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Assessment of Natural Radionuclides and Associated Radiological Health Hazards in Soils around Palm Oil Processing Mills, Delta State, Nigeria

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ABSTRACT

An assessment was carried out in soils of communities that host palm-oil and palm-kernel oil production facilities to ascertain whether their operations have elevated the activity concentrations of the 238U, 232Th and 40K and to examine if the associated radiological hazard indices are within acceptable safety limits set by international regulatory professional bodies on radiological protection. Soil samples was collected for the study and were measured by gamma ray spectrometry using NaI[TI] detector. The mean activity concentration for soil samples was 38.35±2.44Bq/kg, 31.00±2.52Bq/kg and 525.37±2.92Bq/kg respectively for 238U, 232Th and 40K. The values for 238U and 40K are above the world average reference mean of 33Bq/kg for 238U and 420Bq/kg for 40K. 232Th values were lower than the world average reference mean of 45Bq/kg. Values of absorbed dose rates in soils at Ute-Ogbeje and Mbiri communities were higher than the permissible safety standard of 59ηGy/h while the mean value of excess lifetime cancer risk (0.99mSv/y) was above the international safety limit of 0.29mSv/y. The mean values of radiological hazard indices are all below the international permissible safety standards. Thus, no radiological health risk from soil gamma exposure. The mean Clark values indicated soils of uranium enrichment composing more of MAFIC (mg and Fe) minerals than FELSIC (feldspar and silica). However, the high values of 238U, 40K, absorbed dose rates, excess lifetime cancer risk and outdoor annual effective dose equivalent for some communities implies a statistically elevated cancer probability for the inhabitants. Intervention, monitoring, and regulatory review are recommended.

INTRODUCTION

The assessment of naturally occurring radionuclides in the environment is a vital component of public health protection and radiation safety. This is because terrestrial radiation that primarily emanate from primordial radionuclides such as ^{238}U, ^{232}Th and their decay products, along with ^{40}K, is present in soil and rocks (UNSCEAR, 2000). These radionuclides collectively contribute significantly to the radiation dose received by the inhabitants on Earth. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2008) noted that the exposure of human beings to ionizing radiation from natural sources is a continuing and an inescapable feature of life on earth. Hence, establishing baseline data on the activity concentrations of ionizing radiation is very vital for evaluating public exposure and detecting any potential anthropogenic alterations.

Industrial activities, especially those involving natural resources is known as one of such potential anthropogenic sources that elevate the concentration of these naturally occurring radioactive materials (NORMs) in soils. The agricultural and processing industries, including those exclusively committed to palm-oil and palm kernel oil production, often employ large-scale land cultivation and the use of fertilizers to enhance or boost growth and to promote good yield which can, in the process redistribute radionuclides in the soil profile (Akinloye et. al., 2015). Although the physical and chemical processing of these palm-oil and palm kernel oil does not generate artificial radioactivity, yet solid wastes and waste water, often referred to as Palm Oil Mill Effluent (POME) that are discharged into disposal sites and are used as soil conditioners (or manure) on farmland can elevate the concentration level of NORM in the surrounding soil since they would accumulate in the soil over time (Omeje et. al., 2018). Besides, smoke from burnt biomass waste (such as fibres and kernel shells) carries fly ash that contains concentrated radium isotopes and can be deposited through atmospheric fallout onto topsoil surrounding the facility (Akinloye et. al., 2015). UNSCEAR (2016) noted that the combustion of coal and other fossil fuels (including biomass) results in the discharge to the atmosphere of a portion of the radionuclides present in the fuel. Since palm-oil mills are notably biomass burners, if the emitted ash in the smoke is not properly contained, the deposited ash may give rise to an enhanced level of natural radionuclides in the surrounding soil (UNSCEAR, 2016). The report by the International Atomic Energy Agency (IAEA, 2003) noted that industrial processes involving bulk quantities of natural materials have the potential to create enhanced

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or elevated concentrations of radionuclides in products, by-products, and wastes. Regions with a long history of palm-oil plant farming with such processing facilities therefore warrant specific radiological assessment to ensure that routine operations have not unwittingly led to enhanced radiation levels in the surrounding community soils.

The potential negative health effects associated with exposure to these radionuclides are quantified using various hazard indices. When these radionuclides are ingested or inhaled, the radioactive materials can irradiate internal organs, while external exposure fundamentally comes from dermal absorption of gamma radiation that is emitted from the ground. To evaluate these radiological risks researchers employ empirical formula to calculate radiological health indices such as the Annual Effective Dose Equivalent (AEDE), the Radium Equivalent Activity (Raeq), the External and Internal Hazard Indices (Hex and Hin), the Absorbed Gamma Dose Rate (D). These indices are very instrumental for determining whether a community's environment is radiologically safe for habitation and agriculture. According to Agbalagba and Onoja (2011) assessment of radiological hazards is imperative to ascertain that the radiation exposure to the public is within the recommended safe limit. Several authors such as Ononugbo and Anyalebechi (2017), Agbalagba et. al. (2021), Furo et. al. (2023), Esi et. al. (2025) and Ijabor et. al. (2025) have researched on radioactivity level in Delta State, Nigeria, but they did not research on the activity concentration level of natural radionuclides in the soil of the communities in this study. Although the works of Eseka et. al. (2018) was on the radioactivity and estimation of annual gonadal dose of inhabitants of communities in Ika North-East LGA, yet their work did not cover the 6 communities that are about 25km away from this present study. Besides, the inhabitants of the 6 communities in this study mainly engage in palm oil plantation farming as their major occupation with their processing and production facilities stationed in their farmlands and nearby dwelling houses. This scenario thus expose the individuals living within and around the communities to inhalation of the toxic smokes emitted into the air as well as the waste water/ sludge discharged into the soil during production and processing of the palm oil and palm kernel oil. This study therefore aim at establishing a comprehensive baseline of natural radionuclide concentrations and their associated radiological hazards in the soils of these specific communities which have documented history of palm-oil and palm kernel oil production thereby contributing to the body of knowledge on NORM in industrial agricultural settings in the region.

MATERIALS AND METHODS

Study Area

The communities of Owere-Olobor, Otolokpo, Ute-Ogbeje, Igbodo, Mbiri and Ekwuoma are located in Ika North-East Local Government Area (headquarter at Owa-Oyibu) of Delta State, Nigeria with coordinates of Latitudes 5°55' and 6°15' N and Longitudes 6^0 05' and 6°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).

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

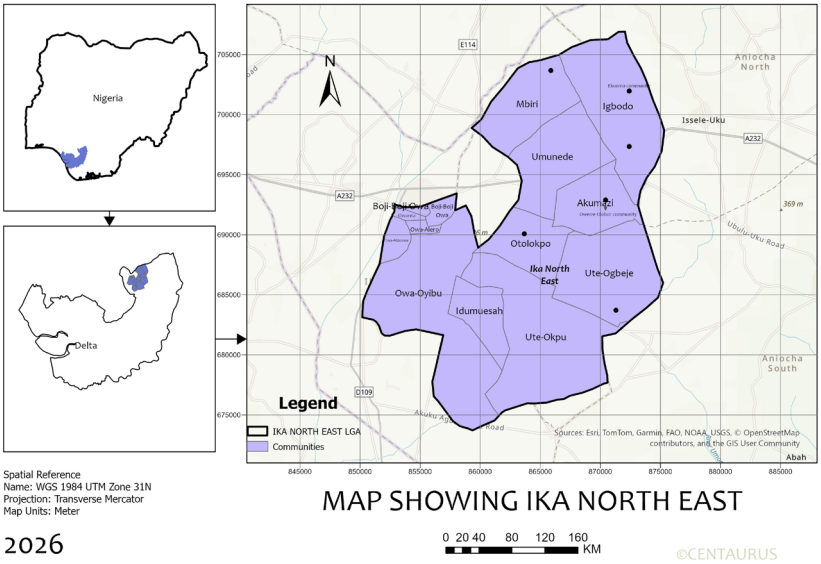

Figure 1: Map of Delta State Showing Communities in Ika North-East Local Government Area

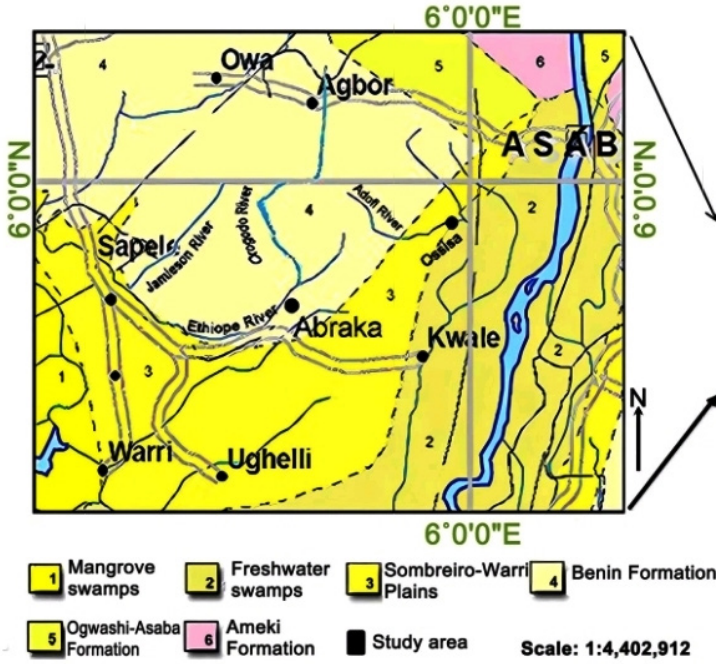

Figure 2: Geological Map of Western Niger Delta Showing the Geologic Formation of communities within Owa Metropolis (Adapted from Irwin and Oghenevwede (2014); Chinyem and Ovwamuedo (2024)).

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.

Sample Analysis (Counting)

The radiometric isotopes of the collected soil samples were determined with a 76mm x 76mm Thallium activated Canberra Sodium Iodide [NaI(Tl)] 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[Tl] detector which was coupled to a multichannel analyzer (MCA) model 1104 through a preamplifier and was adequately shielded by Lead (Pb) to reduce the background radiation by about 95%. The NaI[Tl] 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):

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; Pγ 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).

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

Evaluation of Hazard Indices

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

(i) Radium Equivalent Activity (Raeq): This is a single quantity that is used to assess the combined effect of the radiation hazards from any material that contains ^{238}U, ^{232}Th and ^{40}K (Beretka and Mathew, 1985). The radium equivalent activity was calculated using the relation by UNSCEAR (2000):

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

$$Ra_{eq}\ (Bq/kg) = A_u + 1.43A_{Th} + 0.077A_k \quad \ldots\ldots\ldots\ldots 2$$

In the equation above, it was assumed that 10Bq/kg of ^{238}U, 7Bq/kg of ^{232}Th and 130Bq/kg of ^{40}K produced equal gamma dose so that it will allow for the calculation of the percentage contribution of the three radionuclides to the gross activity in the sample (Zarie and Al Mugren, 2010; Avwiri and Agbalagba, 2014).

(ii) 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):

Where Au, ATh and Ak are respectively the activity concentration of ^{238}U, ^{232}Th and ^{40}K in Bq/kg.

$$D\ (\eta Gy/h) = 0.462A_u + 0.604A_{Th} + 0.0417A_k \ldots\ldots 3$$

(iii) 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) scenerios 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 222Rn 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):

Where D is the absorbed dose rate in air, T is the average time an individual is exposed to radiation from

$$AEDE\ (mSv/y) = D \times T \times OF \times C \quad .. \quad .. \quad .. \quad 4$$

$$AEDE_{(Outdoor)}\ (mSv/y) = D \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \quad .. \quad .. \quad 5$$

$$AEDE_{(Indoor)}\ (mSv/y) = D \times 8760 \times 0.8 \times 0.7 \times 10^{-6} \quad .. \quad .. \quad .. \quad 6$$

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.

(iv) 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):

$$ELCR = AEDE \times DL \times RF \quad .. \quad .. \quad 7$$

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).

(v) Internal Hazard Index (Hin): 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):

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

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \quad .. \quad .. \quad 8$$

(vi) External Hazard Index (Hex): 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 Hex 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):

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

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_k}{4810} \leq 1 \quad .. \quad .. \quad .. \quad .. \quad 9$$

(vii) Clark Value: The Clark value is the average concentration of a radioisotope in the earth crust that is used as a baseline to determine if a material has been enriched in radionuclides arising from industrial processes (IAEA, 2013). Thus, the Clark value is seen as a geochemical concept that distinguishes between natural background radiation levels and the enrichment of radioactive materials through anthropogenic processes, and serving as a baseline for identifying environmental contamination by NORM such that measured concentrations of radionuclides above Clark value for uranium, thorium and potassium imply accumulation of NORM. The Clark value therefore provides the basis for regulatory decisions as regards radiation protection measures since it helps to assess whether the activity concentrations of radionuclides are of natural origin or have been enriched technologically through anthropogenic means. In this study the clark value was computed using the relation by IAEA (2013):

Where [Th] and [U] are respectively the elemental concentrations of thorium and uranium in parts per

$$\text{Clark Value} = 1.01855 \times \frac{[Th]}{[U]} \quad \ldots\ldots 10$$

million (ppm). However, the activity concentration values of Uranium and thorium were converted to ppm using the following relations (IAEA, 1989):

RESULTS AND DISCUSSION

Activity Concentration of Radionuclides in the Communities Soils

$$1\text{ppm eU} = 12.35\text{Bq/kg of } {}^{238}\text{U} \quad \ldots\ldots 11$$
$$1\text{ppm eTh} = 4.06\text{Bq/kg of } {}^{232}\text{Th} \quad \ldots\ldots 12$$
$$1\text{ppm \%K} = 313\text{Bq/kg of } {}^{40}\text{K} \quad \ldots\ldots 13$$

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 six (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.

Evaluation of the Radiological Hazard Indices

(i) The calculated values of radium equivalent activity (Raeq) in the six communities varied from 114.69 to 130.36Bq/kg with a mean value of 123.14Bq/kg. These values are lower than the international recommended world average of 370Bq/kg (UNSCEAR, 2000; Zarie and Al Mugren, 2010). These low values of radium equivalent activity below the permissible limit of 370Bq/kg implies that: (a) the external gamma radiation exposure to the people living or working in the vicinity of the investigated communities is considered within safe limits, hence the soil does not pose a significant radiological hazards arising from the gamma emissions; (b) the soil in the communities is considered safe for residential and agricultural purposes as well as for use in the construction of bricks, concretes or as foundation soil without the need for radiological intervention; (c) the indoor external exposure of radiations from the radionuclides as well as exposure from dwellings on the land remains below the annual dose limit of 1.0mSv/y recommended for the public by international bodies like the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and International Commission on Radiological Protection (ICRP); (d) there is a lower potential for radon exhalation rates from the soil which reduces the risk of indoor radon accumulation that is the leading cause of lung cancer after smoking (UNSCEAR, 2000; IAEA, 2003); and (e) the soil does not require radiological remediation or special precautions during land development because it serves as a clear baseline or benchmark for clean or background soil for environmental impact assessments (EIAs).

The results of Raeq in this study are higher than the values recorded by Avwiri and Agbalagba (2013), Eseka et. al (2018), and Eke et. al (2024), but they are however lower than the values recorded by Darwish et. al (2015). Fig. 3 shows the percentage contribution of each of the three natural radionuclides which was calculated from the parameters in the Raeq formula on the assumption that 10Bq/kg of ^{238}U (^{226}Ra), 7Bq/kg of ^{232}Th and 130Bq/kg of ^{40}K produced equal gamma dose (Avwiri and Agbalagba, 2014). The result revealed that ^{238}U, ^{232}Th and ^{40}K respectively constitute 31%, 36% and 33% of the gross activity of the soil samples with ^{232}Th contributing the highest to the gross activity of the soil sample in the six investigated communities.

(ii) The outdoor values of the absorbed dose rates (D) in air varied from 54.53 to 61.74ηGy/h with mean value

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

Communities	Coordinates		Specific Activity (Bqkg-1)			Radiological Hazard Indices						
								AEDE				
	Easting	Northing	238U	232Th	40K	D(ηGy/h)	Raeq (Bq/kg)	Indoor (mSv/y)	Outdoor (mSv/y)	ELCR (Indoor) (mSv/y)	Hex	Hin
Owere-Olobor	6o 20'33.85"	6o 16'8.71"	38.65±1.45	26.43±3.41	496.67±3.55	54.53	114.69	0.27	0.067	0.945	0.31	0.41
Otolokpo	6o 18'35.83"	6o 14'9.47"	37.82±1.52	30.25±2.10	543.42±3.22	58.40	122.92	0.29	0.072	1.015	0.33	0.43
Ute-Ogbeje	6o 21'17.80"	6o 10'25.81"	39.23±3.20	32.85±2.68	530.71±3.62	60.09	127.07	0.29	0.074	1.015	0.39	0.45
Igbodo	6o 22'12.78"	6o 17'34.64"	36.20±2.06	34.10±3.52	496.51±3.18	58.03	123.19	0.28	0.071	0.98	0.33	0.43
Mbiri	6o 18'33.63"	6o 21'17.34"	39.25±3.70	33.64±1.60	558.45±2.21	61.74	130.36	0.30	0.076	1.05	0.35	0.46
Ekuoma	6o 21'37.04"	6o 21'0.58"	38.93±2.72	28.75±1.80	526.44±1.72	57.30	120.58	0.28	0.070	0.98	0.32	0.43
Average			38.35±2.44	31.00±2.52	525.37±2.92	58.35	123.14	0.29	0.07	0.99	0.34	0.44
International Permissible Standards UNSCEAR (2008), ICRP (2021), WHO (2009)			33	45	420	59	370	0.41	0.07	0.29	≤1.0	≤1.0

of 58.35ηGy/h. 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). Figure 4 shows the percentage contribution of each of the three natural radionuclides to the absorbed dose rate and the result revealed that ^{238}U, ^{232}Th and ^{40}K respectively constitute 30%, 32% and 38% to the absorbed dose with 40K contributing the highest to the absorbed dose rates from the soil samples in the investigated communities. This high percentage of ^{40}K in the soil correlates with presence of clay minerals which does not often favour high uranium retention. It also accounts for the heavy usage of potassium based fertilizers for the oil palm plantations which may have increased the concentration of the ^{40}K in the topsoil surrounding the mills and plantations since natural potassium ores are used for the production of fertilizers and its
high solubility makes it easy to infiltrate into the soil matrix.
However, the implication of high percentage of ^{40}K in the absorbed dose rate is that the geochemical or

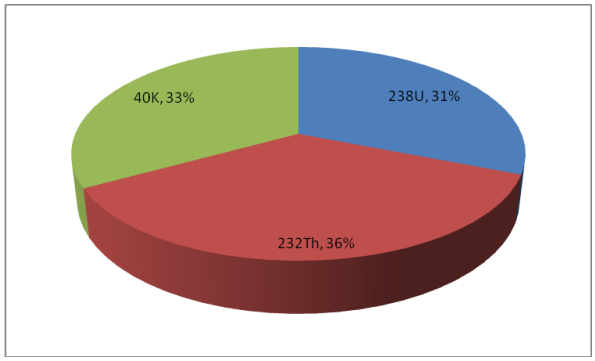

Figure 3: Percentage Contribution of the three Natural Radionuclides to the Gross Activity of the Soil Samples

industrial process of palm oil milling and fertilization is enriching potassium rather than mobilizing uranium or thorium, therefore gives a good indication that the industrial activity in the investigated communities is not creating a significant hazardous radioactive waste from the uranium/Thorium series. While the high percentage of ^{40}K is harmless, it serves as a reminder to constantly monitor the uranium and thorium levels in the mill's boiler ash and effluent. This is because if the burned shells, empty fruit bunches (EFB) and fibers had adhered to the soil containing uranium and thorium, the heavy elements could accumulate in the ash over time thereby posing a futuristic risk, even when the current dose is dominated by ^{40}K.
(iii) 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.

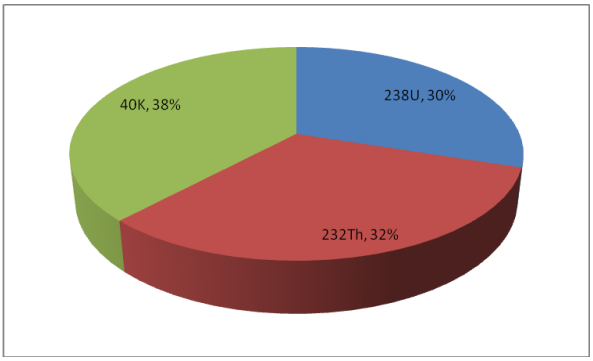

Figure 4: Percentage Contribution of the three Radionuclides in Soil Samples to the Absorbed Dose Rate

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).
(iv) 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. 5, 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).

(v) 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.

(vi) The average elemental concentration of radionuclides in the study area referred to as Clark value ranged from 2.12 to 2.91 with a mean value of 2.51 (Table 2). This mean Clark value as well as the Clark values in the soil in each of the communities is lower than the Earth's crustal average of Th/U mass ratio of 3.8 (Ahrens, 1995; Faure and Mensing, 2005). This indicates: (a) uranium enrichment or thorium depletion in the source rock and that the rock type in the region is more of MAFIC (Mg, Fe, Ca) composition than FELSIC (Feldspar, SiO2, Al) since Faure and Mensing (2005) and Condiel (1993) opined that high ratio of 232Th/238U means more thorium relative to uranium (that is more of FELSIC composition or uranium loss due to weathering) and low ratio of $^{232}Th/^{238}U$ means more uranium relative to thorium (that is more of MAFIC composition or uranium enrichment due to thorium depletion); (b) that uranium fractionated (leached) from thorium due to geochemical process (Faure and Mensing, 2005); and (c) uranium precipitated from groundwater due to oxidation (oxidizing environment) which lead to economic abundance of uranium mineralization thereby creating a distinct geologic unit of radiological signature dominated by the uranium clay chain with a significant radiological hazards from radon gas (Faure and Mensing, 2005). By implication therefore, a geologic unit with a low Th/U ratio <3.8 is a potential source of indoor radon gas which is radiologically hazardous when inhaled paving way for alpha particles into the bronchial epithelium resulting in chronic health effect such as cancer of the lungs and Leukemia (American Lung Association, 2022).

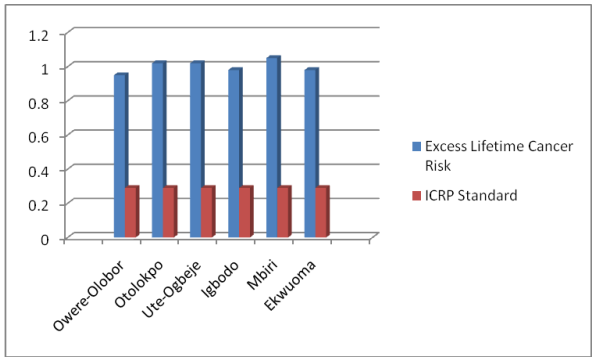

Figure 5: Excess Lifetime Cancer Risk in Soil Samples of the Study Area

Table 2: Elemental Concentration of Natural Radionuclides in the Community Soil Samples and the associated Clark Values (ppm)

Community	**Elemental Concentration**				
	238U (ppm)	232Th (ppm)	40K	Th/U	Clark Value
(%)	Th/U	Clark Value			
Owere-Olobor	3.13±0.12	6.51±0.84	1.59±0.01	2.08	2.12
Otolokpo	3.06±0.12	7.45±0.52	1.74±0.01	2.44	2.48
Ute-Ogbeje	3.18±0.26	8.09±0.66	1.69±0.01	2.54	2.59
Igbodo	2.93±0.17	8.39±0.87	1.59±0.01	2.86	2.91
Mbiri	3.18±0.29	8.29±0.39	1.78±0.01	2.61	2.66
Ekwuoma	3.15±0.22	7.08±0.44	1.68±0.01	2.25	2.29
Average	3.11±0.20	7.64±0.62	1.68±0.01	2.46	2.51
International Permissible Standards (UNSCEAR, 2008; Ahrens, 1995; Faure and Mensing, 2005)	2.67	11.08	1.34	3.8	3.8 – 4.0

CONCLUSION

The activity concentrations of 238U and 40K 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 232Th was found lower than the 45Bq/kg permissible world average value. The average radium equivalent activity of 123.14Bq/kg obtained in this study was lower than the 370Bq/kg recommended by the International Commission on Radiological Protection (ICRP). Moreover, 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 low mean clark values in the soils of the study area indicated uranium enrichment and thorium depletion in the source rock suggesting that the rock type in the region is more of MAFIC composition than FELSIC. Uranium enrichment also indicated that it leached from thorium due to geochemical processes, thus creating a distinct geologic unit of radiological signature dominated by the uranium clay chain associated with significant radiological hazards from radon gas making it a potential source rock for indoor radon gas which is of serious human health consequences.** 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 238U, 40K, absorbed dose rates (>59ηGy/h), excess lifetime cancer risk 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. This triggers the need for intervention, monitoring, and regulatory review.

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