities indicates a statistically elevated cancer probability for the inhabitants, increased radon potential, and a deviation from the normal natural background. The study finds that the radiation sensitivity to body organs were all lower than the international permissible standard of 1.0mSv/y (UNSCEAR, 2000) implying no radiological health risk from soil gamma exposure and that the soils are in full compliance with international safety standards for public exposure. However, the high values of ^{238}U, ^{40}K, absorbed dose rates (>59ηGy/h), and outdoor annual effective dose equivalent (AEDE) (>0.07mSv/y) obtained in this study for the affected communities indicates a statistically elevated cancer probability for the inhabitants, increased radon potential, and a deviation from the normal natural background. The following recommendations are therefore necessary: (i) removal of the top 15-30cm of the contaminated soil and be replaced with clean fill, or using asphalt or concrete paving of driveways in high occupancy area such as yards, children's playgrounds and community gardens. These acts as physical shield that help to attenuate gamma rays from the soil; (ii) shifting outdoor activities to remediated areas or areas with natural low background geology should be encouraged; (iii) residential buildings should be constructed with a polyethylene vapour barrier to reduce radon ingress and provide gamma shielding; (iv) long-term radon testing of between 3-12 months should be carried out in all residential dwellings since ^{238}U progeny (ie ^{222}Ra) is a potential source of internal exposure to lung tissue hence affecting the bronchial epithelium even if the systematic organ sensitivity is low; (v) although ^{40}K is biologically regulated homeostasis ally, yet ^{238}U and its decay products (^{226}Ra) can bio-accumulate. Therefore, root vegetables such as potatoes and carrots, or leafy greens should not be cultivated in the high-soil activity areas due to the high transfer factors root crops have for radium; (vi) the community groundwater should be tested regularly for ^{226}Ra, ^{228}Ra, and uranium to ascertain that their levels do not exceed the maximum contaminant level (MCL) of the permissible safety standards by the United States Environmental Protection Agency (USEPA). If levels exceed the USEPA MCL, the groundwater should be treated with reverse osmosis or ion exchange filtration method at the point-of-use; (vii) since low organ sensitivity to the soil gamma radiation refers to deterministic effects (ie tissue reactions), it does not eliminate stochastic risks (cancer) over a lifetime. Hence, establishing a baseline health registry for the community becomes very necessary because the cumulative effective dose over 50-70 years may still increase the stochastic risk on lung health due to radon progeny; (viii) uranium and radium being both radioactive and heavy metals adhere to soil surface. Suspended soil particulates containing uranium and radium in form of dust would contribute to internal exposure when inhaled. It is therefore advised that suspended dust particles be suppressed on unpaved roads by using calcium chloride ($Cacl_2$) binders or paving; and (ix) the spread of contaminated soil to water bodies should be prevented through proper drainage and silt fencing.

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