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Radiological Assessment of Rock Samples at the National Iron Ore Mining Company (NIOMCO) Itakpe in Kogi State, Nigeria

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Abstract

Mining activities that involve the extraction of mineral ores have the potential to release naturally occurring radionuclides into the surrounding environment, thereby posing elevated health risks to mine workers and nearby communities. This study presents the results of measurements of the activity concentrations of primordial radionuclides in rock samples collected from the National Iron Ore Mining Company (NIOMCO), Itakpe, situated in Kogi State, north central Nigeria. A NaI(Tl) based gamma ray spectroscopy system was employed for the radiometric analysis. The activity concentrations of ^{238}U ranged from 1.00±0.15 Bq/kg to 8.26±1.02 Bq/kg, those of ^{232}Th varied between 3.46±0.21 Bq/kg and 6.85±0.42 Bq/kg, while ^{40}K values spanned from 4.36±0.24 Bq/kg to 252.11±13.91 Bq/kg. The mean activity concentrations for all three radionuclides fell below the globally recommended averages established by the United Nations Scientific Committee on the Effects of Atomic Radiation. The computed absorbed dose rates and annual effective doses likewise remained within permissible thresholds, indicating no immediate radiological threat to the surrounding population. These findings contribute baseline data that are essential for ongoing environmental radiation monitoring in mining regions of Nigeria.

Keywords: Activity concentration; naturally occurring radioactive materials; absorbed dose; gamma ray spectroscopy; iron ore mining; radiological hazard

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1. Introduction

Certain constituents of the earth's crust are inherently radioactive and have remained so since the planet's formation. Naturally occurring radioactive materials (NORMs) pervade the terrestrial environment, existing within geological formations such as rocks, soils, water bodies, vegetation, and the atmosphere (Knoll, 1989). Radiation, in its most fundamental sense, involves the emission of energy in the form of particles or electromagnetic waves as they traverse space or pass through a material medium. Among the broad categories of radiation, ionizing radiation possesses sufficient energy to dislodge tightly bound electrons from atoms, thereby generating ions either through direct or indirect mechanisms (Knoll, 1989). Gamma rays, beta particles, alpha particles, and neutron emissions represent the principal forms of ionizing radiation to which human populations are routinely exposed.

At the time of the earth's formation, approximately four billion years ago, the planet harboured numerous radioactive isotopes, some characterized by relatively short half lives and others persisting over geological timescales (Ibeanu, 1999). Scientific investigations have documented the existence of more than sixty distinct radionuclide species in nature, which are broadly classified into three groups: primordial radionuclides, which predate the formation of the earth; cosmogenic radionuclides, which arise from interactions between cosmic rays and atmospheric constituents; and artificial radionuclides, which result from anthropogenic activities (Eyebiokin, 2005). Human populations are continually subjected to background radiation originating from both external sources and internal pathways.

The radiological consequences of chronic exposure to naturally occurring radionuclides include irradiation of body tissues and inhalation of radon gas together with its decay products. Such exposures have been associated with increased risks of kidney damage, mutagenicity, leukaemia, and cancers of the bladder, lungs, and testes, among other malignancies (Hall, 2012; Ifeoluwa, 2014). The United Nations Scientific Committee on the Effects of Atomic Radiation estimated that the global average annual effective dose attributable to natural radiation sources is 2.4 mSv per person, of which roughly 1.26 mSv derives principally from radon inhalation (UNSCEAR, 2008). Additional radiation exposures stem from artificial sources, including medical diagnostic procedures, nuclear industrial operations, and nuclear weapons testing (Abiye, 2005).

Enhancement of environmental radiation levels is primarily a consequence of human activities such as the mining and milling of mineral ores, nuclear fuel fabrication, and management of fuel cycle residues (Nwankwo et al., 2015). Natural radioactivity that has been amplified through these processes can deliver radiation doses to workers and members of the public on the order of several millisieverts per year. The International Atomic Energy Agency has recommended that safety analyses, including the estimation of radiation doses accumulated by individuals working with radiation sources and the assessment of associated risks to the public, should be carried out systematically (IAEA, 2002). Consequently, evaluating the degree to which radiation doses have been enhanced by anthropogenic operations is essential for ensuring compliance with regulatory limits.

Iron ore constitutes a mineral from which metallic iron can be extracted through heating in the presence of a reducing agent. The principal iron bearing minerals of commercial interest are hematite (Fe_2O_3) and magnetite (Fe_3O_4), and these two oxides underpin virtually all iron and steel production worldwide. Mining operations associated with iron ore extraction, from excavation through beneficiation to transportation, carry environmental implications that can adversely affect air quality, water quality, and biological communities (Rabba et al., 2017).

The investigation of gamma ray activity in Kogi State, Nigeria, is of particular relevance given the mineral wealth of the region and the attendant hazards of radiation exposure. The state hosts active mining operations, including artisanal mining enterprises that often operate without adherence to environmental best practices. Open pit mining at Itakpe, coupled with the

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presence of granitic rock formations that are recognized reservoirs of uranium, thorium, and potassium, renders radiation exposure a matter of genuine concern. The overarching objective of this study is to determine the activity concentrations of naturally occurring radionuclides in rock samples from NIOMCO, Itakpe, and to evaluate the resultant radiological hazards that may affect the local inhabitants.

2. Materials and Methods

2.1 Study area

The National Iron Ore Mining Company (NIOMCO), Itakpe, is located within the Okehi Local Government Area of Kogi State, Nigeria, at geographical coordinates of latitude 7°36′20″N and longitude 6°18′35″E. The geological character of Itakpe is defined by a series of hills in and around the town that contain deposits of iron ore of considerable purity (Nwosu, 2020). The iron ore deposit comprises predominantly hematite with detectable quantities of magnetite, appreciable amounts of quartz, and traces of corundum, distributed across fourteen ore layers grading from 14.8% Fe to 41% Fe, with a composite average grade of 36% Fe, which is of substantial economic significance (NIOMCO Project Report, 1980). The mine supplies the Ajaokuta and Aladja steel plants and also produces ore for export. Figure 1 shows the location of Itakpe within the map of Nigeria.

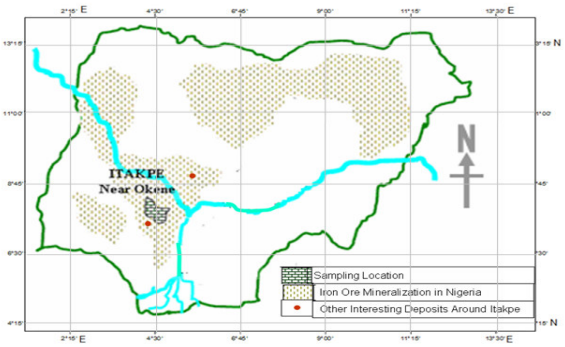

Figure 1: Location map of Itakpe in the Nigerian map (Source: Nwosu et al., 2013)

2.2 Sample collection and preparation

The specimens analysed in this investigation consisted of iron ore bearing rock samples collected through a random sampling protocol from six distinct locations within the NIOMCO mining complex at Itakpe (Table 1). Prior to laboratory analysis, a preliminary radiometric survey was conducted across the study site using a radiation alert monitor (model 4EC) to identify areas exhibiting elevated levels of terrestrial background radiation (Table 2). Following collection, the samples were subjected to open air drying under direct sunlight for a period of two days to remove residual moisture and organic constituents and to achieve a constant mass. The dried samples were then pulverized using a mechanical grinder to obtain a fine, homogeneous powder.

Each powdered sample, weighing 500 g, was transferred into a labelled beaker and hermetically sealed using a combination of candle wax, petroleum jelly, and masking tape to preclude the escape of radiogenic gases, most notably radon (Ra 222). The sealed samples were subsequently stored for a period of thirty days to allow the attainment of radioactive secular equilibrium between the parent radionuclides and their respective decay products. All preparatory procedures were carried out at the environmental laboratory of the National Institute of Radiation Protection and Research (NIRPR), University of Ibadan campus, Ibadan, Nigeria.

2.3 Gamma spectrometric analysis

Radionuclide quantification was performed using a gamma spectrometric system equipped with a sodium iodide detector doped with thallium, NaI(Tl). The detector was interfaced with a computer based multichannel analyser running Genie 2000 software for data acquisition and spectral analysis. To attenuate ambient background radiation, the detector assembly was housed within a cylindrical lead shield of 10 cm wall thickness. Energy and efficiency calibrations were accomplished using standard radioactive sources of americium 241, caesium 137, and cobalt 60, which span a range of gamma ray energies and emission intensities.

Each sample was counted for a live time of 10,800 seconds under reproducible geometric conditions. A

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background spectrum was acquired under identical conditions and the resulting counts were subtracted from the corresponding regions of interest in each sample spectrum. The 1764 keV gamma ray line of bismuth 214 served as the analytical marker for the assessment of ^{238}U activity, whilst the 2615 keV line of thallium 208 was employed for ^{232}Th quantification. The characteristic 1460 keV line of ^{40}K provided the basis for potassium content evaluation (UNSCEAR, 2000).

2.4 Computation of activity concentration

The specific activity concentration (A_i) for each radionuclide in every measured sample was computed according to the expression established by UNSCEAR (2000):

$$A_i = NC_i / (\varepsilon \times y_i \times M \times T) \quad (1)$$

where A_i denotes the activity concentration of the ith radionuclide in Bq/kg, NC_i represents the net count under the photopeak of the ith radionuclide, ε is the detection efficiency at the relevant gamma ray energy, y_i is the emission probability of the gamma ray transition (15.17% for ^{238}U, 35.85% for ^{232}Th, and 10.6% for ^{40}K), M is the sample mass in kilograms, and T is the counting time in seconds.

2.5 Absorbed dose rate and annual effective dose

The absorbed dose rate in air at a height of one metre above the ground surface was calculated for each sample using the dose conversion coefficients recommended by UNSCEAR (2000), as expressed in the following relation (Nwankwo et al., 2015):

$$D_R \text{ (nGy/h)} = 0.462\ A_U + 0.604\ A_{Th} + 0.0417\ A_K \quad (2)$$

where D_R is the absorbed dose rate, and A_U, A_{Th}, and A_K are the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K respectively, each expressed in Bq/kg.

The annual effective dose (E_d) was subsequently estimated using Equation 3 (Nwankwo et al., 2015):

$$E_d \text{ (mSv/y)} = D_R \times O_f \times C_C \times T \quad (3)$$

where O_f is the outdoor occupancy factor (0.2), C_C is the dose conversion coefficient (0.7×10^{-6} Sv/nGy), and T is the annual exposure time (8,760 hours for adults) as stipulated by UNSCEAR (2000).

3. Results

3.1 In situ background radiation measurements

The results of in situ terrestrial background radiation measurements obtained at the six sampling locations within the NIOMCO complex are summarized in Table 2. The average surface dose rates recorded across the surveyed sites ranged from 0.12 µSv/h at the primary and secondary crusher site to 0.16 µSv/h at the tailing site. These values exhibited a progressive increase from the initial ore processing stage through to the final tailing disposal area, which may reflect the cumulative concentration of radioactive constituents as the ore undergoes successive stages of beneficiation. Figure 7 provides a graphical representation of the average surface dose rates across all sampling locations.

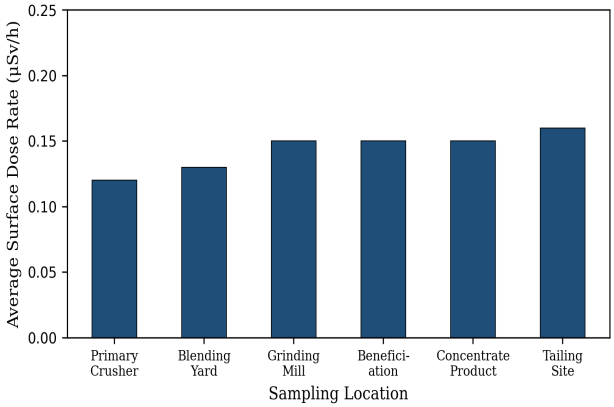

Figure 2: Average in situ surface dose rates measured across sampling locations at NIOMCO, Itakpe

3.2 Activity concentrations of radionuclides

The specific activity concentrations of ^{40}K, ^{238}U, and ^{232}Th determined in the rock samples from NIOMCO, Itakpe are presented in Table 3. The activity concentration of ^{40}K ranged from 4.36±0.24 Bq/kg (sample S_c) to 252.11±13.91 Bq/kg (sample S_a), with a mean value of 137.20±4.00 Bq/kg. For ^{238}U, the recorded values varied between 1.00±0.15 Bq/kg (sample S_d) and 8.26±1.02 Bq/kg (sample S_c), yielding a mean of 4.10±0.60 Bq/kg. The activity concentration of ^{232}Th spanned from 3.46±0.21 Bq/kg (sample S_f) to 6.85±0.42 Bq/kg (sample S_e), with a mean of 5.10±0.30 Bq/kg. Notably, ^{40}K was below the

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detection limit in samples S_d and S_e, while ^{238}U was undetectable in samples S_a and S_b.

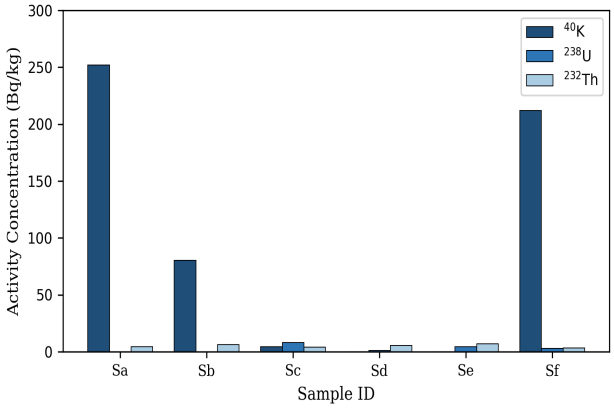

Figure 3: Specific activity concentrations of ^{40}K, ^{238}U, and ^{232}Th in rock samples from NIOMCO, Itakpe

3.3 Comparison with world averages

A comparison of the mean activity concentrations obtained in this study with the world average values recommended by UNSCEAR (2000) is presented in Figure 4. The mean activity concentrations of ^{40}K (137.20 Bq/kg), ^{238}U (4.10 Bq/kg), and ^{232}Th (5.10 Bq/kg) were considerably lower than the corresponding world averages of 400 Bq/kg, 35 Bq/kg, and 30 Bq/kg respectively. This disparity suggests that the rock formations at the NIOMCO site possess a relatively modest natural radioactivity profile when evaluated against the global benchmark.

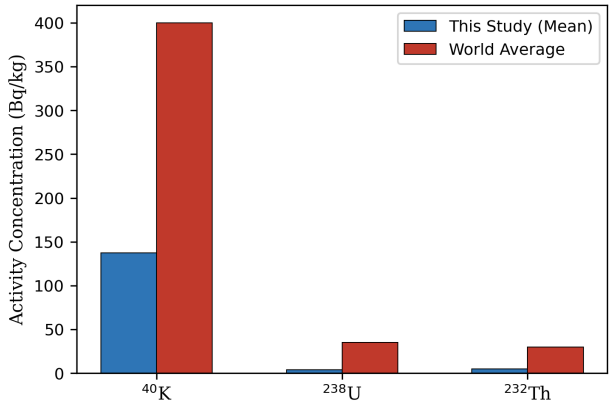

Figure 4: Comparison of mean activity concentrations in this study with UNSCEAR world average values

3.4 Absorbed dose rates and annual effective doses

The computed absorbed dose rates and annual effective doses for each sample are presented in Table 4. The absorbed dose rate ranged from 3.80±0.27 nGy/h (sample S_d) to 13.60±0.70 nGy/h (sample S_a), with a site mean of 7.79±0.56 nGy/h. These values are substantially below the world average absorbed dose rate of 84.0 nGy/h reported by UNSCEAR (2000). The corresponding annual effective doses varied from 0.005±0.001 mSv/y to 0.017±0.001 mSv/y, with a mean of 0.010±0.001 mSv/y. All values fall well within the threshold limit of 1 mSv/y established by the International Commission on Radiological Protection for members of the general public (ICRP, 2006).

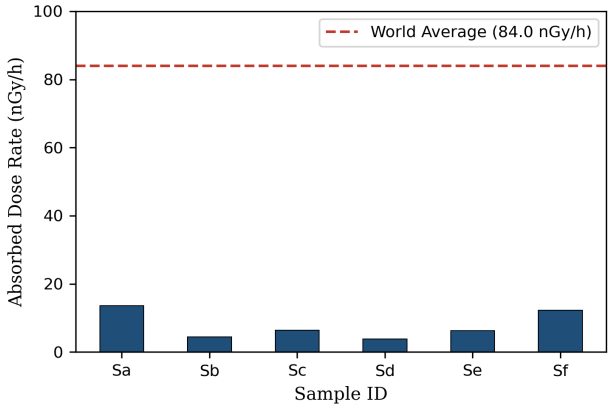

Figure 5: Absorbed dose rates for rock samples from NIOMCO, Itakpe, compared with the UNSCEAR world average of 84.0 nGy/h

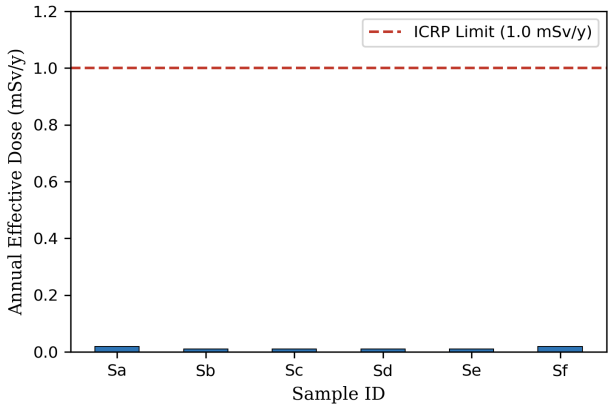

Figure 6: Annual effective dose for each sample compared with the ICRP recommended limit of 1.0 mSv/y for members of the public

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Table 1. Sample identification and locations of rock samples collected from NIOMCO, Itakpe

Sample ID	Location at NIOMCO, Itakpe	Weight (g)
Sa	Primary and Secondary Crusher Site	500
Sb	Blending Yard Site	500
Sc	Reclaiming/Grinding Mill Site	500
Sd	Beneficiation Site	500
Se	Concentrate Product	500
Sf	Tailing Site	500

Table 2. Results of in situ measurements of terrestrial background radiation from NIOMCO, Itakpe

Location Sites	Dose (μSv/h)	Avg (μSv/h)
Primary/Secondary Crusher	0.12, 0.12, 0.11	0.12
Blending Yard	0.13, 0.13, 0.14	0.13
Grinding Mill	0.12, 0.14, 0.15	0.14
Beneficiation Site	0.15, 0.16, 0.15	0.15
Concentrate Product	0.15, 0.15, 0.15	0.15
Tailing Site	0.16, 0.16, 0.17	0.16

Table 3. Specific activity concentrations of radionuclides in rock samples from NIOMCO, Itakpe

Sample ID	^{40}K (Bq/kg)	^{238}U (Bq/kg)	^{232}Th (Bq/kg)
S_a	252.11±13.91	BDL	4.40±0.30
S_b	80.20±4.10	BDL	6.20±0.40
S_c	4.36±0.24	8.26±1.02	4.00±0.30
S_d	BDL	1.00±0.15	5.50±0.30
S_e	BDL	4.40±0.60	6.85±0.42
S_f	212.10±11.30	2.90±0.40	3.46±0.21
Mean	**137.20±4.00**	**4.10±0.60**	**5.10±0.30**
World Average	**400.00**	**35.00**	**30.00**

Table 4. Absorbed dose rates and annual effective doses for rock samples from NIOMCO, Itakpe

Sample ID	Absorbed Dose Rate (nGy/h)	Annual Effective Dose (mSv/y)
S_a	13.60±0.70	0.017±0.001
S_b	4.40±0.40	0.005±0.001
S_c	6.40±0.60	0.008±0.001
S_d	3.80±0.30	0.005±0.001
S_e	6.20±0.50	0.008±0.001
S_f	12.30±0.80	0.015±0.001
Mean	**7.79±0.56**	**0.010±0.001**
World Average	**84.00**	**0.46**

4. Discussion

4.1 Activity concentration of radionuclides

The measured activity concentrations of ^{40}K, ^{238}U, and ^{232}Th in rock samples collected from the NIOMCO mining complex at Itakpe reveal a pattern of naturally occurring radioactivity that is significantly lower than globally established reference values. The mean activity concentration of ^{40}K was 137.20±4.00 Bq/kg, representing approximately 34.3% of the world average of 400 Bq/kg. Similarly, the mean ^{238}U activity of 4.10±0.60 Bq/kg constituted only 11.7% of the global mean of 35 Bq/kg, while the mean ^{232}Th value of 5.10±0.30 Bq/kg amounted to roughly 17.0% of the world average of 30 Bq/kg. These observations confirm that the iron ore bearing geological formations at Itakpe are characterized by a relatively subdued natural radioactivity signature.

The dominance of ^{40}K in the overall radioactivity profile of the samples, as illustrated in Figure 7, is consistent with established geochemical principles. Potassium is one of the most abundant crustal elements, and its radioactive isotope, ^{40}K, constitutes a fixed proportion (0.0117%) of total potassium in nature. The relatively elevated ^{40}K concentrations observed in samples S_a (primary and secondary crusher site) and S_f (tailing site) may reflect the presence of potassium bearing silicate minerals, such as orthoclase and muscovite, which are commonly associated with the host rock of iron ore deposits (Faure, 1986; Ademola, 2008).

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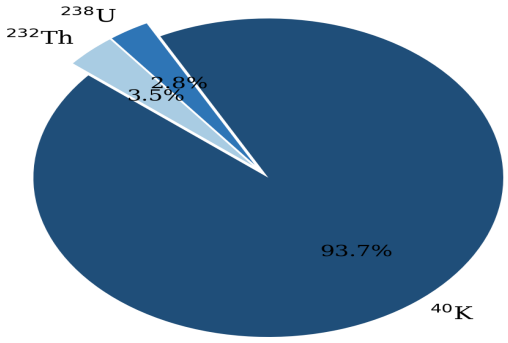

Figure 7: Relative contribution of ^{40}K, ^{238}U, and ^{232}Th to the total mean activity concentration in rock samples

The absence of detectable ^{238}U in samples S_a and S_b is noteworthy and suggests that the geochemical conditions at the primary crusher and blending yard sites may not favour the retention or accumulation of uranium bearing minerals. Uranium mobility in the near surface environment is strongly influenced by oxidation conditions, pH, and the availability of complexing ligands (Langmuir, 1978). The mechanical crushing and blending processes at these locations may promote the physical dispersal of uranium bearing mineral grains, thereby diluting their contribution below the minimum detectable activity of the spectrometric system.

Conversely, sample S_c from the reclaiming and grinding mill site exhibited the highest ^{238}U activity at 8.26±1.02 Bq/kg, which may be attributable to the concentration effect of the grinding process that liberates uranium bearing accessory minerals from the host rock matrix. This finding is consistent with observations by Nwankwo et al. (2015), who reported that mechanical ore processing can concentrate certain naturally occurring radionuclides in specific size fractions of the milled product.

4.2 Absorbed dose rates and radiological significance

The absorbed dose rates calculated for the rock samples ranged from 3.80 nGy/h to 13.60 nGy/h, with a site mean of 7.79 nGy/h. This mean value represents approximately 9.3% of the world average absorbed dose rate of 84.0 nGy/h (UNSCEAR, 2000), signifying a considerably low level of gamma radiation exposure at the NIOMCO facility. The pattern of absorbed dose rate distribution across the sampling sites, as depicted in Figure 5, closely mirrors the activity concentration trends, with the highest dose rates recorded at the primary crusher site (S_a, 13.60 nGy/h) and the tailing site (S_f, 12.30 nGy/h). These two locations coincide with the samples that exhibited the greatest ^{40}K concentrations, corroborating the dominant contribution of potassium to the overall external gamma dose at the site.

The annual effective dose values, ranging from 0.005 mSv/y to 0.017 mSv/y, are far below the regulatory limit of 1 mSv/y recommended by the International Commission on Radiological Protection for public exposure (ICRP, 2006). The maximum annual effective dose observed in this study (0.017 mSv/y at the primary crusher site) represents merely 1.7% of this limit. Furthermore, the site mean annual effective dose of 0.010 mSv/y is approximately 2.2% of the world average of 0.46 mSv/y as reported by UNSCEAR (2000). These findings collectively establish that the radiological exposure associated with the iron ore deposits and processing activities at NIOMCO, Itakpe does not constitute a significant health threat to either mine workers or the surrounding community under present operational conditions.

4.3 Comparison with related studies

The activity concentrations obtained in this investigation are broadly consistent with values reported in comparable studies undertaken at mining sites across Nigeria and other regions. Rabba et al. (2017) conducted a radiological assessment of soil samples within Federal University Lokoja and reported activity concentrations of ^{40}K, ^{238}U, and ^{232}Th that were similarly below global reference values. The relatively low activity concentrations at NIOMCO may be attributed to the predominantly ferruginous character of the ore body, which is dominated by hematite and magnetite, minerals that are not typically enriched in uranium or thorium (Faure, 1986).

In contrast, studies conducted at mining sites where granitic rocks predominate have generally reported higher activity concentrations. Nwankwo et al.

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(2015) investigated radioactivity concentration variation with depth at selected mining sites and found that activity levels can be significantly elevated in regions where granitic intrusions intersect mineralized zones. The comparatively modest radioactivity at Itakpe is therefore a reflection of the mineralogical and petrological characteristics of the deposit, which is dominated by banded iron formation lithologies rather than granitoid assemblages.

The in situ surface dose rate measurements (Table 2) revealed a consistent gradient, with values increasing progressively from the primary crusher site (0.12 µSv/h) to the tailing site (0.16 µSv/h). This spatial pattern is instructive and suggests that the beneficiation process, which separates the desired iron minerals from the host rock matrix, may result in a modest redistribution of radionuclide bearing accessory minerals into the tailing stream. Similar trends have been documented at other mineral processing facilities where the separation of ore from gangue inadvertently concentrates certain radioactive constituents in the waste fraction (Ademola, 2008).

4.4 Limitations and recommendations

While the present findings are reassuring in terms of immediate radiological safety, several limitations warrant acknowledgement. The study was based on six rock samples, which, although representative of the major processing stages within the NIOMCO complex, may not capture the full spatial variability of radionuclide concentrations across the entire mining concession. Furthermore, the measurements were conducted at a single point in time and do not account for potential temporal variations in radioactivity levels associated with seasonal changes in mining intensity or changes in ore source.

Future investigations should consider expanding the sampling network to include a greater number of sites, encompassing overburden dumps, settling ponds, and downstream waterways that may serve as secondary repositories for redistributed radionuclides. Long term monitoring programmes employing continuous dosimetry would provide a more comprehensive assessment of occupational and public exposure. In addition, the incorporation of radon emanation measurements and assessments of internal radiation dose from inhalation and ingestion pathways would offer a more complete picture of the total radiation burden associated with mining operations at Itakpe.

5. Conclusion

This study has determined the terrestrial background radiation from naturally occurring radioactive materials at the National Iron Ore Mining Company, Itakpe, taking into account the geological and geographical characteristics of the site. The specific activity concentrations of ^{40}K, ^{238}U, and ^{232}Th in rock samples collected from six processing locations within the mining complex ranged from 4.36±0.24 Bq/kg to 252.11±13.91 Bq/kg, 1.00±0.15 Bq/kg to 8.26±1.02 Bq/kg, and 3.46±0.21 Bq/kg to 6.85±0.42 Bq/kg respectively. All measured values remained below the globally recommended averages.

The mean annual effective dose for the study site was 0.010±0.001 mSv/y, which is substantially lower than the threshold limit of 1 mSv/y prescribed for members of the general public by the International Commission on Radiological Protection. On the basis of these results, it is concluded that the mining and ore processing activities at NIOMCO, Itakpe do not presently impose any significant radiological hazard on workers or the surrounding community. Nevertheless, the establishment of a systematic and sustained radiation monitoring framework is recommended to ensure the continued safety of all individuals associated with or residing in the vicinity of the mining operations.

Acknowledgments

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