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Radiological assessment of the Bagh Bhairav Temple in Kirtipur, Nepal using in-situ gamma ray spectrometry

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Abstract
In this work, the results of an in-situ radiological survey of the Bagh Bhairav complex in Kirtipur, Nepal, using a portable gamma ray spectrometer equipped with a GPS and data logger unit is presented. The study aims to assess external exposure by evaluating and mapping external absorbed dose rates and radionuclide activity concentrations in the area. The measured absorbed dose rate in air ranged from 100.330 nGy/h to 170.506 nGy/h, with a mean value of 128.661 ± 14.637 nGy/h. The activity concentrations of the gamma radionuclides ^{238}U, ^{232}Th and ^{40}K, outdoor annual effective dose (AED) and excess lifetime cancer risk (ELCR) were found higher than the world average values. The elevated absorbed dose rate is attributed to the high activity concentrations of gamma radionuclides present in soils, rocks at high altitudes. This study provides baseline radiological data for the Bagh Bhairav area and contributes to the limited radiological data available for Nepal.

Keywords
Absorbed dose rate, activity concentration, AED, ELCR, in-situ radiological survey, Nepal

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1 Introduction

Human populations are continually exposed to ionizing radiation from environmental sources, which contributes to their radiation dose. High radiation doses have been reported in various parts of the world, including India, which borders Nepal [1, 2]. Gabdo et al. measured the mean terrestrial gamma radiation dose rate in Pahang state, Malaysia, to be 176 ± 5 nGy/h, with an annual effective dose rate of 0.22 mSv/y for outdoor exposure [3]. A survey by Taskin et al. revealed the average outdoor gamma dose rate in Kirklareli, Turkey, to be 118 ± 34 nGy/h [4]. Ramola et al. studied the average external absorbed dose rates in the Garhwal Himalaya region of India from the radionuclides ^{226}Ra, ^{232}Th and ^{40}K, finding it to be 138 nGy/h [5]. The high concentration of radionuclides in these areas is attributed to various rock types and their chemical properties. Rajasthan and Kerala in India have also reported higher dose rates [6, 7]. Radionuclides present in building materials can further elevate radiation levels [8]. Bala et al. found that the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil and building materials in Una, India, were higher than the world average [9]. In Terengganu state, Malaysia, the mean terrestrial gamma radiation dose rates and annual effective dose were measured to be 150 nGy/h and 0.92 mSv/y, respectively [10]. Gamma ray spectrometry has also been employed to study environmental gamma radiation in some selected areas of Nepal [11–14]. Recently, gamma ray spectrometry has found diverse applications, including lithological mapping [15], qualitative analysis of clay minerals [16], investigation of shutdown radioactivity for the Experimental Advanced Superconducting Tokamak (EAST) [17], radioactivity depth distribution analysis in activated concrete [18], and evaluating tropical soil processes and attributes [19].

The Bagh Bhairav complex is an ancient temple built in the 16th century, located in Kirtipur city, a UNESCO tentative site (https://en.wikipedia.org/wiki/Kirtipur), approximately 5 km southwest of the capital city (Figure 1). The temple lies between latitudes 27.679^0 - 27.680^0 and longitudes 85.276^0 – 85.277^0 at an altitude of 1294.970 – 1352.410 meter. The complex consists of a large temple surrounded by many smaller temples and statues. The bricks, timber, clay mortar, stones, and clay tiles used for construction may have high concentrations of primordial radionuclides, which can produce gamma radiation and elevate background radiation levels. Pilgrims and visitors regularly visit the temple, and the surrounding area is inhabited, making a radiological survey of this area essential to assess any potential radiological hazards to the public. The image of the Bagh Bhairav temple featured on a postage stamp issued by the government of Nepal also underscores its historical significance (Figure 2).

The aim of this study is to evaluate outdoor external exposure in the complex and its surrounding area by measuring the absorbed dose rate in air and calculating the annual effective dose (AED) using in-situ gamma ray spectrometry. The absorbed dose is the radiation energy imparted to a unit mass of matter and AED is a measure of the energy deposited by radiation in organs and tissue per year and it measures the biological effects of radiation to humans. The measured absorbed dose rate in air will be compared with the dose rate calculated from the activity concentrations of terrestrial gamma radionuclides ^{238}U, ^{232}Th and ^{40}K. Additionally, the associated health risks will be assessed by calculating the excess lifetime cancer risk (ELCR). ELCR is the difference between the proportion of people who develop or die from the disease in an exposed population and the corresponding proportion in a similar population without the exposure [20]. The acceptable range of excess lifetime cancer risk (ELCR) is generally contextual and varies based on regulatory frameworks and risk management practices. As a general rule, mitigation (or any action) may not be necessary if the risks originate from natural sources and the dose remains below established thresholds, such as the ICRP's recommended limit of 1 mSv/year for the public.

Figure 1: Google map and location of the survey site.

Figure 2: Postage stamp of Nepal depicting the Bagh Bhairav temple.

2 Material and Methods

The spectrometer (PGIS 2) was carried in a backpack (maintained at a height of 1 m for consistency in measurements) and walked around the study area with a speed less than 2 km/h.

2.1 Gamma Ray Spectrometry

The dose rate is studied using gamma ray spectrometer (PGIS 2 from Pico Envirotec) which can record 512 channels of data in the energy range 20 keV to 3 MeV. It has auto calibration and real-time spectrum stabilization by the natural gamma photo peaks. The activity concentration of ^{40}K is directly measured from its emission line at 1461 keV while the activity concentration of Uranium and Thorium decay series is measured from the gamma emission of ^{214}Bi at 1764 keV and ^{208}Tl at 2614 keV respectively.

2.2 Dosimetry

2.2.1 Annual Effective Dose (AED)

The outdoor annual effective dose (AED) is calculated based on the absorbed gamma dose rate by using the equation [1]:

$$AED\,(\text{nSv}) = D\left(\frac{\text{nGy}}{\text{h}}\right)\times 8760\,\text{h}\times OF\times CF\left(\frac{\text{Sv}}{\text{Gy}}\right) \quad (1)$$

where D is the average absorbed dose rate, CF is the conversion factor, 0.7 Sv/Gy (to convert absorbed dose rate in air to effective dose equivalent for human), OF is the outdoor occupancy factor, 20% and 8760 is hours in one year.

2.2.2 Excess Lifetime Cancer Risk (ELCR)

The excess lifetime cancer risk (ELCR) was calculated using the equation [20]:

$$ELCR = AED \times LE \times RF \quad (2)$$

where LE is the Life Expectancy of people (66.2 year in Nepal) (http://en.worldstate.info/Asia/Nepal) and RF is the overall fatal risk coefficient, 0.05 per Sv as recommended by ICRP for the purpose of radiological protection.

2.2.3 Absorbed Gamma Dose Rate

The absorbed gamma dose rate from the concentration of gamma radionuclides in rocks and soils is calculated using the equation [1]:

$$D_{\text{calculated}}\left(\frac{\text{nGy}}{\text{h}}\right) = 0.0417A_K + 0.462A_U + 0.604A_{Th} \quad (3)$$

where A_K, A_U and A_{Th} is the activity concentration (Bq/kg) of ^{40}K, ^{238}U and ^{232}Th respectively.

3 Theory

The semi-empirical model based on mono-energetic radiation is the simplest approach for modeling gamma ray fields. This model uses a two-layer configuration, with the Earth represented as an infinite half-space of constant density and radioelement concentration, overlaid by a layer of non-radioactive air with constant density. The observed photo peak intensity, dI, is given by:

$$dI = \frac{A\varepsilon}{4\pi r^2} e^{-\mu_e r_e} e^{-\mu_a r_a} N dv \quad (4)$$

where Ndv is the number of gamma rays of energy E_0 emitted per second by the volume element dv, A is the effective cross-sectional area of the detector,

ε is the photo peak efficiency of the detector for gamma rays of energy E_0,

μ_e and μ_a are the linear attenuation coefficients for the Earth and air, respectively; and

r_e and r_a are the distances that gamma rays travel through the Earth and air, respectively, with $R = r_a + r_e$.

4 Results

The measured absorbed dose rate in air of Bagh Bhairav area was obtained in the range of 100.330 to 170.506 nGy/h with an average of 128.661 ± 14.637 nGy/h. The radiological map of measured absorbed dose rate in air is shown in Figure 3. The dose rates were overlaid on the geo-referenced map to find the spatial variability. The higher value was observed in the surrounding area of the temple (yellow colour) with the highest value (red colour) near the temple wall as building materials are also the contributors of gamma dose.

The concentrations of ^{40}K, ^{238}U and ^{232}Th was measured in the range of 1.130 to 5.702%, 0.590 to 20.461 ppm and 3.053 to 40.683 ppm with an average of 3.126 ± 0.749%, 6.903 ± 3.150 ppm and 18.264 ± 6.179 ppm respectively. The activity concentrations of ^{40}K, ^{238}U and ^{232}Th, as calculated following IAEA (2003) was found in the range 701.433 to 1422.147 Bq/kg with an average of 978.901 ± 161.189 Bq/kg, 39.805 to 153.454 Bq/kg with an average of 85.340 ± 21.423 Bq/kg and 42.454 to 111.790 Bq/kg with an average of 74.326 ± 13.899 Bq/kg respectively.

The calculated absorbed dose rates was obtained in the range 90.350 to 167.879 nGy/h with an average of 125.140 ± 18.249 nGy/h and was found nearly equal with the measured dose rate. The dose rate from the particular gamma radionuclides ^{40}K, ^{238}U and ^{232}Th were obtained in the range of 14.748 to 74.423 nGy/h, 3.366 to 116.744 nGy/h and 7.486 to 99.764 nGy/h respectively. The average dose rate from ^{40}K, ^{238}U and ^{232}Th were compared with population weighted average (Table 1).

Table 1: Absorbed dose rate compared with population weighted average [1]

Absorbed dose rate in air (nGy/h)	**Gamma radionuclide**		
	^{40}K	^{238}U series	^{232}Th series
Population weighted average	18	15	27
Present Study	40.806±9.786	39.386±17.976	44.789±15.153

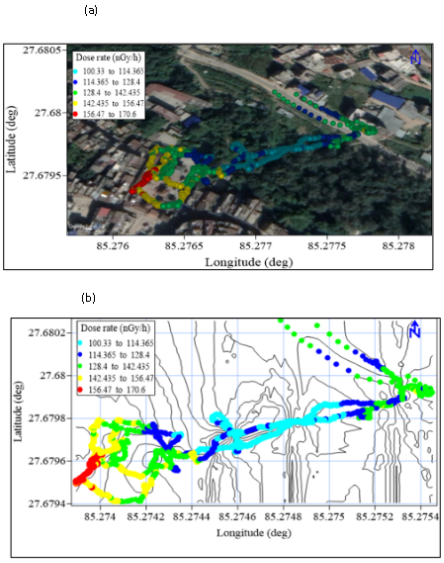

Figure 3: Measured absorbed dose rate map of Bagh Bhairav overlaid on (a) an imagery map (b) a topographical map showing altitude contour.

The average measured dose rate and calculated dose rate were found to 128.661 ± 14.637 nGy/h and 125.140 ± 18.249 nGy/h respectively and the ratio of them (0.972) inferred no discrepancies in survey data. The variation in calculated dose rate was found more than measured dose rate in the studied area (Figure 5).

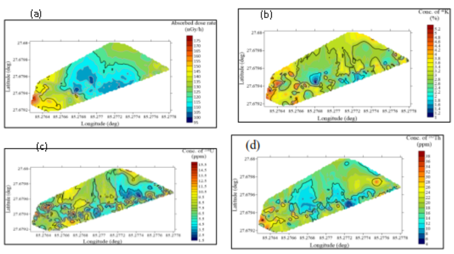

Figure 4: Contour map of absorbed dose rate in air (a), concentrations of ^{40}K (b), ^{238}U (c) and ^{232}Th (d).

The contour maps of measured absorbed dose rate, concentrations of ^{40}K, concentrations ^{238}U and concentrations ^{232}Th with latitude and longitude were shown in Figure 4. The variation of dose rate in the area seems smooth though it had high standard deviation. The variation of concentrations of ^{40}K and ^{232}Th is smooth in the area while ^{238}U concentration shows little roughness.

4.1 Outdoor AED and ELCR

The outdoor AED was found to be 0.157 mSv which is higher than the world average value of outdoor AED from terrestrial gamma dose. The ELCR was calculated from outdoor AED and was found 0.519 $\times 10^{-3}$ which is also higher than the world average.

5 Discussion

The dose rate was found to be higher near the walls of the temples, as the gamma radionuclides ^{238}U, ^{232}Th and ^{40}K present in building materials (mud, clay bricks, and stones) also contribute to gamma radiation. These dose rates are associated with gamma radiation from the Earth's crust (sedimentary rocks of lacustrine deposits) as well as from building materials. The elevated dose rate in the complex is attributed to higher activity concentrations of primordial radionuclides in the area. The terrestrial gamma dose rate varies slightly within the complex, reflecting the activity concentrations of natural gamma radionuclides present in the soils and rocks, which have dispersed in the area due to long-lasting geological processes. The activity concentrations of the gamma radionuclides ^{238}U, ^{232}Th and ^{40}K were found to be higher than the world population-weighted averages of 33 Bq/kg, 45 Bq/kg, and 420 Bq/kg, respectively [1].

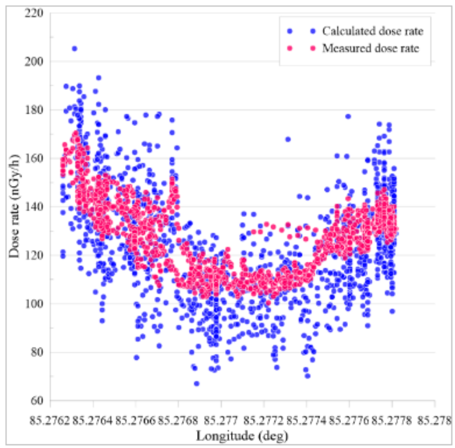

Figure 5: Variation between measured dose rate and calculated dose rate.

The shape and spread of the measured absorbed dose rates and calculated dose rate data show asymmetry, as illustrated in the histogram (Figure 6). The frequency distribution of the concentrations of ^{238}U, ^{232}Th and ^{40}K was also found to be non-symmetric and right-skewed, with most values shifted toward the left, indicating that the mean is greater than the median (Figure 6). The median, dispersion, and range of dose rates from the concentrations of gamma radionuclides ^{238}U, ^{232}Th and ^{40}K were compared using box-whisker plots (Figure 7), with whiskers extending to 1.5 times the interquartile range (IQR). Regression analysis between the activity concentrations of ^{238}U, ^{232}Th and ^{40}K and the measured absorbed dose rate was conducted using a scatter plot (Figure 8). The results of the statistical analysis are presented in Table 2. Hypothesis tests for histogram normal fitting and regression analysis (linear fitting) were performed at a 0.05% significance level.

Radiological data for soil and rocks in Nepal is available for the Hetauda region [21], and while some areas have been monitored for various reasons, comprehensive data is still lacking. Therefore, the data from the present study will serve as baseline data for Nepal. The study determined that the measured absorbed dose rate in air is higher than the world average. The ratio of the absorbed dose rates (calculated and measured) shows a discrepancy of less than 30%, indicating that the survey data is logically representative [1].

The outdoor annual effective dose (AED) calculated was found to be higher than the world average background radiation for outdoor terrestrial radiation, which is typically around 0.07 mSv [1]. The outdoor AED for the study area is compared with neighbouring countries such as India (which shares similar geological and geographical conditions), China, and others (Table 3). The excess lifetime cancer risk (ELCR) value was also found to be higher than the world average of 0.29×10^{-3} [1], but the associated risk of developing cancer remains negligible.

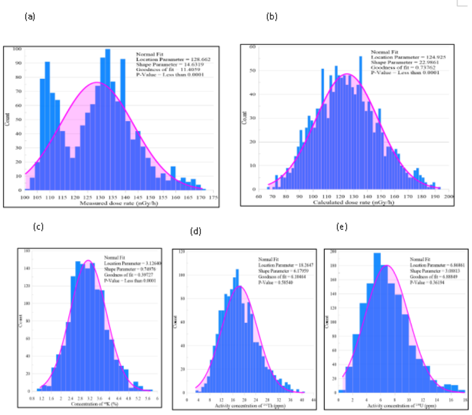

Figure 6: Distribution of (a) measured, and (b) calculated absorbed dose rates, activity concentrations of (c) ^{40}K, (d) ^{238}U, and (e) ^{232}Th.

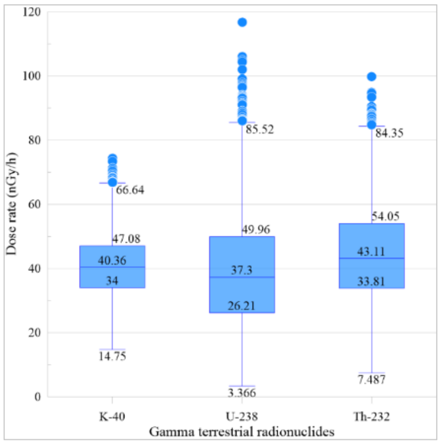

Figure 7: Calculated absorbed dose rates from activity concentrations of ^{40}K, ^{238}U and ^{232}Th.

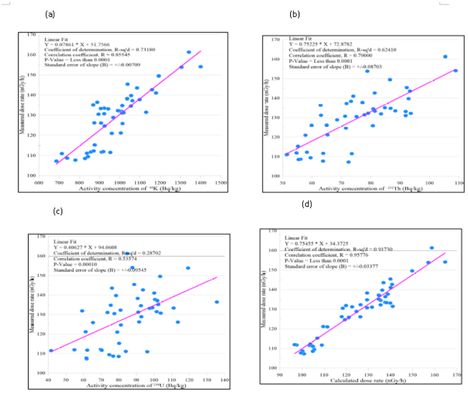

Figure 8: Correlation between measured absorbed dose rate and activity concentrations of (a) ^{40}K (b) ^{232}Th (c)^{238}U and (d) calculated absorbed dose rate.

Table 2: Statistics of the survey data

	Measured dose rate (nGy/h)	Calculated dose rate (nGy/h)	Conc. of ^{40}K (%)	Conc. of ^{232}Th (ppm)	Conc. of ^{238}U (ppm)
Mean	128.661	124.982	3.126	6.903	18.264
Median	130.195	123.916	3.092	6.538	17.581
First quartile	114.845	107.966	2.605	4.586	13.789
Third quartile	138.406	140.085	3.607	8.757	22.042
Standard error	0.391	0.616	0.02	0.084	0.165
Standard deviation	14.637	23.077	0.75	3.151	6.181
Coefficient of variation	0.113	0.184	0.239	0.456	0.338
Skew	0.239	0.261	0.302	0.755	0.564
Kurtosis	-0.466	-0.22	0.103	0.766	0.179

Table 3: Comparative study of outdoor (AED) in different regions of Nepal and the world

S.N.	Sites	Outdoor AED (mSv)	References
1	Hetauda, Nepal	0.12	[22]
2	Garhwal, India	0.17	[5]
3	Una, India	0.1	[9]
4	Kirklareli, Turkey	0.144	[4]
5	Kohistan, Pakistan	0.12	[23]
6	Islamabad, Pakistan	0.16	[24]
7	Pahang, Malaysia	0.22	[3]
8	Baotou, China	1.03	[25]
9	Odha, India	0.17	[26]
10	Mrima Hill environs, Kenya	0.86	[27]
11	Tribhuvan University, Kirtipur	0.142	[28]
12	UNESCO Sites, Kathmandu	0.148–0.186	[29]
13	Tarakeshwar, Kathmandu	0.15	[30]
14	Bishnumati Bridges, Kathmandu	0.906	[31]
15	Present Study	0.157	–
16	World average	0.07	[1]

6 Conclusions

The in-situ radiological survey of the Bagh Bhairav complex was performed using a portable gamma-ray spectrometer equipped with a GPS and data logger unit. The outdoor absorbed dose rate in air was found to be nearly twice the world average. The absorbed dose rate in air was compared with terrestrial data, and statistical analysis revealed a positive linear correlation between them. The distribution showed a skewed pattern and was correlated with the concentrations of terrestrial gamma radionuclides. Additionally, there was a strong agreement between the measured and calculated absorbed dose rates; the ratio of the calculated to measured dose rate was nearly equal to one, indicating no discrepancies in the data. The activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in the complex were approximately 2.5 times higher than the world average, contributing to the elevated dose rates observed. Although the outdoor annual effective dose (AED) and excess lifetime cancer risk (ELCR) were higher than the world averages, the outdoor AED value obtained was below the ICRP-recommended limit for public exposure (< 1 mSv/y). Hence, there is no potential radiological hazard to the public in the complex. Moreover, this study is valuable for establishing baseline data and radiological maps for the area.

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