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Assessment of indoor radon, radon exhalation rate, and radium levels within Kpando Municipality, Volta Region, Ghana

A.S.K. Amable[1,2*], F. Otoo[3,4], P.K. Buah-Bassuah[2], A. Twum[2], E.N. Manso[5], J.P. Adeti[6], E. Ahiave[7]

[1]*School of Basic and Biomedical Sciences, Department of Basic Sciences, University of Health and Allied Sciences, PMB 31, Ho-Volta, Ghana*
[2]*School of Physical Sciences, Department of Physics, University of Cape Coast, Cape Coast, Ghana*
[3]*Radiation Protection Institute, Ghana Atomic Energy Commission, Legon-Accra, Ghana*
[4]*School of Nuclear and Allied Sciences, University of Ghana, Atomic Campus, Accra, Ghana*
[5]*University for Development Studies, Department of Medical Imaging, Tamale, Ghana*
[6]*Nuclear Chemistry and Environmental Research Centre, Ghana Atomic Energy Commission, Ghana*
[7]*Ho Technical University, Department of Mathematics and Statistics, Ho, Ghana*

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Corresponding author:
Anthony S.K. Amable, Ph.D.,
E-mail:
askamable@uhas.edu.gh

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ABSTRACT

Background: Radium, a naturally occurring radioactive substance, and its decay product radon, a radioactive gas, can accumulate in the environment and pose health risks to residents. This study aims to assess levels of radium and radon in soils and dwellings in Kpando Municipality and its potential health risks, ensuring informed decision-making for public safety and environmental protection. ***Materials and Methods:*** Fifty-one soil samples were collected from seventeen (17) different locations within the Kpando Municipality. The samples were prepared and analyzed for radium concentrations using gamma-ray spectrometry and radon exhalation using closed-can techniques and CR-39 detectors. Radon gas concentrations were measured in one hundred and twenty (120) selected dwellings using CR–39 detectors. ***Results:*** The activity concentration of radium, radon levels in dwellings and radon exhalation in soil ranged from 3.4 to 48.1 Bq/kg (23.6 ±4.5 Bq/kg), 23.5 to 124.7 Bq/m^3 (60.5±3.2 Bq/m^3), and 1.3 to 13.3 µBq/m^2h (8.1±0.5 µBq/m^2h), respectively. Strong and weak positive correlations were observed between radium/radon exhalation (0.9) and radium/indoor radon (0.3). Radon levels in dwellings and soil exceeded WHO and UNSCEAR recommendations by 11 % and 14 %, respectively. However, 98 % of estimated annual effective doses were below UNSCEAR and ICRP reference levels. ***Conclusion:*** The mean activity concentrations of radium and radon were less than WHO and UNSCEAR action levels. Elevated radium and radon concentrations in certain dwellings pose health risks. Urgent measures are needed: further investigations, improved building design, ventilation and awareness campaigns to reduce exposure.

INTRODUCTION

Radon, a naturally occurring radioactive gas, is the largest source of natural radiation exposure to the populace [1]. The indoor radon in homes and soil radon gas is influenced by the radium concentration present in the soil. The higher the amount of radium content in the soil, the higher the level of radon gas in the environment [2, 3]. Radon mostly enters the dwellings through openings in foundations and household water usage. When radon gas is trapped in a confined area such as dwellings, it can build up to elevated levels [4-7]. Radon has been classified as a carcinogenic substance causing lung cancer. It was found to be the second largest cause of lung cancer after smoking [6, 8]. The gas decays into radioactive particles called radon progeny that can enter the human body through inhalation. Even longer exposure to lower radon levels can also increase the risk of developing lung cancer [1, 6].

Studies on natural radioactivity and radon levels in the country have mainly focused on indoor radon concentrations [4, 5, 9-14], with few data also reported on radon exhalation in soil [4, 5, 11]. Some of these studies with different techniques for radon measurement in Ghana have reported high values of radon in dwellings and soil [4, 5, 10, 11, 13]). However, no studies were reported on radium, radon exhalation, and indoor radon in the study area. Since most people spend around 80% of their time indoors, natural radioactivity monitoring, and radon measurements in soils and dwellings are critical to the residence of

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Kpando Municipal and the radiation protection point of view [15].

In Ghana, some studies were conducted to find the variation and determine the relationship between radon levels and radium concentration in the soil and dwellings in a few locations [4, 5]. However, there has not been a known study of the correlation between indoor radon, radon soil gas exhalation, radium concentration, and related radiological hazards to the residents of the Kpando Municipal. Given this, the indoor and soil gas radon and radium concentration measurement is essential to the residence. This determines the radiological effect on the populace due to potential radon gas exposure in the study area. Therefore, during this study, we determine the correlation between radium concentration and radon exhalation from soils and indoor radon from the dwellings in some selected communities of Kpando Municipal in the Volta Region of Ghana. The annual effective doses and cancer risk associated with the radon concentration on the occupant were also estimated.

This study contributes uniquely to the field of environmental radioactivity by providing a comprehensive analysis of both radon exhalation from soil and radium levels in the Kpando Municipality. It expands upon the existing body of research, which predominantly focuses on indoor radon concentrations, by also considering the potential health impacts on residents. The research offers valuable insights into the behaviour of radionuclides in this specific geographic area, addressing a gap in the current understanding and aiding in the development of effective radiation protection strategies.

MATERIALS AND METHODS

The study area

The selected study areas for the study are located in Kpando Municipality of the Volta Region in the Southern part of Ghana with Latitudes 6° 20' N and 7° 05' N, and Longitude 0° 17' E. The total land area of the municipal is approximately 820 square kilometers, representing 4.5 % of the Volta Region with almost 30 % of the land submerged by the Volta Lake. The Volta Lake, which stretches over 80 km of the coastal line, demarcates the western boundary. The municipal shares boundaries with Biakoye District in the north, Afadzato South District to the east, and North Dayi District in the south [13].

Building materials

The dwellings in the study area are commonly constructed with sandcrete, clay with cemented walls, clay, concrete blocks with tiled floors, bricks, louvres, cemented floors, clay floors, wooden windows, and burnt clay. Among the dwellings, single -story bungalows were selected for the study. Out of the 120 dwellings studied, 12.5 percent are made of clay with cemented walls and floors, and wooden windows (KM1), 15.8 percent are made of clay, with clay floor and small wooden windows (KM2), 25.8 percent are made of sandcrete with cemented floors and wooden windows (KM3), 20.0 percent are made of concrete blocks with tiled floors and glass louvre windows (KM4), 9.2 percent are made from clay bricks, cemented floor with louvre blade windows (KM5) and 16.7 percent are also from the block, cemented floor with wooden window (KM6). The number of rooms per dwelling varied between 1 to 5, with an average occupant of 5 people. All monitored dwellings did not have air conditioning systems installed.

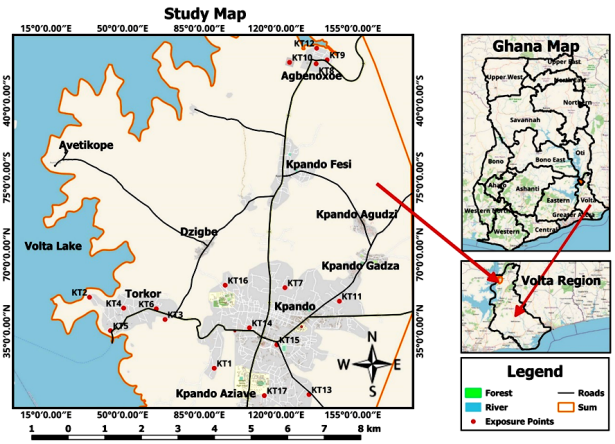


Figure 1. Map of the studied locations showing sampling points.

Sample collection, preparation, and measurement.

The soil samples were obtained from a minimum of three (3) different locations (figure 1) in the same area using labelled black polythene bags. Fifty-one (51) samples were analyzed at the Radiation Protection Institute of Ghana Atomic Energy Commission, Accra, Ghana. Before analysis, the samples were air-dried at room temperature until no moisture was present. They were then homogenized and sieved to a uniform mixture with a particle size of about 5 µm and 500 mL geometry, respectively. Finally, the samples were sealed, weighed, and stored at room temperature for 3-4 weeks to allow the ^{226}Ra and ^{222}Rn decay series to reach radioactive equilibrium with the short-lived progenies and to prevent the escape of radon gas [4, 8]. Gamma emissions of ^{214}Bi and ^{214}Pb were used to determine the activity of ^{226}Ra. Prior to sample measurement, the background was determined with an empty Marinelli beaker under identical measurement conditions. The counting time was 72000 s. The data acquisition, display, and on-line spectrum analysis were carried out using the Genie 2000 V3.3 (1) spectroscopy software from Canberra. The activity concentration (AC) (Bq/kg) of each radionuclide in any given sample was calculated from the spectrum using

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equation (1):

$$Ac\left(^{226}Ra\right)=\frac{N_{sam}}{P(E)\times\eta(E)\times T_c\times M_{sam}} \quad (1)$$

Where; M_{sam} *(kg)* is the mass of the sample, N_{sam} (cps) is the net peak area for the sample in the peak range, *P(E)* is the gamma emission probability, $T_c(s)$ is the counting time in seconds, and $\eta(E)$ is the photo peak efficiency which had been obtained from the standard solution.

Installation of radon detectors and analysis

The passive radon CR-39 Solid State Nuclear Track Detector (SSNTD) was used for this study. One hundred and twenty (120) detectors were obtained from Radosys (Hungary) and traceable to the radon calibration laboratory of the Federal Office for Radiation Protection (BfS) in Germany. Indoor radon measurements were randomly carried out in seventy-five (75) bedrooms, thirty (30) sitting rooms, and fifteen (15) kitchens for 183 days in the communities of Torkor, Agbenoxoe, and Tsakpa respectively. In each building, a detector was placed at a height of 1 to 1.5 m above the floor, at a distance greater than 0.5 m from each wall, and at a minimum of 15 cm from any other object [4]. To understand the radon concentration, differences between the dwellings, indoor hours, ventilation system, frequency of aeration, age, building material, and dwelling structures were noted during the analysis of the results. Exposed radon detectors were sent to the Radiation Protection Institute of Ghana Atomic Energy Commission, Accra, Ghana for analysis [16].

Radon exhalation measurements

Radon exhalation rates in soil samples were determined using a tightly closed vessel technique with a cylindrical jar. A known weight of a sample was placed at the bottom of the cylindrical jar and completely sealed for 1 month to establish the equilibrium between radium and radon. Detection procedures were done by installing CR-39 detector at the top of the chamber covering a distance of 22 cm from the surface of the sample to count for only radon (^{222}Rn) and prevent thoron from evading the surface of the detectors [4]. The radon exhalation measurements were performed by placing the soil samples at the bottom of glass containers with 10 cm diameter (D) and 25 cm height in the cylindrical vessel for 90 days.

Etching and analysis

After the radon indoor and emanation exposure in the dwellings and soil, respectively, the detectors were removed and etched in 6.25 N solution at 90 ^{0}C for 4 hours, 30 minutes and 15 minutes at constant temperature followed by 20 minutes neutralization with 36.0 mL of 96 % diluted acetic acid. Finally, the detectors were dried for four (4) days after washing them in distilled water for twenty (20) minutes to remove any excess chemicals. The latent tracks formed on the detectors were scanned and counted in 144 fields using an optical microscope of a 40 × magnification objective lens [4, 9, 16]. The track densities left on the track films were then used to evaluate the radon concentration. Equations (2) and (3) were used to estimate the indoor radon concentration and exhalation rate, respectively:
The activity of radon concentration

$$C_{Rn}\ (Bq/m^3)=\frac{\varrho}{\varepsilon t} \quad (2)$$

Where; ε is the calibration factor of the detector (track/cm^{2}d/(Bq/m^3), ϱ is the measured surface density of tracks (tracks/cm^2) and t is the exposure time.Radon Exhalation rate:

$$E_{Rn}\ (Bq/m^2h)=\frac{\varrho V_c\,\lambda_{Rn}}{\varepsilon S_a T_c} \quad (3)$$

Where; V_c volume of diffusion chamber (m^3), S_a is the surface area of the sample (m^2), λ_{Rn} is the decay constant of radon (1/s) and T_c is the effective exposure (s) in the diffusion chamber.

Annual effective doses.

The annual effective dose (AED) of exposure to indoor radon gas to the residence of Kpando municipal calculated from the arithmetic mean is given by equation (4).

$$AED = C_{Rn}\times O_f\times D_f\times I_f\times T_\gamma \quad (4)$$

Where; $C_{Rn}$is the arithmetic mean of indoor radon concentration in the dwellings, O_f is the indoor occupancy factor of 0.8, D_f is the dose conversion factor of 6.7 × 10^{-6} mSv/Bqhm^3 with I_f indoor occupancy factor assuming the indoor radon equilibrium factor is 0.4 [1]. T_γ is the number of hours in a year as 8760 h/yr.

Statistical analysis

The Origin Pro 2022 version was used for the statistical analysis. The Origin Pro was used to determine indoor radon frequency distribution, mode, median, arithmetic mean, geometric standard deviation, standard error, and the graphical representation of the data, in addition to the p-value. The determination of the annual effective dose, and excess lifetime cancer risk was all done by using the Origin Pro 2022. For radon mapping, radon concentration has been analysed and aggregated using the ArcMap version 10.7.1 geostatistical interpolation tool. The data from unsampled locations was used to create a continuous matrix to cover the study area using inverse distance weight (IDW) interpolation. The intensity of radon distribution within the communities of the Kpando Municipality was then developed using the data, which was recorded in a grid of 50 by 50 metres. Based on the range of radon intensity values,

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choropleth maps were produced.

RESULTS

The distribution of indoor radon, radon exhalation rate and radium data in the studied locations in the Kpando Municipality of the Volta Region, Ghana, were determined by plotting frequency distribution and spatial map of the indoor radon concentrations as shown in figures 2-5, respectively. From figure 2, the frequency distribution graph for indoor radon data appeared log-normal. The spatial distribution of the indoor radon data as represented in figure 3, shows that the radon gas within the study areas was not uniformly distributed. Therefore, the radon exposure levels varied from one room to the other. This was illustrated in the figure by the intensity of the colour. The frequency distribution of radium concentration and radon exhalation in the soil samples revealed the non-uniform distribution of the data as presented in figures 4 and 5. The uneven distribution of radon and radium data in soil and dwellings could be due to the differences in dwellings, building materials, inhabitant behaviour/occupant lifestyles, frequency of aeration, and variance of the different types of analysed buildings.

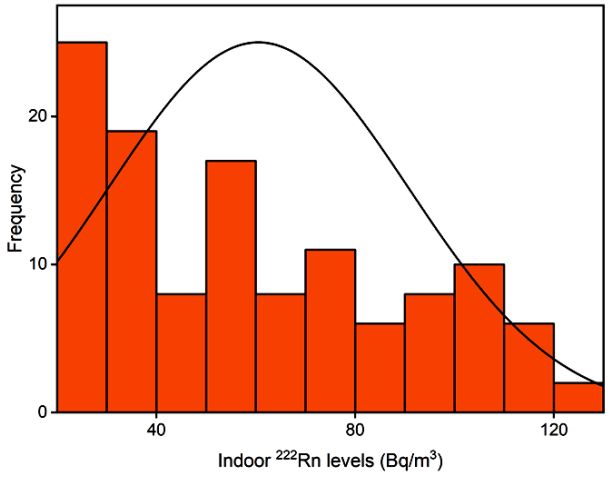


Figure 2. Frequency distribution of indoor radon concentration for study data.

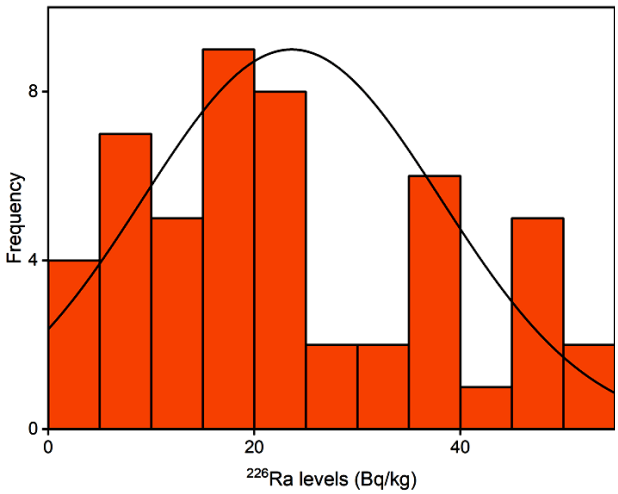


Figure 4. Frequency distribution of radium concentration in soil.

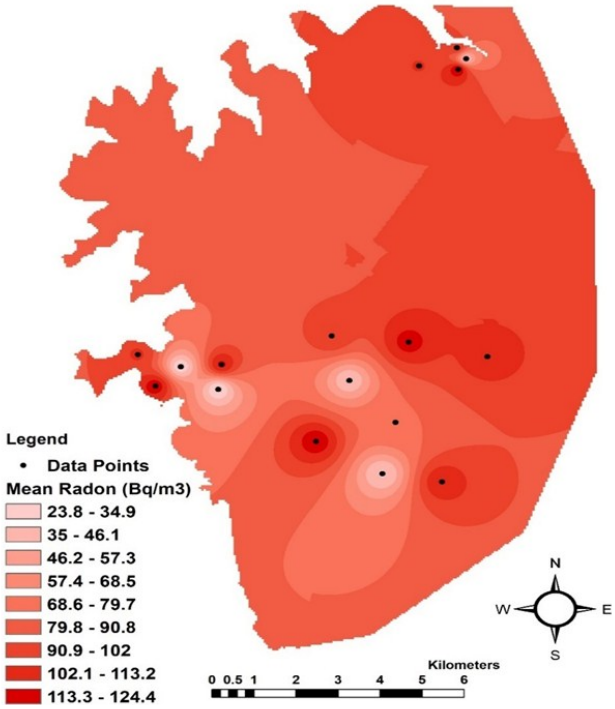


Figure 3. Mapping of the study areas.

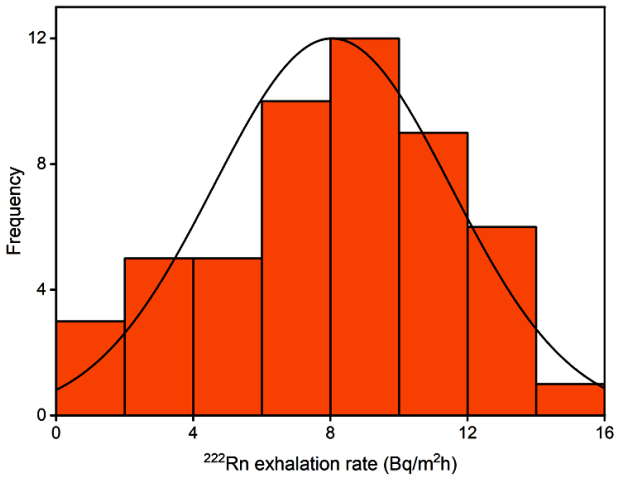


Figure 5. Frequency distribution of radon exhalation rate in soil.

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Tables 1 and 2 present the statistical analysis of indoor radon levels across various dwellings, considering different building materials, towns, and exposure sites. From table 1, the indoor radon concentration across all locations varied from 23.5 Bq/m^3 to 124.7 Bq/m^3, with the overall AM ± SD and GM ± GSD values of 60.5±3.2 and 53.0±2.8 Bq/m^3, respectively, indicating a skewed distribution of radon levels. The overall median radon level was 55.8 Bq/m^3, while the mode was 24.5 Bq/m^3, suggesting that most dwellings had lower radon concentrations. Significant variation in radon levels was observed across different rooms (bedrooms, kitchens, and sitting rooms) and towns (Torkor, Agbenoxoe, and Tsakpe). The highest radon concentration was found in the bedroom, with a range of 24.6 to 124.7 Bq/m^3, with an AM ± SD value of 74.9±7.3 Bq/m^3. The kitchen and sitting room radon levels were comparatively lower, with AM ± SD values of 42.9±3.9 Bq/m^3 and 33.6±1.2 Bq/m^3, respectively. In Torkor, radon levels ranged from 23.5 to 124.7 Bq/m^3, with an AM ± SD value of 58.1±1.2 Bq/m^3, whereas Agbenoxoe and Tsakpa showed slightly lower radon concentrations, with AM ± SD values of 57.6±2.8 Bq/m^3 and 65.9±3.9 Bq/m^3, respectively. From table 2, the measurements revealed that radon concentrations varied significantly depending on the building materials. The KM2 dwellings exhibited a radon concentration ranging from 32.6 to 124.7 Bq/m^3, with an AM ± SD value of 88.4±2.7 Bq/m^3, while KM4 dwellings showed a lower range of 23.5 to 72.8 Bq/m^3 and an AM ± SD of 39.5±1.5 Bq/m^3. The highest arithmetic mean value was observed in KM2 dwellings, emphasizing the potential impact of clay with clay floors and small wooden windows on indoor radon levels.

Table 1. Indoor radon concentration in the rooms and towns used for the study.

Statistics /NR	Bedroom	Study room location			Towns		
		Kitchen	Sitting room	Torkor	Agbenoxoe	Tsakpe	Total
	75	15	30	40	40	40	120
Range (Bq/m^3)	24.6-124.7	24.9-72.8	23.5-88.9	23.5-124.7	24.6-117.6	67.8-119.7	23.5-124.7
AM	74.9	42.9	33.6	58.1	57.6	65.9	60.5
GM	69.1	40.7	31.2	49.8	52.0	57.6	53.0
SDE	3.2	3.6	2.9	5.2	4.2	4.9	2.8
SD	7.3	3.9	1.2	3.7	2.8	3.9	3.2
Median	75.6	45.9	26.7	48.8	54.2	67.8	55.8
Mode	67.8	46.8	42.5	24.5	34.7	67.8	24.5

SDE-Standard error. SD-Standard deviation. AED = annual effective dose. NR = Number of rooms. AM = Arithmetic mean. GM = Geometric mean.

The mean values of radium-226, radon exhalation rate, indoor radon levels and annual effective dose computed across various sampling locations (KT1 to KT17) are tabulated in table 3. The mean radium concentration ranged from 3.4±0.3 to 48.1±4.5 Bq/kg, with an overall mean of 23.6±1.5 Bq/kg. Mean radon exhalation rates varied from 1.3 ± 0.2 to 13.3±0.3 µBq/m^{2}h, with an overall mean value of 8.1±0.5 µBq/m^{2}h and the overall mean indoor radon concentration across locations was 61.7±3.4 Bq/m^3. The AED values ranged from 0.4 to 2.1 mSv/y, with an overall mean value of 1.2±0.2 mSv/y indicating varying levels of potential radiation exposure across different locations.

Table 2. Measured radon concentration in dwellings with different building materials.

Statistics/ NR	Building materials					
	KM1	KM2	KM3	KM4	KM5	KM6
	15	19	24	31	11	20
Range (Bq/m^3)	24.5-58.6	32.6-124.7	55.5-120.5	23.5-72.8	33.9-110.8	24.5-89.7
AM	28.9	88.4	85.0	39.5	75.8	52.7
GM	28.1	81.9	83.0	87.4	68.8	49.2
SDE	2.3	6.8	3.8	2.4	9.2	4.4
SD	8.7	2.7	1.6	1.5	3.5	1.5
Median	25.8	102.5	88.3	34.8	78.9	53.4
Mode	24.7	-	67.8	34.7	-	-

Table 3. Mean radium and radon exhalation rate and annual effective dose.

CODES	^{226}Ra (Bq/kg)	^{222}Rn (µBq/m^{2}h)	^{222}Rn (Bq/m^3)	AED (µSv/y)
KT1	3.4±0.3	1.3±0.2	43.8±2.3	0.8
KT2	11.5±0.4	5.0±0.2	32.5±0.6	0.6
KT3	8.6±0.9	3.9±0.3	36.3±1.2	0.7
KT4	48.1±4.5	13.3±0.3	31.3±0.2	0.6
KT5	46.1±0.9	12.9±0.3	35.4±3.4	0.7
KT6	33.3±2.4	9.8±1.0	49.2±5.2	0.9
KT7	27.0±1.6	8.1±1.4	85.6±5.1	1.6
KT8	37.1±1.7	9.4±1.2	77.9±2.1	1.5
KT9	21.5±2.2	9.1±1.1	29.7±2.1	0.6
KT10	22.1±1.3	8.5±0.4	24.7±0.7	0.5
KT11	45.8±3.4	12.2±1.0	70.6±3.2	1.3
KT12	28.5±1.1	9.6±1.6	57.4±2.4	1.1
KT13	13.1±1.8	6.1±0.6	109.4±9.0	2.1
KT14	17.4±0.3	8.4±0.9	52.5±6.3	1.0
KT15	17.7±1.0	8.4±1.1	65.4±3.6	1.2
KT16	14.9±1.5	7.0±1.7	95.9±3.7	1.8
KT17	5.9 ±1.1	3.7±0.4	21.2±5.2	0.4
MSD	23.6±1.5	8.1±0.5	61.7±3.4	1.2±0.2

*MSD = Overall mean and standard deviation

Figures 6 and 7 illustrate the correlation between ^{226}Ra and ^{222}Rn, and ^{226}Ra and ^{222}Rn exhalation rates, respectively. From figures 6 and 7, positive correlations between ^{226}Ra and ^{222}Rn (r = 0.3) and ^{226}Ra and ^{222}Rn (r = 0.9) exhalation rates were observed.

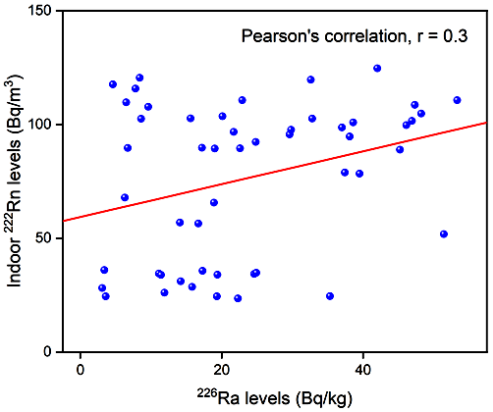


Figure 6. Correlation between ^{226}Ra and ^{222}Rn in dwellings.

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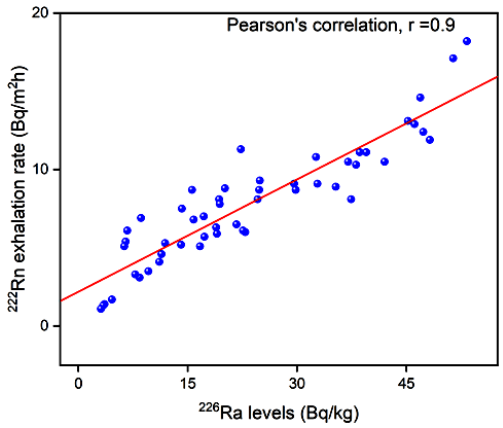


Figure 7. Correlation between ^{226}Ra and ^{222}Rn exhalation rate in soil samples.

DISCUSSIONS

The present study has provided a detailed quantification of radon concentrations across different dwelling types within the Kpando Municipality. Analysis of the radon data confirmed that there is a significant difference (P=0.001) in indoor radon levels, with the highest concentration measured in bedrooms (124.7 Bq/m^3) and the lowest in sitting rooms (23.5 Bq/m^3), as detailed in table 1. This variation reflects differences in building materials and design, which are critical factors influencing radon accumulation. The findings indicate that dwellings constructed with clay, clay floors and small wooden windows (KM2) exhibited higher radon levels, with an arithmetic mean (AM ± SD) of 88.4 Bq/m^3, as opposed to those made of concrete blocks with tiled floors and glass louvre windows (KM4), which showed a lower AM of 39.5 Bq/m^3. This was confirmed by a t-test that show that there is a significant difference ($p<0.05$) in radon concentration found in dwellings with different construction materials. Such discrepancies underscore the potential of certain building materials to either mitigate or exacerbate radon infiltration. The log-normal distribution of indoor radon data is in line with other radon investigations [5, 17-22]. The non-uniformity of the data, suggests the influence of localized geological variations and soil permeability.

The results of this study in comparison with other studies done locally and internationally are presented in table 4. Table 4 shows that indoor radon concentration varies significantly with location and country. The present investigated indoor radon data was found to be 2.1, 1.1, 1.2, 1.7 and 1.1 times more than the studies done in Accra Metropolis [4], Abirem [5], Obuasi [11], South Dayi [13] and Kpong [14], respectively whereas investigation done in Dome [10] was approximately 7.7 times greater than the data of this study. In comparison with the international data, the current study was found to be 1.1, 3.2 and 1.1 times greater than the studies conducted in Aleshtar [23], Duhok City [24] and Shabestar [25] whereas 4.9, 2.3 and 2.1 times less than investigations done in Poli City [26], Douala City [27] and Hazara [28], respectively. The wide variations in the exposure to radon in dwellings in different countries may be due to the differences in climate, building materials, dwelling structure and designs, occupant lifestyle, and other parameters that are not common among countries. The difference in indoor radon values also leads to very different health impacts in different countries.

Table 4. Comparison of current studies with national and international indoor radon studies.

Country	Towns	^{222}Rn (Bq/m^3)		AED (mSv/y)	Ref.
		Range	Mean		
Ghana	Kpando	23.5-124.7	60.5± 3.2	0.4-2.1 (1.2)	This study
Ghana	Accra Metropolis	13.8-58.4	28.3± 1.5	-	[4]
Ghana	Abirem	23.7-125.9	54.7± 23.7	0.8-1.6 (1.2)	[5]
Ghana	Dome	278.1-740.1	466.9± 1.2	-	[10]
Ghana	Obuasi	26.1-119.0	50.5-3.9	0.6±0	[11]
Ghana	South Dayi	11.60-111.1	34.9± 20.2	0.2-1.4	[13]
Ghana	Kpong	4.1-176.3	57.0± 39.0	0.7	[14]
Iran	Aleshtar	1.01-206.5	55.19± 59.32	1.39 ± 1.49	[23]
Iraq	Duhok city	1 -56	19±6.1		[24]
Iran	Shabestar	3.9-520.1	56.2± 46.0	1.4	[25]
Cameroon	Poli	29-2240	294	-	[26]
Cameroon	Douala City	31- 436	139± 47	0.6-9.0	[27]
Pakistan	Hazara	41-254	128	-	[28]

Ref. = reference

Table 5 shows the range and mean values of ^{226}Ra concentrations in various samples in Ghana. From the table, the data of the present study was 1.2, 4.4 and 1.6 times less than studies done in Abirem [5], Obuasi [11] and New Abirem [29] whereas the study done in Greater Accra [30] was found to be about 2.0 times less than this study.

Table 5. Comparison of the range and mean values of ^{226}Ra concentration to other studies in Ghana.

Country	Town	Range (Bq/kg)	Mean (Bq/kg)	Reference
Ghana	Kpando	3.4 - 48.1	23.6±1.5	This Study
Ghana	Abirem	19.5-38.9	29.0±16.0	[5]
Ghana	Obuasi	44.8-257.4	103.5	[11]
Ghana	New Abirem	19.7- 69.9	37.5±15.5	[29]
Ghana	Greater Accra	5.1±0.4 - 23.9±1.3	12.1±2.6	[30]

Figure 6 illustrates a non-linear relationship between radium concentration and indoor radon levels which is in agreement with other studies [5]. The weak positive correlation between ^{222}Rn and ^{226}Ra might stem from a mix of human and natural factors such as local geological variations, soil permeability, differences in dwelling types and sizes,

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pressure disparities between the room and surrounding soil, and resident behaviours. Additionally, the radon gas in the room may not directly originate from the underlying soil's radium concentration. Another contributing factor could be the influence of building materials on indoor radon levels, as suggested in other studies [4-5]. Figure 7 reveals a significant positive correlation between radon exhalation rates and radium concentration, aligning with conclusions from other studies [31-32]. This correlation could be attributed to various factors, including local geological variations, soil permeability, and meteorological conditions, as well as differences in building design, construction, condition, and use. These factors collectively influence indoor radon levels, contributing to the observed correlation. The strong positive correlation ($r = 0.9$) between radium concentration in soil and radon exhalation rates points to the natural radioactivity of the soil as a significant source of indoor radon. However, the weak positive correlation between soil radium and indoor radon levels indicates that factors beyond soil composition, such as building design and ventilation, are also influencing radon accumulation indoors. Despite most locations reporting radon levels below the action levels recommended by WHO and UNSCEAR, the presence of elevated concentrations in specific dwellings necessitates targeted interventions. These include improved building ventilation, the use of radon-resistant construction materials, and regular radon monitoring to safeguard public health. Future research should aim to broaden the scope of the study, examining a wider range of environmental and structural variables. Additionally, long-term monitoring of radon levels could provide a more detailed understanding of temporal fluctuations and their relationship with seasonal changes and lifestyle patterns.

CONCLUSION

The study in Kpando Municipality, Ghana, evaluated indoor radon, radon exhalation, and radium levels. While some radon levels were above WHO and UNSCEAR limits, the overall risk to residents was low. A significant correlation was found between soil radium and radon exhalation, emphasizing soil properties' impact on radon gas levels. Despite elevated levels in some areas, the risk remains manageable. The study highlights the need for continuous monitoring and suggests improved building designs and awareness campaigns. It provides a foundation for future research and emphasizes the importance of ensuring resident safety in similar environments.

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***Conflict of interest*:** None declare.

***Ethical consideration*:** Soil samples were collected from near the dwellings selected for the indoor radon measurements. The results of this study were within the safety limits.

***Author contribution*:** All authors contributed equally to the conception, design, data collection, analysis, interpretation of data, drafting, and critical revision of the article.

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