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ORIGINAL ARTICLE

Radiological Implications of Coal-Mining Activities in Maiganga Coalfield of North-Eastern Nigeria

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Abstract

Background Maiganga coalfield is a newly discovered coal deposit in the north-eastern Nigeria that is currently receiving considerable attention from coal stakeholders. The deposit is also a prime target for power generation by the Nigerian government. Protection of man and the environment from excessive radiation exposures due to anthropogenic activities is, therefore, important.

Purpose The main objective of this study is the assessment of natural radioactivity in the Maiganga coalfield environment of north-eastern Nigeria, with particular emphasis on their environmental and human health implications.

Methods Samples of soil, coal, and mine tailings from Maiganga coalfield were assessed for ^{40}K, ^{226}Ra, and ^{232}Th activity concentrations using HPGe γ-ray spectrometry.

Results Mean activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in coal were 17.8 ± 1.2, 7.6 ± 0.5, and 5.5 ± 0.4, Bq kg^{-1}, respectively, which were below world mean values of 50, 20, and 20 Bq kg^{-1}, respectively, for coals. Mean specific activities of ^{40}K, ^{226}Ra, and ^{232}Th for mine tailings were 91.2 ± 4.3, 20.2 ± 1.0, and 25.7 ± 1.3 Bq kg^{-1}, respectively, while mean values for soil were, respectively, 83.5 ± 4.0, 17.7 ± 0.9, and 27.3 ± 1.3 Bq kg^{-1}. The mean specific activities were below their respective world mean values of 400, 35, and 30 Bq kg^{-1}. Calculated average gamma dose for soil, coal, and mine tailings were 28.1, 7.6, and 28.7 nGy h^{-1}, respectively, with average annual effective dose equivalent of 0.03, 0.01, and 0.03 mSv year^{-1} in sequence. These were all below their respective world average values. Computed average values for other radiation hazard indices were lower than the recommended limits set for radiation protection.

Conclusion Radiation load on mine workers, environment, and the public due to coal-mining operations in Maiganga coalfield is insignificant.

Keywords Natural radioactivity · Dose · Excess lifetime cancer risk · Maiganga · Nigeria

1 Introduction

Naturally occurring radioactive materials (NORM) are widespread and broadly distributed among various environmental samples and in varying concentrations depending on the geological and geographical definitions of any given region (Asaduzzaman et al. 2014). Coal, which is a naturally abundant fossil fuel, contains naturally occurring radioactive materials at varying activity levels (Lu et al. 2012; Hasan et al. 2013). Human activities such as coal mining, redistributes and transports coal radioactivity to the surface thereby enhancing the radioactivity levels above background in the human–environment (Aytekin and Baldik 2011; Charro and Pena 2013). Long-lived radionuclides particularly ^{238}U, ^{232}Th and their radioactive progenies, and ^{40}K are predominantly responsible for human radiation exposure (Cam et al. 2010).

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Mining activities has impacted considerably on man and his environment (Lottermoser and Ashley 2006). Mining operations involve the removal of huge amounts of top soils and production of considerable amount of mining wastes (tailings) with enhanced radioactivity. These large quantities of mine tailings are dumped haphazardly around the mine, where they are transported via atmospheric processes and finally concentrated in the soil environment. Leaching of the tailings can occur during wet climates and thus transfer the radionuclides into surface and groundwater bodies. Utilization of mine tailings as aggregates of building materials and for agricultural purposes are additional exposure pathways for human contamination (Aliyu et al. 2015).

Coal-mining activities in Maiganga coal mine employ the open cast mining which results in the production of large volume of mine tailings heaped around the mine. Both coal workers and the immediate local community are eventually exposed externally to radiation from the easily accessible tailings. The local community also uses the tailings as landfills and for agricultural purposes. It is, therefore, important to assess the radiological contents of coal and coal mine tailings from Maiganga coalfield and to evaluate the impact of coal-mining operations from the point of view of radiation exposure. This investigation is considered a pilot study to estimate the potential radiation exposure baseline and to assess radiological impacts of Maiganga coalfield.

2 Materials and Methods

Maiganga community lies between latitude 10°02′–10°05′ and longitude 11°06′–11°08′ in Akko local government area of Gombe in North-eastern Nigeria (Fig. 1). It is a thermally immature lignite to sub-bituminous coal deposit hosted within the Maastrichtian Gombe formation of Northern Benue Trough in north-eastern Nigeria (Kolo et al. 2016). Exploration work and detail geological investigations are currently ongoing to ascertain the quantity and quality of this deposit. Ten coal samples were collected from Maiganga coalfield for analysis using the grab method. Ten coal mine tailing samples were also collected at random across the mine dumps. Similarly, ten top soil samples were randomly assembled as control from undisturbed area around the mine. Each sample was uniquely packed in clean plastic containers, well-labelled, and tightly sealed. All the samples were conveyed to the laboratory, where they were spread on clean cardboard sheets and left to dry in open for 72 h to obtain moisture free samples. The dry samples were grinded to fine powder and sieved using 2 mm sieve. Sieved samples, each about 384 ± 1.0 g, were neatly loaded into clean Marinelli beakers, labelled accurately, and hermetically sealed. The sealed samples were incubated for 5 weeks to allow long-lived parent nuclides and their respective decay daughters to attain secular equilibrium (Amin et al. 2013a).

Radiometric analysis was carried out on the samples using a high-purity germanium (HPGe) γ-ray spectrometer

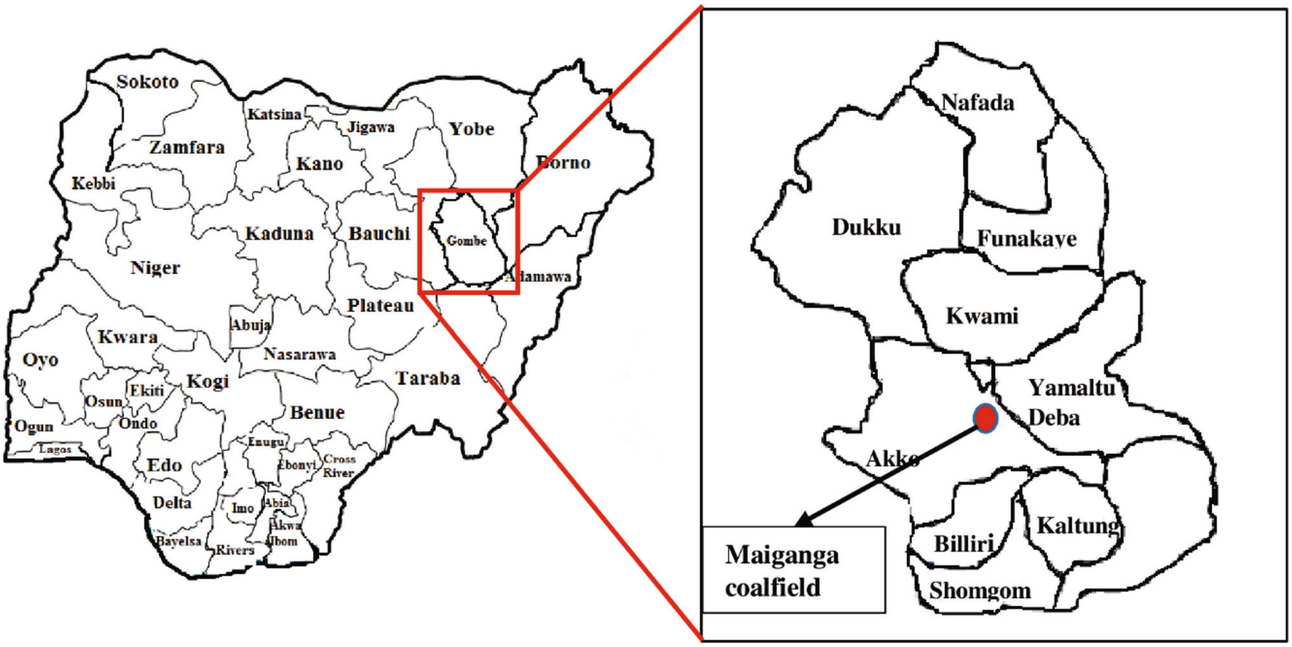

Fig. 1 Map of Gombe state, showing the project site

(P-type coaxial ORTEC GEM-25 model). The detector arrangement was such that very thick cylindrical lead was used to shield the Ge crystal from external radiation interference (Amin et al. 2013b). The overall detector arrangement was coupled to PCA II multi-channel analyzer for data acquisition and analysis. The detector with energy resolution of 28.2% (1.33 MeV ^{60}Co) was operated at +2800 V. A multi-nuclide gamma-ray source with the initial activity of 5.109 µCi was used for detector calibration prior to measurement. The calibration source which was supplied by Isotopes Products Laboratories, Valencia, CA 91355, contained the following nuclides: ^{109}Cd (88.040 keV), ^{60}Co (1173.22, 1332.492 keV), ^{88}Y (898.042, 1836.063 keV), ^{203}Hg (279.195 keV), ^{85}Sr (514.007 keV), ^{137}Cs (661.657 keV), ^{113}Sn (391.698 keV), ^{241}Am (59.541 keV), and ^{57}Co (122.061, 136.474 keV). Activity concentration of ^{226}Ra was evaluated from weighted energy peaks of ^{214}Pb (351.93 keV, 35.6%) and ^{214}Bi (609.32 keV, 45.49%). Weighted mean energy peaks of ^{228}Ac (911.29 keV, 29%; 968.97 keV, 17.4%) and ^{208}Tl (583.187 keV, 85%) were used to estimate the activity concentration of ^{232}Th, while specific activity of ^{40}K was deduced from its single gamma-ray line of 1460.822 keV, (10.66%). Each sample was counted for 86,400 s. Specific activity (A) of ^{40}K, ^{226}Ra, and ^{232}Th was calculated using the equation (Khandaker et al. 2016):

$$A\left(\mathrm{Bq\ kg^{-1}}\right) = \frac{\mathrm{CPS} \times 1000}{\varepsilon_\gamma \times I_\gamma \times W}, \tag{1}$$

where ε_γ (E) is photo-peak efficiency of detector, I_γ is the gamma-ray intensity, CPS is the net counts per second, and W the sample mass in g.

3 Results and Discussion

3.1 Activity Concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in the Samples

Descriptive statistical results of activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th, in coal, mine tailings, and soil samples from Maiganga coalfield are given in Table 1. Average specific activities of ^{40}K, ^{226}Ra, and ^{232}Th in coal samples were 17.8 ± 1.2, 7.6 ± 0.5, and 5.5 ± 0.4 Bq kg^{-1}, respectively. The values were below the world coal mean values of 50, 20, and 20 Bq kg^{-1} documented by UNSCEAR (1982). Specific activities obtained for mine tailings showed very low concentrations, ranging from 38.5 ± 1.9 to 125.9 ± 5.9 Bq kg^{-1} for ^{40}K, 8.3 ± 0.4 to 27.2 ± 1.3 Bq kg^{-1} for ^{226}Ra, and 12.6 ± 0.7 to 32.3 ± 1.6 Bq kg^{-1} for ^{232}Th with average values of 91.2 ± 4.3, 20.2 ± 1.0, and 25.7 ± 1.3 Bq kg^{-1} in sequence.

Table 1 Descriptive statistics of activity concentrations (Bq kg^{-1}) of coal, tailings, and soil samples from Maiganga coalfield

Sample	No.		^{40}K	^{226}Ra	^{232}Th
Coal	10	Min	14.9 ± 1.0	1.9 ± 0.2	1.0 ± 0.2
		Max	26.7 ± 1.6	21.6 ± 1.2	18.3 ± 1.0
		Mean	17.8 ± 1.2	7.6 ± 0.5	5.5 ± 0.4
Tailings	10	Min	38.5 ± 1.9	8.3 ± 0.4	12.6 ± 0.7
		Max	125.9 ± 5.9	27.2 ± 1.3	32.3 ± 1.6
		Mean	91.2 ± 4.3	20.2 ± 1.0	25.7 ± 1.3
Soil	10	Min	56.0 ± 2.7	13.4 ± 0.7	20.9 ± 1.0
		Max	98.4 ± 4.6	22.7 ± 1.1	37.3 ± 1.8
		Mean	83.5 ± 4.0	17.7 ± 0.9	27.3 ± 1.3

Data obtained for studied soil samples recorded average activity values of 83.5 ± 4.0, 17.7 ± 0.9, and 27.3 ± 1.3 Bq kg^{-1} for ^{40}K, ^{226}Ra, and ^{232}Th, respectively. The mean values were below their respective world medians of 400, 30, and 35 Bq kg^{-1} for normal soils documented by UNSCEAR (2000). Coal mine tailings showed very slight elevations in radioactivity content compared to soil, which may be attributed to coal-mining activities. Overall data obtained in this study were within recommended ranges for normal background radiation. Thus, coal-mining activities in Maiganga coalfield has very negligible effect on the radioactivity of the surrounding environment.

3.2 Radium Equivalent Activity (Ra$_{\mathrm{eq}}$)

Radium equivalent activity (Ra$_{\mathrm{eq}}$) is a commonly used radiation hazard index, in which the radiation exposure from different mixtures of ^{226}Ra, ^{232}Th, and ^{40}K in environmental samples is expressed in a single quantity. It was calculated from the equation (UNSCEAR 2000; Khandaker et al. 2012):

$$\mathrm{Ra_{eq}}\left(\mathrm{Bq\ kg^{-1}}\right) = A_{\mathrm{Ra}} + 1.43A_{\mathrm{Th}} + 0.077A_{\mathrm{K}}, \tag{2}$$

where A_{Ra}, A_{Th} and A_{K} are the respective specific activities of ^{226}Ra, ^{232}Th and ^{40}K. To effectively evaluate Ra$_{\mathrm{eq}}$, it was assumed that 4810 Bq kg^{-1} of ^{40}K, 370 Bq kg^{-1} of ^{226}Ra, and 259 Bq kg^{-1} of ^{232}Th produce the same gamma dose (Asaduzzaman et al. 2015). Calculated average for Ra$_{\mathrm{eq}}$ as presented in Table 2 for coal samples was 16.8 Bq kg^{-1}, while for mine tailings and soil samples were 63.9 and 63.1 Bq kg^{-1}, respectively, which were below the precautionary limit of 370 Bq kg^{-1} (UNSCEAR 2000). This showed that the utilization of mine tailings, either as aggregates of building materials, landfills or agricultural purposes poses no radiological consequence to the users.

Table 2 Descriptive statistics of radiation hazard indices for coal, tailing, and soil samples from Maiganga coalfield: mean (range)

Hazard indices	Coal	Tailing	Soil
Ra_{eq} (Bq kg^{-1})	16.8 (4.5–49.8)	63.9 (29.3–79.0)	63.1 (47.7–83.1)
D_R (nGy h^{-1})	7.6 (2.1–22.1)	28.7 (13.1–35.6)	28.1 (21.2–36.9)
AEDE (mSv year^{-1})	0.01 (0.003–0.03)	0.03 (0.02–0.04)	0.03 (0.03–0.04)
H_{ex} (≤ 1)	0.05 (0.01–0.13)	0.2 (0.1–0.2)	0.17 (0.13–0.22)
H_{in} (≤ 1)	0.07 (0.02–0.19)	0.2 (0.1–0.3)	0.22 (0.17–0.28)
$I_{\gamma r}$ (≤ 1)	0.12 (0.03–0.34)	0.5 (0.2–0.6)	0.45 (0.34–0.59)
ELCR ($\times 10^{-3}$)	0.03 (0.01–0.09)	0.1 (0.1–0.2)	0.12 (0.09–0.16)

4 Calculation of Radiation Hazard Indices

4.1 Gamma Absorbed Dose Rate (D_R)

Gamma dose rate in the air (D_R), measured in nGy h^{-1} at 1 m above ground level was computed from known specific activities of ^{40}K, ^{226}Ra and ^{232}Th in environmental samples. D_R was computed using the conversion constants: 0.0417, 0.462, and 0.604 nGy h^{-1}, respectively, for ^{40}K, ^{226}Ra, and ^{232}Th published in UNSCEAR (2008) report from the equation:

$$D_R = 0.462 A_{Ra} + 0.604 A_{Th} + 0.0417 A_K. \tag{3}$$

Results presented in Table 2 indicated that the absorbed gamma dose rate in the air at 1 m above ground varied between 2.1 and 22.1 nGy h^{-1} for coal samples, 13.1 and 35.6 nGy h^{-1} for mine tailings and 21.2 and 36.9 nGy h^{-1} for soil, with respective mean values of 7.6, 28.7, and 28.1 nGy h^{-1}. The values were extremely below the recommended limit of 55 nGy h^{-1} (UNSCEAR 2000). The results showed that coal-mining activities in Maiganga coalfield have no significant influence on the radiation load within the mining environment.

4.2 Annual Effective Dose Equivalent (AEDE)

Annual effective dose equivalent for the studied coal, mine tailings and soil was evaluated from the absorbed gamma dose rate. This was achieved using the two basic transformation parameters: outdoor occupancy factor of 0.2, and conversion coefficient of 0.7 Sv Gy^{-1}, provided in the UNSCEAR (2000) report. AEDE was calculated from the equation:

$$\begin{aligned} \text{AEDE}\left(\text{mSv year}^{-1}\right) &= D_R\left(\text{nGy h}^{-1}\right) \times 8760\left(\text{h year}^{-1}\right) \\ &\quad \times 0.7\left(\text{Sv Gy}^{-1}\right) \times 0.2 \times 10^{-6}\left(\text{mSv year}^{-1}\right) \\ \text{AEDE} &= D_R \times 1.21 \times 10^{-3}. \end{aligned} \tag{4}$$

Average AEDE for coal, tailing, and soil samples were, respectively, 0.01, 0.03, and 0.03 mSv year^{-1} (Table 2). These values were below the average annual effective dose of 0.460 mSv year^{-1} from terrestrial radionuclides in normal background areas as documented in UNSCEAR (2000) report.

4.3 External Hazard Index (H_{ex})

This is a dimensionless token, which expresses the suitability of any environmental sample for use from radiation protection perspective. H_{ex} was calculated from the equation (UNSCEAR 2000):

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810}. \tag{5}$$

H_{ex} must be less than unity for any material to be radiologically safe for use. From the results in Table 2, calculated average H_{ex} was 0.05 for coal samples, 0.2 for mine tailings, and 0.17 for soil samples. All these values were below unity, showing the non-hazardous nature of the studied samples.

4.4 Representative Gamma Index ($I_{\gamma r}$)

Representative gamma index ($I_{\gamma r}$) is a radiation index for screening aggregates of building materials (Asaduzzaman et al. 2016). The index identifies inter-relationships that may exist between annual gamma dose and any excessive external radiation from building materials. $I_{\gamma r} \leq 1$ corresponds to annual effective dose ≤ 1 mSv year^{-1} (NEA-OECD 1979). To identify whether the given dose standard was met, $I_{\gamma r}$ was computed using the equation (Asaduzzaman et al. 2016):

$$I_{\gamma r} = \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_K}{1500}. \tag{6}$$

Average $I_{\gamma r}$ obtained for coal samples was 0.12, while those obtained for mine tailings and soil samples were 0.5 and 0.45, respectively (Table 2). These values were below one (1), indicating that the annual effective dose calculated for radionuclides in the studied samples were ≤ 1 mSv year^{-1}. Thus, utilization of coal mine tailings from Maiganga coalfield for building constructions does not constitute any radiological threat to the general public.

4.5 Excess Lifetime Cancer Risk (ELCR)

The probability of occurrence of cancer and cancer-related diseases among coal workers and the public due to their continuous exposure to low doses of radiation from coal-mining activities cannot be ignored. The risk of exposure called excess lifetime cancer risk (ELCR) was estimated based on 70 years lifetime of continuous population exposure to low-level radiation. It was calculated from the equation (Asaduzzaman et al. 2015):

$$\mathrm{ELCR} = \mathrm{AEDE} \times \mathrm{DL} \times \mathrm{RF}, \tag{7}$$

where RF is the risk factor, having a value of 0.05 Sv^{-1}, AEDE is the annual effective dose equivalent, and DL signifies life duration of 70 years. Calculated mean values of ELCR as shown in Table 2 were 0.03×10^{-3} for coal, 0.1×10^{-3} for mine tailings and 0.1×10^{-3} for soil samples. These values were lower than the world mean of 0.29×10^{-3} (UNSCEAR 2000). In general, results of this investigation indicated that there is no significant radiological incidence for coal mine workers and the general public as a result of the exploitation and utilization of coal from Maiganga coalfield.

5 Conclusions

In view of environmental and human health impacts of coal-mining activities around the world, specific activities of ^{40}K, ^{226}Ra, and ^{232}Th in soil, coal, and mine tailings collected from Maiganga coalfield, north-eastern Nigeria, were measured and analyzed. Results of this study indicated that mean activity concentrations of primordial radionuclides were far below their respective world average values. Calculated values for all radiation hazard parameters were below their respective recommended limits from radiation protection perspective. The results of this investigation showed that coal-mining activities in Maiganga coalfield and the utilization of coal mine tailings for whatever purpose does not constitute any immediate radiological risk to the miners, the environment, and the public in general.

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Wan Hasiah Binti Abdullah Professor Dr. Wan Hasiah Abdullah began her academic career in 1984 upon undertaking a tutorship/postgraduate programme in the UK and started teaching in the Department of Geology, University of Malaya in 1990. She appointed as an Associate Professor in 1999 and a Professor in 2005. Her research interest is in assessing oil-generating potential of coals and determining depositional environments of oil-prone source rocks. In her M.Sc., she worked on the Brent Formation coals of the North Sea, and in her Ph.D., she worked on a succession of sedimentary rocks from Spitsbergen, Svalbard. Throughout the years, Prof. Wan Hasiah presented her research work in Europe, the Middle East, Southeast Asia, and Australia. She published about 70 papers in ISI/SCOPUS journals, supervised 10 M.Sc./Ph.D. students to completion, and conducted many consultation projects for major oil companies, such as Sabah/Sarawak SHELL and PETRONAS. In 2005, she introduced an M.Sc. taught course in Petroleum Geology at the University of Malaya, the first of its kind in Malaysia, whilst the mixed mode (coursework and research) was introduced in 2011. Adopting an innovative approach to teaching allowed many applicants with engineering background and/or non-geological sciences to benefit from these M.Sc. programmes. Through this approach, many of these graduates are presently serving major oil companies in Malaysia, undertaking tasks that are commonly performed by geoscientists. Prof. Wan Hasiah also served as the Head of the Geology Department (2004–2007), as a coordinator for the M.Sc. Petroleum Geology programmes (2005–2015), and is presently holding the position of Deputy Director of the University of Malaya’s Consultancy Unit.