



Radon Concentrations in Indoor and Outdoor Environments of Atomic Energy Centre Dhaka, Bangladesh, and Concomitant Health Hazards

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Specialty section:

This article was submitted to
Radiation Measurements,
a section of the journal
Frontiers in Nuclear Engineering

Received: 22 March 2022

Accepted: 09 May 2022

Published: 21 June 2022

Citation:

Pervin S, Yeasmin S, Khandaker MU
and Begum A (2022) Radon
Concentrations in Indoor and Outdoor
Environments of Atomic Energy Centre
Dhaka, Bangladesh, and Concomitant
Health Hazards.
Front. Nucl. Eng. 1:901818.
doi: 10.3389/fnucn.2022.901818

Realizing the non-negligible health hazards due to radon exposure, the present study was carried out to measure the radon concentrations in indoor and outdoor environments of Atomic Energy Centre Dhaka (AECDC), Bangladesh. A portable electrostatic radon-measuring device (RAD7) was used to determine the indoor radon levels in different laboratories of AECDC, and a RAD7 detector with a stainless steel soil probe was employed to measure the soil gas radon in the surrounding areas of the AECDC campus. The indoor radon concentration in various laboratories was found to vary from 11 ± 7 Bq/m³ to 360 ± 180 Bq/m³ with an average of 63 ± 33 Bq/m³. Overall, the average indoor radon level shows below the action level (300 Bq/m³) recommended by ICRP publication-126 for homes and workplaces. However, the laboratories having poor ventilation show a relatively higher radon level. The average soil gas radon concentration at different depths of 15 cm, 35 cm, and 55 cm was found to be 0.07 ± 0.01 kBq/m³, 2.31 ± 0.31 kBq/m³, and 22.5 ± 1.4 kBq/m³, respectively. The calculated average annual effective dose due to the inhalation of indoor radon in home and workplaces was found to be below the ICRP recommended value of 10 mSv/y. The present results could serve as a reference radon level in the indoor and outdoor environment in Dhaka city, Bangladesh.

Keywords: radon concentration, alpha spectrometry, workplace, soil gas, annual effective dose, reference data

INTRODUCTION

Naturally occurring radioactive materials (NORMs) such as ²³⁸U, ²³²Th, ²³⁵U, and ⁴⁰K are ubiquitous in our dwelling environments such as soil, water, underlying rock, and geological formations with varying concentrations depending on the local geology (Shuaibu et al., 2017). These radionuclides undergo spontaneous and subsequent transformation into long and short-lived progeny. Radon (²²²Rn), Thoron (²²⁰Rn), and Actinon (²¹⁹Rn), all gaseous radionuclides, are produced in the natural decay chains headed by ²²⁶Ra (²³⁸U), ²²⁸Ra (²³²Th), and ²³⁵U, respectively (Balakrishnan et al., 2021). Generally, ²¹⁹Rn cannot encounter indoor air due to its insufficiency and short half-life ($T_{1/2} = 3.96$ s). On the other hand, ²²⁰Rn ($T_{1/2} = 55.6$ s) is sometimes encountered in indoor air, particularly near radon entry points and in soil gas. However, ²²²Rn ($T_{1/2} = 3.82$ days), a relatively long-lived member of the radon family, is the most predominantly found isotope in our dwelling environment.

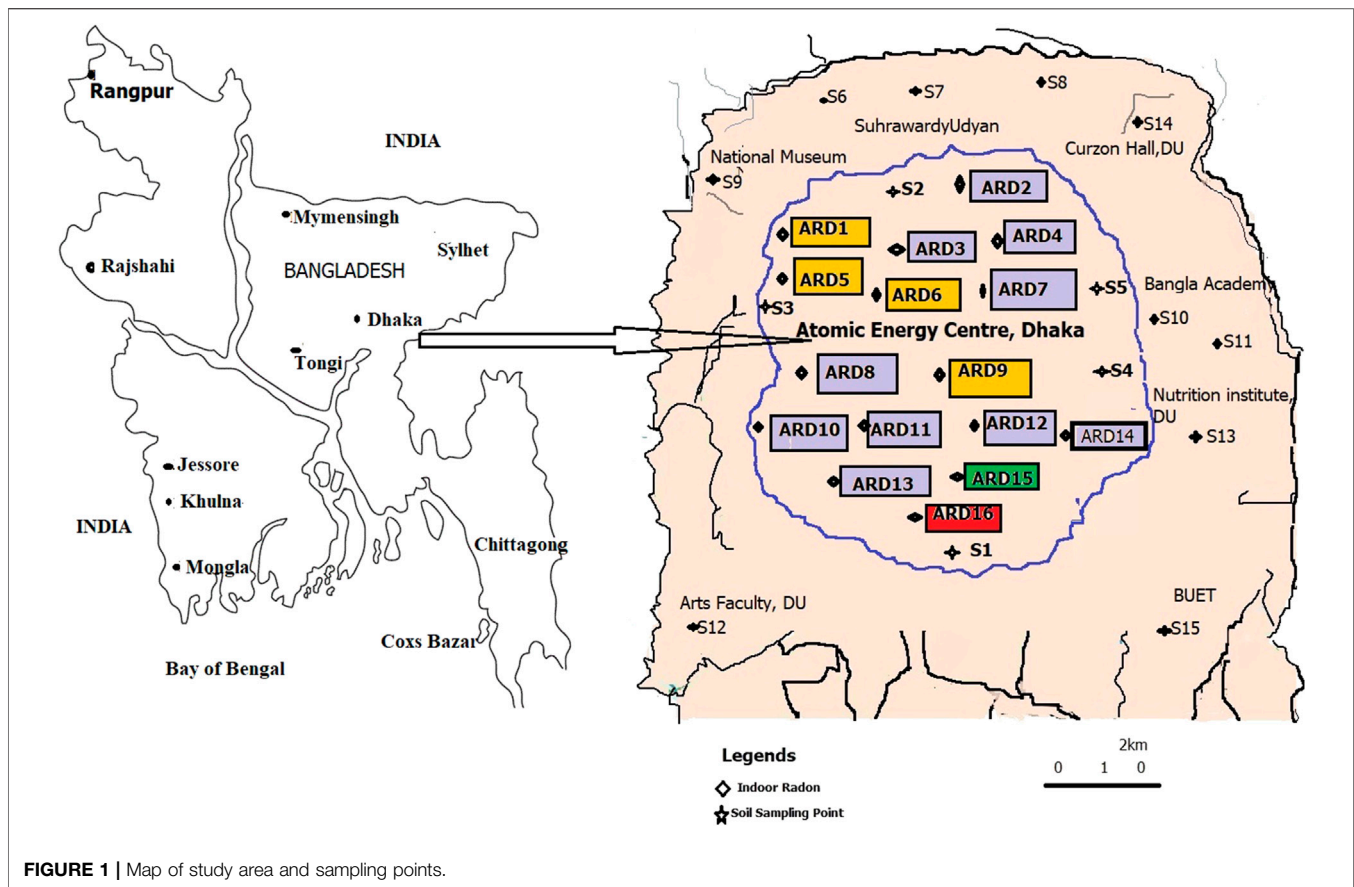
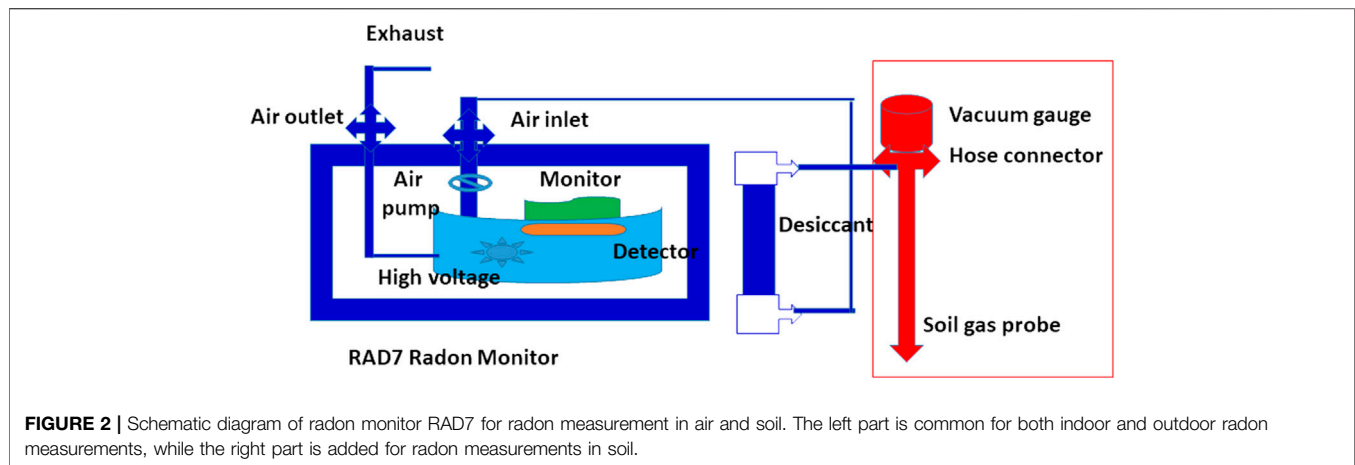


FIGURE 1 | Map of study area and sampling points.

Usually, radon gas is released into the atmosphere from ground formation and significantly contributes to elevated indoor radon levels through some mechanisms including convection *via* cracks and openings, diffusion from the soil *via* the pore space, an emanation from building materials, off-gassing of waterborne radon into the indoor environment, and entry of radon into the structure from outdoor air (Kumar et al., 2007; Pervin et al., 2018; Lee et al., 2020). Other influencing parameters are the radium content and mineralogy of the host rock and soil, porosity, grain size, moisture content, and permeability (Antoci et al., 2007). The nature of ventilation, types of building materials, topography, and meteorological parameters play vital roles in the concentration of indoor radon. Some studies stated that ventilation and atmospheric pressure have a definite influence on the levels of radon concentration (Ashok et al., 2011).

^{222}Rn possesses a density of 0.7 times higher than that of air. ^{222}Rn releases an alpha particle with 5.49 MeV of energy when it decays to polonium-218. Polonium atoms are metals and tend to stick to surfaces when they come in contact with the dust particles in the air. As a result, radon and their short-lived alpha-emitting progeny are responsible for the major background radiation exposures to human beings (United Nations Scientific Committee on the Effects of Atomic Radiation, 1994). Once the contaminated dust particles are inhaled, they damage the DNA of respiratory tissues, leading to respiratory functional

changes, consequently increasing the risk of lung cancer (Bahdan et al., 2010). It has been considered that radon is the second cause of lung cancer after smoking. The combined effect of indoor radon and smoking is responsible for developing lung cancer (United Nations Environment Protection Agency, 1991). It has been reported that due to radon exposure, approximately 21,000 deaths per year in the United States (National Research Council, 1999). Realizing the hazardous nature of radon exposure, several organizations have recommended the action level for indoor radon concentration. Notably, maximum permissible indoor radon concentrations of 100 Bq/m^3 , 150 Bq/m^3 , and $200\text{--}300 \text{ Bq/m}^3$ are recommended by the World Health Organization (WHO), United States Environmental Protection Agency (US-EPA), and International Commission on Radiological Protection (ICRP), respectively (World Health Organization, 2009; International Commission on Radiological Protection, 2010). A considerable number of studies were conducted in different countries in the world including Bangladesh to measure the indoor and soil gas radon concentration *via* various techniques because of the health hazard following exposure (Ali et al., 2015; Sedighian et al., 2015; Tanaka et al., 2017; Sherifat et al., 2019). Concerning earlier studies in Bangladesh, Asaduzzaman et al. (2015) measured radon in different building materials collected from in and around Dhaka city using gamma spectrometry (Asaduzzaman



et al., 2015). Miah et al. (1998) reported the concentrations of different radionuclides including ^{222}Rn in the soil at greater depths in and around Dhaka city (Miah et al., 1998). Talukdur and Khan (2011) measured radon levels in Dhaka city and the other parts of Bangladesh to provide a radon mapping for the country. They utilized CR-39 based Solid-State Nuclear Track Detector (SSNTD) technique, and reported a higher radon level in the old part of Dhaka city (Talukder and Khan, 2011). By using the same SSNTD technique, Khan and Chowdhury (2003) measured the indoor radon concentration of radioactive mineral sands in the Beach Sand Exploitation Centre at Cox's Bazar, Bangladesh (Khan and Chowdhury, 2003). Furthermore, in 2008, the same authors measured radon levels in several urban and rural residential areas in Sylhet city, and also in the Magurchara gas explosion area in Moulvibazar, Bangladesh (Hamid Khan and Chowdhury, 2008). Srivastava et al. (2001) measured indoor radon levels in the dwellings of the Rajshahi and Chuadanga regions of Bangladesh (Srivastava et al., 2001). Deeba et al. (2020) measured radon in soil and groundwater in the west coastal area of Bangladesh (Patuakhali district) using AlphaGUARD PQ2000 PRO (Saphymo, Germany) device (Deeba et al., 2020). However, most of the studies in Bangladesh are relatively old and adopted mostly SSNTD or gamma-ray spectrometry techniques. In addition, to our knowledge, no

data on radon is available in and around the atomic energy center of Dhaka (AECD), Bangladesh. Note that, the AECD is located at the hub of several top-ranked educational institutions in the country. Also, it hosts many laboratories and allows postgraduate students to carry out research in physical, chemical, geological, nuclear, and biological fields. Since its establishment in 1964, it is fully functioning as a leading research center in the country, however, no earlier study on radon level in this area was conducted until this date. In this regard, it is important to know the radon exposure situation in the area under investigation since it serves as the dwelling place for many students and staff. Therefore, the present work aims to measure the indoor radon concentration in the workplace at Atomic Energy Centre, Dhaka, and radon concentration in soil gas around AECD campus and surrounding areas. The obtained radon level is used to evaluate potential health hazards due to radon inhalation.

MATERIALS AND METHODS

Study Area

Dhaka is the capital of Bangladesh with a latitude of 23.8103°N and a longitude of 90.4125°E . Atomic Energy Centre, Dhaka (AECD) is located in the south part of Dhaka city. It was



TABLE 1 | Indoor radon concentration (Bq/m³) in the AECD campus with metrological data.

Monitoring ID	Sampling location	Ventilation conditions	Temp (°C)	Humidity (%)	Indoor radon concentration (Bq/m ³)
ARD1	Carbon Analysis Lab, Chemistry Division (CD)	Poorly ventilated	30.7	8	90 ± 32
ARD2	Sitting room, NDT Division	Poorly ventilated	28	7	45 ± 16
ARD3	Tracer lab, CD	Partially ventilated	31.6	9	18 ± 9
ARD4	Liquid Scintillation Lab, Health Physics Division (HPD)	Partially ventilated	26	9	27 ± 12
ARD5	Store Room, Electronics Division	Poorly ventilated	29.5	8	82 ± 51
ARD6	Gas Proportional Counter, HPD	Poorly ventilated	28.3	8	104 ± 65
ARD7	Environmental Lab, HPD	Partially ventilated	29.2	8	29 ± 12
ARD8	Chemistry lab, HPD	Poorly ventilated	29	8	38 ± 14
ARD9	Scientist sitting room	Poorly ventilated	22.2	8	61 ± 22
ARD10	Storeroom	Poorly ventilated	22	9	29 ± 12
ARD11	Main Laboratory, HPD	Well ventilated	25	8	23 ± 12
ARD12	Office room	Well ventilated	29	8	27 ± 9
ARD13	Library	Partially ventilated	23	7	33 ± 9
ARD14	Office room	Partially ventilated	28	8	27 ± 10
ARD15	Laboratory, Accelerator Physics Division (APD)	Partially ventilated	30.6	9	11 ± 7
ARD16	Underground Laboratory, APD	Poorly ventilated	22	9	360 ± 180

established in the early sixties. It is a radiological facility. Five divisions of AECD have used radioactive materials and radiation generating equipment for service, training, and Research and Development purposes. AECD has high activity industrial radiography sources and radioactive materials storage room where various kinds of radioactive materials stored since the establishment of AECD. Two large hospitals: Bangabandhu Sheikh Mujib Medical University (BSMMU) and Dhaka Medical College Hospital (DMCH), and two top-ranked universities, the University of Dhaka (DU) and Bangladesh University of Engineering and Technology (BUET) are situated around AECD. Several places such as different laboratories (old laboratories, storeroom, laboratory, and scientist sitting room) in the AECD campus were selected for indoor radon measurement, and several locations surrounding the AECD campus were selected for soil gas radon measurement under this study. **Figure 1** shows the map of the study area and sampling points.

Experimental Technique

In this study, measurements of indoor radon concentration and soil gas radon were performed by using a portable electrostatic radon monitor RAD7 (DurrIDGE Co. United States). The DurrIDGE RAD7 uses a solid-state alpha detector. RAD7 detector has an internal sample cell of 0.7-liter hemisphere, coated on the inside with an electrical conductor. The high voltage range of the detector is 2000–2500 V, which creates an electric field throughout the volume of the cell. The electric field propels positively charged particles onto the detector. It detects only alpha particles. The major advantages of this detector are the distinguishing characteristics of old radon daughters from new radon daughters, radon from thoron based on the energy of the alpha particle released, and signals from noise. The RAD7 amplifies, filters, and sorts the signals according to the signal produced by the different isotopes having different energies. RAD7 uses only the ²¹⁸Po signal to determine radon

concentration. The most important accessories of RAD7 were the power cord, the Laboratory Drying Unit (the large tube of desiccant, with a screw cap at one end), an inlet filter (one of the six small filters supplied), the piece of tubing with a 5/16" ID segment at one end and a 1/8" ID segment at the other and an attached printer (RAD7 User Manual, 2012).

Indoor Radon Concentration in Various Laboratories and Office Spaces

The measurement of radon in laboratories and office spaces was conducted according to the EPA protocol (RAD7 User Manual, 2012). Among several setup protocol systems, a 1-day protocol was selected. All windows and doors of the room or laboratories were kept closed for 12 h before the measurement was taken. The air circulations were kept off. During the measurement, the RAD7 detector was placed near the center of the room, about 3–4 feet above the floor. Walls, vents, fireplaces, windows, draft, and direct sunlight were avoided. The RAD7 device was connected to the desiccant or derrite tube. The air inlet filter of RAD7 was connected to the downhole of the desiccant with a probe. The air outlet filter of RAD7 and the upper hole of desiccant were kept open. The detector was purged for at least 10 min to dry the detector and control the humidity, and then the counting was started. During the purge cycle without wasting desiccant, the RAD7 outlet was connected to the open end of the drying tube, making a closed loop for controlling the humidity with 10% or less, because high humidity can damage the sensitivity of the instrument. Then infrared printer of the system was connected to the RAD7 system. After 24 cycles, the RAD7 detector delivered mean radon concentration with standard deviation, highest radon concentration, lowest radon concentration, bar chart, and commutative spectrum. During measurement, each sample was counted four times. Then the standard deviation was taken which has been reported as uncertainty. The uncertainty of the measured radon concentration can be derived using the following **equation** (Ravikumar et al., 2015):

TABLE 2 | The comparison of measured indoor radon concentration with results of the different studies worldwide.

Place of study	Detection techniques	Indoor radon concentration (Bq/m ³)	References
Sylhet, Bangladesh	CR-39 based Solid-State Nuclear Track Detectors (SSNTD)	49–835	Hamid Khan and Chowdhury, (2008)
Beach Sand Exploitation Centre at Cox's Bazar, Bangladesh	CR-39 based SSNTD	116–2042	Khan and Chowdhury, (2003)
Baghdad governorate, Iraq	RAD7 radon monitor	40.67–190.00	Karim et al. (2016)
Northern Rajasthan, India	RAD7 radon monitor	8.75–157.50	Duggal et al. (2012)
Thankassery, Kerala, India	CR-39 based SSNTD	44.3–373.30	Kumar et al. (2007)
Hazara division, Pakistan	RAD-7 detector	41–254	Khan et al. (2012)
Delhi, India	LR-115 type II based SSNTD	43.3–334.70	Gupta et al. (2011)
Zanjan City, Iran	RAD7 radon monitor	7–160	Nejatalahi et al. (2015)
AECD, Dhaka, Bangladesh	RAD7 radon monitor	11–360	This study

TABLE 3 | Radon activity concentration in soil using the RAD7 radon monitor with a soil probe.

Sampling point ID	Location	Radon activity concentration in soil (kBq/m ³) at a depth of		
		15 cm	35 cm	55 cm
S1	East side of AECD campus	0.03 ± 0.01	2.9 ± 0.1	5.9 ± 0.40
S2	West side of AECD campus	0.02 ± 0.01	4.2 ± 0.2	22 ± 1
S3	South side of AECD campus	0.09 ± 0.01	6.9 ± 2.2	24 ± 2
S4	North side of AECD campus	0.02 ± 0.01	0.7 ± 0.1	21 ± 1
S5	Garden, AECD campus	0.02 ± 0.01	4.4 ± 0.3	14 ± 2
S6	Suhrawardy Udyan	0.09 ± 0.01	4.2 ± 0.1	25 ± 1
S7	Suhrawardy Udyan	0.07 ± 0.01	0.9 ± 0.1	5.9 ± 0.40
S8	Suhrawardy Udyan	0.03 ± 0.01	0.4 ± 0.1	33 ± 3
S9	National Museum	0.08 ± 0.01	0.3 ± 0.1	12 ± 3
S10	Bangla academy	0.1 ± 0.01	0.07 ± 0.01	33 ± 1
S11	Bangla academy	0.04 ± 0.01	0.6 ± 0.1	25 ± 2
S12	Arts Faculty, DU	0.07 ± 0.01	3.8 ± 0.1	26 ± 1
S13	Nutrition institute, DU	0.04 ± 0.01	0.4 ± 0.1	25 ± 2
S14	Curzon Hall, DU	0.26 ± 0.01	0.9 ± 0.1	51 ± 3
S15	BUET	0.09 ± 0.01	3.3 ± 0.1	14 ± 1

$$\sigma = \sqrt{\left[\frac{N_s}{T_s^2} + \frac{N_b}{T_b^2} \right]}, \quad (1)$$

where N_s is the measured counts in time T_s and N_b is the background counts in time T_b . The standard deviation ($\pm\sigma$), was then converted into radon concentration in Bq/m³. On the other hand, the associated uncertainties should be contributed by statistical uncertainty (1–7%) and systematic uncertainty (4–6%). However, in this study, the reported uncertainties are the standard deviation obtained from four replicate measurements for the same sampling point.

Measurement of Radon Concentration in Soil

The radon activity concentration in soil gas was measured at 15 different locations surrounding the AECD campus using a RAD7 radon detector equipped with stainless steel soil probe (Durrige Co., United States). In this study, the radon level was measured at different depths of 15 cm, 35 cm, and 55 cm at each sampling point. The necessary accessories for the soil gas probe

were a probe with a pointed tip, 36.4 cm long, an extension 91.4 cm long, both with rod inserts, a T-handle, and a barbed hose adapter. The stainless steel probe with a hollow tube and sampling holes near the tip penetrates the soil to a specified depth, with a rotating handle or immersed with gentle strokes of a hammer where the soil was hard. The probe was then connected to the RAD7 detector through a desiccant tube (drying unit, CaSO₄) and inlet filters by pushing the plug-in hose connector into the probe.

Figure 2 shows the schematic diagram of RAD7 based radon monitoring system for radon measurement in soil gas. The depth of the sampling point was determined by the length of the probe inserted into the ground, taking into consideration the location of the sampling points on the probe shaft.

Care was taken to perform the measurements by choosing the place where the soil is uniform and generally free of rocks, to avoid cracking the probe. Before starting the counting process, the hole made in the soil surface was properly sealed by tamping down the soil around the probe in order to prevent the mixing of soil gas with air. Before each measurement, the system was purged to control the

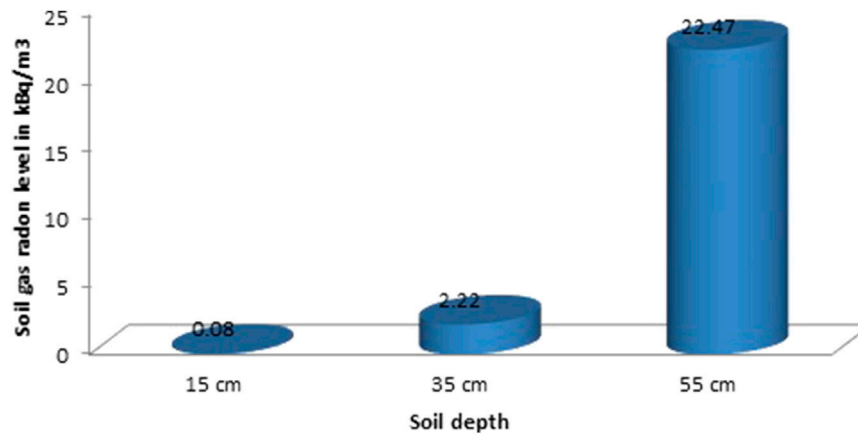


FIGURE 4 | The variations of radon activity concentration in soil among three depths using radon monitor RAD7 with soil probe accessories.

humidity to keep below 10% by using a drierite desiccant which is an important piece of equipment to absorb the moisture from the soil gas. Among several protocols of RAD7 for the soil gas measurements, the protocol that has been used here is called the sniff protocol and grab mode. The RAD7 pumps the soil gas for 5 min into the cell of the detector, and then waits for 5 min and counts only for 5 min. ^{218}Po has a half-life of 3.05 min and it takes about 4 half-lives for the ^{218}Po activity to reach secular equilibrium. The decays of the ^{218}Po would then be counted after 10 min (5 min of pumping plus 5 min of waiting), and within this time 95% of equilibrium would have been reached. At the end of each 30 min time, the RAD7 will print out a summary of the measurement, including data on average radon concentration in the soil-gas from the four 5-min cycle measurements along with the respective bar charts and cumulative spectra for each sample (Ravikumar et al., 2015; RAD7 Soil Probe Manual, 2012).

Figure 2 shows the schematic diagram of radon monitor RAD7 for radon measurement in air and soil. The left part is common for both indoor and outdoor radon measurements, while the right part is added for radon measurements in soil. **Figure 3** shows the photos of radon measurement at 1) indoor environment of AECD campus using the RAD7 monitoring device, in the soil at 2) AECD campus, and 3) DU campus using the same device with soil probe accessories.

Hazard Calculation

The annual effective dose due to inhalation of indoor radon is calculated using the following equation (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000):

$$AED = I_{Rn} \times F \times D \times T, \quad (2)$$

where I_{Rn} is indoor radon concentration in the units of $\text{Bq}\cdot\text{m}^{-3}$. F is the equilibrium factor of 0.4, D is the dose conversion factor of $9 \text{ nSv} (\text{Bq}\cdot\text{m}^{-3}\cdot\text{h})^{-1}$, and T is the home occupancy time, i.e., 7,000 h per year.

On the other hand, the annual effective dose for the lungs is calculated using the following equation (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000):

$$AED_L = AED \times W_t \times R_t, \quad (3)$$

where AED is the annual effective dose, W_t is the tissue weighting factor (0.12 for lung), and R_t is the radiation weighting factor (20 for alpha particles recommended by the ICRP).

Excess lifetime cancer risk (ELCR) is calculated using the following equation (Sherafat et al., 2019):

$$ELCR = AED \times D_f \times R_f, \quad (4)$$

where AED is the annual effective dose, D_f is the average duration of life estimated to be 70 years for Bangladeshi people, and R_f is the fatal cancer risk per Sievert ($5.5 \times 10^{-2} \text{ Sv}^{-1}$) recommended by ICRP.

Lung cancer cases per year per million people (LCC) are calculated using the following equation (Sherafat et al., 2019):

$$LCC = AED \times 18 \times 10^{-6}, \quad (5)$$

where AED is the annual effective dose in mSv/y and the risk factor for lung cancer induction is $18 \times 10^{-6} \text{ mSv}^{-1} \text{ y}$.

RESULTS AND DISCUSSION

The indoor radon concentration was measured in fifteen laboratories on AECD campus using a radon RAD7 detector. **Table 1** presents indoor radon concentration with monitoring ID, ventilation circumstances of the monitoring places, temperature, and internal relative humidity (RH) reading of the device during the counting period.

The indoor radon concentration in different laboratories of AECD varies from $11 \pm 7 \text{ Bq}/\text{m}^3$ to $360 \pm 180 \text{ Bq}/\text{m}^3$. The lowest radon concentration was found in the room having monitoring ID ARD15, which is green color and the highest value was found in the room with monitoring ID ARD16, which is red color as shown in

Figure 1. Results show that radon activity concentration was higher in various laboratories than in the storerooms and scientist sitting rooms. Moreover, the radon activity concentration was found to be minimum at the laboratory that is frequently used compared to the laboratories that are used once or twice a week. The highest indoor radon is found in the underground laboratory where the ventilation condition is very poor. Indoor radon concentration depends on some factors such as soil gas radon concentration, radium concentration, emanation coefficient, and ventilation rate (Mehta et al., 2014). The radon concentration was found to be higher in poorly ventilated rooms compared to the well-ventilated ones. So, it was apparent that the poor ventilation system grounds higher radon concentrations in comparison to a good ventilation system, which is also supported by the literature data (Karim et al., 2016). The Environmental Protection Agency has recommended a value of 148 Bq/m^3 as the action limit for indoor radon levels (United Nations Environment Protection Agency, 1991). Based on International Commission on Radiological Protection (ICRP) recommendation, residential radon should be regulated by a reference level of between 200 and 300 Bq/m^3 (International Commission on Radiological Protection, 2010). The world average value of indoor radon reported by the United Nations Scientific Committee on the Effects of Atomic Radiation is 40 Bq/m^3 (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000). According to the International Atomic Energy Agency (IAEA) Safety Standards Series No. GSR Part 3, the reference level for ^{222}Rn in the workplace should not exceed an annual activity concentration of $1,000 \text{ Bq/m}^3$ (International Atomic Energy Agency, 2014).

From **Table 1**, it is clear that the obtained results of indoor radon value were below the action levels recommended by various international bodies. A comparison of measured radon activity concentration indoors with the results of different studies carried out around the world is given in **Table 2**.

From **Table 2**, it is clear that the results of the present study of indoor radon concentrations are in line with the results reported in different studies around the world. Particularly, the present study shows a higher concentration than the data reported from the Zanjan City of Iran, Hazara division of Pakistan, Northern Rajasthan of India, and Baghdad governorate of Iraq. In the case of Zanjan city of Iran, it was found that the number of monitoring houses was 200, and the main factors for determining the low radon concentration in the studied houses refer to geological characteristics and types of construction and architecture styles. On the other hand, the present study shows lower data than Sylhet city and Cox's Bazar, Bangladesh, Kerala, and Delhi, India. This might be attributed to the old building structures with poor ventilation conditions.

Soil Gas Radon Activity Concentration

Radon concentration in soil gas was measured at fifteen locations of AECD campus and its surrounding areas using the RAD7 radon monitoring system, and the data is shown in **Table 3**. In each location, three different depths (15, 35, and 55 cm) were taken for soil gas radon measurement using a soil probe.

The obtained results show that soil gas radon concentration was varied from $0.02 \pm 0.01 \text{ kBq/m}^3$ to $0.26 \pm 0.01 \text{ kBq/m}^3$ with

an average value of $0.07 \pm 0.01 \text{ kBq/m}^3$ for 15 cm depth, 0.07 ± 0.01 to $6.9 \pm 2.2 \text{ kBq/m}^3$ with the average value of $2.3 \pm 0.3 \text{ kBq/m}^3$ for 35 cm depth, and $5.9 \pm 0.4 \text{ kBq/m}^3$ to $51 \pm 3 \text{ kBq/m}^3$ with the average value of $22 \pm 1 \text{ kBq/m}^3$ for 55 cm depth. The maximum allowed concentration level of radon in the soil is between $0.4\text{--}40 \text{ kBq/m}^3$. It was found that the obtained average values were within the maximum allowed concentration level of radon in soil.

The variation of soil gas radon concentrations among three depths is shown in **Figure 4**. It shows that radon gas in soil was found high at 55 cm depth and minimum at 15 cm depth. Therefore, it is clear that the radon level was variable at different depths and the soil gas radon activity concentration was increased with increasing the depth. Radon activity concentration in soil gas usually increases with increasing depth due to some facts such as moisture content increases with the depth of the soil, increasing water content in the pores. The result of the present study agrees with the findings of some reported values (Duggal et al., 2015; Mittal et al., 2015). It is also reported that high radon concentration depends on high uranium content rocks (Cevik et al., 2011). A comparison of measured radon activity concentration in soil gas with the results of different studies carried out around the world at different depths is given in **Table 4**.

From **Table 4**, it is clearly seen that the radon concentration in the soil of the present study was lower than in the Kangra district of Himachal Pradesh in India, and the Islamabad and Murree area in Pakistan. On the other hand, this study shows higher data than the Kalapara Upazila of Patuakhali district in Bangladesh, Jaintapur, and adjacent areas of Sylhet in Bangladesh, Northern Rajasthan and Ganganagar district of Rajasthan in India, Al-Najaf Al-Ashraf City of Iraq, Islamabad and Murreein Pakistan and Al-Tuwaitha Nuclear site of Iraq. Such a variation of data might be attributed to the variation in soil depth, detection techniques as well as geological characteristics.

The annual effective dose, lungs dose, and excess lifetime cancer risk are calculated due to exposure to indoor radon and presented in **Table 5**.

From **Table 5**, it has been seen that the highest annual effective dose due to inhalation of radon and annual effective dose to lungs were found at 9.07 mSv/y and 21.77 mSv/y , respectively. The value of the annual effective dose of the present study was found to be below the ICRP recommended range of $3\text{--}10 \text{ mSv/y}$ for exposure to ^{222}Rn at workplaces. The calculated value of ELCR ranged from 0.11 to 3.49%, and it was found that two values of ELCR are higher than the action level of ELCR recommended by the US-EPA. The lowest value of LCC was found to be 4.99 in ARD15 and the highest value was 163.30 in ARD16, which was below the range of 170–230 per million people recommended by the ICRP (Sherafat et al., 2019).

CONCLUSION

This study has measured the indoor and outdoor radon levels in various laboratories and office spaces and surrounding areas

TABLE 4 | The comparison of measured soil gas radon concentration with results of other studies around the world.

Region of study	Detection system	Depth (cm)	Radon concentration in soil (kBq/m ³)	References
KalparaUpazila of Patuakhali district, Bangladesh	AlphaGUARD PQ2000 PRO radon monitor	0 to 40	10–4,790 mBq/m ³	Deeba et al. (2020)
Northern Rajasthan (Bikaner and Jhunjhunu districts), India	RAD7 radon detector	69 to 70 (m)	0.094–10.05	Mittal et al. (2015)
Al-Najaf Al-Ashraf City, Iraq	RAD7 radon detector	5 to 60	0.09–9.29	Cevik et al. (2011)
Ganganagar district, Rajasthan, India	RAD7 radon detector	10 to 100	0.09–10.4	Hasan et al. (2011)
Nurpur area, Kangra district, Himachal Pradesh, India	RAD7 radon detector	—	1.10–82.20	Duggal et al. (2014)
Islamabad and Murree, Pakistan	LR-115 plastic track detectors	90	17.34–72.52	Singh et al. (2006)
Al-Tuwaitha Nuclear site, Iraq	RAD7 radon detector	60	8.66–16.004	Ali et al. (2010)
Dhaka, Bangladesh	RAD7 radon detector	15–55	0.02–51	This work

TABLE 5 | Annual effective dose and risks for the AECD dwellers/staffs due to indoor radon exposure.

Sample ID	Annual effective dose (mSv/y)		Risk		
	Inhalation of radon	To lung	ELCR	ELCR (%)	LCC (× 10 ⁻⁶)
ARD1	2.28	5.47	8.8E-03	0.88	41.0
ARD2	1.13	2.72	4.4E-03	0.44	20.4
ARD3	0.45	1.08	1.7E-03	0.17	8.1
ARD4	0.67	1.61	2.6E-03	0.26	12.1
ARD5	2.07	4.96	8.0E-03	0.80	37.2
ARD6	2.62	6.29	1.0E-02	1.01	47.2
ARD7	0.73	1.74	2.8E-03	0.28	13.1
ARD8	0.96	2.31	3.7E-03	0.37	17.3
ARD9	1.54	3.69	5.9E-03	0.59	27.7
ARD10	0.73	1.74	2.8E-03	0.28	13.1
ARD11	0.57	1.36	2.2E-03	0.22	10.2
ARD12	0.69	1.65	2.6E-03	0.26	12.4
ARD13	0.83	2.00	3.2E-03	0.32	14.9
ARD14	0.68	1.63	2.6E-03	0.26	12.2
ARD15	0.28	0.67	1.1E-03	0.11	5.0
ARD16	9.07	21.77	3.5E-02	3.49	163

of the Atomic Energy Centre, Dhaka, Bangladesh. A portable electrostatic RAD7 radon monitor was used in this measurement. Indoor radon concentrations in different laboratories on AECD campus were found in the range from 11 ± 7 Bq/m³ to 360 ± 180 Bq/m³, and only one laboratory room was found to contain radon concentration higher than the safety limit of 148 Bq/m³ recommended by the U.S. Environmental Protection Agency. The annual effective doses were found to be below the recommended value of radon for the workplace by ICRP. The concentration of soil gas radon in the adjacent areas of the AECD campus was measured by employing the RAD7 detector with a stainless steel soil probe. The average soil gas radon concentrations at a depth of 15, 35, and 55 cm were found 0.07 ± 0.01 kBq/m³, 2.3 ± 0.3 kBq/m³, and 22.5 ± 1.4 kBq/m³, respectively. The minimum radon activity concentration was found at 15 cm depth and the maximum concentration was found at 55 cm. The measured radon concentrations in most of the studied places are within the recommended action level, thus the monitoring area is safe from the viewpoint of radon exposure and associated hazards. Overall, this study provides baseline data on indoor and soil gas radon levels at busy work in the capital city of Bangladesh.

The provided data may be helpful for source identification and countrywide mapping of ²²²Rn in the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SP: preparation, analysis, and writing. SY: supervision. MK: review and editing. AB: supervision.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support given to this work by the Health Physics Division and all divisional heads of the AECD campus for permitting to use their laboratory during the measurement.

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