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Research article

Radon mapping, correlation study of radium, seasonal indoor radon and radon exhalation levels in communities around Ghana atomic energy commission

Francis Otoo [a,b,*], Rita Kpordzro [a,b], A.S.K. Amable [c]

[a] *Radiation Protection Institute, Ghana Atomic Energy Commission, P. O. Box LG 80, Legon-Accra, Ghana*
[b] *School Nuclear and Allied Sciences, University of Ghana, Atomic Campus, P. O. Box AE1, Legon-Accra, Ghana*
[c] *School of Basic and Biomedical Sciences, Department of Basic Sciences, University of Health and Allied Sciences, PMB 31, Ho - Volta, Ghana*

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ABSTRACT

Radon mapping and seasonal radon studies have been carried out within the communities around the Ghana Atomic Energy Commission (GAEC), using ArcMap geostatistical interpolation tool. The correlation analysis was done using Pearson's correlation tools. Average seasonal indoor radon variations for C_R (rainy) and C_D (dry) with mean values ranging from 28.9 to 177.2 Bq/m^3 (78.1 ± 38.7 Bq/m^3) and 24.4–125.5 Bq/m^3 (69.9 ± 24.2 Bq/m^3). Average seasonal soil radon exhalation for E_R (rainy) and E_D (dry) with mean values ranging from 39.6 to 100.3 (68.9 ± 24.2 μBq/m^2 h) and 55.2 to 111.9 (77.1 ± 18.7 μBq/m^2 h). Radium concentrations ranged from 8.1 to 42.2 Bq/kg (21.3 ± 9.9 Bq/kg). Annual effective dose and resultant effective dose to lungs were found to be 0.9 to 2.9 (1.9 ± 0.8 mSv/yr), 2.1 to 9.2 (4.6 mSv/yr). The study recorded the highest and lowest positive correlation coefficient was found in the study with higher and lower coefficient values of 0.81 and 0.47 recorded in radium concentration with radon exhalation and indoor radon concentration within the dry season respectively. Pearson correlation result recorded values 0.81 and 0.47 as the highest and lowest positive coefficient values for the radium concentration correlation between radon exhalation and indoor radon concentration. One directional principal component was observed in radium concentration, seasonal radon exhalation, and indoor radon concentration. Two clusters originated from radium and seasonal radon concentrations present in dwellings as well as soils. Pearson's correlation results were in agreed with the principal component and cluster factor analysis. The study obtained the highest and lowest indoor radon concentrations with radon exhalation in rainy and dry seasons. Radium concentration was found to have a considerable effect on indoor radon and radon exhalation in dwellings and soils.

1. Introduction

Radon exists everywhere from workplaces to dwellings as well as soils. Most of the radiation exposure to the public was found to be radon gas, especially in an indoor environment [1–4]. Radon and its progenies get to the body by inhalation. Continuing exposure to elevated radon gas for long periods in enclosed areas has been linked to a higher risk of lung cancer in exposed individuals. Indoor radon exposure is categorised as the most cause of lung cancer cases second to smoking tobacco. About 5% to 20% of lung cancer

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[*] Corresponding author. Radiation Protection Institute, Ghana Atomic Energy Commission, P. O. Box LG 80, Legon-Accra, Ghana.
E-mail address: kwaotoo@yahoo.com (F. Otoo).

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deaths may attribute to radon exposure [2,4]. Radon resulted from the direct progeny of Radium-226 as a decay product of uranium-238 decay series in building materials, rocks, and soil. The amount of radon gas that retains or emanates into the air from soil or rocks in the buildings depends on the dwelling construction type, occupant behavior, building materials, water supplies, radium concentration differences in soil, and rock geology underlying the dwellings [5–8]. Higher lung cancer cases were found to be coming from uranium miners and prolonged indoor radon gas exposure to the public [9,10]. This incident led to an engendering interest in indoor radon and radon exhalation studies in dwellings and soils [9,10].

To determine radon concentration in dwellings and soils, there have been several studies and procedures to assess the risk of radon exposure and identify radon-prone areas [11–15]. The most common techniques mostly used are geostatistical which involve variogram fit and kriging [12–15]. These methods were used to study radon levels and for developing potential radon maps. This procedure can also use to study radon distribution patterns as well as the classification of radon-prone areas [11–15].

Studies report on the radon levels and their distribution in soil and dwellings vary from season to season, type of buildings, and location to location [16–22]. Seasonal indoor radon was found to be affected by the meteorological parameters, geology, radium concentration, construction materials, and building type, as well as the ventilation rate in closed environments [5,22–26]. The indoor radon variation concentration in a given dwelling could be affected by environmental factors. Radon studies indicated that seasonal variational factors were found to be varied with radon levels in soils and dwellings. The winter or rainy season has higher radon concentration mostly occurring in winter or rainy periods than other seasons [16–29]. This is because windows and doors tend to be shut for a period longer than in the dry season leading to an increase in radon levels as a result of the lower ventilation rate [30].

Seasonal radon variation in dwellings and soils was found to be a very important phenomenon and its impacts on the dependence of radium concentration due to radon exposure to the public. Some studies conducted on soils, and building materials indicate radium concentration is a potential source of increasing indoor radon concentration in dwellings [5,16,31].

Some radon studies have been done in other countries to establish the radium concentration dependence on radon gas in soils and dwellings, this is in order to determine radon-prone areas or radon indoor levels [15,16,30]. Studies of seasonal indoor radon with radium concentration and associated effective doses are very important from a radiation protection perspective. This is to help in reducing the likelihood of a higher incidence of lung cancer associated with prolonged exposure to higher radon levels in dwellings [2,4,17,32]. In Ghana, the majority of radon and radium studies have focused on radon exhalation rates in soils, rocks, and building materials [5,27,32,33]. Some studies have reported on seasonal variations of radon between dwellings and soils [16,17,20], but there is no comparable study that establishes a radon map and the determined effects of radium concentration on seasonal indoor radon and radon exhalation in soils and dwellings. Therefore, this study assesses radon mapping, seasonal indoor radon indoor, seasonal radon exhalation, and its dependence on radium concentration. This is to ascertain the influence of radium concentration on radon levels and associated effective doses to residents around the Ghana Atomic Energy Commission (GAEC).

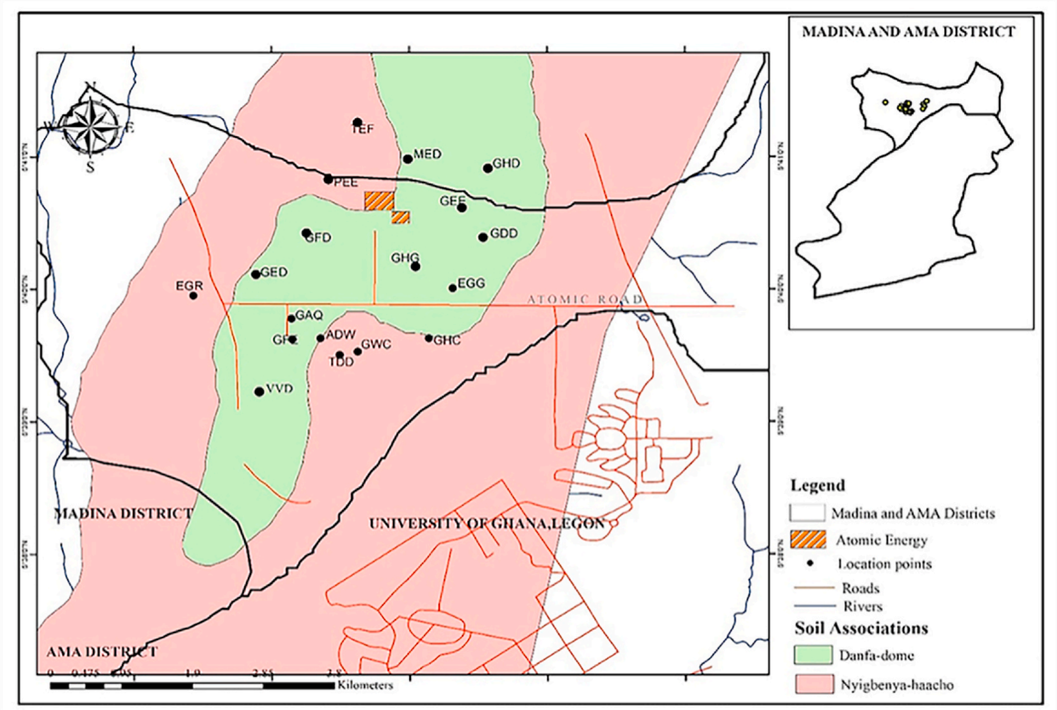

Fig. 1. Geological map of the study areas.

2. Materials and methods

2.1. Geology of the study area

The location of study around GAEC. It is tropical and characterized by slight temperature differences throughout the year with average temperature varying from 24.7 °C to 28.0 °C. The highest and lowest temperature was found to occur in August and March. The average annual temperature within the study areas is 26.8 °C. This study area sits below 1000 m (3300 ft) with daylight being the same throughout the year, as a result of being nearer to the equator along the coast with higher relative humidity.

Soil within the study location comprise four main different types such as: drift materials deposits by windblown erosion; alluvial and marine motted clays below shales; residual clays and gravels come from weathered quartzites, gneiss, and schist rocks while lateritic sandy clay soils obtained from weathered Accraian as a result of the sandstone bedrock structures. Black cotton soils of pockets from the alluvial origin are normally obtained in a weak drained area. The area has a soil enclosed with heavy organic levels, can expand, and contract easily causing breaks in foundations and footings of the buildings. Strongly acidic associated with the study location, weaken the concrete foundation resulting in honeycombing when saturated. Alluvial laterite gravels and sands mainly come from the foothills [34,35].

2.2. Building materials and occupancy

Typical building construction associated with these studied dwellings are used depending on the location, type of building, and cost. Building wall uses cement, sandcrete and concrete blocks for the walls. Wooden structures are not frequently used as a building material compared to blocks, even though it is exported from Ghana, Metal sheets, slate, or asbestos are commonly used for roofing. Materials used for floor consist of concrete or cement, terrazzo, tiles, and ceramic [5,36]. The dwellings consist of a storey, bungalows, compound houses, etc. With the single room having 2–10 occupants.

2.3. Sample collection and preparation

A total of 36 soils from 18 locations within communities around the Ghana Atomic Energy Commission were taken from the locations in Fig. 1. Soils were taken randomly depending on suitability, accessibility, and availability. The soil samples were taken from 2 or 3 different places within the study. Sampled soils were put into labeled different Ziploc bags tightly closed and sent to the radon laboratory of the Radiation Protection Institute, Ghana Atomic Energy Commission (RPI/GAEC).

The sampling equipment was carefully cleaned after each sampling point with a different neat rag to prevent any water droplets and soil particles to prevent cross-contamination. Analyses of radium and radon concentration were done at the RPI/GAEC. Soil collected was standardized, air-dried, and sieved to a particulate uniform mixture size of 2 mm, and sealed in 500 mL beakers. The weight of the beakers and samples was recorded. Prepared samples were kept at room temperature for 4 weeks to permit the radioactive equilibrium between the parent of ^{38}U and ^{226}Ra decay series with short-lived daughter product [32,37].

2.4. Determination of activity concentration of radium

2.4.1. Calibration of HPGe

HPGe detector calibration was done by evaluating the efficiency of the sensor using a multigamma-ray solid varied from 46.5 keV to 1836.1 keV with 1 g/cm^3 density in the same geometry used for the analysis of the samples [38]. The detector was shielded with a lead of 100 mm lined with copper, cadmium, and plexiglass sheets. Calibration was done using the standard source with the following specific activities; ^{210}Pb, 6.63×10^5 Bq; ^{241}Am, 6.60×10^4 Bq; ^{109}Cd, 4.39×10^5 Bq; ^{57}Co, 1.23×10^4 Bq; ^{123} Te ^{m}, 7.65×10^3 Bq; ^{113}Sn, 2.72×10^4 Bq; ^{85}Sr, 1.05×10^4 Bq; ^{137}Cs, 9.81×10^4 Bq; ^{88}Y, 4.63×10^4 Bq, ^{60}Co, 1.16×10^5 Bq. GESPECOR software was used for the self-absorption corrections for the measurement of soils with higher density [39].

2.4.2. Estimation of activity concentration of radium content

The radium concentration was estimated using the energy lines of the decay product. The average energy peak for ^{226}Ra was evaluated using the following lines: ^{214}Bi, (609.31, 1120.29, 1764.49 keV) and ^{214}Pb (295.22, 351.93 keV). Soil samples with more than one peaks for progenies. Their average energy lines were used to estimate the activity concentration of ^{226}Ra. An empty Marinelli beaker of geometric features similar to the counted soil samples with HPGe, was used to determine the background concentration. The ^{226}Ra in the soils were analyzed for 72,000 s. Spectroscopy Genie 2000 V3.3 (1) software from Canberra was used for display, acquisition, and on-line spectrum analysis [32,37]. The ^{226}Ra concentration was determined using equation (1),

$$Ac(226_{Ra}) = \frac{(N_{Sam} - N_B)}{P(E) * n(E) * T_c * M_{sam}} \tag{1}$$

where Ac activity concentration of radium (Bq/kg); M_{sam} mass of the soil sample(kg); N_{sam} net count of sample (cps), N_B count rate for the background (cps); $\eta(E)$ represents the photo peak efficiency from the standard solution; $P(E)$ gamma emission probability, and $T_c(s)$ counting time in seconds.

2.4.3. Radon measurement

2.4.3.1. Indoor radon. Radosys set up with CR-39 detectors enclosed in RSKS type diffusion chambers were used for this study. The calibration factors of the CR-39 are supplied and traceable to the radon calibration laboratory of the Federal Office for Radiation Protection in Germany [40,41]. This study uses one hundred and twenty eight (128) CR-39 passive radon detectors in bedrooms and sitting rooms in 18 communities around Ghana Atomic Energy Commission. The radon detectors were deployed in the bed and sitting rooms for six months, twice a year from April to September and October to March as rainy and dry seasons respectively. The dwellings were randomly chosen based on accessibility and support from the occupant. For each dwelling, a radon detector was deployed in either sitting or bedroom (s). The detector was exposed to 1–1.5 m a height above the floor equivalent to the breathing height of the person, at 0.5 m greater than the distance apart within the room, and 15 cm smaller than from any other items [5,20,21,32]. The detectors were placed in a location evading excessive ventilation. The building features such as room size, structures, building materials, age, and ventilation systems were noted during the result evaluation.

2.4.3.2. Radon exhalation rate. Radon exhalation rate from the soil samples was measured by a firmly closed can technique with CR-39 of 10 and 25 cm of diameter and height respectively. The measurement was done with known weight of a prepared samples in a can covered 78.5 cm^2 surface area. Soil samples were closely airtight and kept at room temperature for 4 weeks to enable ^{226}Ra to establish equilibrium with its progeny [5,27,32,33]. The radon exhalation was determined by placing the CR-39 at the top of the prepared sample in the closed can within the distance of 22 cm from the soil surface. This procedure was used in order to measure only radon alpha particles detected on the track density and stop thoron progeny from touching the surface of the CR-39 [5,27,32,33,42]. The radon exhalation rate measurement was done for ninety days.

2.4.4. Etching and radon concentration estimation

The detector film was detached and etched in a 6.25 mol NaOH prepared solution of 4000 ml of distilled water with 1000 g pellet sodium hydroxide at 90 °C for 4 h and 30 min to broaden the tracks that form on the exposed detectors as a result of the alpha particles produce from radon daughters [5,27,32,33,40,42]. The films were dried for four days. The latent tracks formed on the detector films were scanned with RadoMeter and counted in 144 fields by means of an optical microscope with a 40 times magnification objective lens. The track density from the unexposed radon detector as a background was measured under the similar etching condition. The track density from each detector film was then used to estimate indoor radon concentration and radon exhalation rate from the dwellings and soils using equations (2) and (3) [5,27,32,33,42].

$$\text{Indoor Radon Concentration (C)} = \frac{\varrho}{\epsilon t} \tag{2}$$

$$\text{Radon Exhalation rate (E)} = \frac{\varrho V_c \lambda_{Rn}}{\varepsilon S_a T_c} \tag{3}$$

where, V_c volume of diffusion chamber (m^3), S_a surface area of the sample (m^2), λ_{Rn} decay constant of radon ($1/s$) ϵ calibration factor of the CR-39 (track/cm^2d/(Bq/m^3), ϱ measured surface density of tracks (tracks/cm^2), T_c effective exposure period (s) in the diffusion chamber and t exposure period

2.5. Factors that affect ventilation rate

The ventilation effect on indoor radon gas in dwellings was estimated by considering similar factors in the 69 dwellings within 18 communities of the studied areas. The factors used to explore the ventilation differences in the room of dwellings were: doors, windows, and building materials such as sandcrete, concrete, clay, and wooden structures. The rooms with one (1) door and window were considered poorly ventilated while 2 or more doors and windows were duly classified as well ventilated rooms. At least four rooms made up of different ventilation settings were chosen from each studied community. Indoor radon concentrations were determined in the same procedure as stated previously.

2.6. Spatial radon mapping

The software used in the processing and aggregation of the radon concentration is ArcMap geostatistical interpolation tool. Using inverse distance weight (IDW) interpolation the data from unsampled areas was used to generate a contiguous raster to cover the study area. This was then captured in a 50 × 50-m grid and the intensity of radon distributions within communities of the Ghana Atomic Energy Commission was developed. Choropleth maps were generated using the range of radon intensity values [11–14].

2.7. Data statistical analysis

The Statistical tool used for the analysis of this data includes the Pearson correlation coefficient and Principal components which were performed with SPSS (version 23) [43,44]. This is to know the dependence of indoor radon and radon exhalation on radium-226 concentration within the seasonal periods [5,32,33]. It was also to determine the magnitude of the radon and radium existence in the dwellings, soil as well as the contribution of the radon exposure to the occupants.

2.8. Determination of the effective doses

The annual effective dose (A_D) was estimated based on the mean indoor radon concentration from the study location. The effective doses were calculated from the proposed equation (4) by UNSCEAR [1].

$$A_D = C \times O_{if} \times D_{cf} \times I_{of} \times T_{hy} \qquad (4)$$

where O_{if} indoor occupancy factor (0.8); C average indoor radon concentration (Bq/m^3); T_{hy} number of hours per year (8760 h/yr) [45]; I_{cf} equilibrium factor (0.4) [1] and D_{cf} dose conversion factor 9 nSv/(Bq h m^{-3}) [1].

The estimation of the resultant annual effective dose to lungs (A_L) due to indoor radon exposure to the residents was done using equation (5).

$$A_L = A_D \times W_r \times W_t \qquad (5)$$

where W_r radiation weighting factor of a value of 20 for alpha particles, A_D annual effective dose (mSv/yr); and W_t tissue weighting factor of 0.12 for lungs [3,46].

3. Result and discussion

3.1. Activity concentration of radium and seasonal radon

Results from 18 communities around the Ghana Atomic Energy Commission are presented as the average, range, seasonal radon exhalation (E), seasonal indoor radon (C), and radium concentrations presented in Table 1. The result for seasonal indoor radon variations for C_R (rainy) and C_D (dry) with mean values ranging from 28.9 to 177.2 Bq/m^3 (78.1 ± 38.7 Bq/m^3) and 24.4–125.5 Bq/m^3 (69.9 ± 24.2 Bq/m^3).

Result from indoor radon, radon exhalation, and radium concentrations showed the distributions are not uniform throughout the study areas as indicated in frequency distribution graphs and mapping as depicted in Figs. 2–5. Spatial distribution of the radon map revealed that the radon gas within the study was not uniformly distributed indicating that radon gas exposure levels to the residence within the rooms are not the same. The spatial distribution of the radon map was done by applying the gridded approach. The radon levels were described by displaying the various levels of intensity of estimated mean indoor radon concentration within the locality for each grid area as depicted in Fig. 5.

The non-homogeneous distribution levels of radium and radon in soils and dwellings could be attributed to the cracks in floors and walls, occupancy behavior such as opening and closing of the door and windows, soil permeability, moisture contents, and geological conditions [5–7,47–49]. It may be attributed to the radium concentration differences in construction materials and soil that existed below the dwellings [5,32]. The average values from the study were all found to be less than the reference level from WHO, but 3 study locations recorded values greater than the reference value. The highest and lowest indoor radon was obtained in GHG and GHD communities within the rainy and dry seasons respectively. Closing of windows and doors leading to poor air circulation between indoor and outside environments may contribute to the highest indoor radon, [5,16,17,20,30,32,50]. Moreover, during the rainy

Table 1
Average radium concentrations, seasonal radon levels in soils, dwellings, and annual effective doses.

LC	Samples Description		Average	Seasonal	Radon	Levels	Radium Con.	Effective Dose (mSv/y)	
	SS	DS	Indoor Radon (Bq/m^3)		Radon Exhalation (μBq/m^2 h)		^{226}Ra (Bq/kg)	A_D	A_L
			C_R	C_D	E_R	E_D			
TEE	5	10	51.1 ± 19.1	45.7 ± 18.7	56.5 ± 18.7	55.2 ± 18.7	8.1 ± 7.8.	0.9 ± 0.1	2.1 ± 0.1
PEE	3	7	37.9 ± 3.5	24.4 ± 3.9	96.7 ± 18.7	60.4 ± 18.7	11.8 ± 4.7	1.2 ± 0.1	3.0 ± 0.2
MED	3	11	98.3 ± 22.8	75.8 ± 31.2	43.4 ± 18.7	62.7 ± 18.7	22.6 ± 13.3	2.1 ± 0.3	5.2 ± 0.4
GHD	6	12	51.1 ± 19.1	45.9 ± 18.7	39.6 ± 18.7	55.8 ± 18.7	8.2 ± 7.9	1.5 ± 0.2	3.6 ± 0.4
GEE	4	9	44.2 ± 8.2	53.5 ± 22.6	57.7 ± 6.1	71.6 ± 8.2	12.9 ± 1.5	3.0 ± 0.4	7.2 ± 0.7
GDD	6	14	104.4 ± 78.7	63.1 ± 26.3	64.8 ± 5.1	67.6 ± 5.7	10.8 ± 7.0	3.8 ± 0.5	9.2 ± 0.8
GFD	4	9	130.8 ± 54.8	102.1 ± 38.4	59.8 ± 4.7	105.6 ± 11.7	38.5 ± 4.5	1.4 ± 0.1	3.3 ± 0.2
GHG	3	6	132.5 ± 87.2	104.3 ± 79.6	74.7 ± 8.0	89.9 ± 8.9	29.3 ± 21.5	1.5 ± 0.2	3.6 ± 0.2
EGG	5	11	66.1 ± 29.4	51.9 ± 33.8	42.9 ± 1.7	80.3 ± 7.7	20.9 ± 10.6	1.2 ± 0.1	3.0 ± 0.3
EGR	4	13	96.8 ± 49.2	89.3 ± 11.0	69.8 ± 8.1	100.4 ± 8.9	35.4 ± 6.3	1.8 ± 0.3	4.3 ± 0.5
GED	6	14	61.4 ± 42.4	64.6 ± 20.4	79.7 ± 6.7	88.9 ± 9.9	18.1 ± 13.4	1.8 ± 0.3	4.3 ± 0.4
GAQ	5	13	74.0 ± 28.6	68.9 ± 26.3	87.6 ± 7.7	99.9 ± 9.7	20.3 ± 3.9	1.8 ± 0.3	4.3 ± 0.3
GFE	3	7	74.6 ± 68.1	67.2 ± 42.2	100.3 ± 9.7	99.7 ± 6.7	24.0 ± 24.0	2.3 ± 0.3	5.6 ± 0.4
ADW	4	6	28.9 ± 2.6	68.6 ± 53.9	98.8 ± 7.7	94.7 ± 8.7	18.5 ± 16.5	1.6 ± 0.3	3.8 ± 0.4
GWC	5	8	56.3 ± 27.0	51.1 ± 24.3	68.9 ± 5.7	93.6 ± 8.7	18.8 ± 10.2	1.1 ± 0.1	2.6 ± 0.3
TDD	3	8	49.2 ± 33.3	69.1 ± 24.1	88.9 ± 8.7	100.3 ± 9.7	24.3 ± 8.7	2.4 ± 0.3	5.6 ± 0.6
VVD	3	9	70.7 ± 49.2	69.8 ± 11.0	75.6 ± 6.7	78.8 ± 7.7	18.0 ± 6.3	2.2 ± 0.2	5.3 ± 0.5
GHC	5	11	177.2 ± 91.0	125.5 ± 65.1	49.8 ± 4.7	111.9 ± 12.7	42.2 ± 12.5	2.9 ± 0.3	7.1 ± 0.8
Average			78.1 ± 38.7	68.9 ± 24.2	69.9 ± 19.4	77.1 ± 18.7	21.3 ± 9.9	1.9 ± 0.8	4.6 ± 1.3

DS: Number of monitored dwellings and SS: Number of studied soil samples.

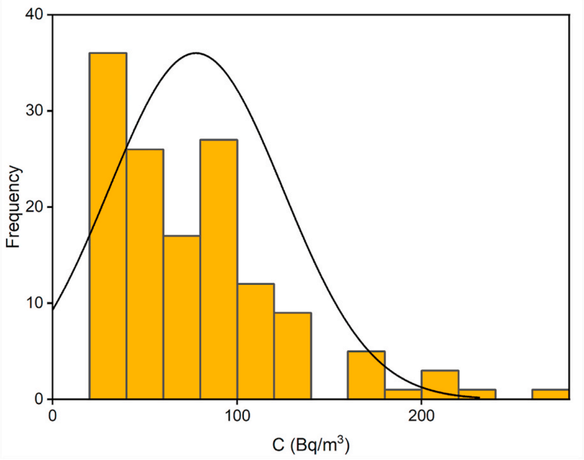

Fig. 2. Indoor radon frequency distribution.

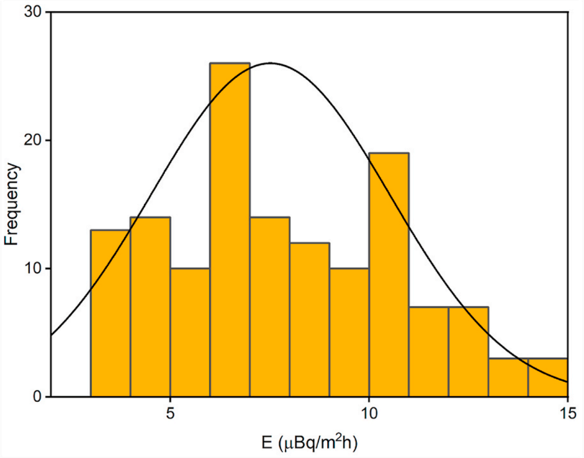

Fig. 3. Radon exhalation frequency distribution in soils.

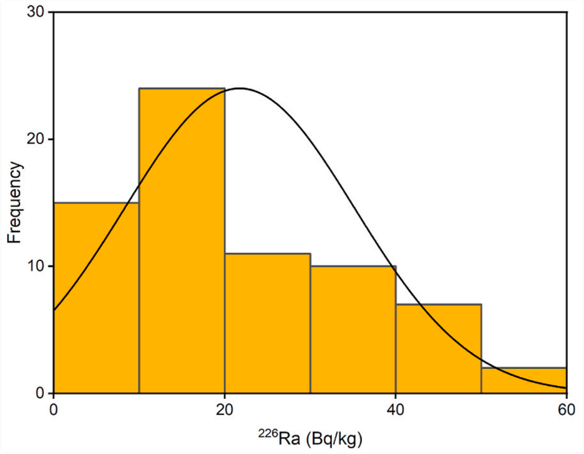

Fig. 4. Frequency of distribution of radium concentration.

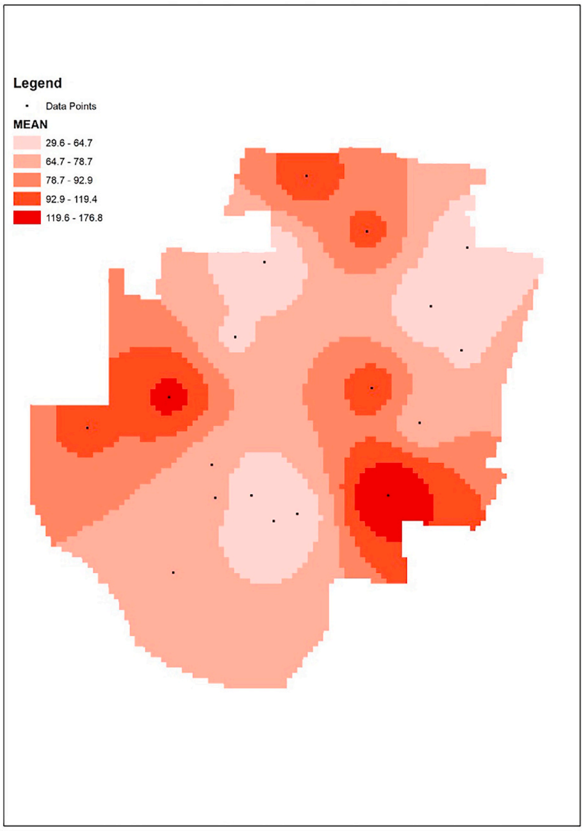

Fig. 5. Radon mapping of the study areas.

season, the soil becomes water statured resulting in the radon gas moving to dry areas beneath the underlying building, which may also be accounted for higher indoor radon gas. Higher radium concentration within the study location may be the cause for the increase in the radon levels [5,32]. Circulation of the air in and out of the rooms may be accounted for the lowest indoor radon value [30].

The average seasonal radon exhalation for E_R (rainy) and E_D (dry) with mean values ranging from 39.6 to 100.3 (68.9 ± 24.2 μBq/m^2 h) and 55.2 to 111.9 (77.1 ± 18.7 μBq/m^2 h). The radium concentrations with mean values were in the range of 8.1–42.2(21.3 ± 9.9 Bq/kg). The communities of GHC and GHD obtained highest and lowest radon exhalation rate within the dry and rainy seasons. Radium concentration recorded the highest and lowest value in locations GHC and TEE respectively. It was noticed from the result of the study that where radium concentration increases, radon exhalation was found to be also increasing, especially during the dry season presented in Table 1. Highest radon exhalation rate obtained in the dry season may be credited to the highest radium content and larger pores space existing within the soil [24,27,28] while the lowest value recorded in the rainy season may be due to high water content which affects radon emanation from the soil surface. The average radon exhalation values from this work were smaller than the average of 125 μBq/m^{2}h proposed by UNSCEAR [1]. The maximum radium concentration from the study was more than 0.9 times

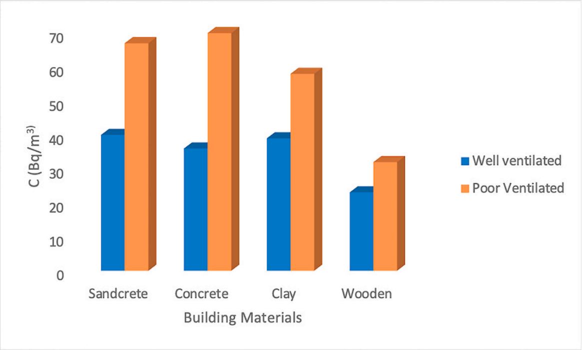

Fig. 6. Variation of ventilation within the study dwellings.

greater while the smallest value was found to be 4.9 times lower than the 40 Bq/kg proposed by UNSCEAR indicated in Table 1.

3.2. Ventilation effects on indoor radon

The effect of ventilation on radon indoor within the dwellings of different materials was studied. Highest average indoor radon concentration was recorded within poorly ventilated concrete room while well ventilated wooden structures obtained the lowest average indoor radon concentration as depicted in Fig. 6. Highest and lowest average values recorded in these dwellings were in an agreement with similar studies in Ghana [5,16,32]. The lower average radon concentration recorded in both well and poorly ventilated wooden dwellings may be attributed to the wood as a building material, not from the earth's crust, therefore, does not contain substantial levels of radium concentration [5,16,33,51]. It is indicative, that differences in changes in ventilation conditions in the rooms have a substantial influence on indoor radon concentration [30]. It is also evident that radon gas is dependent on the circulation of air between indoor and outdoor environments. The differences in the structure of the dwellings such as door, window, and building materials may be the cause of the indoor radon variations within the rooms. The highest indoor radon concentration value obtained from these studies was found to be well below the proposed maximum value but 4% of the studied rooms obtained values greater than the minimum ranged action levels from 200 to 600 Bq/m^3 proposed by the ICRP [3]. The 22% of the results were greater than the WHO reference level of 100 Bq/m^3 [2].

3.3. Seasonal indoor radon variation

Seasonal indoor radon variations showed the dry season had the highest frequency distribution of 36% within range values of 0–40 Bq/m^3 as depicted in Fig. 7 while 30% of the result obtained in the rainy season recorded the highest frequency distribution in the range of 0–40 Bq/m^3 as also depicted in Fig. 7. The 3% and 2% of the dwellings from both rainy and dry seasons recorded the lowest indoor radon distributions from the range of 240–280 Bq/m^3 shown in Fig. 7. The result of the seasonal variation indicated that the rainy season, had 22% of the indoor radon values while the dry season recorded 16% of the values more than the 100 Bq/m^3 as proposed by from WHO. presented in Fig. 7. Higher radon concentration recorded in the rainy season may be due to the fact that during rains the soil becomes water statured which causes the movement of radon gas from wet to dry areas beneath the underlying dwellings. This may result in blocking the radon gas from emanating through the soil surrounding the dwelling, thereby forcing most of the radon gas to pass through the dry soil beneath buildings or plumbing pipelines or cracks within the dry foundation with higher permeability [16,17,20,30,50]. Most of the windows and doors are also closed during the rainy season resulting in poor ventilation. These phenomena may cause the building up of radon gas as a result of the building materials as well as the soil beneath the dwellings, resulting in higher indoor radon gas in the room during the rainy season [7,16–18,22]. Lower values obtained in the dry season may be due to the circulation of air between the room and the outdoor environment due to frequently opening of the windows and doors [16,30,50]. Higher indoor radon concentrations within the rainy season were also in agreement with similar work conducted in other parts of Ghana [16,17,20].

3.4. Statistical analysis of radium and seasonal radon levels

3.4.1. Correlation analysis

Pearson's statistical correlation coefficient was used to study the linkage that exists between the radium concentration, and seasonal radon levels present in the studied dwellings and soils.

The correlation result is presented and described in Table 2. Pearson's positive correlation result was found to exist in the pair of radium concentrations with seasonal radon levels present in the dwellings and soils. The positive correlation associated with this study may attribute to the radon concentration coming from the decay series of the ^{226}Ra which is the direct daughter of ^{222}Rn as stated in Table 2. A positive correlation resulting from the Pearson analysis between radium concentration and seasonal indoor radon indicated that radium content existing in the soil contributes to significant levels of radon exposure to the residents. In other words, increasing

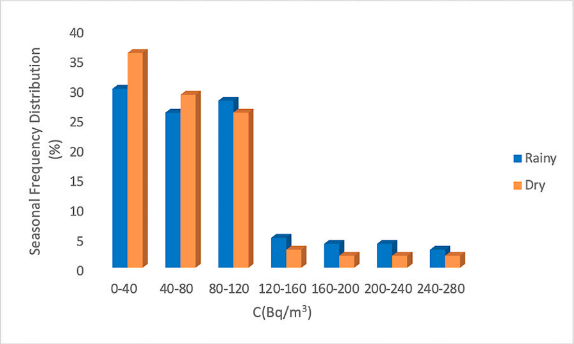

Fig. 7. Variation of season indoor radon concentration.

Table 2

Correlation between seasonal radon concentrations in soil and dwellings with radium concentration.

	C_R	C_D	^{226}Ra	E_R	E_D
C_R	1.00				
C_D	0.64	1.00			
^{226}Ra	0.76	0.47	1.00		
E_R	0.79	0.62	0.73	1.00	
R_D	0.72	0.64	0.81	0.72	1.00

the radium content in the soil will lead to higher indoor radon gas in dwellings [5,26,27].

The highest and lowest positive correlation values of 0.81 and 0.47 were found to be between the correlation of radium concentration with radon exhalation (E_D) and indoor radon (C_D) in soils and dwellings of the dry season respectively. The highest coefficient may be due to the direct radon exhalation resulting from the radium concentration present in the soil. The lowest coefficient recorded in radium concentration with indoor radon within the room might not come from only underlying soil below the dwellings but also from construction materials. This result is in agreement with similar studies [5,26,32]. Variations in the correlation coefficient may be due to differences in soil properties, occupant lifestyle, dwelling characteristics, ventilation conditions, and building materials [5,22–26,47–50]. The higher correlation coefficient values were recorded between indoor radon concentration with radon exhalation than with radium concentration. Result may link to radon gas mobility nature as compared to the radium concentration which is permanently present in the soil.

3.4.2. *Clustering analysis*

Cluster analysis in the form of a dendrogram was used to determine the similarity between E_R, E_D, ^{226}Ra, C_R, and C_D. From the dendrogram in Fig. 8, there were two (2) clusters, and the first cluster is composed of E_R, E_D, and the ^{226}Ra, which is linked to them externally, implying that the three variables are directly correlated. It also indicates that radon exhalation rates from the soil are highly dependent on the radium concentration [5,26,27,32]. Study result was in line with the report by Otoo et al., 2022, 2020, 2018 [5,32,33] and Farid [30]. Indoor radon concentration for rainy and dry seasons (C_R and C_D) was obtained as the second cluster. These two clusters are linked to each other with a high degree of similarity. This is an indication that during the rainy and dry seasons, indoor radon gas may be coming from the same origin such as building materials and the underlying soil beneath the buildings. The result is in line with Pearson's correlation result presented in Table 2 and Fig. 8.

3.3.3. *Principal component analysis*

The discrepancies associated with the study data were determined using Principal Component Analysis (PCA). The statistical tool was used to study the linkage and to identify the variables of radium concentration, seasonal radon levels present in dwellings and soils by applying varimax rotation with the Kaiser Normalization Method [5,27,45]. The PCA result as shown in Fig. 9, indicated only one component from the automatic selection tool of SPSS with an eigenvalue greater than 1.

One directional component existed for the C_D E_R, E_D, ^{226}Ra, and C_R, which was in agreement with the Pearson analysis that accounted for the only positive correlation coefficient values that occurred in the radium concentration with seasonal indoor and l radon exhalation rate as presented in Table 2. Further distance of C_D from E_R, E_D, ^{226}Ra, and C_R, indicated that during the dry season, most of the indoor concentration present in the rooms may come from the soil underlying the building.

3.3.4. *Scree plot analysis*

The factor analysis for radium content with seasonal indoor radon and seasonal radon exhalation rate shows that the data flattens after the second component as depicted in Fig. 10; thus, indicating that two factors were extracted from the study data as shown in Table 3. The first factor consists of E_R, E_D, ^{226}Ra, and C_R accounting for a total variance of 81.013% whiles the second factor accounts for 9.061% and is highly loaded on C_D as shown in Fig. 10 and Table 3. The flattening after the second component and the lower total variance may be the same reason attributed to the further distance between E_R, E_D, ^{226}Ra, C_R, and C_D in the component analysis shown in Fig. 10.

3.4. *Annual effective doses*

The annual effective dose (A_D) associated with indoor radon gas to the residents ranging from 0.9 to 2.9 mSv, with a mean of 1.9 ± 0.8 mSv/yr presented in Table 1. The highest and lower values were found in TEE and GDD. Estimated lung annual effective dose (A_L) was found to range from 2.1 to 9.2 with an overall mean of 4.6 mSv/yr as stated in Table 1. The 3 communities recorded the average annual effective doses bigger than the proposed lower range value of 3 mSv/yr from the ICRP [3] and 2.4 mSv/yr world average value proposed by UNSCEAR [1]. The overall mean value of 1.9 mSv/yr was recorded for this study shown in Table 1 and found to be 1.6 and 1.3 times smaller than the lower action level and world average values recommended by ICRP and UNSCEAR.

3.5. *Comparison study with national and international data*

Comparing this study this work with other studies in Ghana, showed that indoor radon varies in dwellings from one location to

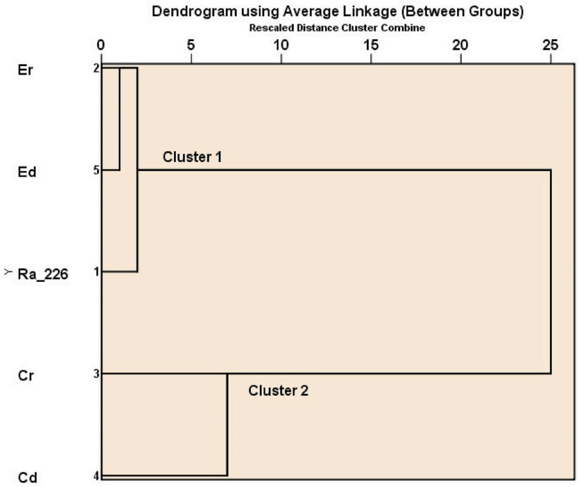

Fig. 8. Clustering of radon and radium concentration variables.

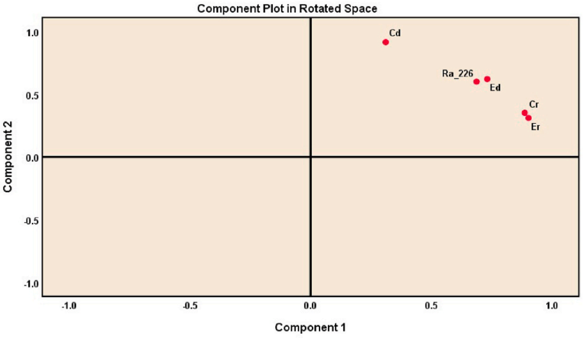

Fig. 9. Component plot in the varimax – rotated space.

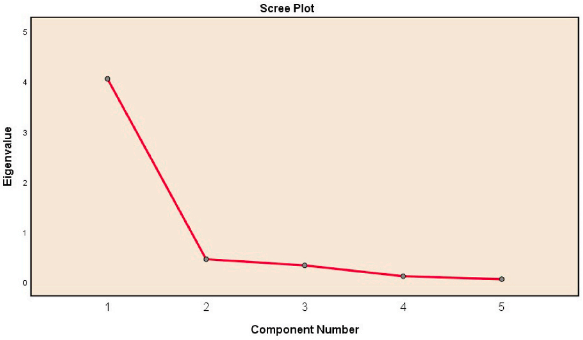

Fig. 10. Scree plot of radium and radon data.

another presented in Table 4. The result of this study agrees with the studies compared. The radium concentration from this study was found to be 1.3 and 1.4 times less than the data from the Greater Accra and Accra Metropolis in Ghana. In comparison with other results from different countries, this work recorded radium concentration smaller than the lower range values from Ethiopia [55] and Kosovo [53] Saudi Arabia [26], and Cameroon [54] but greater than studies from Saudi Araba and Cameroon. The maximum range values were all found to be greater than the current result from Ghana.

The average value from the current study was found to be greater than all the results compared with other countries except the study from Kosovo which had an average value 1.6 times lower than the current study. Season indoor radon values from this study were greater than the similar work from Accra Metropolis [28] but less than the reported seasonal studies from the GA East district

Table 3
Rotated component ladings and explained variance for variables.

Variable	Component	
	1	2
C_R	0.887	0.351
C_D	0.311	0.914
^{226}Ra	0.687	0.600
E_R	0.902	0.310
E_D	0.731	0.620
Eigen value	4.051	0.453
Total Variance (%)	81.013	9.061
Cumulative (%)	81.013	90.074

Table 4
Comparison of the radium, indoor radon, radon, exhalation, annual effective doses, and with other countries and Ghana.

Study Area	Country	^{226}Ra (Bq/m^3)	C (Bq/m^3)	E (μBq/m^2 h)	A_D (mSv/yr)
Rajasthan [18]	India	–	143.2	-	1.9×10^{-3}
Karnataka [19]	India		10	-	0.28
Obuasi [17]	Ghana		50.5–152.0	-	0.6–3.90
Accra Metropoli's [18]	Ghana		28.3		–
Abirem [20]	Ghana	29.0 ± 16.0	54.7	65.1 ± 27.6	1.21 ± 0.2
Meghalava [50]	India		55.9		1.8
South Dayi [52]	Ghana		34.9	-	0.15–1.40
Sombo & Jirapa [53]	Ghana	–	57.0 & 32.3	-	0.7 & 1.52
Kpong [54]	Ghana		39.2	-	1.89
Dome [55]	Ghana		466.9 ± 1.2	–	
Kassena Nakana [56]	Ghana		130	–	–
Greater Accra [5,33]	Ghana	27	77	87 ± 40 77–112.0	–
GA-East [20]	Ghana	–	133.4&721	-	6.9 & 9.8
Metohija [57]	Kosovo	32 (13)	128	-	–
Jeddah city [26]	Saudi Arabia	18.0–33.0	21–52 (36)	-	0.35–0.89
Lomié [58]	Cameroon	19.6–63.8 (34.8)	30–300 (65)	-	0.23–0.72 (0.42)
Wolaita Sodo [59]	Ethiopian	89.3–522.1 (264.5)	30.8–708.1 (236.7)	-	–
This study	Ghana	21.3	77.9 &69.9	69.9&77.1	1.9 ± 0.8

[20]. The result from the current study was far less than the studies in comparison except for the reported data from the Kassena-Nakana [56], Dome [55], and GA East in the greater Accra region. The current result was also found to be greater than the compared lower range values from other countries but less than the maximum range values from Ethiopia and Cameroon as presented in Table 4. The average values for the two seasons were found to be more than the compared studies from other countries except for the result from Ethiopia which had values 3 and 4 times greater than the current study from Ghana. Radon exhalation rate result was greater than the work reported in Abirem [20], but less than the research work reported in greater Accra as shown in Table 4. This study obtained values fall within the range of data report from Oyibi and Pokase [33] in the greater Accra region. The radiological data associated with the indoor radon concentrations from this study reported an average annual effective dose greater than other studies compared in Ghana apart from the result from GA East which was found to be 3.6 and 5.2 times more than the dose from this study shown in Table 4. In general radium studies from Ghana were less than the values from other countries. Indoor radon data from GA-East of Ghana recorded a value greater than all the studies in comparison. Radon exhalation rate value from the greater Accra region was greater than others from Ghana while the GA-East in the same region obtained results far less than the studies from other countries.

4. Conclusion

The radium concentration, seasonal indoor radon, radon exhalation, mapping, and radon distribution in dwellings and soils around the Ghana Atomic Energy Commission have been studied. The radium content and radon levels were found to be not uniformly distributed. This work was compared with similar studies in Ghana and other countries. The maximum and smallest seasonal indoor radon concentrations were recorded within the rainy and dry seasons. Dwellings with poor ventilation recorded higher seasonal indoor radon than well-ventilated rooms. The overall mean radium and indoor radon concentration within the study locations obtained values less than the reference levels recommended by the WHO and UNSCEAR. The four communities recorded average indoor radon values bigger than the recommended reference level from WHO. A positive correlation was found to exist between radium concentration and radon levels in dwellings and soils. One directional component and positive correlation were found to be associated with all the study parameters with dry season recorded higher and lower coefficient values in radium with radon exhalation and indoor radon. Two clusters were observed between radium concentration with seasonal radon levels in dwellings and soils. Pearson's correlation results were in agreed with the principal component and cluster factor analysis. Annual effective doses were also found to be less than the proposed dose limit by ICRP. Statistical analysis indicated that radium concentration was found to have significant effects on radon levels in soil and buildings. However, dwellings with indoor radon levels higher than the reference levels of WHO, are highly recommended to ensure effective improvement in the indoor ventilation conditions to reduce or prevent any risk of developing lung cancer in the future.

Author contribution statement

Francis Otoo: Conceived and designed the analysis; Analyzed and interpreted the data; Performed experiment; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Rita Kpordzro: Performed the experiments; Contributed reagents, materials, analysis tools or data: wrote the paper.

A.S.K. Amable; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

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