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ASSESSMENT OF NATURAL RADIOACTIVE NUCLIDES VARIABILITY AND DISTRIBUTION IN SOILS OF POKHARA, NEPAL

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ABSTRACT

The purpose of this study is to determine the radioactivity concentrations of K-40, Th-232, U-238, and Radiological Equivalent (Ra_{eq}) in soil samples from Pokhara, Nepal. The measurements were performed using a NaI(Tl) detector and Gamma Vision software. The results show that the average radioactivity concentrations of K-40 were detected at 463.00 Bq/kg, Th-232 at 69.20 Bq/kg, and U-238 at 52.80 Bq/kg. Based on these concentrations, the average radioactivity concentration, Ra_{eq}, was determined at 187.00 Bq/kg, which is less than the UNSCEAR safety limit of 370 Bq/kg. The average external index (H_{ex}) and average internal hazard index (H_{in}) derived from measurements of K-40, Th-232, and U-238 were 0.51 and 0.65, respectively, which is less than the global average of 1. The average H_{ex} and average H_{in} derived from measurements of K-40, Th-232, and U-238 was 0.51 and 0.65 respectively, which is less than the global average of 1. The Annual Effective Dose Equivalent (AEDE) was computed based on measurements 0.11-0.13, which remained below the global average limit of 1 mSv/year. The measured result yielded an estimated Excess Lifetime Cancer Risk (ELCR) of 0.39-0.44 × 10^{-3}, somewhat higher than the recommended range of 0.29 × 10^{-3}. The standard error for all measurements in this study is ±0.043 counts per minute.

Keywords: *Radioactivity, soil samples, Pokhara, Nepal, natural radionuclides, K-40, Th-232, U-238*

1. INTRODUCTION

Gamma radiation from natural radioisotopes like K-40, Th-232, and U-238 is humans' main source of external radiation. This radiation comes from trace amounts in soil and rocks. The amount of radiation varies based on the region's geology and geography, affecting how much exposure people get from the environment. A study in Baghdad gathered soil samples from several sites and held them for one month to stabilize the radioactive levels before measuring them. Six radionuclides were discovered: Bi-214, Ra-226 (from the U-238 series), Tl-208, Bi-212, Pb-212 (from the Th-232 series), and K-40 (natural occurrence). The lowest measured activity was Tl-208 at 0.735 Bq/kg, whereas the highest was K-40 at 21.276 Bq/kg. The external radiation dosage from Baghdad soils was measured at 0.325 mSv/year, significantly below UNSCEAR's acceptable limit of 1 mSv/year [1].

The United Nations Scientific Committee [2] reported that the average outdoor gamma radiation dosage is 54 nGy/hr, and interior levels are approximately 20%. United Nations Scientific

Committee [2] reported average outdoor gamma radiation dosage is 54 nGy/hr and interior levels approximately 20%. The radiation exposure occurs in two ways: externally (K-40, Th-232, and U-238) and internally (radon gas). Radon, a colorless, odorless radioactive gas, can emit alpha particles that harm lung tissue and may cause cancer. People spend more than 80% of their time indoors, so radiation protection is needed for us [3]. Several studies have examined radiation levels in various countries, indicating disparities in hazards and concentrations. Bakshi et al. [4] studied background radiation in topsoil around Bharati Station in Antarctica and reported gamma radiation. Ji et al. [5] developed a model that linked gamma dose rates to radium activity around uranium mines. Abbasi [6] discovered high radiocesium and iodine levels in Turkey following the earthquake near the Akkuyu plant. Onda et al. [7] reported inadequate decreases in soil radioactivity at Fukushima. Ghias et al. [8] and Ugbede et al. [9] reported high radioactivity levels in soil from Dera Ghazi Khan and Nigerian rice fields. Osman et al. [10] found elevated levels of Ra-226 and K-40 in South Nile Delta industrial soils.

The NaI(Tl) detector at the Nepal Academy of Science and Technology (NAST) is critical to radiation research in Nepal. Key operations include measuring radiation exposure from terrestrial sources utilizing environmental samples. River sediments in the Kathmandu Valley were studied, and considerable radiation was discovered [11]. Soil studies have supplied critical data on regional exposure [12], while research on construction materials such as cement and bricks aids in assessing building-related radiation dangers [13]. The average annual effective dose (AED) in Kathmandu Valley is approximately 0.475 mSv/yr, with a range of 0.391–0.661 mSv/yr [14]. Background radiation in Bagmati Province averages 0.025 mR/hr [15]. Regional variations include a lower dose in Morang (0.24 mSv/yr) and a higher dose in Pokhara Valley (0.81 mSv/yr) [16, 17]. Continuous monitoring is essential to understand and reduce radiation risks. The study of soil radioactivity in Pokhara Valley is critical due to several factors influencing public health and the city's socioeconomic stability.

Current studies in Nepal have primarily focused on larger areas, leaving a scarcity of detailed data on natural radionuclide concentrations in the Pokhara Valley. Pokhara Valley is densely populated and important as a tourist destination. Elevated amounts of radionuclides in the soil, such as K-40, Th-232, and U-238 are needed because high-level radionuclides impact the inhabitants. Furthermore, the fertile agricultural plains of Pokhara may absorb radioactive elements, pollute food supplies, and jeopardize consumer health. Regular monitoring of soil radioactivity in Pokhara not only aids in the early discovery of potential health problems. It also promotes sustainable tourism and urban growth while protecting the well-being of its citizens. This study provides public awareness, helps in policies, improves safety standards, and protects the city's environment and economy.

2. METHODOLOGY

2.1. Study Area

Pokhara is a major city in central Nepal that is both the capital of the Gandaki Province and the country's tourism hub. The altitude varies from 780 meters in the south to 1350 meters in the north. Pokhara's coordinates are 28.26 degrees latitude and 83.97 degrees longitude. With 599,504 residents who lived in 120,594 households in 2021. It is also the second-most populated city in Nepal after Kathmandu. Western Nepal is regarded as one of the world's most disaster-prone natural disaster areas. In terms of land area, it is the biggest metropolitan city in the nation. Kaski District's headquarters are located in the city. Pokhara, a base for hikers taking the Annapurna Circuit across the Annapurna Nature Conservation Area region. It also includes the Annapurna ranges in the

Himalayas, which was named Nepal's tourism capital in 2024. Studying the radioactivity found in Pokhara's soil is essential because of the city's dense and crowded population.

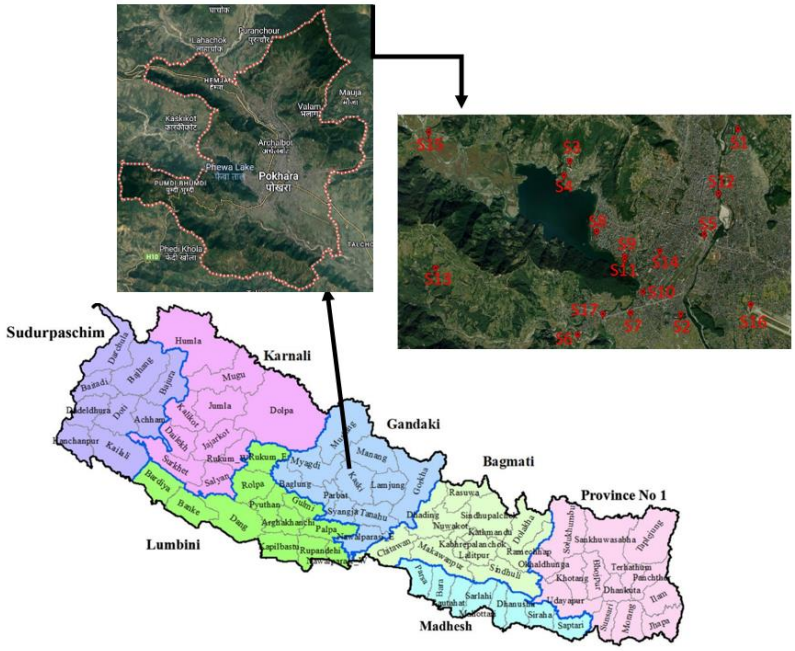

Fig. 1: Sample collection area for radiation research.

Pokhara's geology is diversified, consisting of Precambrian metamorphic rocks such as sandstones, shales, dolomites, quartzites, schists, and gneisses, particularly north of the Main Central Thrust. The region also contains Paleozoic phyllites, schists, and marine calcareous metasediments near the South Tibetan Detachment Zone. The Pokhara Formation, formed by sediment deposition from the Seti Khola River, is made up of coarse sediments from significant debris flow events. The Begnas and Rupa basins also contain loamy to sandy gravel, silt, and clay deposits supplied from the Annapurna range. Pokhara's unique intramontane valley demonstrates developing Himalayan landforms, which contribute to the spectacular panoramas of mountains, lakes, and canyons [18].

2.2. Collection and preparation of samples

Seventeen risk-based soil samples were assembled from various locations within Pokhara, Nepal, focusing on areas with high population density. These samples were collected for research purposes by replacing the top 5 cm of soil and sealing them in plastic bags. The sample was transported to the NAST in Lalitpur, Nepal. Each sample was selected from different risk-based sites within Pokhara city. Upon arrival at the NAST, the samples were dried indoors for five days to ensure grain size uniformity and remove organic waste. Sieves with 1mm x 1mm were used for this purpose. After separating organic waste and ensuring consistent grain size, the samples were heated in an oven at 150°C for 2 hours. Following heating, the samples were cooled to standard atmospheric temperature and pressure. Once cooled, each sample was placed in a Marinelli beaker, accurately weighing 0.5 kg using an electronic scale. The beakers were tightly sealed and undisturbed for 30 days to achieve

secular equilibrium. Secular equilibrium is essential before testing soil samples for radionuclides because it ensures accurate measurement of radioactive elements and their decay products. In natural radioactive series such as U-238 and Th-232, the parent isotopes decay very slowly, while their daughter products decay much faster. Suppose the sample is measured immediately after preparation. In that case, the daughter isotopes may not have built up to a stable activity level relative to their parent isotopes, leading to incorrect or underestimated results. By allowing the sealed samples to sit undisturbed for about 30 days, the activities of the parent and daughter radionuclides reach equilibrium, meaning the rate of decay of the parent equals the rate of production and decay of the daughters. This equilibrium condition provides consistent gamma emissions, allowing the detector to measure the actual radioactivity and obtain reliable data on the concentrations of U-238, Th-232, and K-40 in the soil.

Table 1: Coordinates of location samples for the present study

Sample code	Place name	Latitude	Longitude
S1	Nepal SBI Bank Limited ATM	28.245^0	83.997^0
S2	International Mountain Museum	28.189^0	83.981^0
S3	NG Rest house	28.227^0	83.949^0
S4	Gusto Accommodation	28.224^0	83.947^0
S5	Prithiv Rajmarga Bus Ticket Counter	28.209^0	83.987^0
S6	Furke Khola Bridge	28.184^0	83.951^0
S7	Balodaya Secondary School	28.189^0	83.966^0
S8	Da Yatra St	28.210^0	83.957^0
S9	LK Park	28.204^0	83.965^0
S10	Dam Side	28.195^0	83.970^0
S11	Basundhara Park	28.203^0	83.965^0
S12	Seti Garden River	28.219^0	83.991^0
S13	Thulidbidi Ekikrit Krishi Farm	28.201^0	83.911^0
S14	Rastra Bank Chowk	28.205^0	83.975^0
S15	Pame	28.235^0	83.909^0
S16	BG Soap Industries and Chemical Supplier	28.191^0	84.001^0
S17	Devis Fall Pokhara	28.189^0	83.958^0

2.3. Experimental Method

After the samples achieved secular equilibrium, the NaI(Tl) detector system was calibrated using a Co-60 source with two characteristic energy peaks at 1173 keV and 1332 keV. The calibration ensured that the observed peaks aligned accurately with the centroid energies in the reference library data. This alignment confirmed that the system was calibrated correctly and ready to measure the radionuclide activities in the samples. The calibration time with Co-60 during the measurement is 30 minutes. The experiment was conducted at the Physical Science Unit of the NAST, utilizing the NaI(Tl) detector in conjunction with the Gamma Vision software version. This study chose the NaI(Tl) detector for its higher efficiency, cost-effectiveness, and reliability in environmental radioactivity measurements when properly calibrated. The Gamma Vision software accurately resolves and quantifies gamma-ray peaks of daughter nuclides such as Bi-214, Pb-214, Ac-228, and Tl-208, ensuring reliable determination of parent radionuclide activities (U-238 and Th-232).

The activity of Th-232 and U-238 was calculated using (Bi-214, Tl-208, Pb-212, Ac-228, Pb-214) with their respective decay chains, for Th-232 (Tl-208, Ac-228, and Pb-212) and for U-238 (Bi-214 and Pb-214). After measuring Bi-214, Tl-208, Pb-212, Ac-228, and Pb-214, the average value of the concentration of U-238 and Th-232 using the corresponding chains was tabulated in Table 2. Initially, we determined K, Tl, Ac, Pb, and Bi activity concentrations using the loaded library and Gamma Vision software for each sample. Subsequently, the decay chain relationships separate the daughter nuclei of Th-232 and U-238, enabling the calculation of the amounts of Th-232 and U-238. Radiological hazard parameters such as Ra_{eq}, internal hazardous index (H_{in}), and outer hazardous index (H_{ex}) were calculated using Eqs. (1), (2), and (3) respectively [19-20]. The Ra_{eq} is calculated using the specific activities of K-40 (A_K) Th-232 (A_{Th}), and U-238 (A_U) as shown in Eq. (1):

$$Ra_{eq}\left(\frac{Bq}{kg}\right) = 0.077A_K + 1.43A_{Th} + A_U \tag{1}$$

In equation (1), AK is the average of K-40, ATh is the average of Th-232, and AU is the average of U-238. This equation ensures that the radium equivalent activity provides a standardized measure for comparing the radiological hazards associated with different materials. The coefficients 1.43 and 0.077 adjust for the radiotoxicity and gamma-radiation of thorium and potassium relative to uranium. The H_{in} and H_{ex} hazard indices are used to evaluate the potential radiological health risks posed by the materials, and less than or equal to 1 is considered safe for use in construction. Internal and external hazard indices are given in the equation below [21].

$$H_{in} = \frac{A_K}{4810} + \frac{A_{Th}}{259} + \frac{A_U}{185} \leq 1 \tag{2}$$

$$H_{ex} = \frac{A_K}{4810} + \frac{A_{Th}}{259} + \frac{A_U}{370} \leq 1 \tag{3}$$

These equations account for the exposure risks from radioactive materials, both when incorporated into structures and when present in living environments. The Absorbed Dose Rate in Air (D_γ) is calculated to assess the exposure to gamma-radiation from the materials. It is given by equation (4),

$$D_\gamma\left(\frac{nGy}{h}\right) = 0.0432A_K + 0.662A_{Th} + 0.462A_U \tag{4}$$

This equation uses specific activities to determine the dose rate, reflecting the different contributions of uranium, thorium, and potassium to the gamma-radiation dose. The AEDE quantifies the annual radiation dose received by individuals, both outdoors and indoors [2]:

$$AEDE_{in}\left(\frac{mSv}{y}\right) = D_\gamma \times 8760 \times 0.8 \times 0.7 \times 10^{-6} \tag{5}$$

$$AEDE_{ex}\left(\frac{mSv}{y}\right) = D_\gamma \times 8760 \times 0.2 \times 0.7 \times 10^{-6} \tag{6}$$

Here, 8760 is the number of hours a year, 0.2 and 0.8 are the occupancy factors for outdoors and indoors, respectively, and 0.7 is the dose conversion factor. The ELCR is calculated using the formula [23]:

$$\mathrm{ELCR} = \mathrm{AEDE} \times \mathrm{DL} \times \mathrm{RF} \times 10^{-3} \tag{7}$$

where AEDE, DL, and RF are annual effective dose equivalent, duration of life (70 years), and risk factor (0.05 Sv^{-1}), respectively.

2.4. Calculation of Standard Deviation

The following formula was used to determine the net count rates' standard deviation to assess the collected data:

$$\sigma_r = \sqrt{\frac{G}{t_G^2} + \frac{B}{t_B^2}} \tag{8}$$

In this context, G represents the total number of gamma-ray counts detected from the soil samples during the measurement period t_G. Similarly, B represents the total number of gamma-ray counts detected from the background radiation during the measurement period, t_B is 6 hours. The counting time for soil samples is 6 hours; t_G refers to the duration over which the soil sample measurements were taken. Longer counting times generally improve the statistical accuracy of the measurement. Likewise, t_B refers to the duration over which the background radiation measurements were taken. As with the soil sample counting time, a longer duration for background measurements helps obtain a more accurate estimate of the background radiation [24]. Table 2 lists the energy peaks that detect specific radioactive elements in soil samples. For instance, K-40 is identified at an energy peak of 1461.00 keV, while Ac-228 is detected at 911.21 keV. Similarly, Tl-208, Pb-214, Pb-212, and Bi-214 are detected at 583.19 keV, 351.92 keV, 238.63 keV, and 609.13 keV, respectively. These energy peaks help accurately measure the activity levels of these radionuclides in the soil.

Table 2: Energy peak used in the measurement of the activity of soil

Element	Energy Peak (keV)
K-40	1461.00
Ac-228	911.21
Tl-208	583.19
Pb-214	351.92
Pb-212	238.63
Bi-214	609.13

The energy calibration of the detector system used for measurements was performed using a Co-60 source with an initial activity (A_0) of 1 μCi at the time of manufacture in 2017, and its activity in 2024, considering a half-life of 5.27 years, is calculated to be approximately 0.350 μCi with a standard deviation of 0.059 μCi during the measurement. The activity calculations were based on the radioactive decay law $A=A_0\times e^{-\lambda t}$, where λ is the decay constant derived from the half-life Co-60. These calculations ensure accurate calibration and quantification of the detector's performance, accounting for the decay characteristics of the standard source.

3. RESULTS AND DISCUSSION

3.1. Radioactive Concentration of K-40, Th-232, U-238 and Ra_{eq}

The K-40 radioactivity concentrations vary greatly, with S9 having the highest amount at 560.00 Bq/kg, followed by S10 at 540.00 Bq/kg. This suggests a significant K-40-related radiological impact (Fig. 2a). The average radioactivity concentration for K-40 is 463.53 Bq/kg. Compared to prior research in Nepal, such as Lamichhane et al. [12], which found a range of 342.50 to 897.71 Bq/kg in soil of Kathmandu valley. This shows that the areas sampled for this study have lower natural K-40 radioactivity than other parts of Nepal. Th-232 radioactivity concentrations range from 45.90 Bq/kg (S15) to 109.00 Bq/kg (S10), with an average of 69.21 Bq/kg, which is much higher

than the UNSCEAR 2010 limit of 33 Bq/kg. It is also different and higher from eastern 42.6 [13] and Kathmandu 69.59 [13] of Nepal. All samples (S1–S17) exceed this limit for Th-232, as shown in Fig. 2b. U-238 radioactivity concentrations range from 32.10 Bq/kg (S15) to 73.30 Bq/kg (S10), with an average of 52.80 Bq/kg, which is somewhat higher than the recommended 45.00 Bq/kg level. Only samples S6, S8, S12, and S15 fall below this limit. In contrast, the others surpass it, as illustrated in Fig. 2c. The Raeq values differ significantly, indicating various radiological dangers (Fig. 2d), with S10 having the highest (270.74 Bq/kg) and S8 having the lowest (152.18 Bq/kg). The average Raeq across all 17 soil samples is 187 Bq/kg, indicating that Raeq does not exceed safe levels as shown in Table 3. Figure 2d illustrates further details.

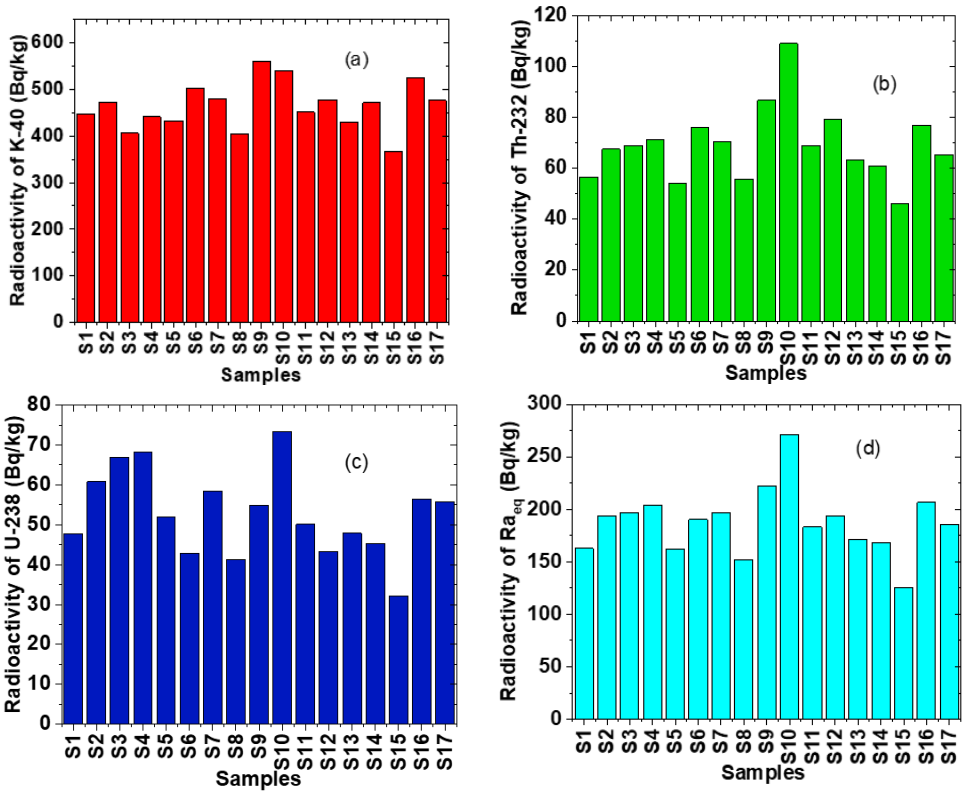

Fig. 2: Radioactive concentration of (a) K-40, (b) Th-232, (c) U-238 and (d) Ra_{eq} in different samples collected from Pokhara.

Table 3 is the comparative study of the measurements of each sample and its validation with previous work. K-40 levels range from 366.00 Bq/kg to 560.00 Bq/kg, with S9 and S10 displaying the highest concentrations. Th-232 concentrations span from 45.90 Bq/kg to 109.00 Bq/kg, with S10 again showing notably high levels. Similarly, U-238 concentrations vary from 32.10 Bq/kg to 73.30 Bq/kg, with sample S10 exhibiting the highest values. The activity concentration is higher in various areas of Pokhara. Implementing exposure minimization strategies and conducting regular environmental and health monitoring could be beneficial. Public awareness campaigns to educate the local population about potential risks and safety measures would also help promote their well-being.

Table 3: Radioactivity concentration on different samples of Pokhara soil

Sample	Present Work				SD (counts per minute)
	K-40 (Bq/kg)	Th-232 (Bq/kg)	U-238 (Bq/kg)	Ra_{eq} (Bq/kg)	
S1	446.00	56.50	47.70	162.84	0.05
S2	473.00	67.50	60.80	193.74	0.04
S3	406.00	68.90	66.90	196.68	0.04
S4	441.00	71.30	68.10	204.00	0.04
S5	432.00	54.00	52.00	162.47	0.04
S6	502.00	76.00	42.90	190.23	0.04
S7	479.00	70.60	58.40	196.25	0.04
S8	405.00	55.70	41.30	152.11	0.04
S9	560.00	86.70	54.80	221.91	0.05
S10	540.00	109.00	73.30	270.74	0.05
S11	450.00	69.00	50.10	183.46	0.04
S12	477.00	79.30	43.30	193.43	0.04
S13	430.00	63.30	47.90	171.53	0.04
S14	471.00	60.80	45.30	168.50	0.04
S15	366.00	45.90	32.10	125.93	0.04
S16	526.00	76.80	56.40	206.70	0.05
S17	476.00	65.30	55.70	185.72	0.04
Average	463.53	69.21	52.80	187.43	0.04
Reference					
[25]	100–700	7–50	16–116	-	
[26]	-	-	-	370	-
[27]	279.58 - 964.62	53.680-161.030	20.130-60.400	-	-

The activity levels of natural radionuclides and manufactured caesium in soil and leafy plants in Al-Yusiefya were determined using a NaI (Tl) detector. The average activity concentrations in the veggies were K-40 (283±93 Bq/kg), Th-232 (14.8±4.7 Bq/kg), U-238 (12.4±3.8 Bq/kg), and Cs-137 (1.06±0.99 Bq/kg). In soil samples, the amounts were slightly greater. Radiation hazard indicators (radium equivalent, external hazard index, etc.) were within safe levels, except lifetime cancer risk. K-40 had the most significant transfer factor from soil to plants, measuring 1.02±0.30 [28]. The Raeq readings for building materials average 50.68 Bq/kg, which is significantly lower than the recommended limit of 370 Bq/kg [2]. Gamma-ray spectrometry was used to determine the K-40, Th-232, and U-238 activity levels in building materials. K-40 concentrations averaged 831 ± 42 Bq/kg. U-238 has an average of 378 ± 19 Bq/kg, whereas Th-232 has an average of 290 ± 15 Bq/kg. These values surpass the global requirements of 420 Bq/kg for K-40, 45 Bq/kg for Th-232, and 33 Bq/kg for U-238 [29]. Raeq is used to evaluate the overall influence of these radionuclides, and acceptable values are less than 370 Bq/kg [30].

3.2. Hazard Index Associated with the Soil Sample

The estimated value of H_{in} is based on equation (2) of 17 samples of soil shown in Fig. 3a, and H_{ex} is based on equation (3) as shown in Fig. 3 b. The observations show that the estimated value of H_{in}

is higher than H_{ex} in the corresponding sample. In addition, H_{in} for S10 is found to be 0.93, which is higher among the measured samples and below the–acceptable limit, and the lower 0.43 was measured in S15 among all 17 samples. Similarly, the estimated value of H_{ex} is 0.73, which is higher than the sample and within an acceptable limit, and 0.34. On average, the H_{in} is found to be 0.65, the Hex is found to be 0.51, and both Hin and Hex are within an acceptable limit of 1 [31].

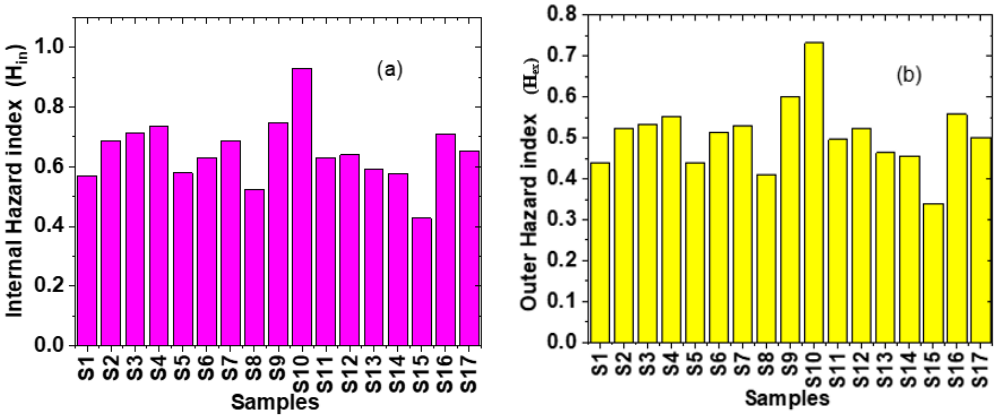

Fig. 3: Hazard index (a) Internal and (b) external associated with the soil sample collected from Pokhara.

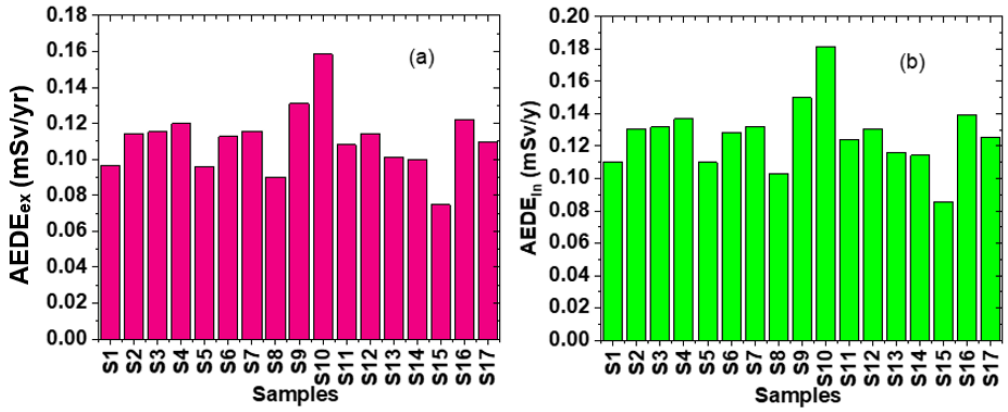

Fig. 4: AEDE (a) outdoor and (b) indoor associated with soil samples collected from Pokhara.

3.3. Annual Effective Dose Equivalent

The AEDE values, both $AEDE_{in}$ and $AEDE_{ex}$, were calculated for each sample to assess radiation exposure and visualized in Fig. 4a and outdoor and Fig. 4b for indoor. $AEDE_{ex}$ values range from 0.075 mSv/y (S15) to 0.16 mSv/y (S10). $AEDE_{in}$ values range from 0.09 mSv/y (S15) to 0.18 mSv/y (S10). Indoor exposure is generally higher than outdoor exposure, with S10 again showing the maximum indoor dose. The average AEDE values (indoor and outdoor) are both well below the UNSCEAR 2008 limit of 1 mSv/y.

An outdoor AED of 0.10 mSv/y to 0.70 mSv/y and an average value for soil was reported as 0.30 mSv/y on Eloor Island, India [32]. In agricultural soils, the Raeq, Dγ, AED rate, as well as H_{ex} were 458.79 Bq/kg, 141.62 nGy/hr, and 0.17 mSv/y; in virgin soils, the corresponding values were 214.29 Bq/kg, 87.47 nGy/hr, and 0.11 mSv/y, with an average H_{ex} of 0.53 [33]. Additional research on soil and rock samples from Kisii soapstone quarries [34] revealed that the AED ranged from 1.03 mSv/y-1.27 mSv/y. The H_{ex}, AED rate, and Ra_{eq} activity absorbed dose rate averaged 321.67±12.4 Bq/kg, 151.76±5.65 nGy/hr, 0.74±0.02 mSv/y, and 0.88±0.03, respectively [35]. Ra_{eq}, H_{ex}, H_{in}, outdoors absorbed dose rate, indoor absorbed dose rate, and outdoor and indoor AED rates were found to be 256.00±13.00 Bq/kg, 0.69±0.04, 0.95±0.05, 120.99±6.07 nGy/hr, 166.67±8.31 nGy/hr, 0.30±0.02 mSv/y, and 0.61±0.06 mSv/y, respectively [36]. 367.10±7.30 Bq/kg, 171.20±3.40 nGy/hr, 0.42±0.01 mSv/y, 0.99±0.02, and 1.17±0.02 were the mean readings for Ra_{eq} activity, absorbed dose rate, AED rate, H_{ex}, as well as H_{in}, respectively [37].

3.4. Excess lifetime cancer risk

The ELCR measurements for both indoor and outdoor environments for various samples are shown in Fig. 5a and Fig. 5b, respectively. Analyzing the $ELCR_{in}$ dwellings allows us to assess the potential cancer risks associated with radiation exposure for each sample, as shown in Fig. 5*a*. Among the samples, Sample S15 demonstrates the lowest $ELCR_{in}$ value at 0.30×10^{-3}, indicating minimal excess lifetime cancer risk indoors. At the same time, Sample S10 exhibits the highest $ELCR_{in}$ value at 0.64×10^{-3}, signifying the most significant cancer risk indoors. As the ELCR is directly related to the concentrations of Th-232 and U-238, higher values of these radionuclides result in an increased ELCR. The elevated concentrations of Th and U observed in the soil samples from Pokhara can be attributed to the local geology, which is primarily composed of Precambrian metamorphic rocks such as gneisses and schists. These rocks contain significant amounts of accessory minerals like monazite, zircon, allanite, and uraninite, all ~~of which are~~ rich in thorium and uranium [38-39]. Consequently, the high absorbed dose rate and elevated ELCR in the study area are likely due to the natural enrichment of Th and U within these geological formations.

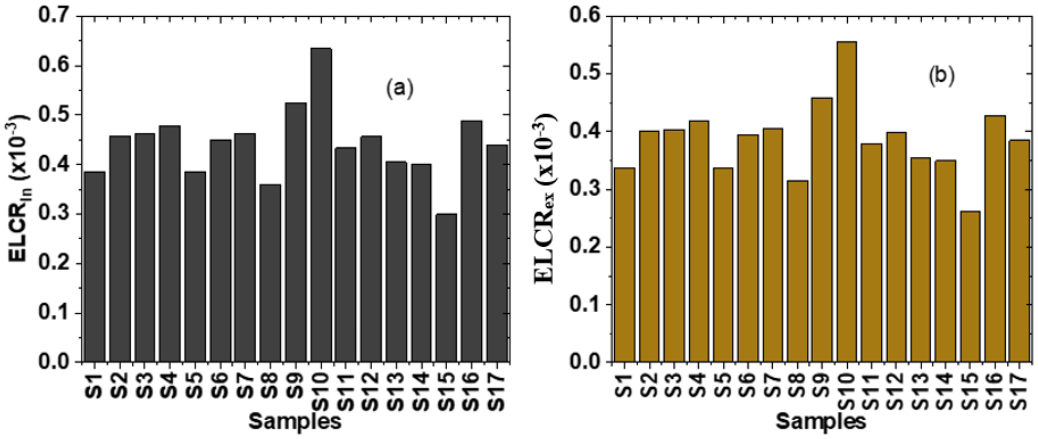

Fig. 5: ELCR (a) indoor and (b) outdoor associated with soil samples collected from Pokhara.

Analyzing the $ELCR_{ex}$ dwellings provides insight into the potential cancer risks associated with outdoor radiation exposure for each sample, as shown in Fig. 5, *b*. S15 exhibits the lowest $ELCR_{ex}$ value at 0.26×10^{-3} and is safe from cancer risk because the world average of each is 0.29×10^{-3} [40]. But S10 displays the highest value at 0.56×10^{-3}, indicating the most significant cancer risk outdoors because it is 1.93 times higher than the world average ELCR. In addition, another sample, except S15, has a higher value than the world average in the research area considered to be Pokhara Valley; more details can also be observed in Table 4. Table 4 shows the calculated AEDE and ELCR for 17 soil samples taken from Pokhara. $AEDE_{ex}$ values range from 0.08 to 0.16 mSv/y, with S15 having the lowest AED_{ex} and S10 having the highest. $AEDE_{in}$ values range from 0.09 to 0.18 mSv/y, with S15 having the lowest and S10 having the highest $AEDE_{in}$. The AEDE value of 17 samples is less than UNSCER 1 mSv/y [26], while the ELCR value is higher than the world average of 0.29×10^{-3} [27]. See Table 3 for further details. The average $AEDE_{ex}$ was 0.11 mSv/y, whereas $AEDE_{in}$ was 0.13 mSv/y, for a total average of 0.119 mSv/y. Furthermore, the average $ELCR_{in}$ was 0.44 and $ELCR_{ex}$ was 0.39, yielding an average ELCR of 0.42.

Table 4: Summary of AEDE and ELCR in the soil sample of Pokhara

Sample	**Present Work**			
	$AEDE_{ex}$(mSv/y)	$AEDE_{in}$ (mSv/y)	$ELCR_{ex}$ (10^{-3})	$ELCR_{in}$ (10^{-3})
S1	0.10	0.11	0.34	0.39
S2	0.11	0.13	0.40	0.46
S3	0.12	0.13	0.40	0.46
S4	0.12	0.14	0.42	0.48
S5	0.11	0.11	0.34	0.39
S6	0.11	0.13	0.39	0.45
S7	0.12	0.13	0.41	0.46
S8	0.09	0.10	0.32	0.36
S9	0.13	0.15	0.46	0.52
S10	0.16	0.18	0.56	0.64
S11	0.11	0.12	0.38	0.43
S12	0.11	0.13	0.40	0.46
S13	0.10	0.12	0.36	0.40
S14	0.10	0.11	0.35	0.40
S15	0.08	0.09	0.26	0.30
S16	0.12	0.14	0.43	0.49
S17	0.11	0.13	0.38	0.45
Average	0.11	0.13	0.39	0.44
Limit UNSCEAR, 2008 [26]	1			
Limit UNSCEAR, 2010 [27]			0.29	

Table 5 compares radiation levels by region. Nepal has moderate amounts of K-40 (463 Bq/kg) and Th-232 (69.2 Bq/kg), with a Raeq of 187 Bq/kg. Araba Valley, Jordan, has a high K-40 concentration (660-860 Bq/kg), but Bangladesh has great variance, particularly in Th-232 (up to 685.74 Bq/kg), with a hazard score of 5.27. Nigeria and Punjab, India, have modest amounts, whereas Romania

(Banat Mountains) has high U-238 (up to 396.23 Bq/kg) and a Raeq of 458.31 Bq/kg. China (Guangdong) has an extraordinarily high K-40 level (4982.94 Bq/kg). These discrepancies show that radiation dangers vary by region, with Bangladesh and Romania having higher potential hazards.

Table 5: Comparative summary of radioactivity and hazardous indexes

Country	K-40	U-238	Th-232	Ra_{eq}	H index	AEDE (mSv/y)	ELCR $\times 10^{-3}$	Reference work
Nepal	463.00	52.80	69.20	187.00	0.51-0.65	0.11-0.13	0.39-0.44	Present
Araba valley, Jordon	660-860	25.50 - 31.90	28.80-43.80	-	-	-	-	[41]
South-Eastern Part, Bangladesh	87.20-184.37	20.94-66.96	38.62-685.74	28.64-480.42	0.26-5.27	0.05-0.81	-	[42]
Ogun State, Nigeria	249. 15-542.62	2.54-38.25	25.12-55.36	90.88-135.95	0.25-0.44	0.05-0.08	0.18-0.28	[43]
Punjab, India	260.10-728.20	BDL-41.90	29.50-88.10	134.80	0.36-0.42	0.08-0.30	-	[44]
Banat Mountains, Romania	497.32 - 615.32	32.12-396.23	7.23-48.16	118.33-458.31	0.32-1.24	-	-	[45]
Guangdong Province, China	4982.94	-	25.36	142.92	0.38-0.47	0.03 - 0.12	-	[46]

3.6. Statistical analysis

Table 6 shows the association between K-40, Raeq, Th-232, and U-238 activity concentrations. Ra_{eq} and Th-232 have a robust correlation of 0.975, indicating that they are highly dependent on one another, which means that changes in one will have a significant impact on the other. Also, Raeq and U-238 correlate 0.814, indicating a strong dependency in which alterations in one affect the other. Th-232 and U-238 have a modest correlation of 0.667, indicating that changes in one have a visible but insignificant impact on the other. Furthermore, K-40 and Ra_{eq} have a correlation of 0.780, indicating a high reliance, implying that changes in Raeq considerably affect K-40 concentrations and vice versa. K-40 and Th-232 have a strong correlation of 0.831, indicating a high level of reliance, which means that changes in Th-232 concentration are likely to significantly impact K-40 levels. K-40 and U-238 have a moderate correlation of 0.401, indicating a weaker association, with changes in one having a detectable but less significant impact on the other. All measurements in this study have a standard error of ±0.043 count per minute.

Table 7 presents the correlation between the activity concentration of K-40 and various dose-related metrics, including $AEDE_{in}$, $AEDE_{ex}$, $ELCR_{in,}$ and $ELCR_{ex.}$ K-40 has excellent associations with dose metrics such as $AEDE_{in}$, $AEDE_{ex}$, $ELCR_{in}$, and $ELCR_{ex}$ (between 0.756 and 0.757), showing that greater K-40 levels greatly increase radiation doses and cancer risks. Nearly perfect correlations (near to 1.0) between AEDE, ELCR, and their indoor/outdoor versions indicate that these measurements are highly interdependent.

Table 6: Correlation of radioactivity concentration in soil samples

Correlation	K-40	Ra_{eq}	Th-232	U-238
K-40	1.000			
Ra_{eq}	0.790	1.000		
Th-232	0.809	0.965	1.000	
U-238	0.402	0.796	0.618	1.000

Table 7: Correlation of K-40 radioactivity with hazard parameters

Correlation	K-40	$ELCR_{ex}$	$ELCR_{in}$	$AEDE_{ex}$	$AEDE_{in}$
K-40	1.000				
$ELCR_{ex}$	0.756	1.000			
$ELCR_{in}$	0.757	0.999	1.000		
$AEDE_{ex}$	0.757	0.999	0.999	1.000	
$AEDE_{in}$	0.757	0.999	0.999	0.999	1.000

Table 8 displays the correlation coefficients among variables: Th-232, $ELCR_{ex}$, $ELCR_{in}$, $AEDE_{ex}$, and $AEDE_{in}$. For instance, Th-232 and $ELCR_{ex}$ exhibit a correlation coefficient of 0.970, indicating a strong positive linear relationship. Similarly, the correlation coefficients between $ELCR_{in}$ and $AEDE_{ex}$ is 0.271, respectively, suggesting a weaker positive relationship.

Table 8: Correlation of Th-232 radioactivity with hazard parameters

Correlation	Th-232	$ELCR_{ex}$	$ELCR_{in}$	$AEDE_{ex}$	$AEDE_{in}$
Th-232	1.000				
$ELCR_{ex}$	0.970	1.000			
$ELCR_{in}$	0.970	0.999	1.000		
$AEDE_{ex}$	0.969	0.999	0.999	1.000	
$AEDE_{in}$	0.970	0.999	0.999	0.999	1.000

Table 9 represents the correlation coefficients between different variables: U-238, $ELCR_{ex}$, $ELCR_{in}$, $AEDE_{ex}$, and $AEDE_{in}$. For instance, the correlation between U-238 and $ELCR_{ex}$ is 0.817204, indicating a strong positive linear relationship. Similarly, the correlation coefficients between other variables provide insights into their associations: $ELCR_{in}$ and $AEDE_{ex}$ a correlation of 0.271, suggesting a weaker positive relationship.

Table 9: Correlation of U-238 radioactivity with hazard parameters

Correlation	U-238	$ELCR_{ex}$	$ELCR_{in}$	$AEDE_{ex}$	$AEDE_{in}$
U-238	1.000				
$ELCR_{ex}$	0.817	1.000			
$ELCR_{in}$	0.827	0.999	1.000		
$AEDE_{ex}$	0.828	0.999	0.999	1.000	
$AEDE_{in}$	0.828	0.999	0.999	0.999	1.000

Table 10 shows the association between Raeq and other dose-related parameters, including $AEDE_{in}$, $AEDE_{ex}$, $ELCR_{in}$, and $ELCR_{ex}$. The correlation research reveals that Raeq has an almost perfect positive association (coefficients close to 0.999) with dose-related metrics such as $AEDE_{in}$, $AEDE_{ex}$, $ELCR_{in}$, and $ELCR_{ex}$, implying that as Raeq rises, so do the radiation exposures and cancer risks. Similarly, these dose indicators are virtually perfectly connected, indicating high interdependence.

Table 10: Correlation of Ra_{eq} radioactivity with hazard parameters

Correlation	Ra_{eq}	$ELCR_{ex}$	$ELCR_{in}$	$AEDE_{ex}$	$AEDE_{in}$
Ra_{eq}	1.000				
$ELCR_{ex}$	0.999	1.000			
$ELCR_{in}$	0.999	0.999	1.000		
$AEDE_{ex}$	0.999	0.999	0.999	1.000	
$AEDE_{in}$	0.999	0.999	0.999	0.999	1.000

4. CONCLUSIONS

The analysis of soil samples collected from Pokhara, Nepal, shows a significant variation in the natural radioactivity levels, particularly in K-40, Th-232, and U-238 concentrations. The activity concentrations range from 210.45 to 612.32 Bq/kg for K-40, 45.78 to 118.64 Bq/kg for Th-232, and 32.56 to 97.42 Bq/kg for U-238. Among all samples, S9 and S10 exhibit the highest radionuclide concentrations. The calculated Ra_{eq} values range between 122.34 and 312.87 Bq/kg, with samples S9 and S10 exceeding the UNSCEAR safety limit of 370 Bq/kg. Similarly, the absorbed dose rate varies from 58.76 to 145.63 nGy/h, while the AEDE is found between 0.071 and 0.179 mSv/year for indoor and outdoor exposure, respectively. The ELCR ranges from 0.24×10^{-3} to 0.62×10^{-3}, with sample S10 posing the highest indoor and outdoor exposure risks. These results emphasize the necessity for continuous monitoring and managing natural radioactivity in Pokhara to minimize potential radiological health hazards. Moreover, the strong correlations among K-40, Th-232, U-238, and Raeq highlight their interdependent role in determining overall radiation exposure and risk, contributing valuable insights for environmental safety and radiation protection strategies.

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