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*Full Length Research Paper*

# Activity concentrations and dose assessment of $^{226}$Ra, $^{228}$Ra, $^{232}$Th, $^{40}$K , $^{222}$Rn and $^{220}$Rn in soil samples from Newmont-Akyem gold mine using gamma-ray spectrometry

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**In this study 14 soil samples were measured for natural radioactivity levels including radon-222 ($^{222}$Rn) and radon-220 ($^{220}$Rn) concentration at Akyem-Gold Mine premises, surrounding communities in Ghana. Both radon and radioactivity concentrations of radium-226 ($^{226}$Ra), thorium-232 ($^{232}$Th) and potassium-40 ($^{40}$K) were determined by means of gamma spectrometry system equipped with high purity germanium detector. The studied samples gave natural radioactivity levels of 28, 12 and 11 Bq/kg, respectively compared to global $^{226}$Ra, $^{232}$Th, and $^{40}$K concentrations of 37, 33 and 400 Bq/kg, respectively, according to UNSCEAR (2000) report. The annual effective dose rate (AED) due to external and internal gamma exposure ranged from 0.060 to 0.18 mSvy$^{-1}$ with a mean value of 0.11 ± 0.03 mSvy$^{-1}$ compared to the recommended value of 1 mSvy$^{-1}$. There is a correlation between $^{226}$Ra and $^{222}$Rn in soil gas with a good linear coefficient of ($R^2$ =1). The availability of $^{226}$Ra and $^{222}$Rn shows that there is a source of uranium-238 ($^{238}$U) and thorium-232 ($^{232}$Th) bearing minerals within the adjacent geologic units of Akyem. This implies that most of the radon in the soil gas comes from $^{226}$Ra. The assessment of radium equivalent activity varied from 19.71 to 69.88 Bq/kg with mean value of 37.53 ± 15.51 Bq/kg lower than the global limit of 370 Bq/kg. The internal hazard index ranged from 0.07 to 0.25 Bq/Kg with a mean value of 0.13 ± 0.05 Bq/Kg, also lower than the accepted value of unity, while external hazard index ranged from 0.05 to 0.19 Bq/Kg with a mean value of 0.10 ± 0.04 Bq/Kg.**

**Key words:** Radon, thoron, natural radioactivity, annual effective dose, radium equivalent index, external and internal hazard index.

## INTRODUCTION

Humans are exposed to ionizing radiation from natural sources which are on a large scale in the earth's environment and remains in several geological formations in soils, rocks, plants, water and air. The public exposures to ionizing radiation include natural radiation sources such as cosmic and terrestrial radiation.The exposure pathways include external irradiation, inhalation or ingestion. Information on radioactivity levels in soil is necessary for the estimation of possible radiological hazards to human health**.** Studies have shown that over 50% of total radiation exposure comes from radon (USEPA, 2007).

There are several isotopes of radon but $^{222}$Rn (Radon) and $^{220}$Rn (Thoron) are of interest because of their availability in the environment due to their negative health impacts on the humans. Each nuclide has its own contribution to radiation exposure, for instance radon's half-life of 3.8 days is adequate enough to diffuse into the indoor environment and bring a rise in indoor concentration. On the contrary the half-life of thoron is only 56 seconds which implies that its presence is limited to close proximity (Yamada et al., 2006). However, recent studies in some countries have shown that in certain circumstances the doses from thoron and its progeny are notable and comparable to those from radon (Sciocchetti et al., 1992).

Uranium ($^{238}$U) and Thorium ($^{232}$Th) are the ultimate progenitors of $^{222}$Rn (Radon), $^{220}$Rn (Thoron), respectively. The immediate mother radionuclides of radon, thoron are radium-226, radium-224, respectively. Despite the fact that Rn-220 comes from the disintegration of Ra-224, it is often characterized as a decay product of Ra-228, which is a longer- lived parent ($t_{1/2}$ = 5.75y), commonly analyzed in the environmental samples such as soil and water.

Exposures to natural sources are often not much for safeguard concern. However, there are conditions where exposures to natural sources of radiation may need attention if some measures are not followed. A good scenario is the accumulation of high concentrations of radon and thoron in air. Another case is the mining and/or processing of mineral ores or materials where the activity concentrations of radionuclides of natural origin in the material itself, or in any substance arising from the process, are significantly elevated. Such materials have come to be called Naturally Occurring Radioactive Materials (NORM) (IAEA, 2005).

The radionuclides embedded in bedrocks are weathered off chemically or physically and by means of transportation they end up deposited in rivers, lakes or seas. Other human practices such as mining and mineral processing increase the concentration of both end products or wastes to produce Technologically Enhanced Naturally Occurring Radioactive Material (TENORM). Both NORM/TENORM contain materials with a lot of radioactive elements found in the environment, such as $^{238}$U, $^{232}$Th series and their progenies $^{228}$Ra, $^{224}$Ra, $^{226}$Ra as well as $^{40}$K. These radioisotopes can pollute the environment and bring constraints to public well-being (Peroni et al., 2012).

While mining has been seen as one of the principal sources of exposure to NORM/TENORM, the mining companies are not given guidelines for these radioactive materials in most countries due to insufficient safeguards for their regulation by the Regulatory Authorities. The health concern of NORM/TENORM is focused primarily on the production and release of radon, thoron gases produced through the radioactive decay of $^{226}$Ra, $^{224}$Ra, respectively. The inhalation of radon has been accompanied with high risk of cancer of the lung (BEIR IV, 1988).

Ghana is conducting numerous mining activities which means that possibility of producing NORM which is the main source of radon and thoron gases is very enormous.

For radiation protection purposes it is preferably important to monitor the presence and concentration of radon decay products, while for the identification of the sources and origin of radon the measurement of its concentrations in air or water, and sometimes its exhalation from soil and building materials, is more significant (Tykva and Sabol, 1995).

It is critical to evaluate the soil gas radon and thoron concentrations as literature has shown that most indoor radon emanates from the soil. Therefore with mining and mineral processing activities conducted at Newmont Akyem Gold Mine, it is likely that the levels of NORMs have been elevated.

The aim of the study was to determine activity concentration and dose assessment for NORMs including soil gas radon and thoron.

## Study area

The Newmont Ghana's - Akyem Gold Mine (AGM) is situated roughly three kilometers west of the district capital New Abirem,133 km west of Koforidua, the regional capital and 180 km northwest of Accra, the national capital (Akyem Gold Mining Project, 2008). Akyem in the Eastern region of Ghana is found amongst the following communities: Afosu, New Abirem, Old Abirem, Mamanso, Yayaaso, Adausena, Adjenua, Hweakwae, Ntronang and Yaw Tano. The Eastern region of Ghana covers a land area of 19,323 kilometres which constitutes 8.1% of the total land area of Ghana. It is the

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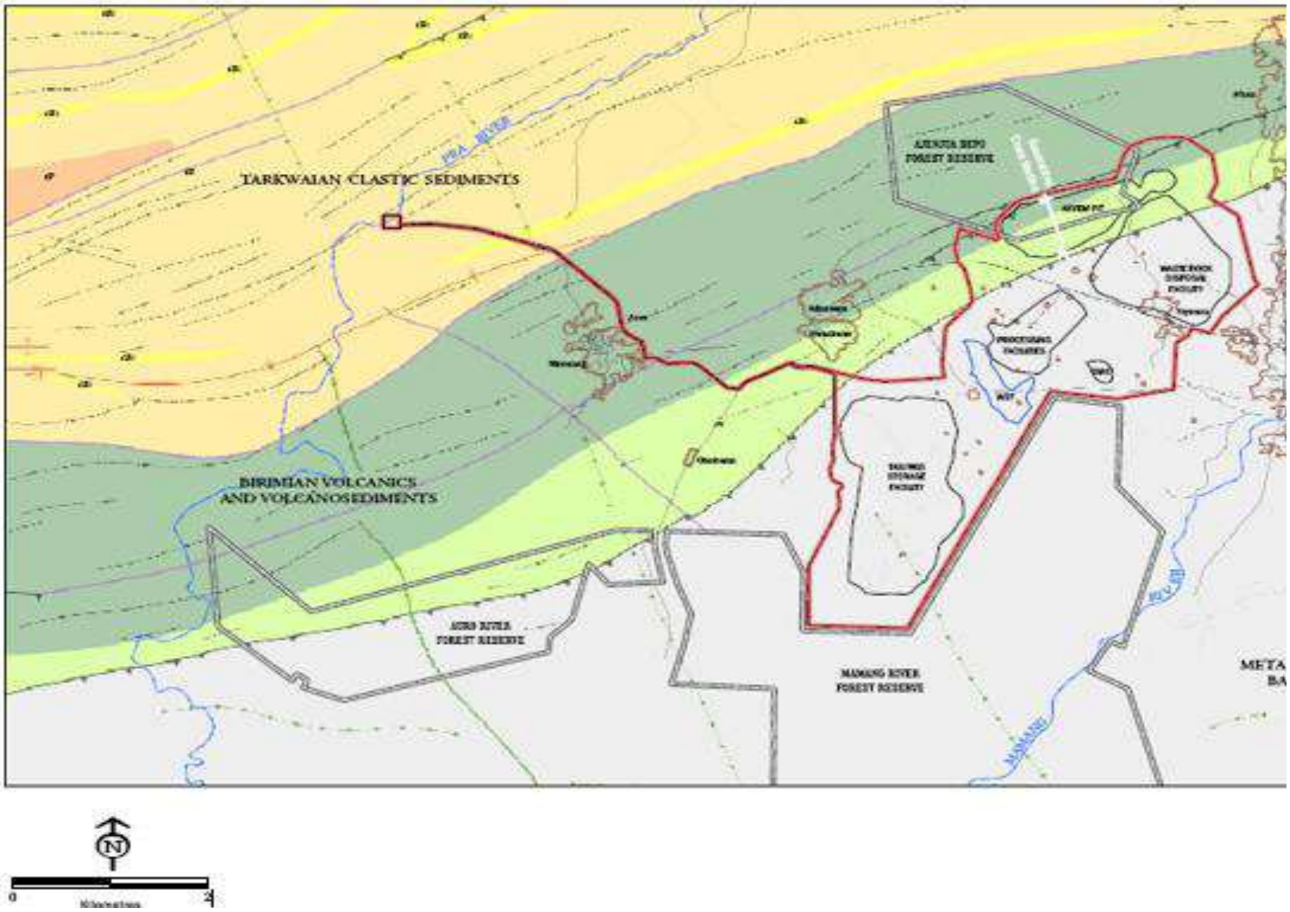

**Figure 1.** Geology of Akyem Study Area (AGM-EIS, 2008).

sixth largest region in terms of land area and lies between latitudes 60 and 70 North between longitudes 10 30’ West and 00 30’ East. The region shares common boundaries with the Great Accra, Central, Ashanti, Brong Ahafo and Volta Regions.The region contains minerals such as gold, diamond, bauxite-tantalite, limestone, kaolin and clay. Gold and diamond are however the only minerals that are being mined commercially.

The geologic section at the Akyem deposit is outlined graphically on Figure 1 and depicts rock units, the shear or thrust fault zone, ore zone, and proposed Akyem pit outline. Main geologic units in the hanging wall of the thrust fault include greywacke, a quartz-epiclastic unit, graphitic shear breccia and graphitic rubble. Mafic metavolcanics consist of the foot wall of the shear zone.

## METHODOLOGY

### Sampling and sample preparation

There were 14 soil samples that were randomly collected from the mining area and in the communities surrounding the mine. Figure 2 shows Akyem-Newmont Gold Mine and sample locations. The soil samples were brought to the laboratory where they were air dried in sample trays for a period of 7 days and thoroughly dried in the oven for 12 to 24 h at 105°C. The samples were then ground and sieved through a 2 mm mesh and placed into 1-litre Marinelli beakers where they were sealed and left for 30days to attain secular equilibrium between Ra-226, Th-232 and their progenies.

### Calibration of HPGe and sample measurement

Gamma Spectrometry System equipped with High Purity Germanium detector coupled with Genie 2000 was used to determine $^{226}$Ra, $^{228}$Ra, $^{232}$Th, $^{40}$K, $^{222}$Rn and $^{220}$Rn, respectively. The aim of energy calibration was to derive a relationship between peak positions in the spectrum which correspond to gamma-ray energy. This was carried out before measuring the samples.

The energy calibration (channel number of the Multi- Channel Analyzer (MCA) versus the Gamma-ray energy) of the detector system was accomplished at a fixed gain, using standards containing known radionuclides. The standards were sealed in a container and emitted different γ-ray energies covering the range of interest from 60 keV to 1836 keV in order to test for system linearity. The standard radionuclides used for both Energy and Efficiency calibration were: Am-241 (60KeV), Cd-109 (88KeV), Ce-139 (166KeV), C0-57 (122KeV), Co-60 (1173, 1333KeV), Cs-137

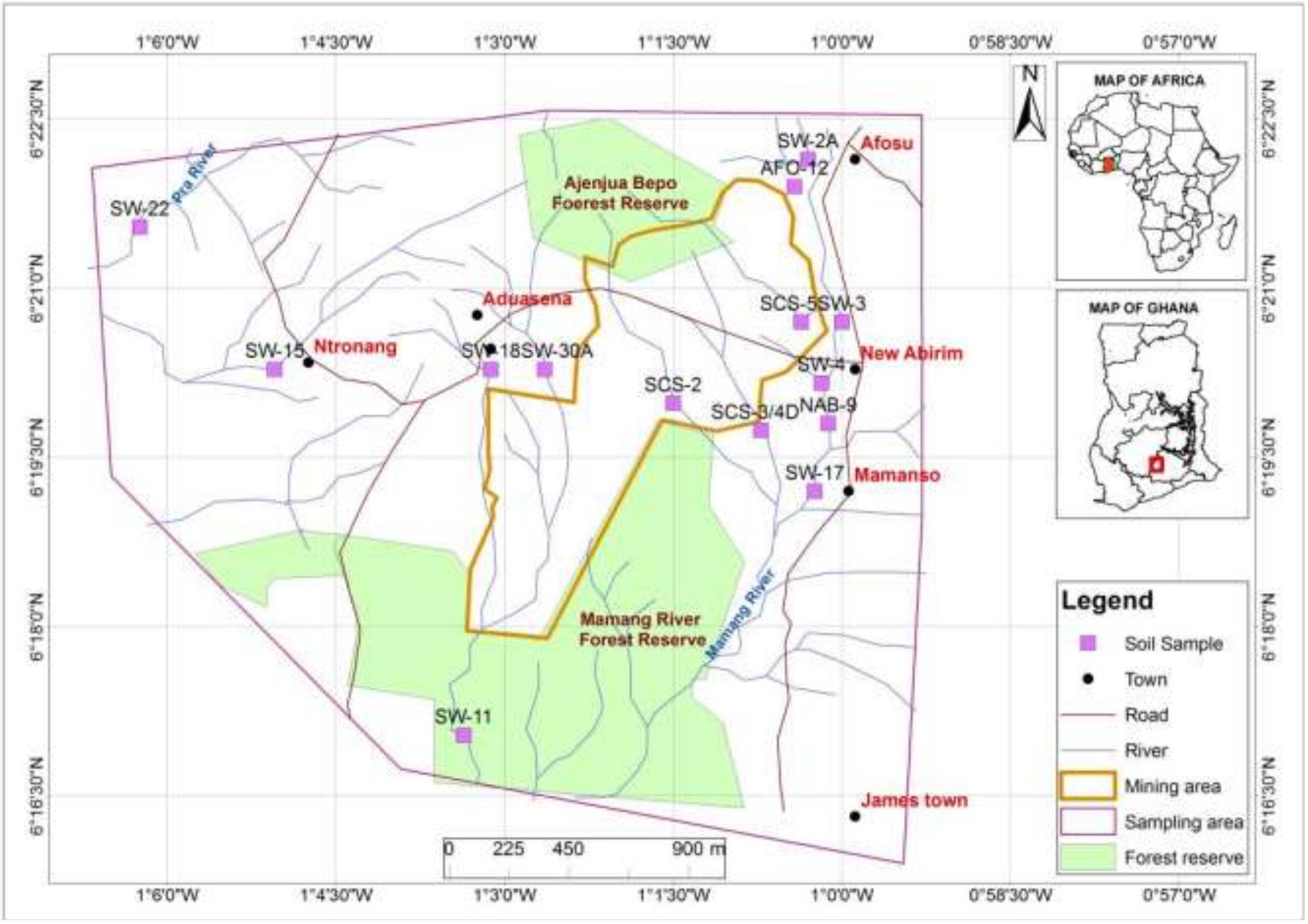

**Figure 2.** Layout of Akyem Gold Mine showing soil sampling points.

(662KeV), Sn-113 (392 KeV), Sr-85 (514KeV) and Y-88 (898, 1836KeV). Both Energy and Efficiency calibration were completed by firstly counting a blank Marinelli beaker with deionized water for 10 h in order to determine background radiation that was applicable in correcting the net peak area of each radionuclide analysed.

### Activity concentration of $^{226}$Ra, $^{228}$Ra, $^{232}$Th and $^{40}$K

The determination of the activity concentration of each of the following radionuclides :$^{226}$Ra, $^{228}$Ra, $^{232}$Th, $^{40}$K was done as follows: $^{40}$K was based on the only γ-energy of 1.461Mev, $^{232}$Th was taken from the sum of energies of $^{228}$Ac and $^{212}$Pb at energies 0.911,0.239 MeV, respectively, $^{228}$Ra was according to $^{228}$Ac energy, and $^{226}$Ra was based on the average of $^{214}$Pb , $^{214}$Bi at 0.352 ,0.609 Mev, respectively. The specific activity concentrations (**$C_{sp}$**) of $^{226}$Ra, $^{228}$Ra, $^{232}$Th, $^{40}$K were calculated using the following equation (Darko et al, 2005; Faanu, 2011)

$$C_{sp} = \frac{N_{sam} * \exp(-\lambda Td)}{P_E \cdot T_C * \varepsilon * M_{sam}} \quad (1)$$

Where: $N_{sam}$ is the net counts of the radionuclide in the sample, $P_{E*}$ is the gamma ray emission probability (gamma yield), ε is the total counting efficiency of the detector system. Td is the delay time between sampling and counting, exp (λTd) is the correction factor between sampling and counting, Tc is the sample counting time and $M_{sam}$ is mass of the sample (kg) or volume (L).

### Activity concentration of radon and thoron

The specific activity concentrations Ra-226, Ra-228 were used to estimate the concentrations of Rn-222 and Rn-220 using the expression according to UNSCEAR (2000) and Nazaroff et al. (1988) in which the amount of radon, thoron [ CRn-222,Rn-220 ], in soil gas, in the absence of radon, thoron transport is given as:

$$C_{Rn,Tn} = C_{Ra-226,228} \cdot f \cdot \rho_s \cdot \varepsilon^{-1} (1 - \varepsilon)(m[K_T - 1] + 1)^{-1} \quad (2)$$

Where: $C_{Rn,Tn}$ is the radon, thoron concentration in soil (Bq/m$^3$), $C_{Ra-226,228}$ is the activity concentration in dry mass of $^{226}$Ra, $^{228}$Ra in soil (Bq/kg), F is the soil emanation factor: radon (0.2) and thoron (0.1), $\rho_s$ is the density of soil (kgm$^{-3}$), ε is the porosity (0.25), m is the porosity fraction that is water filled and is zero if the soil is dry, $k_T$ is the radon partition coefficient between water and air phases and if the soil samples are dried before measurement, then m is zero, thus the last term of equation above is omitted.

## Dose and hazard assessment of natural radioactivity

### Annual effective dose

Effective dose is meant for use as a safeguard quantity. The main uses of effective doses are the proposed dose assessment for planning and optimization in radiological protection, and demonstration of compliance with dose limits for regulatory objectives (ICRP, 2007). To evaluate the year-long effective dose rates, the conversion coefficient from absorbed dose in the air to effective dose (0.7Sv.Gy$^{-1}$) and outdoor occupancy factor (0.2Sv.Gy$^{-1}$) suggested by UNSCEAR (2008) was applied.

In Ghana, the average time spent indoors and outdoors (Occupancy Factors) are 0.6 and 0.4, respectively (Asumadu-Sakyi et al., 2012). According to UNSCEAR (2008), world average indoor and outdoor occupancy factors are 0.8 and 0.2, respectively. Therefore, the effective dose rate in units of mSvy$^{-1}$ was estimated using the formula according to Aguko et al. (2013); Mohanty et al. (2004) and UNSCEAR (1998).

$$\text{Indoor effective dose rate (mSv y}^{-1}\text{)} = \text{Dose rate (nGyh}^{-1} \times 8760\text{h)} \times 0.4 \times 0.7\ \text{SvGy}^{-1} \times 10^{-6} \quad (3)$$

$$\text{Outdoor Effective Dose rate (mSv y}^{-1}\text{)} = \text{Dose rate (nGyh}^{-1} \times 8760\text{h)} \times 0.6 \times 0.7\ \text{SvGy}^{-1} \times 10^{-6} \quad (4)$$

### Radium equivalent activity ($\boldsymbol{Ra_{eq}}$)

The radium equivalent activity ($\boldsymbol{Ra_{eq}}$) is a weighted addition of activity concentration of $^{226}$Ra,$^{232}$Th, and $^{40}$K in which the sum of their proportion is the same gamma-ray dose rates as given by the following formula (Nada, 2004):

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (5)$$

Where; $C_{Ra}$, $C_{Th}$ and $C_K$ are the activity concentrations of $^{226}$Ra,$^{232}$Th, and $^{40}$K. The coefficients 1, 1.43 and 0.077 indicate that 370 Bq/kg of $^{226}$Ra, 259 Bq/kg of $^{232}$Th and 4810 Bq/kg of $^{40}$K produce the same gamma-ray dose rate. The above criterion only considers the external hazard due to gamma rays in building materials. The maximum recommended value of ($\boldsymbol{Ra_{eq}}$) in raw building materials and products must be less than 370 Bq/kg for safe use. This means that the external gamma dose must be less than1.5 mSv/year.

### Internal hazard index (Hin)

Another factor signifying radiological hazard due to radon is, the internal radiation exposure related to radioactivity and is expressed by the following equation (Saher et al., 2013).

$$H_{in} = C_{Ra}/185 + C_{Th}/259 + C_K/4810 \quad (6)$$

The calculation of internal hazard index was based on radon and its daughters. This is considering that, radon and its short-lived products are also hazardous to the respiratory organs. For construction materials to be considered safe for building of dwellings, the internal hazard index should be less than unity.

### External hazard index (Hex)

External hazard index is also applicable when it comes to external irradiation of gamma rays from radionuclides and is given by Saher et al. (2013):

$$H_{ex} = C_{Ra}/370 + C_{Th}/259 + C_K/4810 \quad (7)$$

where $C_{Ra}, C_{Th}$ and $C_K$ represents activity concentration in (Bq/Kg) of $^{226}$Ra, $^{232}$Th and $^{40}$K, respectively. In order to keep the radiation negligible, the value of $\boldsymbol{Ra_{eq}}$ must be less than 370 while $\boldsymbol{H_{in}}$ and $\boldsymbol{H_{ex}}$ must be less than unity.

## RESULTS AND DISCUSSION

### Concentration of soil gas radon and thoron

The results of Rn-222, Rn-220 are shown in Figures 3 and 4. The concentrations vary from 4.194 to 21.114 kBqm$^3$ with mean value of 11.362 ± 4.590 kBq/m$^3$ for radon and 0.544 to 13.222 kBq/m$^3$ with mean value of 5.062 ± 3.051 kBq/m$^3$ for thoron. Some research findings by Tabar et al. (2013) and others have shown that the soil gas radon concentration may differ widely due to weather pattern, conditions and soil varieties. The season of sampling may also affect radon soil concentration due to disturbance of site condition by fault movement. Table 2 compares radon results in this study with various research findings carried out around the world.

It is clear to notice that the radon values in soil gas at Akyem area are within the range of those reported in different parts of the world except a few. Moreover, the values determined in this study are much below the agreed levels according to USEPA (2005). In terms of thoron /radon ratio, Ramachandran (2010) and Giammanco et al. (2007) in studies carried out elsewhere found values of 0.530 and 0.503, respectively while this study found a mean value of 0.444 ± 0.140 which is within the range.

### Correlation between radium and radon

There is correlation between Ra-226 and Rn-222 in soil gas. Figure 5(a) shows that Rn-222 is a linear function of Ra-226 with a good linear coefficient of ($R^2$ =1 ) . The availability of Ra-226 and Rn-222 shows that there is source of U-238 and Th-232 bearing minerals within the adjacent geologic units of Akyem. This implies that most

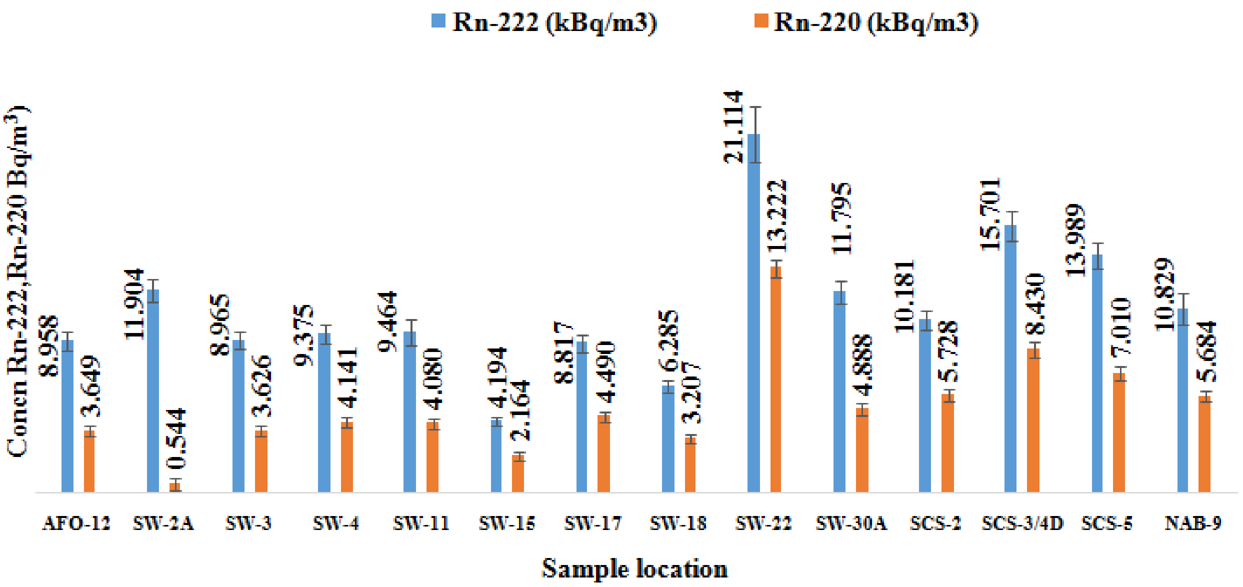

**Figure 3.** Rn-222 and Rn-220 concentration in soil samples.

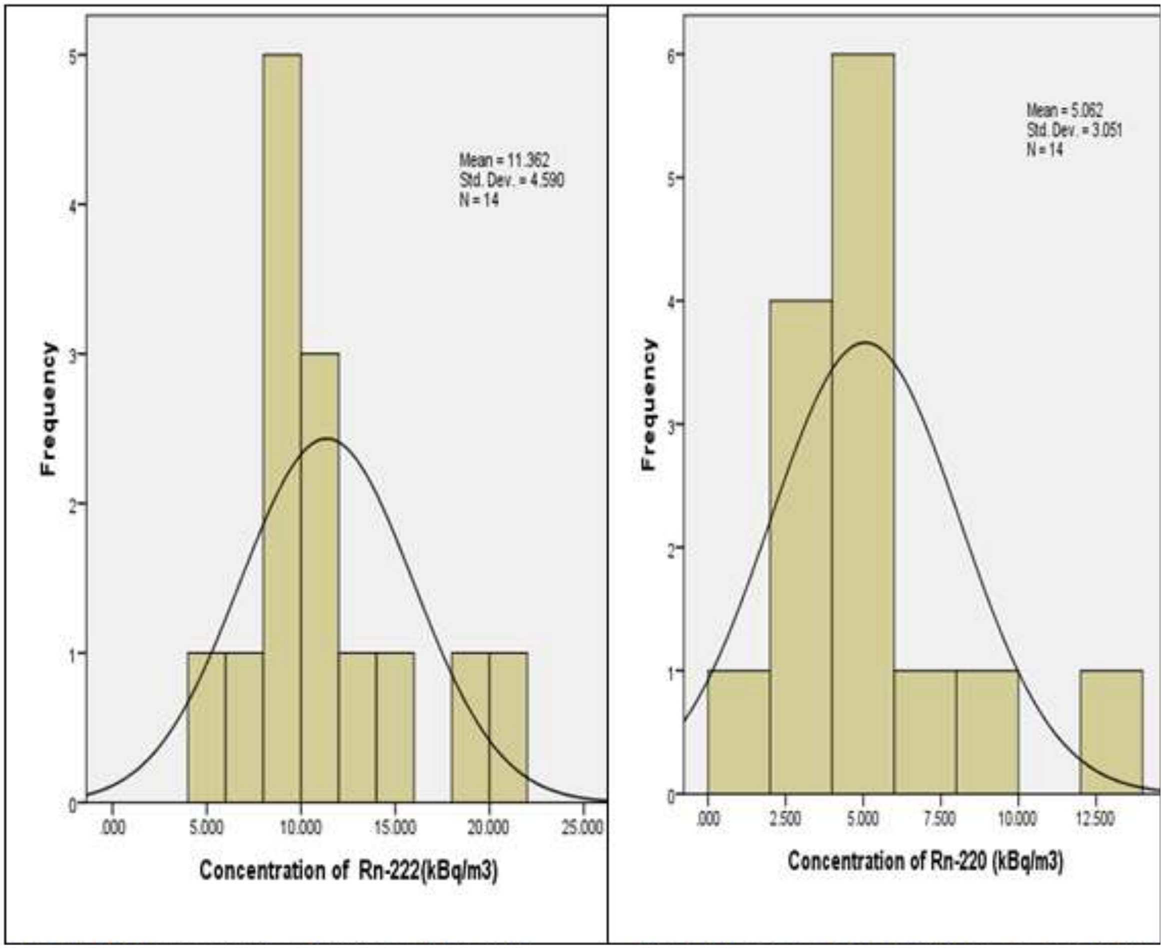

**Figure 4.** (a) Frequency distribution of Rn-222. (b) frequency distribution of rn-220.

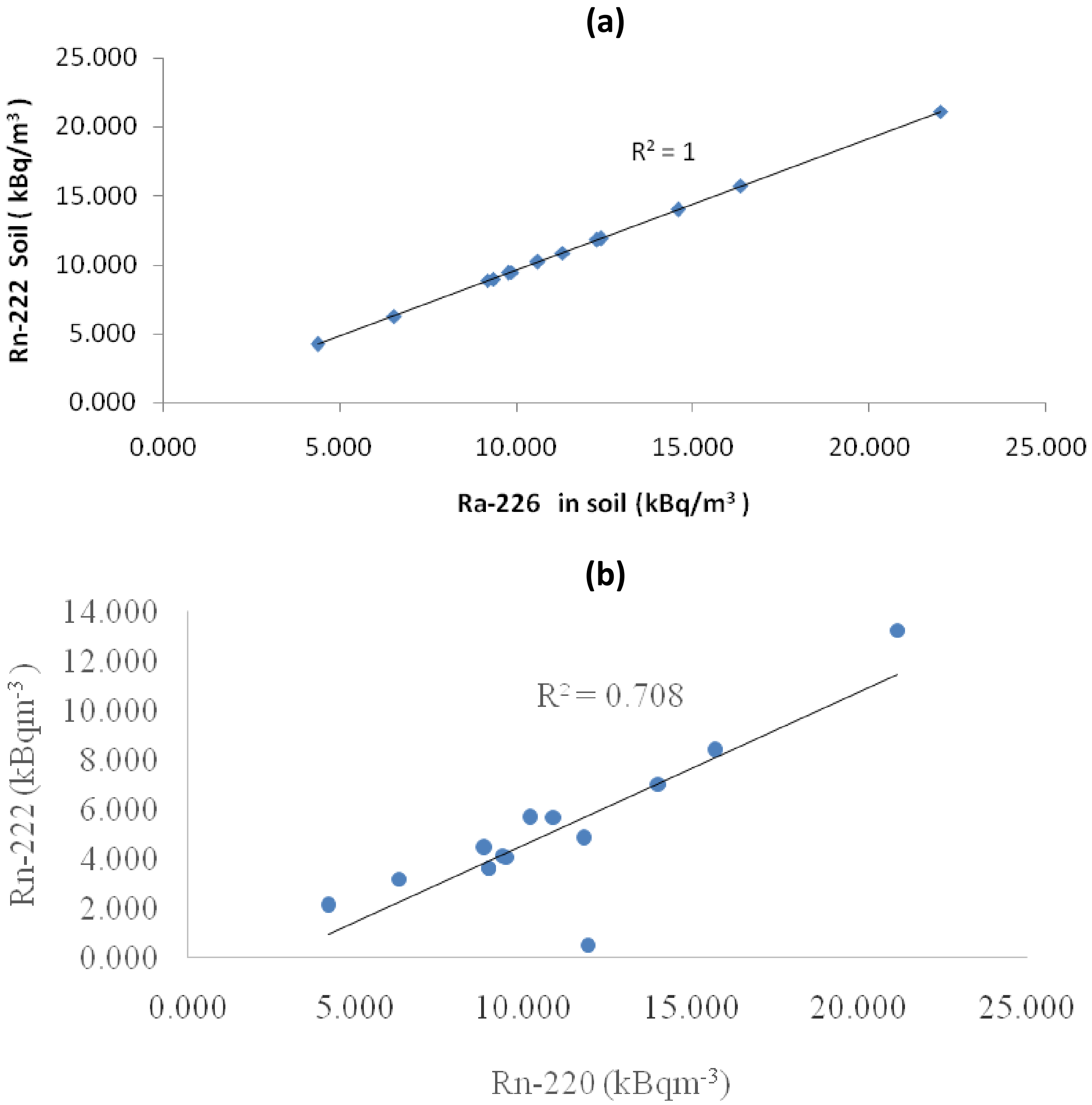

**Figure 5. (a)** Correlation Ra-226 and Rn-222; **(b)** Correlation Rn -222 and Rn-220.

of the radon in the soil gas comes from Ra-226. While the correlation for radon, thoron in the soil is roughly 0.7. Figure 5b shows that radon gas in the soil co-exist with thoron.

## Hazard assessment due to natural radioactivity and radon in the soil

Table 1 shows that activity concentration of soil gas radon ranged from 4.194 to 21.114 kBq/m$^3$ with a mean value of, 10.829 ± 4.130 kBq/m$^3$ while for thoron, was 0.544 to 13.222 kBq/m$^3$ with a mean value of 5.062 ± 3.051 kBq/m$^3$. Soil gas radon concentration in this study compared very well with previous studies in Ghana and elsewhere (Table 2). Figure 6 depicts several averages, kurtosis and skewness coefficients and the nature of frequency statistical distribution for natural radioactivity and the measured absorbed dose rates. It is noted that the absorbed dose rates and the activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K are normally distributed with mean values of 56.56 nGy/h and 11.35, 12.23, 113.78 Bq/Kg, respectively (Figure 6a to d).

Table 3 shows the average values of Radium equivalent activity ($Ra_{eq}$), Internal and External hazard index ($H_{in}, H_{ex}$) and Annual Effective Dose (mSvy$^{-1}$). The $Ra_{eq}$ was calculated and ranged from 19.708 to

**Table 1.** Soil Rn-222 and Rn-220 concentration.

| Sample Location | Concentration, Bq/Kg | | Concentration, kBq/m$^3$ | |
|---|---|---|---|---|
| | Ra-226 | Ra-228 | Rn-226 | Rn-226 |
| Afo-12 | 9.332 ± 0.560 | 7.602 ± 0.302 | 8.958 ± 0.538 | 3.649 ± 0.290 |
| SW-24 | 12.400 ± 0.514 | 1.133 ± 0.359 | 11.904 ± 0.658 | 0.544 ± 0.345 |
| SW-3 | 9.339 ± 0.402 | 7.554 ± 0.310 | 8.965 ± 0.515 | 3.626 ± 0.298 |
| SW-4 | 9.766 ± 0.424 | 8.628 ± 0.310 | 9.375 ± 0.543 | 4.141 ± 0.298 |
| SW-11 | 9.859 ± 0.623 | 8.499 ± 0.335 | 9.464 ± 0.798 | 4.080 ± 0.322 |
| SW-15 | 4.369 ± 0.226 | 4.509 ± 0.232 | 4.194 ± 0.289 | 2.164 ± 0.223 |
| SW-17 | 9.185 ± 0.400 | 9.354 ± 0.329 | 8.817 ± 0.511 | 4.490 ± 0.316 |
| SW-18 | 6.547 ± 0.304 | 6.682 ± 0.288 | 6.285 ± 0.388 | 3.207 ± 0.276 |
| SW-22 | 21.994 ± 1.307 | 27.545 ± 0.520 | 21.114 ± 1.672 | 13.222 ± 0.499 |
| SW-30A | 12.286 ± 0.519 | 10.183 ± 0.370 | 11.795 ± 0.664 | 4.888 ± 0.355 |
| SCS-2 | 10.605 ± 0.453 | 11.933 ± 0.363 | 10.181 ± 0.580 | 5.728 ± 0.348 |
| SCS-3/4D | 16.355 ± 0.665 | 17.562 ± 0.457 | 15.701 ± 0.851 | 8.430 ± 0.439 |
| SCS-5 | 14.572 ± 0.606 | 14.605 ± 0.428 | 13.989 ± 0.775 | 7.010 ± 0.411 |
| NAB-9 | 11.312 ± 0.704 | 11.841 ± 0.349 | 10.859 ± 0.902 | 5.684 ± 0.335 |
| Minimum | 4.369 ± 0.226 | 1.133 ± 0.520 | 4.194 ± 0.289 | 0.544 ± 0.290 |
| Maximum | 21.994 ± 1.307 | 27.545 ± 0.520 | 21.114 ± 1.672 | 13.222 ± 0.499 |
| Mean±StDev | 11.280 ± 4.301 | 10.545 ± 6.357 | 10.829 ± 4.130 | 5.062 ± 3.051 |

**Table 2.** Comparison of Soil with other Studies.

| Country | Sampling location | Measurement technique | Concentration, Bq/m$^{-3}$ | | Ratio | Reference |
|---|---|---|---|---|---|---|
| | | | Rn-222 | Rn-220 | Rn-220/Rn-222 | |
| Ghana | G.Mine | HPGe | 4,194 - 21,114 | 544 -13,222 | 0.444 | This study |
| Ghana | G.Mine | Alpha Guard | 56-268 | - | - | Andam and Amoo, 1994 |
| Ghana | Mine | Alpha Guard | 43-878 | - | - | Andam and Amoo, 1994 |
| Ghana | Mine | HPGe | 12,500-41,300 | - | - | Faanu, 2011 |
| Ghana | Fault | - | 9,910 - 42,10 | - | - | Amponsah, 2008 |
| Turkey | Geotherm. Area | SSNTD | 98 - 8594 | - | - | Tabar et al., 2013 |
| Italy | Volcanic Mt | RAD7 radon meter | 232-104,300 | 10-23,350 | 0.503 | Giammanco et al., 2007 |
| India | - | RAD7 radon meter | 3,200-17,200 | - | - | Mehra et al., 2015 |
| India | *Dwellings | SSNTD | - | - | 0.503 | Ramachandran, 2010 |
| Russia | - | - | 1,700 - 24,000 | - | - | Iakovleva and Ryzhakova, 2003 |
| Sudan | soil | SSNTD | 5,500 -15,100 | - | - | Elmoniem and Elzain, 2015 |

G.: Gold Mt.:Mountain SSNTD: Solid State Nuclear Track Detector *Indoor thoron and radon

69.880 Bq/Kg with mean value of 37.527 ± 15.508 Bq/Kg compared to the global limit of 370 Bq/Kg. The value for $H_{in}$ ranged from 0.065 to 0.248 Bq/Kg with a mean value of 0.132 ± 0.053 Bq/Kg which is lower than the accepted value of the unity. While for total annual effective dose due to external and internal gamma dose the range was 0.060 to 0.175 mSvy$^{-1}$ with the mean value of 0.11 ± 0.025 mSvy$^{-1}$ against the world value of 1 mSvy$^{-1}$. Comparison of $Ra_{eq}$, $H_{in}$, $H_{ex}$, and AED with the other studies in Ghana and elsewhere was made and Figure 7 clearly shows that values of $Ra_{eq}$ ,$H_{in}$ ,$H_{ex}$and AED obtained are much lower than those recommended values of 370, 1, 1, 1 Bq/Kg, respectively by UNSCEAR (2008).Figure 7 also shows that the concentration of Ra-226, Th-232, K-40 in this study are lower than the global values of 37, 33, 400 Bq/Kg, respectively.

## Conclusion

Studies at Newmont-Akyem, was carried out using

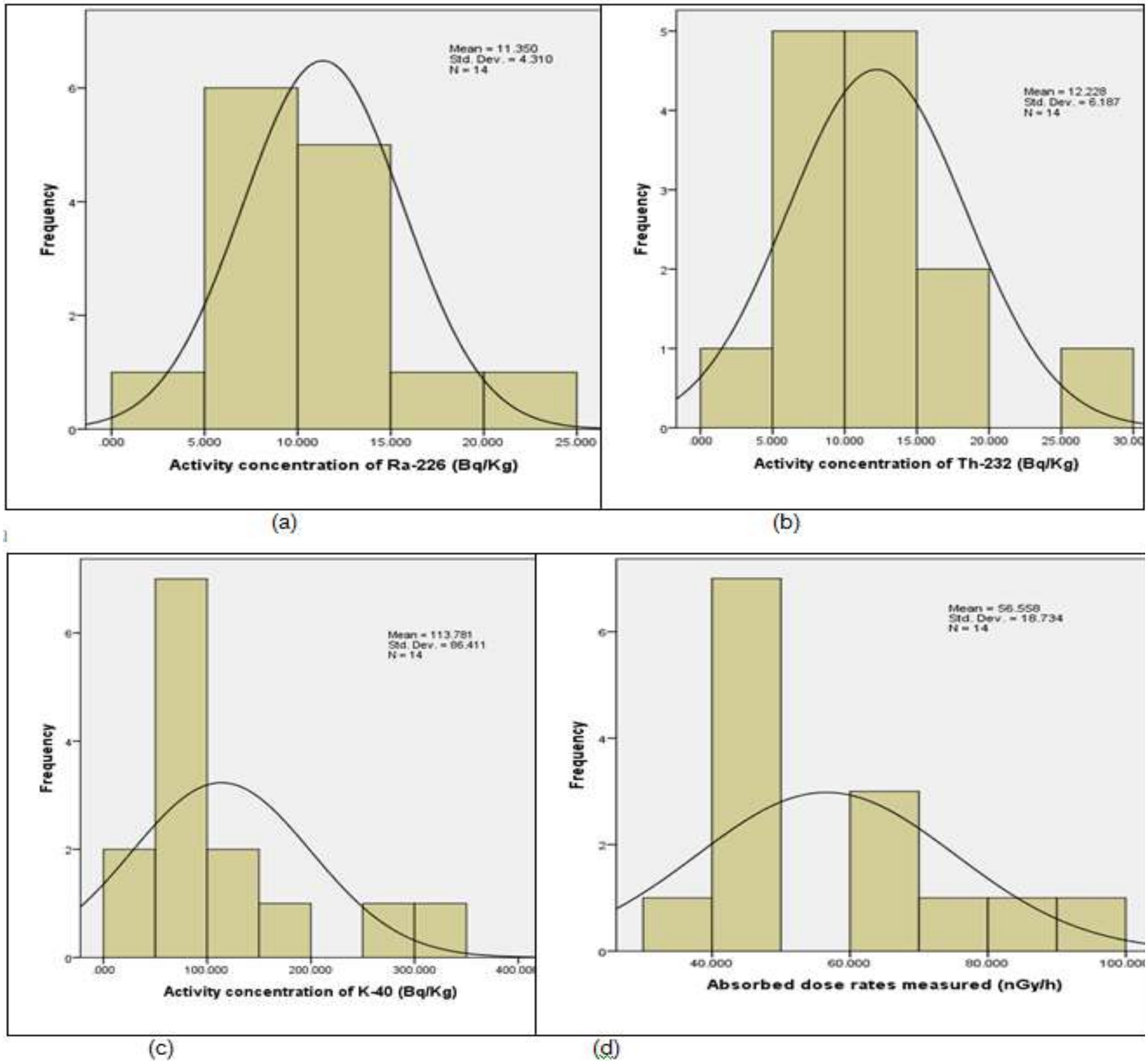

**Figure 6.** (a) Frequency distribution of $^{226}$Ra. (b) Frequency distribution of $^{232}$Th. (c) Frequency distribution of $^{40}$K. (d) Frequency distribution of the measured absorbed dose rates in the field.

Gamma Spectrometry System equipped with High Purity Germanium detector. The samples were analyzed in order to assess the dose and hazards due to $^{226}$Ra, $^{228}$Ra, $^{232}$Th, $^{40}$K, $^{222}$Rn and $^{220}$Rn. The soil gas radon concentration correlated with that of radium showing that, radium is the source of soil gas radon. The study has shown that the annual effective dose due to $^{226}$Ra, $^{232}$Th, $^{40}$K is lower than the world averages.

Although, soil gas radon and thoron concentrations were calculated, it was difficult to find AED based on soil gas radon and thoron as literature indicates that it gives limited results. Therefore it would still be recommended to conduct direct measurement of indoor radon and thoron and compare the results. Thus, it is very difficult to conclude whether people at Akyem are safe from radon without AED based on ambient radon and thoron. However the results for soil gas radon have shown that, the people may safely use the soil with very minimal

**Table 3.** Annual effective dose, Radium Equivalent Index ($Ra_{eq}$), internal and EXTERNAL harzard indices ( $H_{in}$, $H_{ex}$) of soil samples.

| Sample location | Concentration, $BqKg^{-1}$ | | | AED, $mSvy^{-1}$ | | |
|---|---|---|---|---|---|---|
| | Raeq | Hin | Hex | External | Internal | $\Sigma_{AED}$*(ext,int)* |
| AFO-12 | 22.633 ± 1.664 | 0.086 ± 0.006 | 0.061 ± 0.004 | 0.025 ±0.0019 | 0.038 ± 0.0028 | 0.063 ± 0.003 |
| SW-2A | 31.851 ± 2.112 | 0.120 ± 0.007 | 0.086 ± 0.006 | 0.036 ±0.0024 | 0.053 ± 0.0036 | 0.089 ±0.004 |
| SW-3 | 26.623 ± 1.628 | 0.097 ± 0.005 | 0.072 ± 0.004 | 0.031 ±0.0018 | 0.046 ± 0.0028 | 0.077 ± 0.003 |
| SW-4 | 30.395 ± 1.807 | 0.108 ± 0.006 | 0.082 ± 0.005 | 0.035 ± 0.0021 | 0.053 ± 0.0031 | 0.088 ± 0.003 |
| SW-11 | 32.051 ± 2.077 | 0.113 ± 0.007 | 0.087 ± 0.006 | 0.038 ± 0.0023 | 0.056 ± 0.0035 | 0.094 ± 0.004 |
| SW-15 | 19.708 ± 1.092 | 0.065 ± 0.004 | 0.053 ± 0.003 | 0.024 ± 0.0013 | 0.036 ± 0.0019 | 0.06 ± 0.002 |
| SW-17 | 30.380 ± 1.857 | 0.107 ± 0.006 | 0.082 ± 0.005 | 0.035 ± 0.0021 | 0.053 ± 0.0032 | 0.088 ± 0.003 |
| SW-18 | 24.384 ± 1.498 | 0.084 ± 0.005 | 0.066 ± 0.004 | 0.029 ± 0.0017 | 0.043 ± 0.0026 | 0.072 ± 0.003 |
| SW-22 | 69.880 ± 4.889 | 0.248 ± 0.017 | 0.189 ± 0.013 | 0.058 ±0.0055 | 0.087 ± 0.0082 | 0.145 ± 0.008 |
| SW-30A | 51.271 ± 2.407 | 0.172 ± 0.008 | 0.138 ± 0.007 | 0.069 ± 0.0046 | 0.103 ± 0.0070 | 0.172 ± 0.007 |
| SCS-2 | 36.028 ± 2.136 | 0.126 ± 0.007 | 0.097 ± 0.006 | 0.061 ± 0.0027 | 0.091 ± 0.0041 | 0.152 ± 0.004 |
| SCS-3/4D | 55.948 ± 3.260 | 0.195 ± 0.011 | 0.151 ± 0.009 | 0.048 ± 0.0026 | 0.072 ± 0.0040 | 0.12 ± 0.004 |
| SCS-5 | 60.720 ± 3.034 | 0.203 ± 0.010 | 0.164 ± 0.008 | 0.063 ± 0.0036 | 0.095 ± 0.0055 | 0.158 ± 0.006 |
| NAB-9 | 33.501 ± 2.403 | 0.121 ± 0.008 | 0.090 ± 0.006 | 0.070 ±0.0013 | 0.105 ± 0.0054 | 0.175 ± 0.005 |
| Minimum | 19.708 ± 1.092 | 0.065 ± 0.004 | 0.053 ± 0.003- | 0.024 ± 0.0013 | 0.036 ± 0.0019 | 0.06 ± 0.002 |
| Maximum | 69.880 ± 4.889 | 0.248 ± 0.017 | 0.189 ± 0.013 | 0.070 ± 0.0013 | 0.105 ± 0.0054 | 0.175 ± 0.005 |
| Mean ± StDev | 37.527 ± 15.508 | 0.132 ± 0.053 | 0.101 ± 0.042 | 0.044 ± 0.0170 | 0.066 ± 0.0248 | 0.11 ± 0.025 |

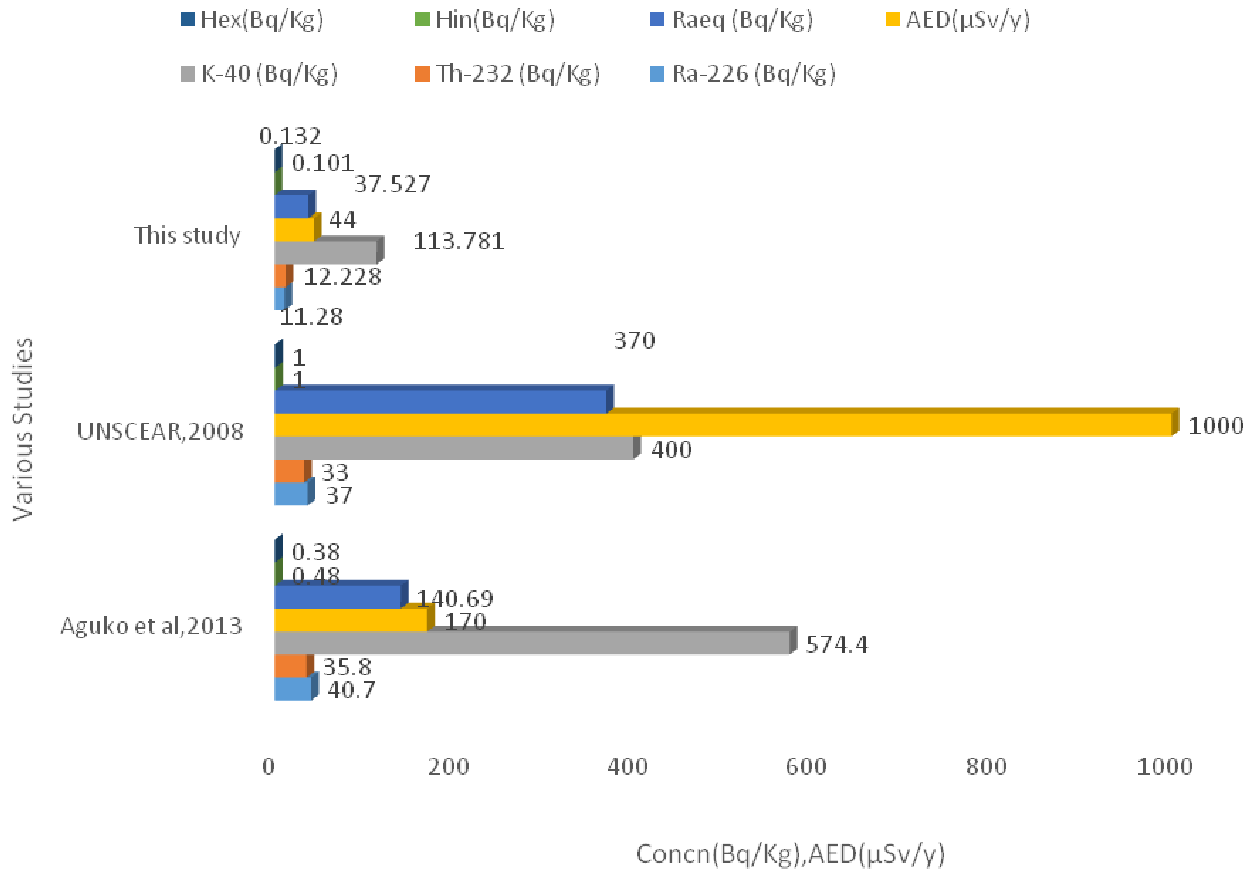

**Figure 7.** $Ra_{eq}$, $H_{in}$, $H_{ex}$, AED of NORMs compared to the world average values.

radiological risks.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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