Arch Environ Contam Toxicol (2016) 70:783–792
DOI 10.1007/s00244-016-0271-y

Environmental-Impact Assessment of Natural Radioactivity Around a Traditional Mining Area in Al-Ibedia, Sudan

Hajo Idriss[1,2] · Isam Salih[2,3] · Abdulaziz S. Alaamer[1] · Almuaiz Saleh[4] · M. Y. Abdelgali[5]

Received: 30 November 2015 / Accepted: 26 February 2016 / Published online: 16 March 2016

Abstract Recently, in the Sudan, traditional gold mining has been growing rapidly and has become a very attractive and popular economic activity. Mining activity is recognized as one of the sources of radioactivity contamination. Hence, the radioactivity concentration and radiological hazard due to exposure of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K were evaluated. The measurements were performed using gamma-ray spectrometry with an NaI (Tl) detector. The results show that ^{226}Ra, ^{232}Th, and ^{40}K activity concentration ranged from 2.66 to 18.47, 9.20 to 51.87, and 0.17 to 419.77 Bq/kg with average values of 7.54 ± 4.91, 20.74 ± 11.29, and 111.87 ± 136.84 Bq/kg, respectively. In contrast, ^{222}Rn in soil, ^{222}Rn in air, and ^{226}Ra in vegetables along with radiation dose were computed and compared with the international recommended levels. Potential radiological effects to miners and the public due to ^{226}Ra, ^{232}Th, ^{40}K, and ^{222}Rn are insignificant. ^{226}Ra transferred to vegetables appears to be negligible compared with the allowable limit 1.0 mSv/year set by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The average value of the annual gonadal dose equivalent (AGDE) is lower than the global average of 300 μSv/year (UNSCEAR 2000). However, some locations exhibit values >300 μSv/year. To the best of our knowledge, so far there seems to be no data regarding radioactivity monitoring in traditional mining areas in the Sudan.

People are exposed to ionizing radiation from radionuclides that present in different types of natural sources (Ghosh et al. 2008). Owing to the health risks associated with exposure to natural radionuclides, international and local organizations—such as the International Commission on Radiological Protection and the United States Environmental Protection Agency (USEPA)—have set standards and legislation to minimize such exposure (Hammond et al. 2007; Saleh and Shayeb 2014). Traditional gold mining in the Sudan has become increasingly attractive in the last decades owing to rising gold prices. For this reason, gold markets have prospered in many Sudanese provinces. The miners might be exposed to ionizing radiation from primordial radionuclides during gold extraction and processing. People residing close to the mines may be directly exposed to radionuclides through the ingestion of drinking water or uptake through the food chain. In addition, the general public may also be exposed to ionizing radiation because of reuse of mine wastes as construction materials (International Commission on Radiological Protection [ICRP] 1991). Indiscriminate mining, for example, removes vegetation and soil leading to an imbalance in the ecosystem and resulting devastation and destruction of the agricultural land. In addition, mining activities may sometimes produce toxic waste that can cause health problems and contamination (USEPA 2007). Radioactivity in soil is a good indicator of the distribution

✉ Hajo Idriss
hjoidriss@gmail.com

[1] Committee on Radiation and Environmental Pollution Protection, Physics Department, College of Science, Al Imam Mohammad Ibn Saud Islamic University, Riyadh 11642, Kingdom of Saudi Arabia

[2] Sudan Atomic Energy Commission, Khartoum, Sudan

[3] Department of Physics, Taibah University, Al-Madinah Al-Munawarah, Kingdom of Saudi Arabia

[4] Sudan Academy of Sciences, Khartoum, Sudan

[5] Department of Mineral Wealth Faculty of Petroleum and Minerals, Al Neelain University, Khartoum, Sudan

and accumulation of radioactivity in the ecosystem. Furthermore, the concentration of primordial radionuclides provides helpful data for monitoring environmental radioactivity (UNSCEAR 2000). Much consideration has been directed to natural radioactivity in the soil around gold-mining sites, and estimations have been made in numerous countries by many researchers (Ademola et al. 2014; Africa et al. 2000; Anjos et al. 2010; Durand 2012; Doyi et al. 2013; Vivian et al. 2011). Minerals are mined by artisanal miners using different methods such as digging pits and opening small, narrow holes up to several meters in depth. Mining activities in Sudan are not subject to radiological regulatory control. Therefore, there is no general awareness and knowledge about the radiation hazards and exposure levels to natural radioactivity in these mining areas. Thus, the current study aimed at examining the radioactivity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil samples and assessing the radiological hazards. In addition, it lays focus on increasing the awareness and knowledge about radioactivity in mining areas.

Materials and Methods

Study Area

The area under consideration (Fig. 1) is located around 18°12′37″N and 33°57′7″E in a northern Berber town 18 km from the Al-Ibedia locality in the River Nile State, Sudan. It is bordered by the Nile to the west, the Albaoukh and Mberekhto areas to the north, the Red Sea to the east, and the Alhfab area to the south. Mining activities for the extraction of gold such as drilling, leaching, handling, storing, and transportation of raw materials—as well as the use of contaminated equipment, and the contaminated waste produced—have caused various environmental problems. Furthermore, some of the naturally occurring radioactive materials soluble in water, which have a tendency to leach into water bodies and farmlands, are an environmental and public health concern. The reasons mentioned above are the basis for the choice of the study area.

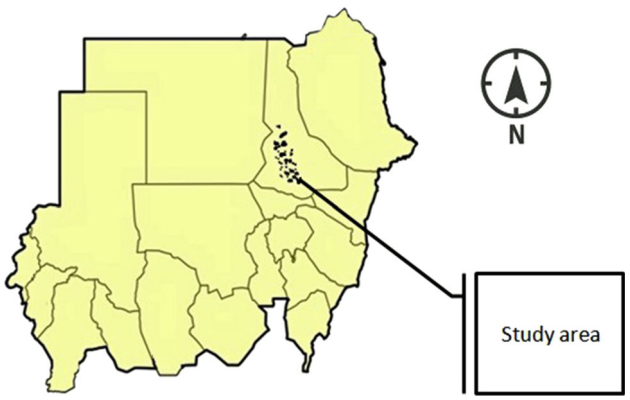

Fig. 1 Location map of the study area (Idriss et al. 2014)

Geology of the Study Area

The study area consists of a series of outcrops of Upper Proterozoic green schist assemblage. Mafic–ultramafic lenses exist along the contact consisting of a variety of rock types: peridotites, pyroxenites, and layered gabbros. East of the River Nile, the mafic–ultramafic lenses are intercalated with volcano-sedimentary sequences, highly sheared and transformed to talc, and rich in talc carbonate (Ali and Abdelrahman 2011). The core of the synform is dominated by highly deformed volcano-sedimentary sequences and intruded by syntectonic granitoid plutons. The mafic–ultramafic succession consists of a basal unit of serpentinite and talc-chlorite schist overlain by thick cumulate facies of peridotites, pyroxenites, and layered gabbros as well as basaltic pillow lava associated with thin layers of carbonates and metachert (Fig. 2). Hydrothermally ferruginated chert is observed at Qurun Mountain (Mohamedai 2014). The basal ultramafic rocks are in contact with the volcano-sedimentary rocks and subjected to very strong deformation and intense shearing giving rise to boudinage structures (Ali and Abdelrahman 2011). The area of mineralizations consists of metavolcano-sedimentary rocks intruded by syntectonic granitoid splutons. Both had been subjected to dynamic metamorphism and obliterated by recrystallization forming rock units of variable composition of greenschist facies (Küster and Liégeois 2001; Kuster et al. 2008). Mineral deposits in Al-Ibedia are divided into two parts. First, the upper portion of the mineralized zone has been weathered and transported for deposition forming a conglomeratic placer lying on top of the intrusive body. Later, these mineralized horizons eroded forming a thick overburden, which is mined by artisanal miners as a medium for native gold grains and flakes (Kuster et al. 2008). The lower portion is a hydrothermal solution primarily composed of auriferous quartz veins and stringers filling into tectonic fissures in the host rock. The hydrothermal system related to a magmatic solution of high temperature is associated with granitoid intrusion and contains high concentrations of ^{226}Ra, ^{232}Th, and ^{40}K (Mohamedai 2014).

Sample Collection and Preparation

A total of 35 soil samples were taken from different locations around the open-pit of traditional gold mining sites at Al-Ibedia as shown (Fig. 3). The study area comprised gold mine waste and tailings dumps. The soil

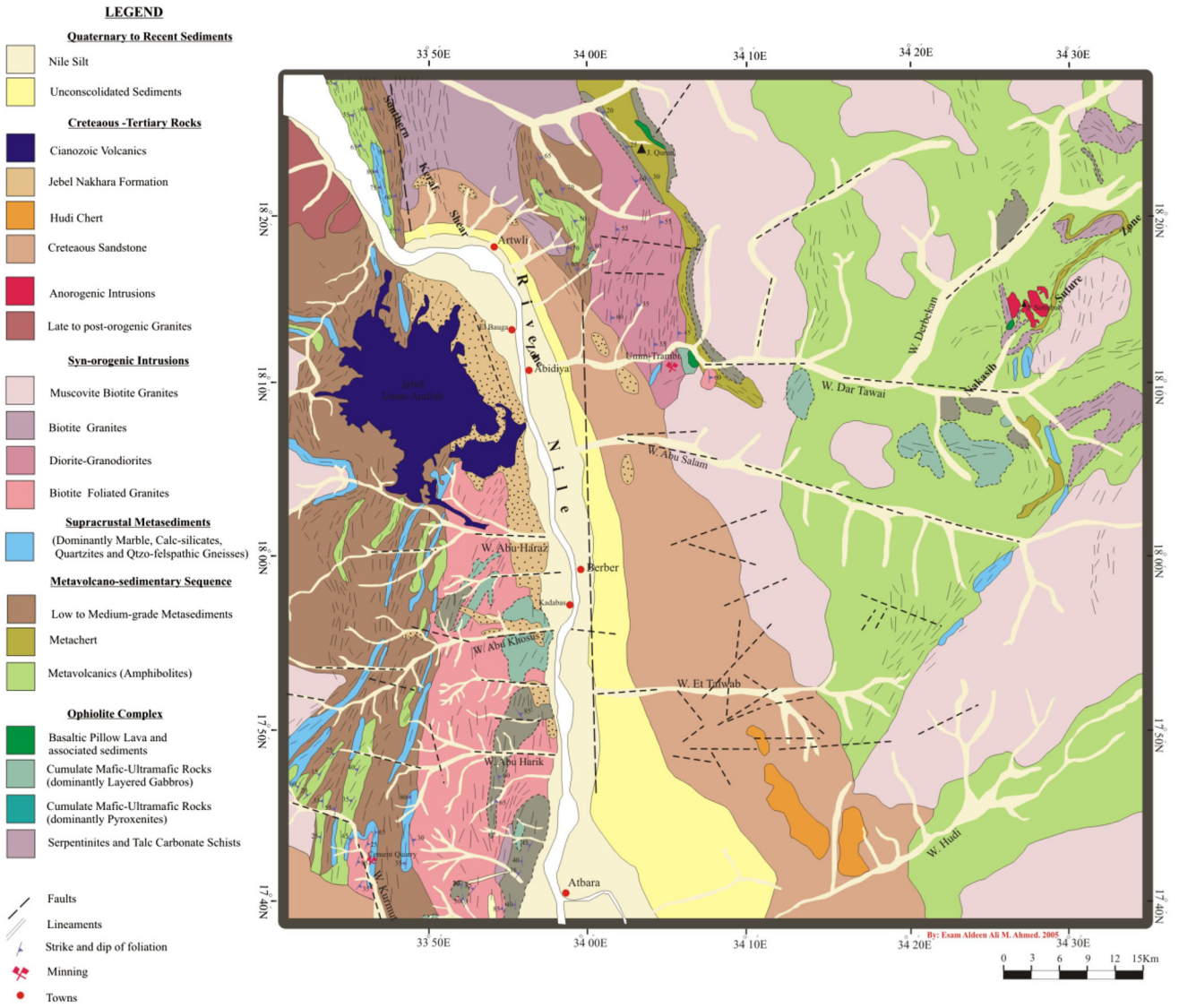

Fig. 2 Geological map of the study area (Küster and Liégeois 2001; Küster et al. 2008)

samples were crushed into a fine powder and sieved through a 100-μm sieve. The samples were then sealed in 500-ml plastic containers for approximately 4 weeks to allow radon (half-life 3.8 days) and its short-lived decay daughters, ^{214}Bi and ^{214}Pb, to reach secular equilibrium with the long-lived ^{226}Ra precursor in the samples. The sample weights ranged from 240 to 564 g. A background sample was also prepared using a similar empty container.

Gamma Spectrometric Measurement

The gamma-ray spectrometry set-up used in this analysis consisted of a highly shielded and well calibrated 7.6 × 7.6-cm NaI (Tl) detector enclosed in a 5 cm-thick lead shield to assist in reducing background radiation. In addition, the set-up was coupled with a computer-based multichannel analyzer, which was used for data acquisition and analysis of gamma spectra. The spectrometer was tested for its linearity and then calibrated for energy using gamma sources supplied by the International Atomic Energy Agency, Vienna. This was achieved by collection of spectra data from standard sources with energies in the range of 0.25–2.62 MeV. The channel numbers of the photopeaks corresponding to the different gamma energies were recorded after 900 s, and the energy-channel linear relationship was obtained. The efficiency calibration of the system was performed using a known source (Mixed Gamma Standard, Amersham) and then validated with three well-known reference materials obtained from the International Atomic Energy Agency for K, Ra, and Th activity measurements: RGK-1, RGU-1, and RGTH-1. The background count was determined by counting an

Fig. 3 Photographs (**a** through **e**) showing different activities of artisanal gold mining (digging, crushing, and ore processing)

empty container of the same dimension as those containing the samples and subtracting from the gross count. Each sample was measured during an accumulating time between 10 and 24 h. Activity concentrations of the samples were determined using the net area under the photopeaks using Eq. 1. The activity concentration (Bq/kg) of ^{232}Th was determined from the photo-peaks of ^{208}Tl (583 keV) and ^{228}Ac (911 keV); that of ^{226}Ra was obtained from the gamma-lines of ^{214}Pb (352 keV) and ^{214}Bi (609 keV); and that of ^{40}K was measured directly from the photo-peaks at 1460 keV. This spectral analysis was performed with the aid of computer software Genie 2000 obtained from CANBERRA. The software uses an interactive photo-peak fit that corrects for interferences from various energies. Manual calculations were also performed to validate the results by defining the region of interest for each energy obtained for the sample and comparing it with the reference material (has the same matrix). The detection limit was required to estimate the minimum detectable activity in a sample, and it was obtained using the equation given elsewhere. Detection limits obtained were 2.7, 9.2, and 0.2 for ^{226}Ra and ^{232}Th, and ^{40}K, respectively (IAEA 1989; Kolapo 2014; Godfred et al. 2015).

$$A_c\,(\mathrm{Bq/kg}) = C_n/P\gamma M\varepsilon, \tag{1}$$

where A_c is the activity concentration of the radionuclide in the sample given in Bq/kg; C_n is the net count rate under the corresponding peak; $P\gamma$ is the absolute transition probability of the specific γ-ray; M is the mass of the sample (kg); and ε is the detector efficiency at the specific γ-ray energy (Kolapo 2014).

Calculation of ^{222}Rn Activity Concentrations in Soil

^{222}Rn activity concentrations in soil were determined using Eq. 2 obtained from UNSCEAR (2000):

$$^{222}\mathrm{Rn}_{\mathrm{Soil}} = C_{\mathrm{Ra}} \times f \times \rho_{\mathrm{s}} \times \varepsilon^{-1}\,(1-\varepsilon)\,(m[K_{\mathrm{T}}-1]+1)^{-1}, \tag{2}$$

where $^{222}\mathrm{Rn}_{\mathrm{Soil}}$ is the ^{222}Rn activity concentrations in soil (kBq/m^3); C_{Ra} is the concentration of Ra in soil (Bq/kg); f is the emanation factor; ρ_{s} is the density of the soil grains (2700 kg m^3); ε is the total porosity including both water and air phases; m is the fraction of the porosity that is water-filled (also called the "fraction of saturation"); and K_{T} is the partition coefficient for radon between the water and air phases. For dry soil, m is zero, and the last term on the right side of the equation can be omitted. Warm, moist soil (25 °C, $K_{\mathrm{T}} = 0.23$, m 0.95) with typical soil parameters ($f = 0.2$, $\varepsilon = 0.25$).

Table 1 Mean concentrations with associated SDs of ^{226}Ra, ^{232}Th, and ^{40}K activity concentrations in soil samples around Al-Ibedia traditional mining area

Sample no.	^{226}Ra	^{232}Th	^{40}K
1	6.500	20.100	264.100
2	8.600	19.200	108.800
3	8.100	20.100	264.100
4	18.500	11.700	419.800
5	6.100	18.400	230.200
6	8.100	12.600	230.200
7	6.300	15.900	237.000
8	11.600	33.500	284.400
9	9.200	31.000	264.100
10	6.600	20.100	223.400
11	10.000	31.800	270.800
12	2.700	15.900	0.200
13	16.800	9.200	1.800
14	3.500	12.600	0.300
15	3.100	16.700	0.200
16	4.000	23.400	0.200
17	4.100	18.400	0.200
18	3.000	13.400	0.200
19	3.100	14.200	0.200
20	3.200	14.200	0.200
21	9.500	13.400	0.700
22	2.700	15.900	0.200
23	16.800	9.200	1.800
24	3.500	12.600	0.300
25	3.100	16.700	0.200
26	4.000	23.400	0.200
27	4.100	18.400	0.200
28	3.000	13.400	0.200
29	3.100	14.200	0.200
30	3.200	14.200	0.200
31	9.500	13.400	0.700
32	14.200	47.700	270.800
33	16.400	51.900	291.100
34	15.000	48.500	311.400
35	12.900	41.000	237.000
Minimum	2.700	9.200	0.200
Maximum	18.500	51.900	419.800
Average	7.500	20.700	111.900
SD	4.900	11.297	136.850

Rn in air ($^{222}Rn_{air}$) was calculated using Eq. 3 (UNSCEAR 1988):

$$^{222}Rn_{air} = {}^{222}Rn_s \times \left(\frac{D_{soil}}{D_{air}}\right)^{\frac{1}{2}}, \quad (3)$$

where $^{222}Rn_{air}$ is the ^{222}Rn concentration in the air (Bq/m^3); $^{222}Rn_s$ is the ^{222}Rn concentration in soil (Bq/m^3); D_{soil} is the diffusion rate constant of ^{222}Rn in the soil (0.5×10^{-4} m^2/s); and D_{air} is the diffusion rate constant of ^{222}Rn in the air (5 m^2/s).

Calculation of Uptake of Radium by Vegetables

Uptake of radium by vegetables from the soil around the studied area was determined using Eq. 4 (UNSCEAR 1988; IAEA 1996):

$$^{226}Ra_{AC} = A \times {}^{226}Ra_{soil}, \quad (4)$$

where $^{226}Ra_{AC}$ is the ^{226}Ra activity concentration in vegetables (Bq/kg); A is the transfer coefficient of ^{226}Ra from soil to vegetables (0.04) (IAEA 1990); and $^{226}Ra_{soil}$ is the ^{226}Ra activity concentration in soil samples (Bq/kg).

Calculation of Absorbed Dose Rate

The absorbed dose rate was calculated using Eq. 5:

$$D\left(\text{nGyh}^{-1}\right) = 0.461\,(A_{Ra}) + 0.623\,(A_{Th}) + 0.0414(A_K), \quad (5)$$

where A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively (Kocher and Sjoreen 1985; Leung et al. 1990).

Calculation of Annual Effective Dose

The annual effective dose was calculated using Eq. 6:

$$H\ (\mu\text{Sv/year}) = D\left(\text{nGh}^{-1}\right) \times 24\ \text{h} \times 365.25\ \text{days} \times 0.2 \times 0.7\ \text{SvGy}^{-1} \times 10^{-3}, \quad (6)$$

where 0.7 Sv/Gy is the quotient of annual effective dose rate to absorbed dose rate in air for environmental exposure to gamma rays, and 0.2 is the outdoor annual occupancy factor (Hamed et al. 2012).

Ra-Equivalent Activity

Ra-equivalent activity (Ra_{eq}) is expressed mathematically using Eq. 7:

$$Ra_{eq} = A_{Ra} + 1.43\,A_{Th} + 0.077A_K, \quad (7)$$

where A_{Ra}, A_{Th}, and A_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq/kg, respectively (UNSCEAR 1993).

Calculation of the External Hazard Index

The external hazard index (H_{ex}) was calculated using Eq. 8:

Table 2 Comparison of ^{226}Ra, ^{232}Th, and ^{40}K concentrations in soil samples around Al-Ibedia traditional mining areas and with those in some other countries as given in UNSCEAR (2000)

Country	^{226}Ra		Th^{232}		^{40}K	
	Range	Average	Range	Average	Range	Average
United States	8–160	40	4–130	35	100–700	370
Switzerland	10–900	40	4–70	25	40–1000	370
Bulgaria	12–210	45	7–160	30	40–800	400
China	2–440	32	1–360	41	19–1800	440
Hong Kong	20–110	59	16–200	95	80–1100	530
India	7–81	29	14–160	64	38–760	400
Japan	6–98	33	2–88	28	15–990	310
Thailand	11–78	48	7–120	51	7–712	230
Iran	8–55	28	5–42	22	250–980	640
Denmark	9–29	17	8–30	19	240–610	460
Belgium	5–50	26	5–5 0	27	70–900	380
Luxembourg	6–52	35	7–70	50	80–1800	620
Malaysia	38–94	67	63–110	82	170–430	310
Egypt	5–64	17	2–96	18	29–650	320
Poland	5–120	26	4–77	21	110–970	410
Romania	8–60	32	11–75	38	250–1100	490
Greece	1–240	25	1–190	21	12–1570	360
Portugal	8–65	44	22–100	51	220–1230	840
Spain	6–250	32	2–210	33	25–1650	470
Hungary	14–76	33	12–45	28	79–570	370
The current study	2.7–18.5	7.5	9.2–51.9	20.7	0.2–419.8	136.8

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1, \quad (8)$$

where A_{Ra}, A_{Th}, and $_{AK}$ are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq/kg, respectively. The values of this index must be less than unity to keep the radiation hazard significant (Beretka et al. 1985).

AGDE

The organs of interest considered by UNSCEAR (1988) are the gonads, active bone marrow, and bone surface cells. Therefore, AGDEs were calculated using Eq. 9.

$$AGDE\,(\mu\mathrm{Sv/year}) = 3.09\,A_{\mathrm{Ra}} + 4.18\,A_{\mathrm{Th}} + 0.314\,A_{\mathrm{K}}. \quad (9)$$

Calculation of the Annual Effective Dose Due to ^{222}Rn Inhalation and Vegetable Consumption (Xinwei et al. 2006)

The overall annual effective dose due to ^{222}Rn inhalation and vegetable consumption was determined using Eq. 10 (IAEA 1996).

$$H_{\mathrm{p}} = C_{\mathrm{p}} \times I_{\mathrm{p}} \cdot \mathrm{DCF}, \quad (10)$$

where H_{p} is the dose rate due to ^{222}Rn inhalation or vegetables consumption in (Sv/year); C_{P} is the ^{226}Ra concentration in vegetables (Bq/kg) or the concentration of ^{222}Rn in the air (Bq/m^3); I_{p} is the amount of consumption of vegetables per year (90 kg/year) and for air outside the home (600 m^3/year) (IAEA 1990); and DCF is the dose-conversion factor for ^{226}Ra (2.8×10^{-7} sv/Bq) and ^{222}Rn (1.3×10^{-9} sv/Bq) (UNSCEAR 1988).

Results and Discussion

Table 1 lists the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil samples from Al-Ibedia's traditional mining area, which ranged from 2.66 to 18.47, 9.20 to 51.87, and 0.17 to 419.77 Bq/kg with an average value of 7.54 ± 4.91, 20.74 ± 11.29, and 111.87 ± 136.84 Bq/kg, respectively. ^{226}Ra, ^{232}Th, and ^{40}K activity concentrations in soil samples varied within the study area due to differences in geological structure. The literature has repeatedly indicated that ^{226}Ra, ^{232}Th, and ^{40}K concentrations in soil vary according to geological formation, physico-geological characteristics of soil types, topographical differences, geomorphology, and meteorological conditions of the region. Geologically these locations are characterized by sedimentary rocks known as

Table 3 Activity concentrations of ^{222}Rn in soil and air, ^{226}Ra in vegetables, and radiation dose of ^{222}Rn due to inhalation and ^{226}Ra due to vegetable consumption

Sample no.	^{222}Rn in soil (kBq/m^3)	^{222}Rn in air (Bq/m^3)	^{226}Ra in vegetables (Bq/kg)	Dose of ^{222}Rn due to inhalation	Dose of ^{226}Ra due to vegetable consumption
1	10.530	33.299	0.260	0.030	0.007
2	13.932	44.057	0.340	0.030	0.009
3	13.122	41.495	0.320	0.030	0.008
4	29.970	94.773	0.740	0.070	0.019
5	9.882	31.250	0.240	0.020	0.006
6	13.122	41.495	0.320	0.030	0.008
7	10.206	32.274	0.250	0.030	0.006
8	18.792	59.426	0.460	0.050	0.012
9	14.904	47.131	0.370	0.040	0.009
10	10.692	33.811	0.260	0.030	0.007
11	16.200	51.229	0.400	0.040	0.010
12	4.374	13.832	0.110	0.010	0.003
13	27.216	86.065	0.670	0.070	0.017
14	5.670	17.930	0.140	0.010	0.004
15	5.022	15.881	0.120	0.010	0.003
16	6.480	20.492	0.160	0.020	0.004
17	6.642	21.004	0.160	0.020	0.004
18	4.860	15.369	0.120	0.010	0.003
19	5.022	15.881	0.120	0.010	0.003
20	5.184	16.393	0.130	0.010	0.003
21	15.390	48.667	0.380	0.040	0.010
22	4.374	13.832	0.110	0.010	0.003
23	27.216	86.065	0.670	0.070	0.017
24	5.670	17.930	0.140	0.010	0.004
25	5.022	15.881	0.120	0.010	0.003
26	6.480	20.492	0.160	0.020	0.004
27	6.642	21.004	0.160	0.020	0.004
28	4.860	15.369	0.120	0.010	0.003
29	5.022	15.881	0.120	0.010	0.003
30	5.184	16.393	0.130	0.010	0.003
31	15.390	48.667	0.380	0.040	0.010
32	23.004	72.745	0.570	0.060	0.014
33	26.568	84.015	0.660	0.070	0.017
34	24.300	76.843	0.600	0.060	0.015
35	20.898	66.085	0.520	0.050	0.013
Min	29.970	13.832	0.110	0.010	0.003
Max	4.374	86.065	0.740	0.070	0.019
Average	12.224	35.683	0.301	0.030	0.008
Std	7.981	26.535	0.198	0.020	0.005

Nubian sandstone, basement rocks, and modern sedimentary rocks with 2 m of soft sand and mudstone on top. The basement rocks are metamorphic consisting of a variety of schist and gneiss (Küster and Liégeois 2001).

The highest activity concentrations of ^{226}Ra (18.47 Bq/kg) and^{40}K (419.77 Bq/kg) were measured in location no. 4 and those of ^{232}Th (51.87 Bq/kg) in location no. 33. These areas are characterised mineralogically by a hydrothermal solution composed mainly of auriferous quartz veins and stringers filling into the tectonic fissures in the host rock. The hydrothermal system relates to a magmatic solution of high temperature associated with granitoid intrusion containing high values of elements such as ^{226}Ra, ^{232}Th, and ^{40}K. The average values of ^{226}Ra ^{232}Th,

Table 4 Ra concentrations in air and action levels in different countries as given in UNSCEAR (2000)

Country	Average level (B/m^3)	Action level average level (B/m^3)
Czech Republic	140	200
Finland	123	400
Germany	50	250
Ireland	60	200
Lithuania	37	100
Norway	51–60	200
Russia	19–250	–
Sweden	108	400
Switzerland	70	1000
United Kingdom	20	200
USA	46	150

and ^{40}K of the present study are less than the world average of 35, 45, and 420 Bq/kg, respectively (UNSCEAR 2000) and were thus compared with those from similar investigations in other countries as shown (Table 2). Regression analysis showed that no correlation emerged.

^{222}Rn gas, which constitutes 40 % of the annual accumulated dose (UNSCEAR 1993; Isam et al. 2014), is considered to be the primary source of human exposure to natural radioactivity. Moreover, exposure to radon and its progeny is believed to be associated with an increased risk of developing several types of cancer (Clamp and Pritchard 1998; Idriss et al. 2011, 2015). Therefore, mathematical models obtained from UNSCEAR (1988, 2000) were used to determine ^{222}Rn concentrations in soil and air samples. ^{222}Rn concentrations in soil and air were computed to characterize the building materials as an indoor radon source; knowledge of the radon-exhalation rate from these materials is very important. The activity concentrations of ^{222}Rn in soil and air were determined in various locations throughout the study area shown (Table 3). ^{222}Rn activity concentrations in soil ranged from 4.374 to 29.97 kBqcm^3 with an average value of 12 ± 224 kBq/m^3. On comparing the results with global data, it was discovered that the obtained values of ^{222}Rn in the soil were considerably lower then the reported range for Slovenia (0.9–32.9 kBq/m^3) (Vaupoti et al. 2010). However, the range of ^{222}Rn concentrations in the soil observed in this study is significantly high relative to similar studies reported from Syria [76–3143 Bq/m^3 (Shweikani and Hushari 2005)], India (0.4–25.78 kBq/m^3, Prasada et al. 2008), Libya (31.17–469 Bq/m^3, Saad et al. 2013), Portugal (102–2.982 Bq/m^3, Pereira et al. 2011), and Sudan (20–1.359 Bq/m^3, Idriss et al. 2014). ^{222}Rn concentrations in air were in the range of 13.832–86.065 Bq/m^3 with an average of 35.683 ± 26.535 Bq/m^3.The concentrations of radon in air were far below the action level of 200–600 Bq/m^3 recommended by the International Commission on Radiological Protection [ICRP] 1991); the 200 Bq/m^3 set by the National Radiological Protection Board (1990), UK; the reference level of 100 Bq/m^3 set by the World Health Organization (WHO 2009); and the recommended activity concentration of 148 Bq/m^3 set by the USEPA (2004).

Table 5 Corresponding, H_{ex}, Ra_{eq}, and AGDE and percentage contributions to the total dose rate from ^{238}U, ^{232}Th, and ^{40}K in soil samples around Al-Ibedia traditional mining area

Location no.	D	H	H_{ex}	Ra_{eq}	AGDE
1	26.420	32.420	0.150	55.500	186.800
2	20.450	25.100	0.120	44.480	141.140
3	27.150	33.320	0.150	57.080	191.680
4	33.190	40.730	0.180	67.540	237.830
5	23.810	29.230	0.140	50.160	168.110
6	21.100	25.890	0.120	43.800	149.860
7	22.610	27.750	0.130	47.270	160.300
8	37.940	46.560	0.220	81.290	264.840
9	34.450	42.280	0.200	73.780	240.680
10	24.780	30.410	0.140	52.460	174.320
11	35.610	43.700	0.210	76.270	248.690
12	11.130	13.660	0.070	25.400	74.690
13	13.550	16.630	0.080	30.100	90.940
14	9.460	11.610	0.060	21.510	63.490
15	11.880	14.580	0.070	27.080	79.690
16	16.430	20.170	0.100	37.480	110.250
17	13.370	16.410	0.080	30.450	89.710
18	9.710	11.920	0.060	22.120	65.170
19	10.320	12.660	0.060	23.490	69.210
20	10.340	12.690	0.060	23.540	69.370
21	12.730	15.620	0.080	28.660	85.410
22	11.130	13.660	0.070	25.400	74.690
23	13.550	16.630	0.080	30.100	90.940
24	9.460	11.610	0.060	21.510	63.490
25	11.880	14.580	0.070	27.080	79.690
26	16.430	20.170	0.100	37.480	110.250
27	13.370	16.410	0.080	30.450	89.710
28	9.710	11.920	0.060	22.120	65.170
29	10.320	12.660	0.060	23.490	69.210
30	10.340	12.690	0.060	23.540	69.370
31	12.730	15.620	0.080	28.660	85.410
32	47.450	58.230	0.280	103.200	328.110
33	51.910	63.710	0.310	112.950	358.780
34	50.010	61.380	0.290	108.310	346.790
35	41.270	50.650	0.240	89.710	285.440
Min	9.460	11.610	0.060	21.510	63.490
Max	51.910	63.710	0.310	112.950	358.780
Average	21.030	25.810	0.120	45.810	145.120
Standard deviation	12.803	15.713	0.074	27.055	90.262

The average concentration of ^{222}Rn in the air was compared with data from different countries (Table 4). Radium transfer to vegetables was in the range of 0.11–0.74 with an average value of 0.301 ± 0.198 Bq/kg. The results of ^{226}Ra transferred to vegetables appear to be negligible compared with the allowable limit (UNSCEAR 1988). Table 5 lists the values of corresponding absorbed dose rates, H_{ex} index, Ra_{eq}, AGDE, annual effective dose rates, and percentage contribution to the total dose rate from ^{226}Ra, ^{232}Th, and ^{40}K in soil samples around the Al-Ibedia traditional mining area. The absorbed dose rates were computed from the measured activity concentrations of ^{40}K, ^{232}Th, and ^{226}Ra in the soil using the UNSCEAR (1993) dose-rate conversion factors of 0.0414, 0.623, and 0.461 nGy/h/Bq/kg, respectively. Factoring in the calculation of dose-rate conversion factors was built on the premise that all daughters of ^{238}U and ^{232}Th series are in radioactive equilibrium with the parent, that the soil density is 1.4 g/cm^3, and that activity distribution is homogeneous up to 1 m in depth.

The estimated absorbed dose rate ranged from 9.46 to 51.91 with an average value of 21.03 ± 12.80 nGy/h (Table 5). The observed absorbed dose in this study was lower than the global average of 60 nGy/h (UNSCEAR 2000). Calculation of the relative contribution of ^{226}Ra, ^{232}Th, and ^{40}K to the total absorbed dose in air showed that the majority of the contribution comes from ^{40}K (79.72 %).

The computed annual effective dose varied from 11.61 to 63.71 with an average value of 25.81 ± 15.71 μSv/year shown (Table 5). The estimated effective dose was below the allowable limit of 20 mSv/year for occupational exposure control as recommended by the ICRP (1991). To assess gamma radiation hazards to humans associated with the use of the soil surrounding the mining sites for the construction of houses (filling and local brick-making); this provides a single index that describes the gamma output from a different mixture of ^{226}Ra, ^{232}Th, and ^{40}K in the samples.

Ra_{eq} activity was in the range of 21.51–112.95 with average values of 45.81 ± 27.06 Bq/kg (Table 5). Evidently the results were lower than the maximum allowable limit for materials to be used in the construction of dwellings of 370 Bq/kg (UNSCEAR 1982). The estimated H_{ex} index ranged from 0.06 to 0.31 with an average of 0.12 ± 0.07. These values were below the criterion of unity. AGDE ranged from 63.49 to 358.78 with an average of 145.12 ± 0.26 μSv/year (Table 5). The average value of AGDE is lower than the global average of 300 μSv/year (UNSCEAR 2000). However, locations nos. 32 (328.11 μSv/year), 33 (358.78 μSv/year), and 34 (346.79 μSv/year) exhibit values >300 μSv/year. The overall annual effective dose due to radon inhalation and vegetable consumption range between 0.01 and 0.07 and 0.003 and 0.019 mSv/year with an average of 0.03 ± 0.02 and 0.008 ± 0.005 mSv/year, respectively (Table 3). The overall annual effective dose for radon inhalation and vegetable consumption were lower than the recommended reference dose level of 1.0 mSv/year set by UNSCEAR (2000), the 1.0 mSv/year set by the FAO (1977), and the 1.0 mSv/year set by the IAEA (1996).

Conclusion

Radionuclide measurements of ^{226}Ra, ^{232}Th, and ^{40}K in soil samples from traditional mining areas are necessary from the perspective of environmental radiation protection. Activity concentrations measured for ^{226}Ra, ^{232}Th, and ^{40}K in soil samples within the Al-Ibedia traditional mining area are relatively normal. Potential radiological effects to miners and the public due to ^{226}Ra, ^{232}Th,^{40}K, and ^{222}Rn are insignificant. ^{226}Ra transferred to vegetables appears to be negligible compared with the allowable limit of 1.0 mSv/year set by UNSCEAR. Ra_{eq} activity, absorbed dose rate, H_{ex} index, and annual effective dose equivalent were all lower than the allowable limits proposed by ICRP (1991) and UNSCEAR (2000). In contrast, the average value of AGDE is lower than the global average of 300 μSv/year (UNSCEAR 2000). However, locations 32 (328.11 μSv/year), 33 (358.78 μSv/year), and 34 (346.79 μSv/year) exhibit values >300 μSv/year. There is a need to initiate a comprehensive nation-wide radiation survey of mining to bring this industry under regulatory control. Legislation resulting in mandatory radiation monitoring in national mining is critical for the protection of workers and the public from the dangers posed by natural radionuclides.

References

Ademola AK, Bello AK, Adejumobi AC (2014) Determination of natural radioactivity and hazard in soil samples in and around gold mining area in Itagunmodi, southwestern Nigeria. J Radiat Res Appl Sci 7(3):249–255

Africa T, Rösner A, van Schalkwyk A (2000) The environmental impact of gold mine tailings footprints in the Johannesburg region, South Africa. Bull Eng Geol Environ 59(2):137–148

Ali EA, Abdelrahman EM (2011) New ophiolite in Sudan and constraint on the western boundary of the Nubian shield: petrographical and geochemical evidence. J Afr Earth Sci 59:101–110

Anjos RM, Umisedob N, da Silva AA, Estillata L, Rizzotoc M, Yoshimura EM et al (2010) Occupational exposure to radon and natural gamma radiation in the La Carolina, a former gold mine in San Luis Province, Argentina. J Environ Radioact 101(2):153–158

Clamp GE, Pritchard J (1998) Investigation of fault position and sources of radon by measurement of ^{238}U decay series radionuclide activity in soil samples. Environ Geochem Health 20:39–44

Darko G, Faanu A, Akoto O, Acheampong A, Goode EJ, Gyamfi O (2015) Distribution of natural and artificial radioactivity in soils, water and tuber crops. Environ Monit Assess 187:339

Doyi I, Oppen OC, Glover ET, Gbeddy G, Kokroko W (2013) Assessment of occupational radiation exposure in underground artisanal gold mines in Tongo, Upper East Region of Ghana. J Environ Radioact 12:77–82

Durand JF (2012) The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province, South Africa. J Afr Earth Sci 68:24–43

Food and Agriculture Organization of the United Nations (1977) Review of food consumption surveys, Recommendations, Africa, vol. 102

Ghosh D, Deb A, Bera S, Sengupta R, Patra KK (2008) Measurement of natural radioactivity in chemical fertilizer and agricultural soil: evidence of high alpha activity. Environ Geochem Health 30:79–86

Hamed Bashier E, Salih I, Khatir Sam A (2012) Gis predictive mapping of terrestrial gamma radiation in the Northern State, Sudan. Radiat Prot Dosim 151(3):500–510

Hammond DS, Gond V, de Thoisy B, Forget PM, DeDijn BP (2007) Causes and consequences of a tropical forest gold rush in the Guiana Shield, South America. Ambio 36(8):661–670

Idriss H, Salih I, Sam AK (2011) Study of radon in ground water and physicochemical parameters in Khartoum state. J Radioanal Nucl Chem 290(2):333–338

Idriss H, Salih I, Alaamer AS, Abdelgali MY, Salih SA, Hasan AM et al (2014) Study of radon in soil gas, trace elements and climatic parameters around South Kordofan state, Sudan. Environ Earth Sci 72:335–339

Idriss H, Salih I, Alaamer AS, Abdelgali MY, Salih SA, Hasan AM et al (2015) Characterization of ^{222}Rn and meteorological parameters in Uro houses at South Kordofan state. Indoor Built Environ 24(5):650–657

International Atomic Energy Agency (1989) Measurement of radionuclides in food and environment. Technical Reports Series No. 295. IAEA, Vienna

International Atomic Energy Agency (1990) The environmental behavior of radium. Technical Report Series I 310. IAEA, Vienna

International Atomic Energy Agency (1996) International basic safety for protection against ionizing radiation and for the safety of radiation sources. Safety Series No. 115. IAEA, Vienna

International Commission on Radiological Protection (1991) Recommendation of the International Commission on Radiological Protection (ICRP). Oxford Publication 60, Annals of the ICRP 210-3. Pergamon Press

Kocher DC, Sjoreen AL (1985) Dose-rate conversion factors for external exposure to photon emitters in soil. Health Phys 48:193–205

Küster D, Liégeois JP (2001) Sr, Nd isotopes and geochemistry of the Bayuda Desert high-grade metamorphic basement (Sudan): an early Pan-African oceanic convergent margin, not the edge of the East Saharan Ghost Craton? Precambrian Res 109:1–23

Küster D, Liegeois J-P, Matukov D, Sergeev S, Lucassen F (2008) Zircon geochronology and Sr, Nd, Pb isotope geochemistry of granitoids from Bayuda Desert and Sabaloka (Sudan): evidence for a Bayudian event (920–900 Ma) preceding the Pan-African orogenic cycle (860–590 Ma) at the eastern boundary of the Saharan Metacraton. Precambrian Res 164:16–39

Leung KC, Lau SY, Poon CB (1990) Gamma radiation dose from radionuclides in Hong Kong soil. J Environ Radioact 11:279–290

Mohamedai MA (2014) Detailed exploration of gold mineralization in Um Trambishi area, River Nile State, Sudan. Doctoral Thesis, Faculty of Petroleum and Minerals, Al Neelain University

National Radiological Protection Board (1990) Statement by the national radiological protection board. limitation of human exposure to radon in homes. NRPB Doc 1:15–16

Pereira AJSC, Barbosa SM, Neves LJPF, Aumento F (2011) Soil-gas radon monitoring in an active granite quarry from central Portugal. Nat Hazards Earth Syst Sci 11(7):1845–1849

Prasada Y, Prasada G, Gusaina GS, Choubeyb VM, Ramolaa RC (2008) Radon exhalation rate from soil samples of South Kumaun Lesser Himalayas, India. J Radiat Meas 43:S369–S374

Saad AF, Abdallah RM, Hussein NA (2013) Radon exhalation from Libyan soil samples measured with the SSNTD technique. J Appl Radiat Isot 7:163–168

Saleh H, Shayeb HM (2014) Natural radioactivity distribution of southern part of Jordan (Ma′an) Soil. Ann Nucl Energy 65:184–189

Salih I, Alib S, Eisa S, Idriss H (2014) Radiation exposure of workers in storage areas for building materials. J Taibah Univ Sci 8(4):394–400

Schueler V, Kuemmerle T, Schröder H (2011) Impacts of surface gold mining on land use systems in Western Ghana. Ambio 40(5):528–539

Shweikani R, Hushari M (2005) The correlations between radon in soil gas and its exhalation and concentration in air in the southern part of Syria. J Radiat Meas 40(2):699–703

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1982) Sources and effects of ionizing radiation. New York

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1988) Sources and effects of ionizing radiation. New York

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1993) Sources and effects of ionizing radiation. New York

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2000) Exposures from natural sources. Report to General Assembly. Annex B, United Nations, New York

United States Environmental Protection Agency (2007) Ionizing radiation fact book. USEPA Office of Radiation and Indoor Air. EPA-402-F-06-061

United States Environmental Protection Agency (USEPA) (2004) A citizen's guide to radon: the guide to protecting yourself and your family from radon. Indoor Environments Division (6609J), USEPA, Washington, DC

Vaupoti J, Gregori A, Kobal I, Zvab P, Kozak K, Mazur J et al (2010) Radon concentration in soil gas and radon exhalation rate at the Ravne fault in NW Slovenia. Nat Hazards Earth Syst Sci 10:895–899

World Health Organization (2009) Handbook on indoor radon: a public health perspective. WHO, Geneva

Xinwei L, Lingqing W, Xiaodan J, Leipeng Y, Gelian D (2006) Specific activity and hazards of Archeozoic-Cambrian rock samples collected from the Weibei area of Shaanxi, China. Radiat Prot Dosim 118(3):352–359