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Radiation distribution and associated hazard risks due to naturally occurring radioactive minerals at workplace

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ABSTRACT

The study investigates radioactivity concentration and its associated health hazard indices as a part of workplace radiation monitoring. Institute of Nuclear Minerals (INM) deals with naturally occurring radioactive minerals (NORMs) and uses nuclear technology for the exploration of mineral resources for which elevated radioactivity is found at the workplace. A total of 34 measurements were conducted to identify those anomalous radioactive zones in and around INM. The measured radioactivity concentration of ^{238}U, ^{232}Th, and ^{40}K were in the range of 52.49-170.31 bq/kg, 36.05-72.88 bq/kg and 291-697.99 bq/kg, respectively and corresponding dose rates were 0.09-0.21 µSv/h. The radioactivity levels found that its average concentration in the investigated area surpassed the world average values for each of uranium, thorium, and potassium. Concerning radiological risk measurements, radium equivalent activity index (Ra_{eq}), external hazard index (H_{ex}), and internal hazard index (H_{in}) were generally below the world accepted limits, except for one case. Nevertheless, the recorded absorbed dose rate (DR) and the average annual effective dose equivalent (AEDE) from all devices exceeded world standards. The radioactivity distribution showed higher dose rates resulting from higher radionuclide presence in various types of samples collected from different geologically potential areas. Increased dose rates evident at the northern side of the building is probably from the combined effect of various radioactive samples, uncovered old mosaic floor and radon in air concentration in old storage.

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I. Introduction

Bangladesh Atomic Energy Commission (BAEC) is the national hub for ionizing radiation related research in Bangladesh. It has specific programs on radiation uses and the protection from radiation doses for the workers engaged in various types of research activities. Besides artificial radiation sources, BAEC also performs activities that deal with the environmental radiation. All the institutes who use such radiation sources or use nuclear technology, come under routine monitoring on radiation doses. Radioactivity distribution at respective workplaces falls under such routine radiation monitoring.

The Institute of Nuclear Minerals (INM) at the Atomic Energy Research Establishment (AERE) under BAEC is specialized in studying NORMs and exploring mineral resources, particularly heavy minerals, using artificial radiation sources. INM regularly conducts fieldwork in different geologically potential areas and collects various natural samples which may contain radioactivity higher than the background. These radioactive samples are primarily sourced from the southeastern coastal region of Bangladesh, which boasts abundant economically valuable heavy minerals containing radioactive elements (Bari et al. 2003; BSMEC 2003; Rahman et al. 2008; Rajib et al. 2019; Sasaki et al. 2015; Zaman et al. 2016). Moreover, samples are collected also from Tertiary sediments from the north-eastern part of the country during routine exploration surveys for radioactive and nuclear minerals (Majumder et al. 2014, 2021; Dina et al. 2022).

Laboratories of INM analyze different geological samples from those areas which may contain radioactivity. Occupational workers in different laboratories who deal with those natural as well as artificial radioactive sources receive additional radiation doses at their workplaces. Working in the higher radiation dose range areas may require safety measures for the employees of the institute. The present study is aimed to investigate the possibility of additional doses any person of INM could receive during their stay at working hours. People are consistently subjected to the inherent ionizing radiation present in the environment, emanating from NORMs and cosmic radiation. Accordingly, persons engaged in the vicinity of such radiation sources experience supplementary exposure through external radiation by several mechanisms. The quantification of this external radiation exposure can be directly assessed using various types of personal dosimeters.

Once collected, the geological samples are initially stored in the main storage facility of INM. Afterward, they undergo a series of meticulous preparation and analytical procedures. This includes sample preparation, sieving, and grain size analysis, as well as assessment of heavy mineral content via heavy liquid separation using bromoform. These processes take place across several laboratories, each equipped for different phases of sample processing and geochemical analysis. Given these workflows, our primary focus is to carefully monitor the rooms involved, especially the storage area and laboratories directly associated with sample handling and radioactive geochemical assessments. This is essential to ensure both effective sample management and a safe working environment for laboratory personnel handling materials with potential radiological hazards.

Approximately 80% of the annual radiation exposure a person receives accounts from natural background radiation from sediment, soil, water and rock, turning them into the focal point of the studies on radioactivity measurement (Al-Jundi et al. 2003). People are exposed to various levels of ionizing radiation from sources beyond earth, mainly radiation originating from the outer atmosphere and the presence of naturally-occurring radioactive substances like gamma rays emitted by ^{40}K, as well as radionuclides from the decay series of ^{238}U and ^{232}Th found in soil, rocks, and water (Arıman and Gümüs 2018; Prasad et al. 2020; Tawfic et al. 2021; UNSCEAR 1988). Living on the earth's surface, it is inevitable for us to passively accept background radiation which varies in different areas at different altitudes. The presence of those radionuclides in rock is determined by the distribution of radioactive elements in the original rock and the physical and chemical processes that lead to their concentration. The primary contributors to elevated natural background radiation include ^{238}U and its radioactive decay products in soil and rocks, along with ^{232}Th found in monazite sands (Al-Hamarneh and Awadallah 2009). Phosphate rocks can release radioactive particles into the environment by various means, such as incorporating phosphogypsum in construction projects (Ramli et al. 2005). Therefore, conducting a comprehensive investigation into the measurement of various levels of various radionuclides (such as ^{226}Ra (the radioactive decay product of ^{238}U), ^{232}Th, and ^{40}K) is crucial to assess the potential health hazards they pose to humans. This is also important for radiation safety, geoscientific investigations, and the development of guidelines for mitigating these radioactive substances (Prasad et al. 2020).

In recent times, occupational exposure to ionizing radiation is a common concern in various industries, including medical institutions, educational and research settings, and nuclear facilities. Ensuring adequate radiation protection for these workers is crucial to maintaining both the safety and acceptability of radiation and radioactive materials use. It is essential that occupational workers have a fundamental awareness of the risks posed by radiation exposure and a clear understanding of the presence and sources of radiation within their work environment. Effective radiation protection protocols rely not only on awareness but also on regular and accurate monitoring of radiation levels.

Keeping the eternal documentation of the levels of exposed doses occupational workers enables those individuals at risk and the administration need to be notified about the levels of radiation exposure they have encountered. This also demonstrates that the professional limits are not surpassed. These data should be provided for investigation of dosage patterns in the workplace. This occupational information allows identification of the levels of exposure among different groups of individuals and assesses, ensuring the monitoring and management of radiation exposures are as low as reasonably achievable (ALARA).

This study focuses on the spatial distribution of radioactivity across a large working area. As an initial step, we have started a pilot study focused on the institutional building of INM. By systematically mapping radiation levels in this area, this study will serve as a baseline for future, more extensive radiation monitoring efforts. Additionally, the study aims to evaluate the potential health risks associated with exposure to these radioactive elements. Such monitoring is vital for assessing and maintaining the safety standards for radiation works, as well as for identifying any potential hot spots of radiation that may require additional protective measures. The findings of this study aim to support a safer work environment by providing essential data to inform routine safety checks, enhance radiation awareness, and ultimately contribute to the health and well-being of workers exposed to ionizing radiation in occupational settings.

II. Materials and Methods

Study area

The study area, INM, is situated within the premises of the Atomic Energy Research Establishment (AERE) in Savar, Bangladesh. Its geographic coordinates are approximately 23° 57 '10"N latitude and 90° 16' 37"E longitude. The primary purpose of the INM is to conduct research and exploration related to uranium, thorium, and other atomic minerals within various prospective zones across Bangladesh. These minerals are of significant interest due to their potential applications in nuclear energy production, medical diagnostics and treatments, as well as various industrial processes. Within the study area, scientists and researchers at the INM utilize various geological and geophysical techniques to identify, map, and assess the distribution and abundance of uranium, thorium, and associated valuable minerals. This involves fieldwork, sample collection, laboratory analysis, and interpretation of data to understand the geological formations and potential mineral deposits present in the region. The INM plays a crucial role in the country's efforts to harness its natural resources, particularly in the realm of nuclear energy development and strategic mineral reserves. Overall, the study area at the INM serves as a hub for interdisciplinary research and collaboration aimed at unlocking the potential of atomic minerals in Bangladesh while contributing to global knowledge as well in the field of geology and mineral resource management.

Data collection

Simultaneous measurement of radioactivity as well as corresponding dose rate were carried out in the entire INM and its surroundings using GF gamma-ray spectrometer (Gamma surveyor II) along with a Geiger counter (that can measure both nuclear and electromagnetic radiation) and personal dosimeter (FS2011) at different rooms, laboratories and surroundings of INM as a part of radiation monitoring at the workplace. The physical principal of the gamma surveyor is based on gamma-ray capture in top quality BGO scintillation detector with consequent 1024-channel spectral analysis and mathematical processing. In addition to measuring the gamma dose rates, the Gamma surveyor assesses the levels of specific elements like uranium (U) and thorium (Th) in parts per million (ppm), as well as potassium (K) concentration in percentage (%). Geiger counter can detect all the ionizing radiation and provides the real-time dose rate, including the mean value. The threshold setting of this machine is based on the EMF project of the World Health Organization (WHO). Currently, it has been widely used in nuclear physics, medical research and environmental monitoring and industrial fields because of its high sensitivity and wide detection range. Finally, personal dosimeters provide a 5-minute average dose rate. The dosimeter is known as an alarm device which is collocated with a highly flexible geiger counting pipe as detector. It is mainly responsible for monitoring the different radiations in various radioactive work areas and in safety protection in nuclear facilities and their vicinity for radioactive activity in laboratory settings. The calibration process including the gamma surveyor, portable geiger counter, and alarm dosimeter, was conducted in accordance with standardized protocols to ensure precise and reliable measurements of radioactivity. Each instrument was calibrated using certified radioactive sources with known activity levels to achieve high measurement accuracy.

For the gamma surveyor, calibration involved exposure to multiple radionuclides (such as Cs-137 and Co-60) that emit gamma radiation at different energy levels. This procedure allowed us to adjust the instrument response across a range of energy levels, simulating the conditions expected in fieldwork and laboratory settings. The portable dosimeter calibration was aligned with International Atomic Energy Agency (IAEA) standards, using a controlled dose rate from a reference radiation source to verify dose measurement accuracy. All calibration took place under controlled laboratory conditions, with regular recalibration intervals following the recommendations and regulatory guidelines.

Figure 01. (a) Gamma surveyor (b) Geiger counter and (c) Personal dosimeter.

The instruments used in this study are presented in Figure 01. To handle measurement uncertainties, we implemented multiple safeguards. For each measurement point, a minimum of three readings was taken, and the mean value was calculated to mitigate random errors. We also corrected for background radiation by measuring ambient levels and subtracting them from field readings. Calibration certificates, along with documented error margins, were maintained for each instrument, ensuring traceability and compliance with our quality assurance protocols. This rigorous approach to calibration and error management was essential to achieving accurate, reproductive results in both our field and laboratory assessments. The spatial distribution data was carefully verified and organized within a Microsoft Excel database. Geographic information system (GIS) software was utilized to geo-reference the Google Earth imagery and to create spatial maps illustrating the radioactivity levels through contour maps at the INM.

Radio-elemental analysis: The measured concentrations of elements eU and eTh were initially expressed in parts per million (ppm), while potassium was expressed in percentages. Utilizing conversion factors outlined by the International Atomic Energy Agency (IAEA 1989), these elemental concentrations can be transformed into activity concentrations measured in Becquerels per kilogram (Bq/kg). These recommended conversion factors are as follows: 1 ppm of U equates to 12.35 Bq/kg of ^{238}U; 1 ppm of Th equates to 4.06 $Bqkg^{-1}$ of ^{232}Th; and 1% of K equates to 313 $Bqkg^{-1}$ of ^{40}K.

Radiological hazard

Radium equivalent activity concentration index (Ra_{eq}): The Radium Equivalent Activity (Ra_{eq}) can be denoted as represented by Eq. (1), which involves a calculated combination of three specific radionuclides: ^{226}Ra, ^{232}Th, and ^{40}K (Beretka and Mathew 1985).

$$Ra_{eq}\ (\mathrm{Bq/kg}) = C_{Ra} + 1.43C_{Th} + 0.077C_K \tag{1}$$

In this equation, C_{Ra}, C_{Th}, and C_K refer to the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, measured in Bq/kg.

Absorbed dose rate (D): The absorbed dose rate (D) is computed to evaluate the level of gamma radiation exposure at a height of 1 meter above the Earth's surface (UNSCEAR 2008). This calculation involves C_{Ra}, C_{Th}, and C_K, which represent the activities of ^{226}Ra, ^{232}Th, and ^{40}K in (Bqkg^{-1}). Additionally, the values 0.462, 0.604, and 0.0417 serve as conversion factors, transforming these activities into doses (Uosif 2011).

$$DR\ (\mu\mathrm{Sv/h}) = 0.462C_{Ra} + 0.604C_{Th} + 0.0417C_K \tag{2}$$

The annual effective dose equivalent (AEDE): AEDE was determined to assess the impact on health resulting from the absorbed dose, which was computed using Eq. (3). The absorbed gamma dose rate, denoted as *DR* and calculated in Eq. (2), formed a crucial component in this assessment.

$$AEDE\ (\mathrm{mSv/y}) = DR \times DCF \times OF \times T \tag{3}$$

As per UNSCEAR 2000 guidelines, the dose conversion factor (DCF) and outdoor occupancy factor (OF) were established at 0.7 SvGy^{-1} and 0.2 respectively. Additionally, the time factor, represented as T and equivalent to 8760 hours, was factored into the calculations. However, in the present case, all measurements were made in a research institute where people typically work around 2112 h per year (considering 22 days a month and 8 hours a day). The Eq. 3 also considers The OF value of 0.2, which is derived based on the assumption that humans typically spend approximately 20% of their time outdoors (Debertin and Helmer 1988). For this case, the total hour stands at 1752 (20% of 8760 hours). Comparing these two values, an approximate value of 2000 hours is considered in Eq-3 to calculate AEDE in the present scenario with an OF value 1 (100% of 2000 hours) (Table-1).

External hazard index (H_{ex}): The external and internal hazard indices were computed to ensure that the radiation exposure from ^{226}Ra, ^{232}Th, and ^{40}K in the tested samples remains within the permissible dose equivalent of 1 mSv/y (Beretka and Mathew 1985). Eq. (4) is employed for ascertaining the external hazard index.

$$H_{ex} = (C_{\mathrm{Ra}}/370 + C_{\mathrm{Th}}/259 + C_{\mathrm{K}}/4810) \leq 1 \tag{4}$$

Internal hazard index (H_{in}): The internal hazard index (H_{in}) was determined through the application of Formula (5) (Ramasamy et al. 2011).

$$H_{in} = (C_{Ra}/185 + C_{\mathrm{Th}}/259 + C_K/4810) \leq 1 \tag{5}$$

Here, C_{Ra}, C_{Th}, and C_K retain the same definitions as in Eq. (4). Radiation risks are deemed negligible if the resulting index value is below.

Statistical analysis: Statistical analyses including factor analysis, principal component analysis (PCA), and correlation coefficients were conducted with SPSS (version 23) to analyze the interrelationships between combinations of radionuclides and variables derived from activity concentration through Pearson correlation coefficient and PCA. This aimed to assess the extent to which these radionuclides collectively exist in close proximity, highlighting their potential positive associations.

III. Results

A total of 34 measurements were collected from approximately the middle of each 22 rooms and other 12 values from equal distance from the institute building to obtain distribution of radioactivity and radioactive doses.

The uranium distribution map (Figure 2a) indicates that the highest concentration of ^{238}U was recorded as 13.79 ppm, while the lowest concentration was 4.25 ppm. The sample storage facility of INM displayed the highest recorded value. When examining the thorium distribution map (Figure 2b), the recorded radiation levels for ^{232}Th fell within the range of 8.88 to 17.95 ppm. The highest recorded value of 17.95 ppm was found in S-104, primarily due to the keeping of radioactive minerals, particularly monazite for display purposes.

Elevated levels of radiation from potassium were detected in Figure 2c at sampling locations S-105, S-108, S-109, S-114, and S-115, with the measured concentration of potassium-40 (^{40}K) exceeding 2.1%. This could potentially be attributed to a combined influence of background radiation originating from uncovered, old mosaic floors (Songlin and Tinghui 2021) and the presence of radon gases in old storage areas.

Figure 3a displaying the distribution of gamma dose rates revealed that measured dose rate above 0.09 μSv/h, was detected in the storage room where various geological samples collected from the aforementioned radioactive mineral-rich regions are kept prior to processing.

The distribution map of Geiger counter dose rates indicates that higher radiation levels are observed on the northern side of the building, with recorded dose rates falling within the range of 0.13 to 0.21 microsieverts per hour (μSv/h) in Figure 3b. The individual radiation monitoring device displays an alternate radiation dosage pattern, spanning from the northern to central sections of the structure, with radiation levels varying between 0.09 to 0.18 microsieverts per hour (Figure 3c).

Table 01 displays the calculated concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq/kg across all samples. The activity concentrations of ^{226}Ra ranged from 52.5 to 170.3 Bq/kg averaging 89.4 Bq/kg while the world standard activity is 35 Bq/kg and 33 Bq/kg at Dhaka (Miah et al. 1998; UNSCEAR 2000). ^{232}Th values ranged from 36.05 to 72.88 $Bqkg^{-1}$ with an average activity concentration of 51.64 $Bqkg^{-1}$ and the world average is 30 $Bqkg^{-1}$ and 55 Bq/kg at Dhaka. Comparing the mean concentration of ^{226}Ra and ^{232}Th with the world average value and other study, it is found that the study area had high ^{226}Ra concentration whereas average activity concentration of ^{232}Th is similar to the previous study at Dhaka but still higher than world average. In case of ^{40}K concentration, the activity ranged from 291.1 to 697.9 $Bqkg^{-1}$ while the minimum value is quite less albeit to containing higher mean value, 527.3 $Bqkg^{-1}$ than the world average, 400 Bq/kg but similar with Dhaka study (Miah et al. 1998; UNSCEAR 2000). Regarding linear relationship, the graphs illustrate a strong to moderate positive relationship between the gamma dose rate and the elements U, Th, and K where the R-square values fall within the range of 0.5 to 0.75 (Figure 04). Geiger counter Dose rate showed low positive correlation with ^{238}U, ^{232}Th, and ^{40}K and R-square values are about 0.30 (Figure 05).

Table 01. Elemental and Activity concentration, absorbed dose rate (*DR*), annual effective dose rate (AEDE), radium equivalent activity (*Ra_{eq}*), external (*H_{ex}*) and internal (*H_{in}*) hazard indices

ID*	U (ppm)	Th (ppm)	K (%)	DR_{gam} (µSv/h)	DR_{gei} (µSv/h)	DR_{per} (µSv/h)	C_{Ra} (bq/kg)	C_{Th} (bq/kg)	C_k (bq/kg)	Ra_{eq} (bq/kg)	AEDE (gam)	AEDE (gei)	AEDE (per)	H_{ex}	H_{in}
101	7.32	12.41	1.8	0.096	0.16	0.18	90.4	50.38	563.4	205.8	0.134	0.224	0.25	0.56	0.80
102	7.78	13.36	1.93	0.102	0.15	0.11	96.1	54.24	604.1	220.2	0.14	0.21	0.15	0.59	0.85
103	8.1	12.28	1.87	0.101	0.17	0.13	100	49.86	585.3	216.4	0.14	0.22	0.18	0.58	0.85
104	6.06	17.95	2.06	0.105	0.18	0.12	74.8	72.88	644.8	228.7	0.15	0.25	0.17	0.62	0.82
105	9.08	15.43	2.23	0.119	0.18	0.16	112.1	62.65	697.9	255.5	0.17	0.25	0.224	0.69	0.99
106	7.71	12.65	1.9	0.1	0.18	0.13	95.2	51.36	594.7	214.5	0.14	0.25	0.18	0.58	0.84
107	7.17	12.29	1.88	0.096	0.18	0.16	88.5	49.9	588.4	205.2	0.13	0.25	0.224	0.55	0.79
108	7.93	13.17	2.06	0.104	0.2	0.16	97.94	53.47	644.8	224	0.15	0.28	0.22	0.6	0.87
109	7.78	14.04	2.2	0.108	0.19	0.13	96.08	57	688.6	230.6	0.15	0.27	0.18	0.62	0.88
110	7.86	12.56	1.9	0.1	0.18	0.09	97.07	50.99	594.7	215.8	0.14	0.25	0.126	0.58	0.85
111	7.51	12.63	1.79	0.097	0.18	0.09	92.75	51.28	560.3	209.2	0.14	0.25	0.13	0.57	0.82
112	13.79	13.98	1.61	0.134	0.21	0.11	170.3	56.76	503.9	290.3	0.19	0.29	0.15	0.78	1.24
113	8.86	14.4	2.14	0.114	0.2	0.12	109.4	58.46	669.8	244.6	0.16	0.28	0.168	0.66	0.96
114	8.7	14.5	2.21	0.114	0.18	0.12	107.4	58.87	691.7	244.9	0.16	0.25	0.17	0.66	0.95
115	7.95	14.26	2.03	0.107	0.18	0.13	98.18	57.9	635.4	229.9	0.15	0.25	0.18	0.63	0.89
116	8.33	13.49	1.99	0.107	0.19	0.16	102.9	54.77	622.9	229.2	0.15	0.27	0.224	0.62	0.9
117	7.73	12.61	1.85	0.099	0.18	0.18	95.47	51.2	579.1	213.3	0.14	0.25	0.25	0.58	0.83
118	5.33	16.06	1.72	0.092	0.18	0.12	65.83	65.2	538.4	200.5	0.13	0.25	0.168	0.54	0.72
119	8.09	12.49	1.7	0.099	0.18	0.12	99.9	50.71	532.1	213.4	0.14	0.25	0.17	0.58	0.85

120	8.12	13.19	1.94	0.104	0.17	0.11	100.3	53.55	607.2	223.6	0.15	0.24	0.15	0.6	0.88
121	8	13.13	1.97	0.104	0.18	0.11	98.8	53.31	616.6	222.5	0.14	0.25	0.154	0.6	0.87
122	7.97	13.91	1.69	0.102	0.17	0.11	98.43	56.47	528.9	219.9	0.14	0.28	0.15	0.59	0.86
123	4.25	16.28	1.25	0.08	0.16	0.12	52.49	66.1	391.3	177.1	0.11	0.224	0.17	0.48	0.62
124	6.39	10.06	0.93	0.07	0.17	0.1	78.92	40.84	291.1	159.7	0.1	0.24	0.14	0.43	0.64
125	6.11	10.77	1.2	0.077	0.15	0.15	75.46	43.73	375.6	166.9	0.1	0.21	0.21	0.45	0.65
126	5.53	10.74	1.19	0.073	0.13	0.09	68.3	43.6	372.7	159.3	0.1	0.18	0.13	0.43	0.61
127	7.23	11.47	1.13	0.084	0.17	0.12	89.3	46.57	353.7	183.1	0.12	0.238	0.17	0.49	0.74
128	5.72	9.92	1.26	0.073	0.17	0.15	70.64	40.28	394.4	158.6	0.1	0.24	0.21	0.43	0.62
129	5.89	11.19	1.46	0.08	0.16	0.11	72.74	45.43	456.9	172.9	0.11	0.224	0.15	0.47	0.66
130	5.68	10.35	1.38	0.076	0.18	0.09	70.15	42.02	431.9	163.5	0.1	0.25	0.13	0.44	0.63
131	5.28	9.52	1.07	0.067	0.15	0.14	65.21	38.65	334.9	146.3	0.09	0.21	0.19	0.4	0.57
132	5.04	8.88	1.2	0.066	0.17	0.12	62.24	36.05	375.6	142.7	0.09	0.238	0.17	0.36	0.55
133	5.9	12.08	1.27	0.08	0.17	0.18	72.87	49.04	397.5	173.6	0.11	0.24	0.25	0.47	0.67
134	5.97	10.41	1.47	0.079	0.17	0.15	73.73	42.26	460.1	169.6	0.11	0.238	0.21	0.46	0.66
Max	13.79	17.95	2.23	0.134	0.21	0.18	170.3	72.88	697.9	290.3	0.19	0.29	0.25	0.78	1.24
Min	4.25	8.88	0.93	0.066	0.13	0.09	52.49	36.05	291.1	142.7	0.09	0.18	0.13	0.39	0.55
Mean	7.24	12.72	1.68	0.094	0.17	0.13	89.41	51.64	527.3	203.9	0.13	0.24	0.18	0.55	0.79
World average		UNSCEAR (2008)			0.055		35	30	400	370	0.07			1.00	1.00
Dhaka		Miah et al. (1998)			0.073		33	55	574	156	0.09			0.42	0.51

** ID 1-122 represents the room numbers of the institute, whereas 123-134 are data collections points around the institute building.*

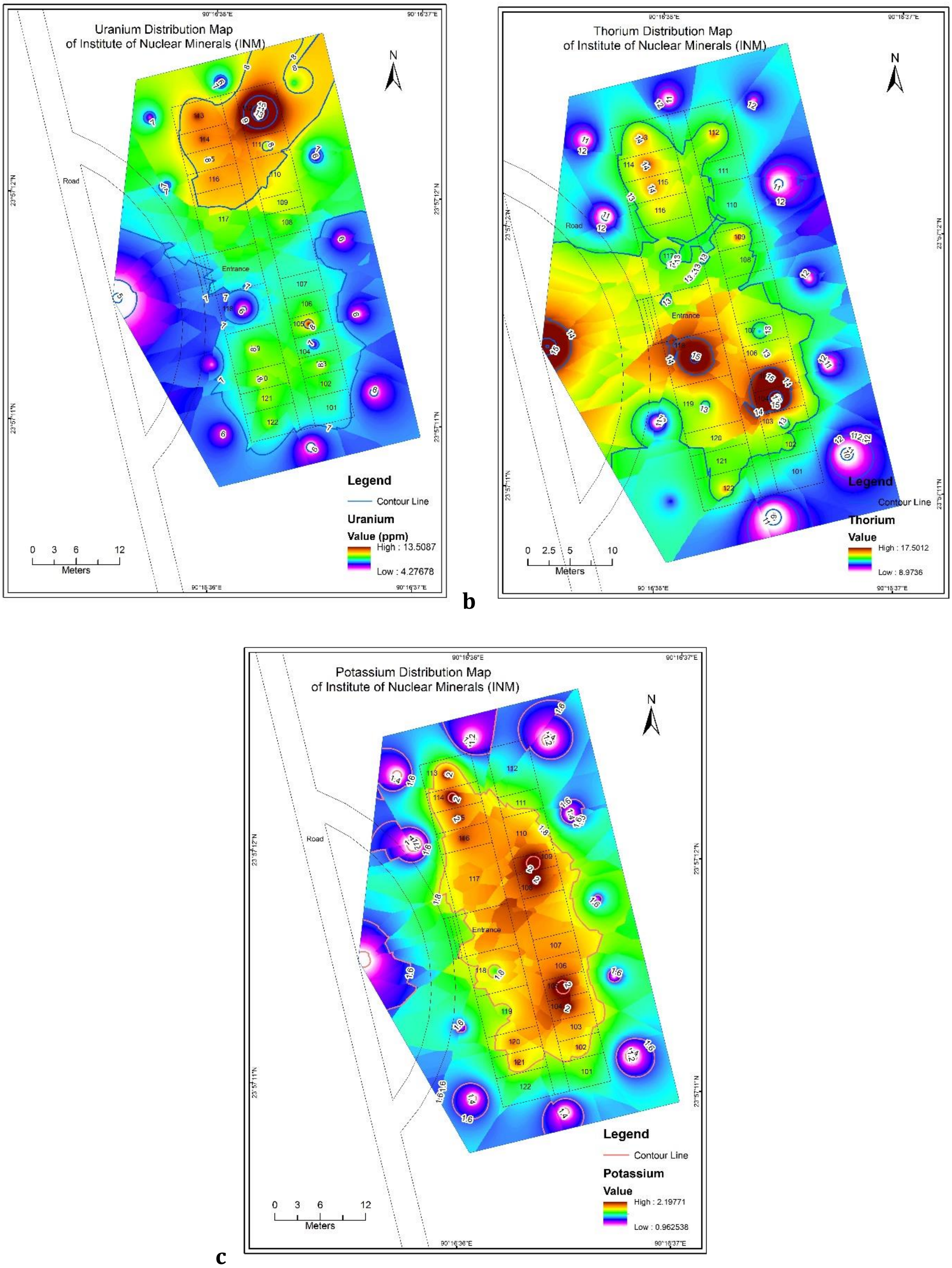
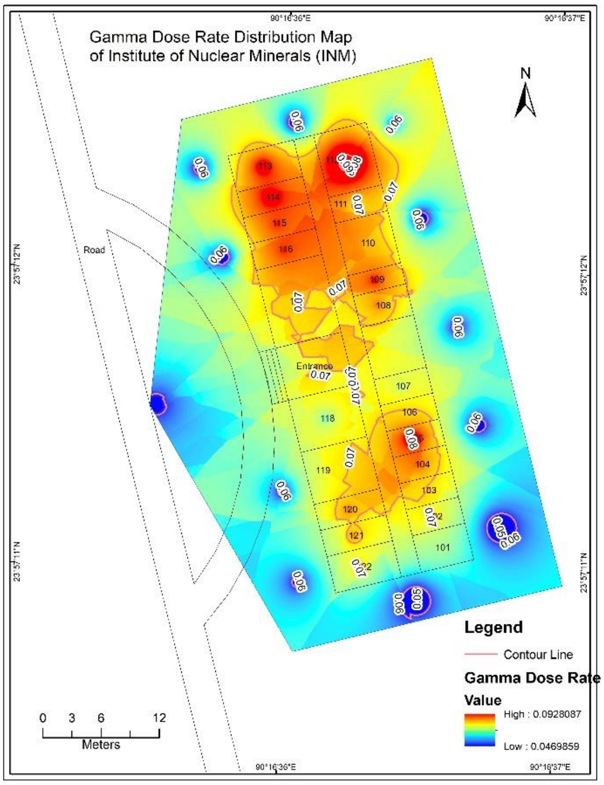


Figure 2. (a) Uranium distribution Map, (b) Thorium distribution Map, and (c) Potassium distribution Map.



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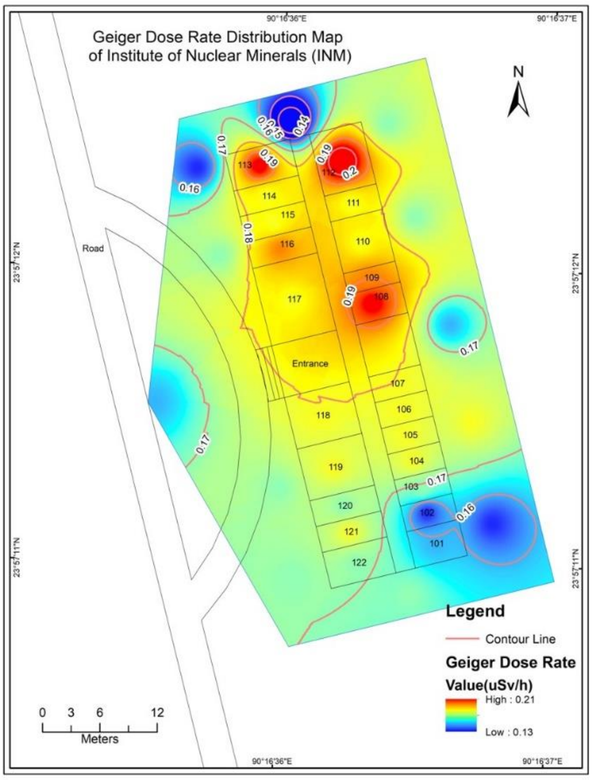

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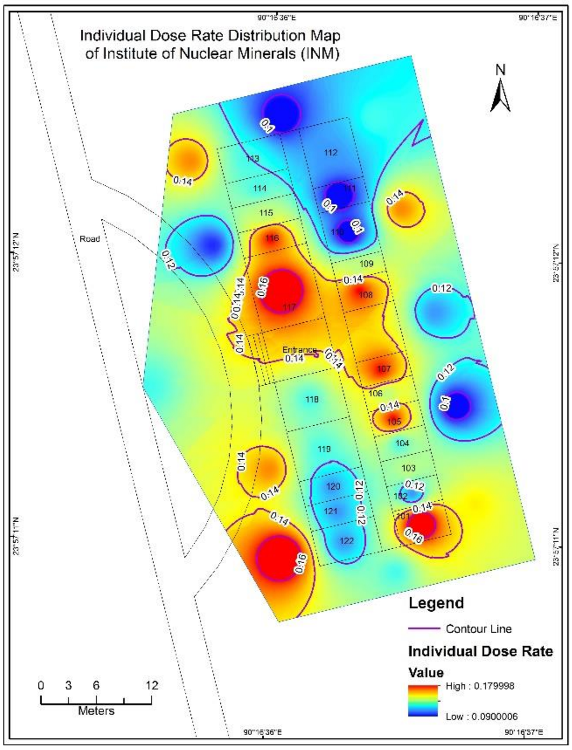

c

Figure 3. (a) Gamma Dose rate distribution Map, (b) Geiger counter Dose rate distribution Map, and (c) personal dosimeter Dose rate distribution Map.

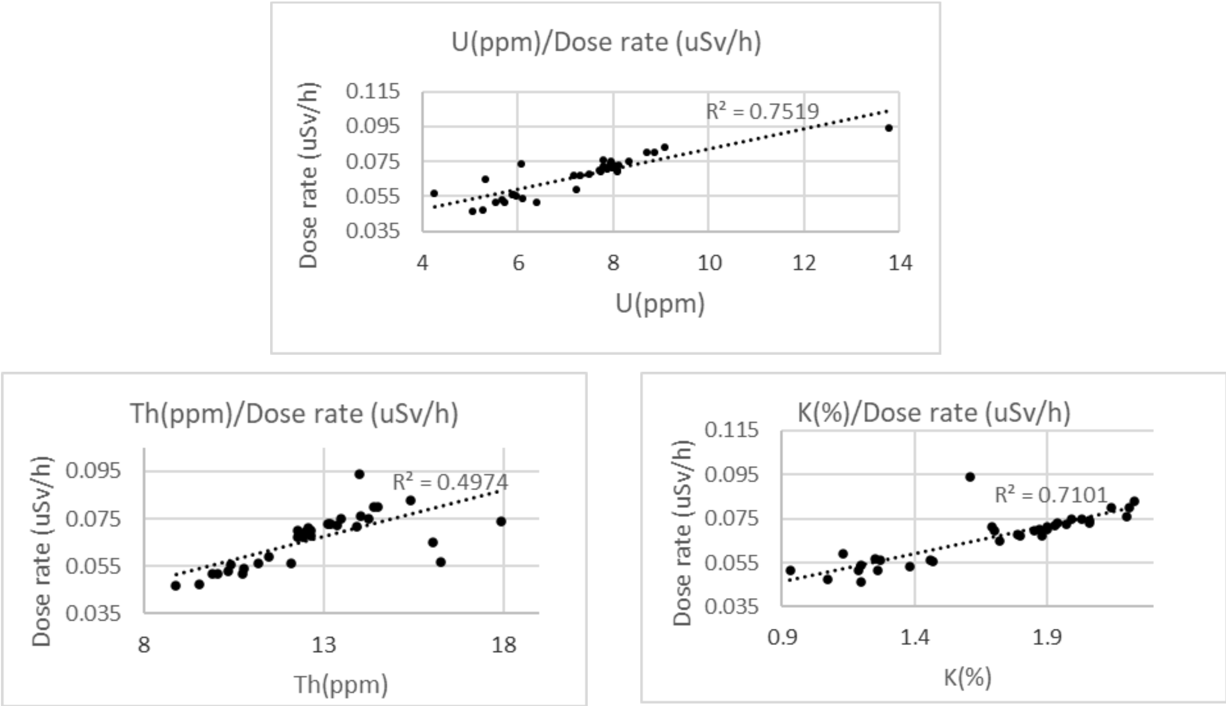

Figure 04. Correlation of elemental concentrations (U, Th and K) with absorbed Dose rate (Gamma)

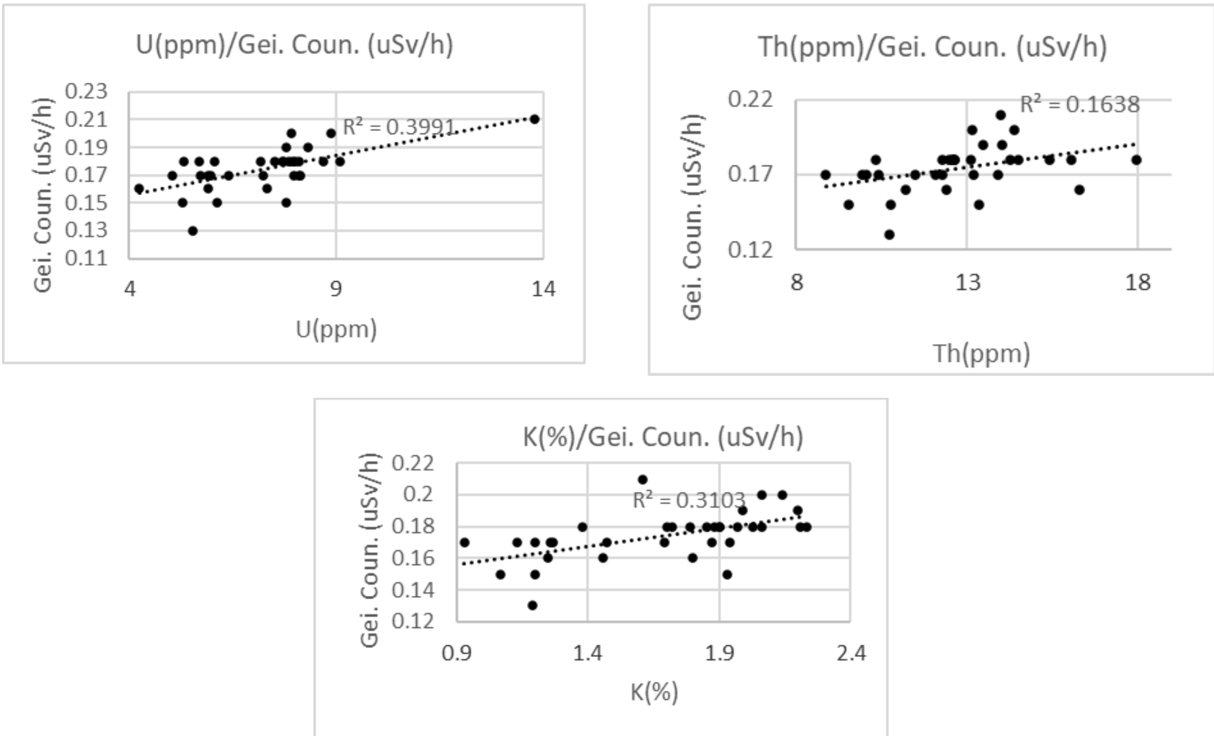

Figure 05. Correlation of elemental concentrations (U, Th and K) with Absorbed Dose rate (Geiger)

IV. Discussion

Generally, exposure to low-levels of radiation does not cause immediate health effects, but that can cause a small increase in the risk of cancer over a longer period of time. Many studies show that radiation exposure increases the chance of getting cancer, and the risk increases as the dose increases. Conversely, cancer risk from radiation exposure declines as the dose falls.

In the present scenario, the measured Ra_{eq} ranged from 142 to 290 $Bqkg^{-1}$ with an average of 203 $Bqkg^{-1}$. Average Ra_{eq} value exceeded measured value at Dhaka, 156 Bq/kg (Miah et al. 1998) but fell below the permissible maximum of 370 Bq/kg. The absorbed dose rates, as indicated in (Table 1), from gamma surveyor, vary from 0.066 to 0.134 µSv/h with the average value of 0.094 µSv/h, these values exceeded the accepted limit 0.055 µSv/h (UNSCEAR 2000) and measured value 0.073 µSv/h at Dhaka. The highest rates of absorbed dose are observed in S-112 from both gamma surveyor and geiger counter where ^{226}Ra concentrations is uppermost. Furthermore, the study identifies the peak concentration of ^{232}Th in sample no S-104 whereas maximum potassium concentration was found in S-105 location.

Table 02. Component matrix of absorbed dose rate and associated hazard parameters with activity concentration

Component Matrix[a]

Particulars	Components		
	Factor 1	Factor 2	Factor 3
C_{Ra}	.861	-.080	-.179
C_k	.837	.091	.262
C_{Th}	.691	-.046	.467
Ra_{eq}	.989	-.041	.121
DR_{gam}	.990	-.035	.117
DR_{gei}	.775	.085	-.561
DR_{per}	.050	.996	.049
$AEDE_{gam}$	.990	-.035	.117
$AEDE_{gei}$	.775	.085	-.561
$AEDE_{per}$	.050	.996	.049
H_{ex}	.989	-.041	.121
H_{in}	.971	-.058	.007

Extraction Method: Principal Component Analysis.
a. 3 components extracted.

Where,

C_{Ra}, C_{Th}, and C_K are activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively
Ra_{eq} is radium equivalent activity concentration index
DR_{gam}, DR_{gei} and DR_{per} are absorbed dose rate, measured by gamma surveyor, geiger counter and personal dosimeter respectively
$AEDE_{gam}$, $AEDE_{gei}$ and $AEDE_{per}$ are annual effective dose equivalent calculated by gamma surveyor, geiger counter and personal dosimeter values, respectively
H_{ex} is external hazard index, and
H_{in} is an internal hazard index.

The annual equivalent dose values ranged between 0.09 and 0.19 mSv/y, averaging 0.13 mSv/y for the gamma surveyor. For the geiger counter and personal dosimeter, the respective values were 0.18 to 0.29 mSv/y and 0.13 to 0.25 mSv/y, with averages of 0.24 mSv/y and 0.18 mSv/y. These readings for all instruments slightly exceeded the global average of 0.07 mSv/y for annual effective dose. The external hazard index values (presented in Table 1) ranged from 0.39 to 0.78, with a mean of 0.55. Internal hazard index values varied between 0.55 and 1.24, averaging 0.79. Notably, all external and internal hazard indices were below the globally permissible value of 1 (UNSCEAR 2000), except for the internal hazard index at the S-112 location, which recorded a value of 1.24.

A Bivariate Pearson correlation matrix was conducted to examine the association among the concentration of radioactivity and absorbed dose rate and associated health hazard indices such as radium equivalent activity concentration, annual effective dose equivalent, external and internal hazard index. The component matrix, revealing factor loadings of the examined variables, indicates the presence of three distinct factors. Factor 1 encompasses C_{Ra}, C_{Th}, C_K, Ra_{eq}, DR_{gam}, $AEDE_{gam}$, H_{ex} and H_{in} whereas factor 2 includes DR_{per} and $AEDE_{per}$ fall under factor 2 and factor 3 comprises $AEDE_{gei}$ and DR_{gei} (Table 02, Figure 06).

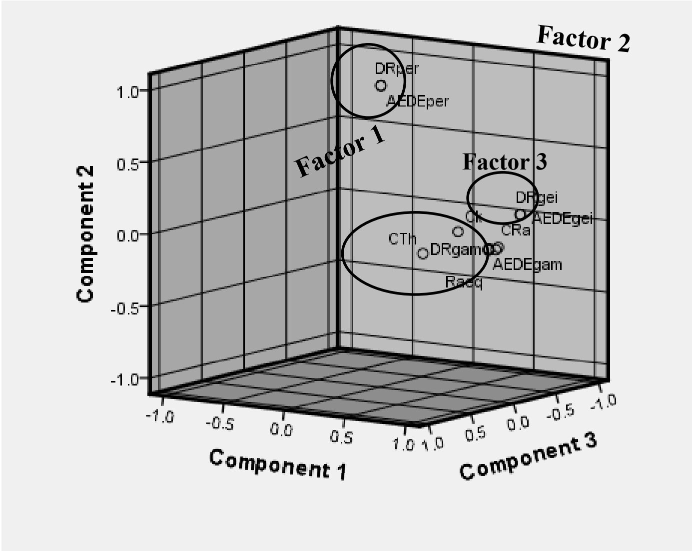

Figure 06. Radioactivity concentration and associated health hazard indices fell into three factors in component matrix

The outcomes of Pearson's correlation of radioactivity concentration, absorbed dose rate and its associated health hazard index express some substantial positive and negative connections among the measured parameters (Table 03). The positive correlation indicates gamma surveyor measured dose rate considering only radioactivity from uranium, thorium and potassium whereas negative values depict that personal dosimeter measured not only radiation of ^{238}U, ^{232}Th, and ^{40}K but also radiation from other sources.

Table 03. Pearson correlation coefficients for radioactive variables within the analyzed samples

	C_{Ra}	C_{Th}	C_k	DR_{gam}	DR_{gei}	DR_{per}	Ra_{eq}	$AEDE_{gam}$	$AEDE_{gei}$	$AEDE_{per}$	H_{ex}	H_{in}
C_{Ra}	1											
C_{Th}	.314	1										
C_k	.55**	.67**	1									
DR_{gam}	.87**	.70**	.84**	1								
DR_{gei}	.63**	.41*	.56**	.68**	1							
DR_{per}	-0.019	-0.005	0.12	0.02	0.08	1						
Ra_{eq}	.87**	.71**	.83**	1.0**	.68**	0.019	1					
$AEDE_{gam}$	.87**	.703**	.84**	1.0**	.68**	0.024	1.0**	1				
$AEDE_{gei}$	.63**	.405*	.56**	.67**	1.0**	0.082	.68**	.68**	1			
$AEDE_{per}$	-0.019	-0.005	0.12	0.02	0.08	1.0**	0.019	0.03	0.08	1		
H_{ex}	.87**	.71**	.83**	1.0**	.68**	0.019	1.0**	1.0**	.68**	0.019	1	
H_{in}	.95**	.58**	.75**	.98**	.68**	0.005	.98**	.98**	.68**	0.005	.98**	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

In the current study, the use of GIS software allowed researchers to map and visualize the patterns of radiation on the INM. The analysis indicated that specific locations, such as the sample store room and the overall northern area, had noticeable concentrations of radiation dose rate. This is particularly noteworthy in the case of the store room, where unprocessed radioactive minerals were found to be a significant source of this heightened radiation, additionally, the northern side of INM, as illustrated in Fig. 4, also displayed concentrated radiation dose rate. The presence of radioactive minerals such as zircon and monazite in S-104 location, suggests that there are likely to be areas with higher concentrations (Rajib et al. 2019) of these radioactive materials, mainly thorium as depicted in Figure 3b.

According to Carvalho et al. (2011), heavy minerals incorporate ^{226}Ra and ^{232}Th radionuclides within their crystal building, however light portions such as quartz and feldspar may exhibit relatively elevated levels of ^{40}K. The plausible explanations for increased activity concentration comprise samples collected from the southeastern coastal region of Bangladesh as well as radioactive minerals in both recent and ancient dune areas and different formations in Jaintiapur, located within the Dauki Fault Belt (DFB) zone. This zone lies near the Mahadek uranium belt on the southern edge of the Shillong plateau. Furthermore, naturally occurring radioactive minerals from the southeastern coastal region of Bangladesh, where sands contain an average of 23% heavy minerals (Bari et al. 2003; BSMEC 2003).

The observed dose rates from several dosimeters were found to be in the range of 0.09-0.21 μSv/h. The distribution of radioactivity showed that the laboratories and/or rooms which have various geological samples pose higher radioactivity and corresponding dose ranges. Before processing those samples, they are usually kept in the sample store where radioactivity was found higher than average. In addition, higher dose rates can also be observed from the uncovered building materials, e.g., old mosaic materials at floors of the building.

Correlation expresses the connections among the sets of radiation hazard indices and to investigate the connections between variables and causative factors, aiming to identify the origins of the analyzed elements. Gamma dose rate has a very strong correlation with radioactivity concentration of ^{238}U, ^{232}Th, and ^{40}K (significance level, $p < 0.01$) whereas geiger counter showed significant correlation with ^{232}Th ($p < 0.05$) albeit to having very strong correlation with uranium and potassium. Negative correlation was noticed among dose rates from personal dosimeters with concentration of ^{238}U and ^{232}Th. Furthermore, the dose rate from the geiger counter showed a significant strong correlation with the gamma dose rate although there is no strength of gamma and geiger dose rate with those of personal dosimeters. Annual effective dose rate (AEDE) from gamma surveyor and geiger counter, radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}) and internal hazard index (H_{in}) all have very strong positive correlation with radioactivity when significance level, $p < 0.01$. Only AEDE of personal dosimeters showed insignificant correlation whereas negative correlation with uranium and thorium though strong relation with dose rate of this instrument. Moreover, insignificant relationships suggest that the courses of these pathways are not dependent on one another and probably derived from various origins. The radiation detected in the study area is likely to have originated from a variety of sources, encompassing elements derived from sample processes, construction materials used in buildings, and the weathering of rocks and minerals.

Excessive exposure to ionizing radiation has adverse health effects although the radiation cannot be seen, felt or sensed by the human body in any way. Therefore, radiation measuring instruments are required in order to monitor the presence of such radiation and avoid excessive exposure to the occupational workers as well as the general public. Suitable and effective use of monitoring instruments enables exposures to be controlled so that the doses received can be kept following ALARA (as low as reasonably achievable) principle.

There are two categories of health hazards linked to radiation exposure. Short-term health consequences encompass symptoms like nausea, vomiting, skin reddening, hair loss, minor burns, and cellular and molecular damage. In contrast, long-term health impacts encompass issues such as tissue and organ function impairment, fertility damage, radiation-induced burns, cancer development, and even fatality. A comprehensive investigation into the process of measuring radioactivity levels plays a crucial role in ensuring the safety of individuals exposed to radiation in a workplace setting. This systematic study involves the careful examination and assessment of radiation levels and is essential for effective radiation protection measures.

The advised dosage thresholds, as per the International Commission on Radiological Protection (ICRP) guidelines from 2007, stipulate that the maximum permissible dose for occupational workers, averaged over a defined 5-year period, is 20 millisieverts per year for whole-body exposure. Conversely, the dose limit for non-occupational individuals stands at 1 mSv/yr. As a result of the study, it was found that the dose rates are within the allowable limit as regularly monitored by Thermoluminescence Dosimeter (TLD) for the employees of INM. Moreover, the risk of radiation exposure for the staff working at the mineral processing laboratory of INM is at a minimum level. This low risk is ensured by keeping the minerals stored at a considerable distance from the areas where work is regularly conducted. This approach aligns with the ALARA principle, which emphasizes minimizing radiation exposure as much as possible. In other words, by maintaining a safe distance between minerals and workspaces, the study has demonstrated that the radiation safety for personnel in these facilities is effectively optimized.

In the analysis of radiological hazards, it was observed that the absorbed dose rate and annual effective dose rate in the examined samples surpassed the established limits for radiological safety, and all elements exhibited radioactivity exceeding standard thresholds. While the radium equivalent activity and external/internal hazard indices fell within the globally recommended average values (Table 01), it is essential not to dismiss their significance. This is particularly crucial considering the application of the Linear No Threshold Model (LNT), which suggests that there is no threshold for the occurrence of cancer. Consequently, even at low doses, there remains a risk of cancer development (Siraj et al. 2023) as occupational workers spend at least 8 hours/day in different labs and rooms.

Therefore, the measured data is useful for future perspective, especially in tomorrow's radiation distribution study which has a broad aspect covering the whole area of Atomic Energy Research Establishment.

Many policies, regulations, and practices are recommended by ICRP to limit harmful radiation at workplaces. These guidelines follow three fundamental principles: justification, optimization, and dose limitation. In essence, it is crucial to perform worker monitoring for all individuals employed in radiation zones. Well-established procedures and practices need to be followed at those areas specifically to effectively manage and control radiation exposures. In instances where radiation is utilized in other areas, ongoing assessment of working conditions is recommended, although specific protocols may not be essential. Continuous observation of employees is advisable unless it is confirmed that their radiation doses will be consistently low.

V. Conclusion

A comprehensive investigation into the assessment of radioactivity levels and their associated health hazards is vital for safeguarding against radiation exposure in a workplace setting. This survey at INM, conducted for the first time, not only highlights the immediate radiation concern but also lays the groundwork for a broader initiative that can be expanded to encompass all institutions engaged in radiation research at the AERE. The implications of these findings are significant, particularly for occupational radiation safety. By establishing baseline data for radioactivity levels, this research can inform policies aimed at improving health management practices for staff. Although employees of INM are regularly monitored using Thermoluminescence Dosimeter (TLD), further enhancement in safety protocols are essential. It is recommended that training programs can be implemented to systematically instill the ALARA principles among workers, emphasizing strategies such as maximizing distance from radiation sources and minimizing exposure time with NORMs. Moreover, the current study provides a foundation for continuous monitoring of radiation levels in research institutions, which is critical for ongoing health risk mitigation. Future research should focus on longitudinal studies to assess changes in radioactivity over time and evaluate the effectiveness of implemented safety measures. Additionally, policy developments should prioritize the integration of radiation safety training for all employees and regular reviews of monitoring protocols to ensure the highest standards of occupational safety. This initiative is not only beneficial for staff but also plays a crucial role in managing the health risk for hundreds of visitors who frequently visit these institutions for academic and professional activities. By fostering a culture of safety and awareness, we can better protect all individuals interacting with radiation-prone environments.

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