

Determination of Correlations between Soil Physical Parameters and Radon Exhalation Rates

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Abstract

In this study, we investigated the influence of some soil physical parameters on radon exhalation rates. Soil samples from five different locations, suspected to have different soil textural structures, were analyzed for particle size distribution, ²²⁶Ra concentration, ²²²Rn exhalation rates, hydraulic conductivity, moisture retention, bulk density, and porosity. The ²²⁶Ra activity concentration and ²²²Rn exhalation rates were determined using gamma-ray spectrometry and the closed-can technique, respectively, while the particle size distribution, hydraulic conductivity, moisture retention, bulk density, and porosity were determined using mechanical sieving, constant head, gravimetric, ring test and theoretical calculation methods, respectively. Results of the particle size distribution classified the soil samples into: sandy, sandy loam, loamy sand, and sandy clay loam. The loamy sand sandy clay loam soils presented the highest (0.02050 cm/s) and lowest (0.00043 cm/s) hydraulic conductivity values, respectively. Sandy clay loam had the highest moisture retention (90.40 g), while sandy loam gave the lowest (55.07 g). Sandy clay loam contained the highest ²²⁶Ra activity concentration (237.55±31.37 Bq/kg) while loamy sandy gave the lowest (96.93±29.96 Bq/kg). The average ²²²Rn mass (0.1056 Bqkg⁻¹ h⁻¹) and surface (4.4776 Bqm⁻²h⁻¹) exhalation rates from sandy clay loam were higher than all the other soil textures, indicating that areas with sandy clay loam soil may be prone to higher radon exhalations. Generally, the correlation of ²²²Rn mass and surface exhalation rates were strongly positive with ²²⁶Ra concentrations ($r = 0.7369$), moderately positive with soil moisture retention ($r = 0.6020$) and porosity ($r = 0.4018$), but moderately negative with bulk density ($r = -0.4018$), and weakly negative with hydraulic conductivity ($r = -0.2771$). The results revealed that ²²⁶Ra concentration and soil moisture retention were the most important factors influencing soil ²²²Rn exhalation rates among the soil textural types examined in this study.

KEYWORDS: Radon Exhalation Rate, Radium Concentration, Gamma-ray Spectrometry, and Radon Accumulation Chamber Technique.

1. Introduction

Radon is one of the naturally occurring radioactive elements in the environment. It is an odorless, colorless, tasteless, inert gas produced from the radioactive decay of radium isotopes in the uranium (²³⁸U), Thorium (²³²Th), and actinium (²³⁵U) decay series (ICRP, 1993). Hence the expectation of

direct relationships between the concentrations of the radon isotopes and their precursors in the soil (Shashikumar *et al.*, 2008). Infiltration of radon gas (^{222}Rn) from the soil has been identified as one of the main mechanisms influencing indoor radon levels in many buildings. It was reported that a worldwide average of 60% of indoor radon comes from the ground and the soil surrounding buildings (Qiuju *et al.*, 2004). Radon activity concentration in soil and its exhalation rate depend on the geology of the area, the terrain structure, soil physical parameters, the associated ^{238}U mineralization and other environmental/meteorological factors (Rottger *et al.* 2021). Therefore, in radon control, it is possible to delineate high radon potential zones by combining the local geological and radiometric data (Dabayneh, 2007; Dabayneh, 2008; Dabayneh *et al.*, 2008).

Radon poses significant health risks due to its carcinogenic nature when inhaled, particularly at high concentrations found in enclosed environments. Soil is the primary source of radon and its precursors; therefore, it is reasonable to envisage dependence of indoor radon concentration on radon exhalation rate from soil, radium concentration in the soil, and other soil physical parameters. The study of the influence of soil physical parameters and radon exhalation rate is crucial for assessing the potential health risk of indoor radon.

2. Related Works

This research progress as well as achievement in this area of study were documented in the literature as follows:

Radon Exhalation Rate

Abodunrin and Akinloye (2020) determined radon exhalation rates from soils around selected buildings in Lagos, Nigeria using passive measurement technique. The results showed weak correlations between the concentrations of radon exhaled from the soil samples and the indoor radon concentrations. The concentrations of radon exhaled from dry soil are higher than in wet soil, this suggest that the presence of moisture may results in reduction of radon concentrations in soil samples. Chauhan (2011) evaluated exhalation rates from stone and soil samples of Aravali hills in India. For the measurement of radon concentration exhaled from these samples, alpha-sensitive LR-115 type II plastic track detectors were used. The results indicated normal to some higher levels of radon concentration exhaled from stone and soil samples collected from Aravali range of hills.

Radium/Uranium Concentration and Radon Exhalation Rate

Khalil (2018) determined radon exhalation rates in soil samples using sealed can technique and CR-39 detectors. The author reported a strong positive correlation between the radium content in soils and the area or mass exhalation rate of radon from soil. The values of radium content in all samples under test were found to be quite lower than the corresponding global value of 30 Bqkg⁻¹. Therefore, radiological health implication to the population that may result from these doses is found to be low. Abd-Elmoniem (2015) determined radium concentration and radon exhalation rate in soil samples using CR-39. From this study, a positive correlation has been observed between radium concentration and area exhalation rate in soil of the study area. The values of radium concentration were found to be less than the permissible value of 370 Bq.kg⁻¹ as recommended by Organization for Economic Cooperation and Development (OECD) but larger than the global value of 30 Bqkg⁻¹ as quoted by UNSCEAR. In Al-Jundi *et al.*, (2023), specific activity and the gamma-absorbed dose rates of the

terrestrial naturally occurring radionuclides were determined in roadside soil cores obtained from eight sites along Amman Aqaba National Highway (AANH), using HPGe gamma-ray spectrometry. The soil activity ranged from 22–104 Bq kg⁻¹ for U, 21–103 Bq kg⁻¹ for ²³²Th, and 138–601 Bq kg⁻¹ for ⁴⁰K, measured using HPGe gamma-ray spectrometry. The highest radioactivity was found near the Al-Hassa phosphate mine. The highest mean value was found in the core samples obtained from a site close to Al-Hassa phosphate mine. The study yielded an annual effective dose equivalent in the range of 40 Bq kg⁻¹. Which implies that the average value falls within the global range of outdoor radiation exposure. Zubair and Shafiqullah (2020). Determines the activity concentrations of natural radionuclides in sandy-loamy soil samples from Sijua, Dhanbad, India. Radiation Hazard Assessment was also calculated the annual effective dose to the general public and finds it below the safety limit, concluding that the soil does not pose a radiological hazard. The findings Presents radiological parameters like radium equivalent activity, absorbed dose rate, and external and internal hazard indices for the study area. Bossew *et al* (2020), detailed the concept, history, and experiences related to the Geogenic Radon Hazard Index (GRHI) and its use in assessing public health risks associated with indoor radon exposure. GRHI Mapping Methodology, examining methodologies for creating GRHI maps, including the use of various geogenic quantities, and details the development of a methodology to create such maps covering most of Europe. Soil Data Classification, Presenting methods for classifying and combining categorical predictor data, such as soil type, soil granulometry, and geological units, to assess radon risk and determine GRHI levels. Ishimori *et al.* (2013) carried out measurement and calculations of radon releases from NORM residues. The authors reported the effect of some factors on radon exhalation such as radium distribution, particle size and shape, moisture content and mineralogy. The effects of these factors are: if radium were uniformly distributed throughout a grain, the exhalation coefficient would approach an inverse proportion to the particle diameter if this were greater than approximately 0.1µm. On the other hand, if radium were mainly distributed on the grain surface, the exhalation coefficient would be constant regardless of the particle diameter; water is more effective at stopping radon atoms within the pore space; if radium were uniformly distributed throughout a grain, exhalation coefficient of radon depends on a number of mineralogical. Zubair *et al.* (2012) measured radium concentration and radon exhalation rates of soil samples collected from some areas of Bulandshahr district, Uttar Pradesh, India using plastic track detectors. The authors observed a strong correlation coefficient between radium concentration and radon exhalation rate. The values of radium concentration in all the soil samples were found to be lower than the recommended limit by Organization for Economic Cooperation and Development (OECD). Hence, there is no matter of concern to the population living in the region. Shakir *et al.* (2011) carried out radium concentration and radon exhalation studies of soil. Tracketch technique LR-115 plastic track detectors has been used to measure the effective radium content and radon exhalation rates in soil samples. The values of radium and radon exhalation rates found is below the safe limit recommended by Organization for Economic Cooperation and Development (OECD).

3. Materials and Methods

Geographical Map of Study Area

The study was carried out at Federal University of Agriculture, Abeokuta along Alabata road in Odeda local government area. Odeda local government is one of the twenty Local Governments in Ogun State, Nigeria, created in October 1985 and it located along Abeokuta-Ibadan Road, which is

about 10 kilometers from Abeokuta (the State Capital). The Local Government shares boundaries with Ibarapa and Iddo Local Government Areas of Oyo State in the north and east, and with Obafemi and Owode Local Government Areas to the south and west respectively. Geographically, Odeda is situated on latitude $7^{\circ} 13'00.00''$ N to $7^{\circ} 17'47.26''$ N and longitudes $003^{\circ} 31'00.00''$ E and $003^{\circ} 31'13.04''$ in Ogun state as shown in Figure 5. The landmass is of varying elevation with lower and highest elevation ranges from 55.51- 84.16 m and 135.91-164.57 m respectively.

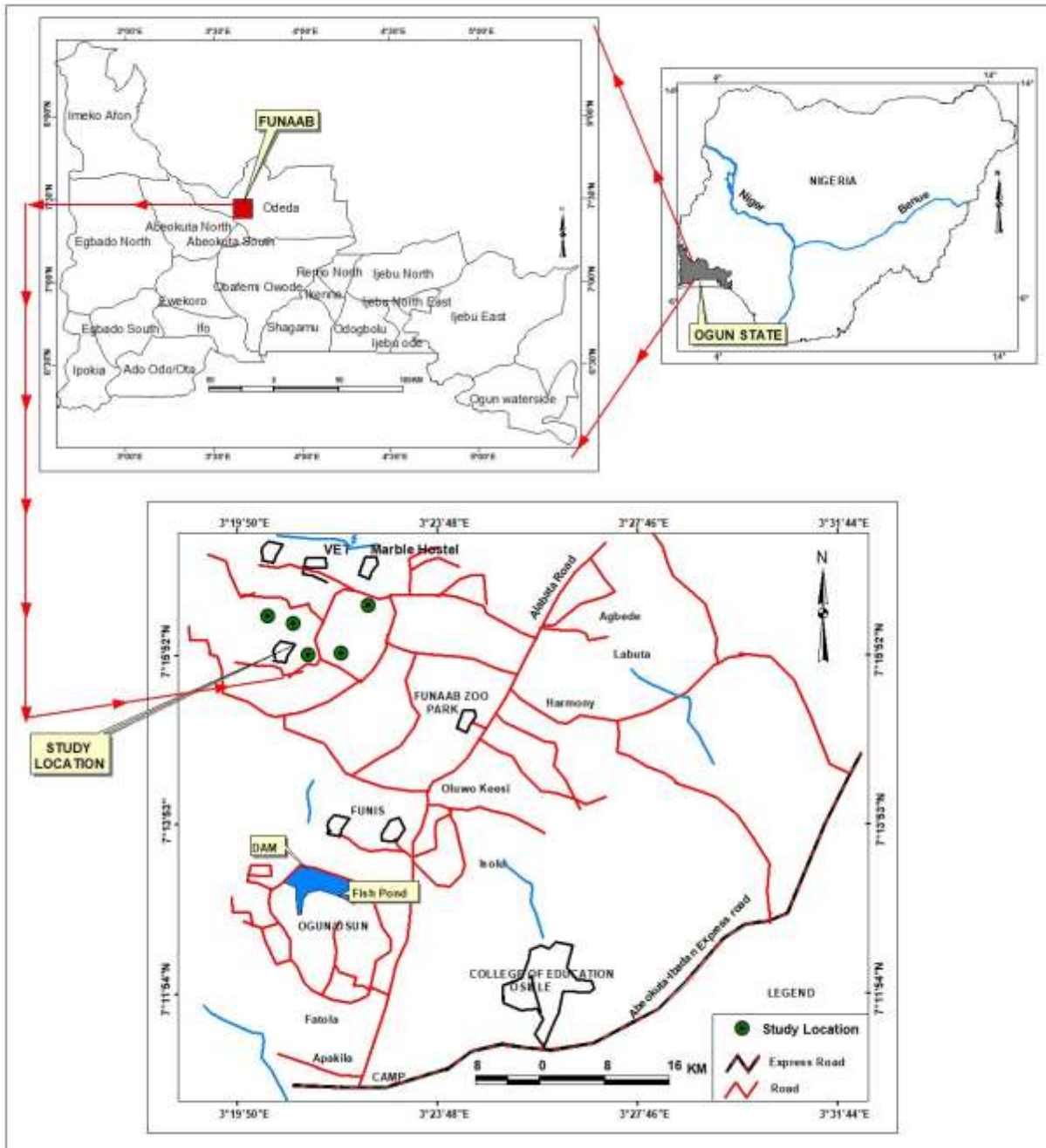


Figure 1: Map of Odeda Local Government Area showing FUNAAB

Soil Sample Collection

Soil samples were collected from five distinct locations comprising Main Gate, Health Center, Cashew Processing Unit, Dufarm Dam (Under Bridge), and Fadama. Representing various land uses and representing a range of textural classes, including sandy, sandy loam, loamy sand, and sandy clay loam. At each location, two sites were chosen ten meters apart (Soil Survey Staff, 2014).

At each site the top layer of the soil which contained plant and animal wastes was removed, to avoid its mixture with soil sample before digging to a depth of 20 cm and about 4 kg of soil sample was collected with an auger, for radon exhalation rate, radium concentration measurements and particle size distribution test as shown in plate 1a. Another set of soil samples from the same sites were also collected using a core sampler (see plate 1a), for soil physical parameters determination.



(a)



(b)
Plate 1: (a) collection of the different soil samples (b) preparation of soil sample for Rn Exhalation rate and measurement Ra concentration

Determination of Physical Properties of Soil Sample

Particle size distribution (PSD) analysis

Particle size distribution (PSD) analysis of soil samples representing soil of different textural classes, was conducted using mechanical sieving methods as described by Davidson (1955).

The percentages of Sand, Clay, and Silt were calculated using equations 1 to 3 (Day, 1953):

$$\%SAND = 100 - [H_1 + 0.2 (T_1 - 68) - 2.0]2 \quad (1)$$

$$\%CLAY = [H_2 + 0.2 (T_2 - 68) - 2.0]2 \quad (2)$$

$$\%SILT = 100 - (\%SAND + \%CLAY) \quad (3)$$

Where H_1 , is the first hydrometer reading, H_2 is the second hydrometer reading, T_1 is the first temperature reading ($^{\circ}F$), and T_2 is the second temperature reading ($^{\circ}F$).

Determination of Hydraulic conductivity

Hydraulic conductivity analysis of soil samples was carried out using the constant head method.

Equation (4) was used to calculate the hydraulic conductivity (K) (Musa et al., 2020).

$$K = \frac{V}{AD_H} \frac{L}{t} \quad (4)$$

Where V , is the volume of the water (cm^3), L is the length of the core sampler (cm), A is the cross-sectional area, D_H , is the constant head (cm), t , is the time (s).

The porosities of the soil samples were determined using equation (5) (Knutsson and Morfeldt, 2002):

$$\begin{aligned} \phi &= \frac{\text{volume of pores}}{\text{total volume of soil}} = \frac{(\text{mass of saturated soil} - \text{mass of dry soil}) / \text{density of water}}{\text{total volume of soil}} 100\% \\ &= \left(\frac{V_w}{V_s}\right) 100\% \end{aligned} \tag{5}$$

Where ϕ is the porosity; V_w is the volume of water that filled the pores in the saturated soil (cm^3); and V_s is the total volume of soil material and pores (cm^3).

Soil bulk density (ρ_b) was determined by dividing the mass of the dry soil sample M_S (g) by the volume of the soil sample as V_b in cm^3 as it's written in equation (6) (Musa *et al.*, 2020).

$$\rho_b = \frac{M_S}{V_b} \tag{6}$$

Where ρ_b soil bulk density, $\frac{g}{cm^3}$

M_S , is the mass of dry soil sample, gram (g)

$$V_b, \text{ is the volume of the soil sample} = \pi r^2 h \text{ (} cm^3 \text{)} \tag{7}$$

h , is the height of the core sampler, (cm).

Determination of activity Concentration of Radionuclides (^{40}K , ^{226}Ra and ^{232}Th) in soil

Concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in the soil samples were determined using a 2''x2'' Bicon NaI(Tl) scintillation gamma-ray spectrometer. Each of the soil samples was air-dried to the same level of dryness. Five hundred grams of each sample was sealed in a plastic container, and kept for about 30 days to achieve secular equilibrium between ^{226}Ra and its decay products. After the equilibrium period, the samples were analyzed using the gamma-ray spectrometer (Kumar S. 2015). Plate 2 a & b. show the gamma-ray spectrometer setup: (a) an open lead shield revealing the top of the NaI(Tl) detector and (b) lead shield enclosing the detector.



(a)



(b)

Plate 2: The gamma-ray spectrometer setup showing (a) open lead shield revealing top of the Bicron NaI(Tl) detector (b) and closed lead shield enclosing the Bicron 2"x2" NaI(Tl)

Efficiency Calibration

In this study, IAEA-certified standard materials of RGU-1, RGTh-1, and RGK-1 were used to determine the full peak efficiencies of gamma energies 1764keV for ^{238}U , 2614keV for ^{232}Th and

1460 keV for ^{40}K . The standard materials were weighed into cylindrical sample containers of about 360ml each and counted until the peaks of the radionuclides of interest were fully resolved. Certified activities and the number of counts in the peaks were used to calculate the detector efficiency using the formula in equation 8 (Mustapha, 1999):

$$\varepsilon(E) = \frac{C_n}{A_{c(std)}P_\gamma m(std)} \quad (8)$$

Where $\varepsilon(E)$ is the efficiency of detecting gamma-rays of energy E by the detector, C_n is the net count rate under the photo peak corresponding to the gamma energy, P_γ is the photon emission probability of the gamma-rays of energy E emitted by the radionuclide of interest, $A_{c(std)}$ is the certified activity concentration of the radionuclide in the standard sample and $m(std)$ is the mass of the standard sample.

Estimation of Background Count Rate

To estimate the level of background radiation around the detector, an empty sample container was counted in the same geometry as the standards. The background count rate was subsequently subtracted from the sample count rate before calculating the activity concentration of radionuclides in the samples.

$$C_s - C_b = C_n \quad (9)$$

C_s is the sample count rate, C_b is the background radiation count rate, C_n is the net count rate of the sample.

Estimation of Activity Concentrations of Radionuclides in the Soil Samples

The activity concentration in the soil sample was evaluated using the equation (10)

$$C_{sample} = \frac{C_{Net}}{\varepsilon(E)P_\gamma m_s} \quad (10)$$

Where: C_{sample} is the activity concentration of radionuclides in the soil sample (Bqkg^{-1}), m_s is the mass of the soil sample (kg), C_{Net} (cps) is the net count rate in the region of interest (ROI), $\varepsilon(E)$ (cps per Bqkg^{-1}) is the counting efficiency of the NaI(Tl) detector for the gamma energy of interest and P_γ is the emission probability for the gamma energy (Mustapha, 1999).

4. Results and discussion

The results and analysis revealed that the percentage of sand in the soil sample ranged from 74.8 to 90.8% of sand, 5.2 to 23.64% of clay, and 4 to 19.6% of silt. In Sandy soil has 90.8% of sand, 5.2% of clay, and 4% of silt. Sandy loam has 74.8 to 80.8% of sand, 13.2 to 17.2% of clay, and 6 to 8% of silt. Loamy Sand soils have 82.8 to 86.8% of sand, 9.2% of clay, and 6 to 10% of silt. Sandy Clay Loam soils have 60.4 to 60.8% of sand, 20.64 to 23.2% of clay, and 16 to 18.96% of silt, as shown in Table 1.

Table 1: Result of Particle Size Distribution Analysis of Soil Sample

LOCATION	H_1	$T_1(^{\circ}\text{C})$	$T_2(^{\circ}\text{C})$	H_2	$T_2(^{\circ}\text{F})$	$T_2(^{\circ}\text{F})$	% SAND	% CLAY	% SILT	SOIL TEXTURE
1A	11	30	86	7	30	86	74.8	17.2	8	SANDY LOAM
1B	8	30	86	5	30	86	80.8	13.2	6	SANDY LOAM
2A	3	30	86	1	30	86	90.8	5.2	4	SAND
2B	3	30	86	1	30	86	90.8	5.2	4	SAND
3A	5	30	86	3	30	86	86.8	9.2	4	LOAMY SAND
3B	6	30	86	3	30	86	84.8	9.2	6	LOAMY SAND SANDY CLAY
4A	18	30	86	10	30	86	60.8	23.2	16	LOAM SANDY CLAY
4B	18	30.5	87	8	32	89.6	60.4	20.64	18.96	LOAM
5A	6	30	86	3	30	86	84.8	9.2	6	LOAMY SAND
5B	7	30	86	3	30	86	82.8	9.2	8	LOAMY SAND

NOTE:

H_1 and H_2 , represent the first and second hydrometer reading,

T_1 and T_2 first temperature and second temperature reading.

Activity Concentrations of Radionuclides (^{40}K , ^{226}Ra and ^{232}Th) in the Soil Sample

^{40}K Concentrations (Bq/g), exhibit varying levels across the soil textural classes sampled. The highest concentration of ^{40}K is found in Sandy Clay Loam 4a (628.44 ± 58.02 Bq/kg), while the lowest is in Sandy Loam 1b (247.91 ± 51.99 Bq/kg) as shown in Table 2. The variability in potassium levels can be traced to the mineral composition of the soils; sandy soils generally have lower potassium content than loamy textures, which are richer in organic matter and minerals. The standard deviations suggest relatively low variability, indicating consistent levels of potassium across replicate samples.

^{226}Ra concentrations across the samples show a notable range. Sandy Clay Loam 4b has the highest ^{226}Ra concentration (291.82 ± 30.31 Bq/kg), while the lowest concentration is found in Loamy Sand 5b (80.36 ± 24.67 Bq/kg) as shown in Table 2. The presence of radium in soils is often linked to the parent material and its geological composition, as soils with higher clay content (like Sandy Clay Loam) typically retain more radium compared to sandy textures due to their higher cation exchange

capacity. The standard deviations indicate some variability, particularly in sandy soils, which may reflect natural fluctuations in radionuclide distribution and localized geological differences.

²³²Th concentrations are relatively consistent across different soil textures but show some interesting trends. Notably, Sandy Loam 1a samples shows the highest levels around (410.32±30.23 Bq/kg), while Loamy sand of 5b samples shows the lowest levels (144.42±15.67 Bq/kg) as shown in Table 2, suggesting that thorium content might be affected by soil texture and mineralogy (Wang *et al.*, 2019).

Table 2: Results of Activity Concentration of Radionuclide (⁴⁰K, ²²⁶Ra and ²³²Th)

Location	Soil Texture	⁴⁰ K		²²⁶ Ra		²³² Th	
		(Bq/kg)	±SD	(Bq/kg)	±SD	(Bq/kg)	±SD
1A	Sandy Loam	270.51	48.98	253.05	50.75	410.32	30.23
1B	Sandy Loam	247.91	51.99	185.38	38.06	391.85	33.59
2A	Sand	414.44	45.96	141.68	28.90	214.4	20.71
2B	Sand	309.7	33.16	100.8	30.31	198.16	14.55
3A	Loamy Sand	488.28	61.04	110.67	43.00	363.86	28.55
3B	Loamy Sand	616.38	61.79	130.4	43.00	338.11	25.19
4A	Sandy Clay Loam	628.44	58.02	291.82	30.31	310.68	20.15
4B	Sandy Clay Loam	620.15	48.23	183.27	32.42	248.54	23.51
5A	Loamy Sand	262.23	24.87	113.49	35.24	144.42	15.67
5B	Loamy Sand	324.77	28.63	80.36	24.67	180.25	19.59

Influenced of Soil Textural Parameter on Radon Exhalation

Exhalation rates and soil texture the radon exhalation rates in terms of area and mass (E_x and E_m) exhibit significant variability across different soil textures. Notably, Sandy Clay Loam shows the highest exhalation rates (4.4177 and 4.5374 Bq kg⁻¹ h⁻¹) as shown in Table 3, indicating a potential for greater radon release compared to other textures (Mahmood *et al.*, 2016). In contrast, Loamy Sand and Sandy textures exhibit lower exhalation rates (e.g., 0.8624 and 2.3142 Bq kg⁻¹ h⁻¹) as shown in Table 3, showing that not all sandy or loamy materials contribute to high radon levels equally. Suggesting that these lighter soils may not hold radon as effectively (Müller *et al.*, 2020). This indicates that the mineral composition and particle size distribution could significantly impact radon mobility and exhalation. Hydraulic Conductivity Insights Hydraulic conductivity values across the different soil types reveal crucial relationships impacting radon dynamics. While sandy soils often show higher rates (0.00210 and 0.02960 cm/s) as shown in Table 3, suggesting good moisture movement, Sandy Clay Loam presents remarkably low hydraulic conductivity values (0.00034 and 0.00051 cm/s) as shown in Table 3. This low conductivity can prevent water from moving readily

through the soil, potentially allowing for localized radon accumulation (Suh *et al.*, 2017). Therefore, despite having a denser structure, sandy clay loam can trap radon, leading to increased exhalation rates compared to sands that promote rapid water movement.

Bulk Density and Porosity Relationships The table also provides information on bulk density and porosity, which are key factors in assessing soil structure and its capacity to retain gases like radon. For instance, higher bulk density values in Sandy Clay Loam (1.24 and 1.32 g/cm³) as shown in Table 3, might restrict the movement of radon, yet the accompanying porosity (around 50%) indicates sufficient pore spaces for gas migration (Rachidi *et al.*, 2020). Interestingly, while Sandy soils exhibit lower bulk densities, their porosity (over 47%) suggests they can still retain and exhale radon efficiently. This balance between bulk density and porosity often determines how effectively a soil can release radon into the atmosphere.

Intra-Texture Variability and Environmental Implications the data reveal considerable intra-textural variability, underscoring that even soils categorized similarly can exhibit differing radon behaviors. For example, the two measurements for Loamy Sand show exhalation rates (0.8624 and 2.3142 Bq kg⁻¹ h⁻¹) as shown in Table 3, highlighting the need for more localized studies to assess radon risks accurately. Such differences can arise from specific soil management practices, historical land use, and organic matter content, which may substantively impact radon mobility and exhalation rates (Ghosh and Choudhury, 2019).

Table 3: Influenced of Soil Textural Parameters in Radon Exhalation

Soil Texture	²²² Rn	²²² Rn	Hydraulic Conductivity (cm/s)	Moisture Retention (g)	Bulk Density (g/cm ³)	Porosity (%)
	Exhalation Rate (E_x) (Bq kg ⁻¹ h ⁻¹)	Exhalation Rate (E_m) (Bq kg ⁻¹ h ⁻¹)				
Sandy Loam	2.9677	0.0699	0.02960	48.11	1.31	50.74
Sandy Loam	2.4990	0.0589	0.00926	62.03	1.29	51.16
Sandy	1.0334	0.0244	0.00210	74.28	1.24	53.11
Sandy	1.0484	0.0247	0.00457	65.01	1.39	47.60
Loamy Sand	0.8624	0.0203	0.02946	48.02	1.53	42.37
Loamy Sand	0.9593	0.0226	0.00837	63.75	1.41	46.63
Sandy Clay Loam	4.5374	0.1070	0.00051	88.09	1.32	50.15
Sandy Clay Loam	4.4177	0.1041	0.00034	92.71	1.24	53.33
Loamy Sand	2.0303	0.0479	0.02062	56.01	1.60	39.76
Loamy Sand	2.3142	0.0545	0.02037	58.02	1.53	42.41

Correlation Matrix for Radon Exhalation Rates, Soil Physical Parameters, and Activity Concentration of Radionuclides

Exhalation Rate (A) and Exhalation Rate (m): These two parameters are perfectly correlated (correlation =1) with each other.

Hydraulic Conductivity (K) has a weak positive and negative correlation with Exhalation Rates (A and m) (0.2771 and -0.2771) as shown in Table 4, suggesting that as hydraulic conductivity decreases, the exhalation rates may increase, or vice versa. Bulk Density has a moderate negative correlation with Exhalation Rates (A and m) (0.4018 and -0.4018) but have a moderate positive correlation with hydraulic conductivity (0.6056) as shown in Table 4, indicating that as bulk density increases, the exhalation rates tend to decrease. Soil Moisture is moderate positively correlated with Exhalation Rates (A and m), suggesting that higher soil moisture is associated with higher exhalation rates (correlation = +0.6020), strong negative correlation with hydraulic conductivity (-0.8907) and moderate negative correlation with bulk density (-0.5956) as shown in Table 4. Porosity is also moderate positively correlated with soil moisture (correlation +0.401831676), moderate negative with hydraulic conductivity (-0.6056), perfect negative correlation with bulk density (-1), Moderate positive correlation with soil moisture (0.5956) as shown in Table 4, indicating that higher porosity typically relates to higher soil moisture content.

Potassium (^{40}K) has a complex relationship with other variables, showing moderate correlations with several. For example, it has a moderate positive correlation with Soil Moisture (0.6439) as shown in Table 4, but is negatively correlated with K, bulk density, and porosity.

Radium (^{226}Ra) shows a complex interaction with multiple factors. Notably, it has a strong positive correlation (0.7369) with Exhalation Rates (A and m), moderate positive with soil moisture and porosity, indicating that as moisture and porosity increase, radium concentration tends to increase as well. It has moderate negative correlations with K and bulk density as shown in Table 4.

Thorium (^{232}Th) shows a moderate positive correlation with Porosity (0.5547) as shown in Table 4, suggesting higher porosity is also associated with higher concentrations of thorium.

Summary Insights

Overall, the table suggests that variables like soil moisture and porosity generally have positive interrelationships, while parameters like bulk density and hydraulic conductivity tend to have negative correlations with exhalation rates and moisture retention. The presence of radioactive isotopes may also be influenced by the physical properties of the soil such as bulk density and porosity, which are critical for understanding soil dynamics and potential environmental impacts, especially when concerning exhalation rates of potentially radioactive material

Table 4: Correlation Matrix for Radon Exhalation Rates, Soil Physical Parameters, and Activity Concentrations of Radionuclides

	Exhalation Rate E_x , (Bqm ⁻² h ⁻¹)	Exhalation Rate E_m , (Bqkg ⁻¹ h ⁻¹)	K (cm/s)	Bulk Density (g/cm ³)	Moisture Retention (g)	Porosity (%)	⁴⁰ K (Bq/g)	²²⁶ Ra (Bq/g)	²³² Th (Bq/g)
Exhalation Rate E_x , (Bqm ⁻² h ⁻¹)	1								
Exhalation Rate E_m , (Bqkg ⁻¹ h ⁻¹)	1	1							
K (cm/s)	-0.2771	-0.2771	1						
Bulk Density (g/cm ³)	-0.4018	-0.4018	0.6056	1					
Moisture Retention (g)	0.6020	0.6020	-0.8907	-0.5956	1				
Porosity (%)	0.4018	0.4018	-0.6056	-1	0.5956	1			
⁴⁰ K (Bq/g)	0.2963	0.2963	-0.4683	-0.2468	0.6439	0.2468	1		
²²⁶ Ra (Bq/g)	0.7369	0.7369	-0.1973	-0.6104	0.3979	0.6104	0.2670	1	
²³² Th (Bq/g)	0.1134	0.1134	0.2542	-0.3537	-0.2222	0.3537	0.1391	0.5547	1

NOTE:

E_x , surface exhalation rate, E_m , mass exhalation rate, K, hydraulic conductivity, ⁴⁰K potassium - 40, ²²⁶Ra, radium – 226 and ²³²Th Thorium - 232

5. Conclusion

This research revealed that soil texture significantly influences key physical parameters such as hydraulic conductivity, moisture retention, bulk density, porosity, and radionuclide concentrations, particularly focusing on the naturally occurring ones including ⁴⁰K, ²²⁶Ra and ²³²Th from selected locations within the main campus of the Federal University of Agriculture, Abeokuta (FUNAAB). Four textural classes, namely sandy loam, sandy, loamy sand, and sandy clay loam were established among the soil samples obtained from different locations within the study area (FUNAAB), and the variations in their physical properties. Sandy loam exhibited the highest hydraulic conductivity, whereas sandy clay loam demonstrated substantially lower values. Sandy soils retained the least moisture compared to the high moisture retention of sandy clay loam, emphasizing the critical link between soil texture and water retention capacity. Moreover, bulk density and porosity assessments highlighted how soil structure and composition affect gas migration, including radon. The gamma-ray spectrometric analysis of naturally occurring radionuclides revealed significant variability among soil textural classes, with sandy clay loam showing highest levels of ²²⁶Ra, which has important implications for public health due to increased radiation exposure risks from indoor radon. There were variations in the ²²²Rn exhalation rates across the different soil textural classes, with sandy clay loam showing the highest values, emphasizing the role of soil structure in radon dynamics. The study also established that ²²⁶Ra concentration, soil moisture retention and porosity correlated positively with ²²²Rn exhalation rates, indicating that the complex interrelationship among soil properties

warrants careful monitoring.

Generally, the correlation of ^{222}Rn mass and surface exhalation rates were strongly positive with ^{226}Ra concentrations ($r = 0.7369$), moderately positive with soil moisture retention ($r = 0.6020$) and porosity ($r = 0.4018$), but moderately negative with bulk density ($r = -0.4018$), and weakly negative with hydraulic conductivity ($r = -0.2771$). The study revealed that ^{226}Ra concentration and soil moisture retention were the most important factors that influence soil ^{222}Rn exhalation rates as exemplified by sandy clay loam soil.

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