Heliyon 10 (2024) e39516

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Radiometric hazard assessment of soil and water samples adjacent to Bangladesh's first nuclear power plant before commissioning: Insights into human health and environmental radiological dynamics

S. Yeasmin [a,*], S.K. Das [b], M.M. Mahfuz Siraz [a], A.F.M. Mizanur Rahman [c], M.S. Rahman [a]

[a] Health Physics Division, Atomic Energy Centre Dhaka, Dhaka, 1000, Bangladesh
[b] Department of Physics, Jagannath University, Dhaka, 1100, Bangladesh
[c] Nuclear Power and Energy Division, Bangladesh Atomic Energy Commission, Dhaka, 1000, Bangladesh

ARTICLE INFO

Keywords:
Rooppur nuclear power plant
Soil
Radioactivity
HPGe detector
Radiological hazards

ABSTRACT

The current study provides a comprehensive examination of both natural and anthropogenic activity concentrations found in soil and surface water samples near the Rooppur nuclear power plant (RNPP), the first of its kind under construction in Bangladesh. The investigation covers a range of activity concentrations including ^{226}Ra, ^{232}Th, and ^{40}K in fifty soil and fifty water samples, revealing values ranging from 18 to 38, 18–51, and 310–560 Bqkg^{-1} for soil, and 2.1–6.1, 2.1–5.5, and 67–115 Bqkg^{-1} for water, respectively. Although outdoor absorbed dose rate, outdoor effective dose, and gamma representative level index values in some soil samples exceed global averages, other radiological hazard parameters such as radium equivalent activity, annual effective dose, external and internal hazard indices, and lifetime carcinogenic risk for both soil and water samples consistently remain below safety thresholds established by international organizations. These findings indicate that the soil and water samples collected from the vicinity of the RNPP do not pose significant radiological hazards to the nearby populations. This study's comprehensive dataset is anticipated to play a crucial role in facilitating the identification and evaluation of any changes in environmental radioactivity, thereby assisting in the effective management and regulation of nuclear power plant activities in the years to come.

1. Introduction

One of the inherent and irrefutable aspects with regard to life on Earth involves exposure to ionizing radiation from the surrounding environment [1]. Naturally occurring radiation sources, such as cosmic rays and terrestrial radiation, encompass what is commonly known as 'naturally occurring radioactive materials (NORMs)'. These include ^{40}K, ^{238}U, ^{232}Th, and their progenies, which are prevalent within vegetation, rocks, soils, and water. Artificial sources of radiation inside the ecosystem stem from fallout from nuclear weapon testing, nuclear reactors, and radioactive applications in medicine. Gamma radiation is encountered externally through

* Corresponding author.
E-mail address: selinayeasmin@yahoo.com (S. Yeasmin).

https://doi.org/10.1016/j.heliyon.2024.e39516
Received 17 April 2024; Received in revised form 19 August 2024; Accepted 16 October 2024

cosmic rays and terrestrial radiation, whereas internal exposure transpires through the inhalation and ingestion of radionuclides that are found in food and water. Terrestrial radiation accounts for an estimated 80 % of the overall exposure, while the remaining fraction is ascribed to cosmic rays and manmade sources [1]. Radiation exposure varies in magnitude according to geographic location and the particular attributes of the geological formations present in that region [2–8]. Certain regions globally, including Iran, Australia, Canada, Brazil, the United States, and India [9–13], are classified as High Background Radiation Areas (HBRAs) on account of distinctive geochemical and geological characteristics that result in heightened levels of terrestrial radiation. Prolonged radiation exposure can induce detrimental consequences for human health, including but not limited to chronic lung diseases, anaemia, acute leukopenia, and cancers that impact organs including the lungs, breasts, and pancreas [14,15]. In-depth investigations are ongoing in these regions to identify potential threats to public health and assess the need for lifestyle adaptations among the local population [16–18]. As a result, it is critical to analyze the active concentration of NORMs in the soil and water and the corresponding radiological dangers related to the external dosage of gamma radiation to the population. When conducting a radiological examination of a site prior to selecting it for the construction of a nuclear power plant, this assessment becomes very crucial.

The Environmental Impact Assessment (EIA) is an essential component in evaluating the environmental consequences of a facility, offering a concise synopsis of the ways in which the infrastructure affects the surrounding ecosystem. Preparatory to post-decommissioning environmental monitoring data must be meticulously documented as part of the EIA operations encompassing a nuclear facility. A comprehensive examination of multiple environmental factors such as air quality, soil quality, and water quality-is crucial for feasibility studies and for gaining an understanding of the long-term consequences associated with a nuclear site [19]. Presently under construction in the People's Republic of Bangladesh is the Rooppur Nuclear Power Plant (RNPP), which will house two VVER-1200 reactors with a combined capacity of 2400 MW and an expected operational life of sixty years. The RNPP, being the inaugural nuclear power plant in the nation and among the most expansive in southern Asia, is located along the Padma River, which provides the facility with its principal water supply and serves as the principal pathway for construction operations in the area. The river is thus exposed to a possible hazard of contamination as a result of development and heightened naval operations. Furthermore, upstream city sewage, industrial effluents, and local agricultural runoff may all contribute to elements contamination in the river system. In light of these considerations, it becomes crucial to assess environmental radiation and background radioactivity prior to the commercial operation of the power plant. Consistent monitoring is required prior to construction to assess potential effects on environmental and public health factors, hence guaranteeing uninterrupted operations during the operational phase. This level of inspection is also applicable to epidemiological investigations, as it aids in the detection of possible alterations in environmental radioactivity that may be the result of anthropogenic, industrial, and nuclear endeavours.

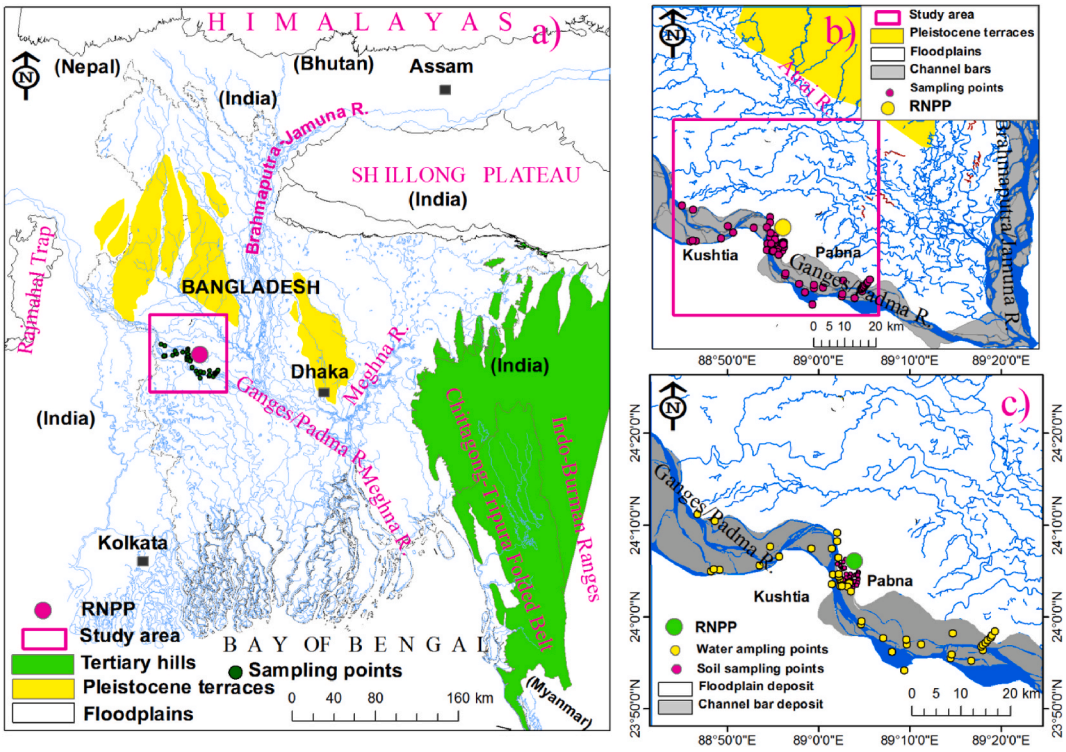

Fig. 1. a) Key physiographic characteristics of Bangladesh and its environs (modified after Rashid et al., 2021 [39]), as well as the location of the current study area; b) the study area and its surroundings (based on Landsat image 2018 interpretation (image collected from the website http://glovis.usgs.gov), and sampling points; C) the study area, its geomorphology (based on Landsat image 2018 analysis and field checking), and location of sampling points.

Radiation protection measures at diverse levels, exemplified by radiological surveys and hazard assessments, have been carried out both before and after the selection of sites in numerous countries. This proactive approach is evident in countries like India, specifically at the location of the Kudankulam Nuclear Power Plant and the Barakah Nuclear Power Plant in the United Arab Emirates [20,21]. Radiological assessments conducted at both the Al-Nigella and Nuclear Power Plant IV in Egypt and Taiwan, respectively have identified the artificial radionuclide ^{137}Cs in the soil of these respective locations [22,23]. Comparable research endeavours have been conducted in Bangladesh in the vicinity of the RNPP [24–34]. Jannat et al. [24] collected soil samples from forty places surrounding the proposed RNPP site, determining that the activity levels of naturally occurring radionuclides are consistent with the corresponding global average values. Conversely, Hayder et al. collected a total of 20 samples, including 10 soil and 10 sediment samples, from upstream and downstream locations of the Padma River near the RNPP in Rooppur, Pabna; the study concluded that the measured natural radionuclide values in the samples surpassed the world average. The soil, water, and sediment samples collected around RNPP indicated the absence of any artificial radionuclides, as confirmed by the researchers [24,26,28,35]. On the other hand, Panov et al. [31,36] identified artificial radioactivity, specifically ^{137}Cs, in soil, drinking water, cows' milk, beef, poultry, fish, and vegetables collected around RNPP. Hence, the principal aim of this research is to systematically compare and assess these contrasting perspectives, aiming to ascertain the accuracy and significance of divergent measurements. This study seeks to provide a thorough and current evaluation of the radiological hazards associated with water and soil samples in the vicinity of RNPP through a comprehensive follow-up analysis. Furthermore, prior research in this domain has been constrained by a limited number of examined samples. To address this limitation, the current study endeavours to overcome the restrictions of prior investigations through the implementation of a comprehensive investigation utilizing a significant sample size.

The Padma River's water will serve as the Rooppur Nuclear Power Plant's tertiary coolant, set to be operational in 2024. Simultaneously, this water source is utilized by numerous residents along the riverbanks for various purposes such as drinking, washing, cooking, and bathing. One of the principal aims of this investigation is to carry out the inaugural measurement of radioactivity in the Padma River water and assess the associated radiological risks. The anticipated data from the radioactivity analysis of both Padma River water and soil samples collected around RNPP is expected to contribute to the evaluation of radioactivity scenarios during regular plant operations and potential accidental incidents at the RNPP.

2. Methodology

2.1. Geology of the study area

The study area is situated in the northwestern part of Bangladesh (Fig. 1a). Physiographically, it falls in the Ganges River Floodplain [37]. Geomorphologically, it comprises floodplain deposits and channel bar deposits (Fig. 1c). The floodplain deposits consist of silty clay to clayey silt sediments and channel bar deposits consist of medium to very fine-grained sand and silty sand sediments. The tropical monsoon environment is humid. June–October is monsoon season. Winter lasts from late November to late February. Summer lasts from March until May. The maximum and minimum yearly temperatures are ~43.9 °C and 4.4 °C, respectively [38]. The average yearly rainfall is ~1500 mm. Relative humidity varies from ~64 % to ~83 % [38].

2.2. Sampling and sample preparation

A comprehensive study was conducted around the RNPP in January 2023 during the winter season, resulting in the collection of fifty surface soil samples (0–5 cm) from various locations. These included the main gate of the reactor, the paper mill, the primary school, the mosque, the bottle factory, the nursery, the EPZ (export processing zone), the EPZ residential area, Green City (where RNPP employees live), and more. As directed by IAEA guideline [40], the soil samples were collected using the judgmental sampling technique. With this approach, the sample team's expert judgment and subjective standards, such as visual inspections, are given precedence when choosing sampling locations. This approach's main benefit is that it gives the team more authority to select more representative samples. As a result, when compared to other approaches, this can produce more accurate results and accomplish the same goals more quickly and cheaply.

In our research, conducted in January 2023 during the winter season, we utilized a stratified systematic sampling strategy [40] to collect fifty surface water samples from the Padma River, situated adjacent to the RNPP, which is designated to serve as the tertiary coolant for the facility. This method involves dividing the population into distinct groups or strata. Unlike random sampling, stratified sampling is more intricate and requires a greater depth of prior knowledge. The advantage of this approach lies by means of population fragmentation into smaller groups, more homogeneous groups. Specific factors including sampling depth, soil horizon, pollutant concentration, and source-distinguish each stratum and influence the measured parameter of interest. Considering the proximity of the Hardinge Bridge to the RNPP, we strategically obtained more samples in its vicinity (Fig. 1c). Two more subdivisions were considered in Rajshahi and Kustia, upstream and downstream of the Padma River. Systematic sampling was carried out in these areas by regularly gathering samples over the course of the study period on both sides of the river.

Upon removing any undesired components, such as roots, pebbles, and plant debris, along with additional contaminants, every soil sample, approximately weighing 1 kg, was promptly stored in sterile, airtight, zip-lock polyethene bags that were appropriately labelled. Following that, these samples were delivered to the Atomic Energy Center Dhaka's Health Physics Division (AECD). After being sun-dried for couple of days, the samples were properly dried in an oven at 105 °C–110 °C for 24 h. After that, they were homogenized, put through a test filter, and kept in an airtight plastic Marinelli beaker. Before obtaining the spectra using gamma-ray spectroscopy, the samples were kept at room temperature for 40 days to allow ^{226}Ra, ^{232}Th, and their progenies to attain secular

equilibrium [41].

Before accommodating the collected water samples, 1-L bottles were sterilized. Pyrex beakers, each with a capacity of 1 L, underwent a thorough cleaning process using distilled water and were dried to prevent the introduction of moisture into the samples. To inhibit the accumulation of organic material and maintain the ions' oxidation state, 1 mL of concentrated HNO_3 was added to each water sample [42]. Subsequently, a water bath treatment at 105 °C was employed to gradually reduce the water samples' volume to 500 mL. For every sample, a Marinelli beaker was utilized. Following a storage period of four weeks, equilibrium was reached between the gaseous and non-gaseous decay products of naturally occurring radionuclide series.

2.3. Measurement procedures and data analysis

The high-resolution coaxial HPGe gamma-ray spectrometer (p type, Model no. GCD-30185, manufacturer's name- NATS (North American Technical Services)) was utilized to ascertain the activity concentrations of radionuclides in the samples. The detector was housed inside a cylindrical lead shielding (15 cm of lead thickness) apparatus with a sliding cover and a fixed base to reduce interference from outside noise. With a relative efficiency of 30 %, the energy peak at 1.33 MeV, which corresponds to ^{60}Co, showed an energy resolution of 1.67 keV at full-width half-maximum (FWHM). Samples and background were counted over a predetermined period of 120,000 s.

The detector's energy calibration was performed using typical point sources such as ^{60}Co, ^{109}Cd, ^{133}Ba, ^{137}Cs, and ^{152}Eu (each activity 1 μCi) [43]. By mixing a known activity of ^{152}Eu with an Al_2O_3 matrix and creating it in the same containers as the samples, the detector's efficiency for solid samples was determined [44]. A standard source was prepared by combining a known quantity of ^{152}Eu with 1N HCl (in deionized water) in containers that were the same as those used for the samples to ascertain the detector efficiency for liquid samples.

Each radionuclide's activity concentration was determined using Equation (1) [45–47]:

$$A = \frac{N}{\varepsilon \times \rho_\gamma \times w} \tag{1}$$

The specific activity measured in Bqkg^{-1} is denoted by "A" in the equation, the count rate in counts per second (cps) is represented by N, the counting efficiency of the HPGe detector at the given gamma-ray energy is indicated by ε, the absolute transition probability of the particular gamma ray is represented by ρ_γ , and the sample weight in kilograms is indicated by w (kg).

The minimal detectable activity concentration (MDAC) for the gamma-ray measurement system method was calculated using Eq (2) as stated in Ref. [45]:

$$MDA = \frac{K_\alpha \times \sqrt{B}}{\varepsilon \times \rho_\gamma \times T \times w} \tag{2}$$

where K is the statistical coverage factor, with a value of 1.64 (at the 95 % confidence level), B is the number of background counts for the relevant radionuclide, T is the counting time, and ρ_γ and w (in kg) have the same usual meaning as in Eq (1). The MDAs for ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs were determined to be 0.35 Bqkg^{-1}, 0.64 Bqkg^{-1}, 2.2 Bqkg^{-1} and 0.8 Bqkg^{-1} respectively.

Equation (3) was the mathematical formula used to estimate the uncertainty of the determined radioactivity [44].

Combined Standard uncertainty

$$= A_i \times \sqrt{\left(\frac{u(N)}{N}\right)^2 + \left(\frac{u(T)}{T}\right)^2 + \left(\frac{u(\rho_\gamma)}{\rho_\gamma}\right)^2 + \left(\frac{u(w)}{w}\right)^2 + \left(\frac{u(\varepsilon)}{\varepsilon}\right)^2} \tag{3}$$

The counting time, sample counts, sample weight, gamma-ray emission probability, and counting efficiency are represented by the symbols T, N, w, ρ_γ, and ε, in that order. The estimated uncertainty of the radionuclides ranges from 5 % to 10 %.

2.4. Radiological hazard parameters

2.4.1. Radium equivalent activity

The radium equivalent activity of soil samples is a radiological metric utilized to determine the total radium radioactive content of the samples. It offers a consolidated quantification of the amalgamated radioactivity emitted by several radioactive isotopes found in the soil, including ^{226}Ra, ^{232}Th, and ^{40}K. By utilizing Equation (4), one can ascertain the radium equivalent activity [44].

$$Ra_{eq} = S_{Ra} + 1.43S_{Th} + 0.077S_K \tag{4}$$

In Bqkg^{-1}, S_{Ra}, S_{Th}, and S_K denote the mean activity of ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

2.4.2. The absorbed dose rate in the air

The amount of energy absorbed by the air per unit mass from ionizing radiation is known as the absorbed dose rate in the air. Radiation from a variety of sources, such as nuclear activities, ionizing radiation using medical treatments, and natural background radiation (such as cosmic rays and radon), can affect the absorbed dose rate in the air.

Equation (5) was used to determine the external absorbed dose rate, D_{out}, that resulted from the gamma rays released by the sample

under examination at a height of 1 m above the ground [43].

$$D_{out} = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (5)$$

The absorbed dose rate (in nanograys per hour or nGy/h) resulting from external gamma radiation exposure is denoted by the symbol D_{out}, while the standard definitions of the remaining symbols are maintained.

Due to the fact that individuals spend more time indoors than outdoors, indoor exposure is more crucial. Equation (6) is employed to compute the indoor exposure value, D_{in} [4,48].

$$D_{in} = 1.4\mathrm{D}_{\mathrm{out}} \quad (6)$$

Table 1
Concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil sample.

Sl	Coordinates of soil sample		Activity Concentration (Bqkg^{-1}) of soil sample		
	Latitude (N)	Longitude (E)	Ra-226	Th-232	K-40
1	24°04′25.86″	89°03′35.28″	22 ± 2	37 ± 3	360 ± 33
2	24°04′38.94″	89°03′25.98″	25 ± 2	33 ± 3	470 ± 43
3	24°04′28.14″	89°03′8.88″	37 ± 3	38 ± 3	430 ± 41
4	24°04′28.26″	89°03′3.06″	20 ± 2	28 ± 2	470 ± 43
5	24°04′40.62″	89°02′59.94″	26 ± 2	27 ± 2	310 ± 29
6	24°05′19.38″	89°02′50.7″	18 ± 1	23 ± 2	360 ± 33
7	24°05′13.68″	89°02′39.54″	33 ± 3	43 ± 4	520 ± 47
8	24°05′25.02″	89°02′28.8″	27 ± 2	36 ± 3	440 ± 41
9	24°05′31.56″	89°02′22.56″	27 ± 2	33 ± 3	430 ± 39
10	24°05′40.8″	89°02′18.66″	30 ± 3	44 ± 4	490 ± 45
11	24°05′50.22″	89°02′7.56″	24 ± 2	35 ± 3	480 ± 43
12	24°06′17.94″	89°02′55.26″	24 ± 2	34 ± 3	440 ± 41
13	24°05′59.28″	89°02′41.4″	28 ± 2	41 ± 4	470 ± 43
14	24°05′44.58″	89°02′45″	18 ± 1	27 ± 2	360 ± 33
15	24°05′23.34″	89°02.‘49.58″	22 ± 2	37 ± 3	390 ± 35
16	24°04′32.22″	89°03′58.5″	29 ± 2	42 ± 4	500 ± 45
17	24°04′21″	89°02′6.72″	38 ± 3	49 ± 4	530 ± 47
18	24°04′17.88″	89°03′24.24″	26 ± 2	35 ± 3	450 ± 41
19	24°04′3.06″	89°03′26.4″	28 ± 2	41 ± 4	550 ± 49
20	24°03′58.08″	89°03′23.46″	28 ± 2	41 ± 4	460 ± 41
21	24°03′56.04″	89°03′23.64′	25 ± 2	36 ± 3	430 ± 39
22	24°03′48.36″	89°03′12.72″	26 ± 2	28 ± 2	470 ± 41
23	24°03′29.82″	89°03′16.74″	29 ± 2	41 ± 4	530 ± 49
24	24°03′27.6″	89°03′30.9″	27 ± 2	39 ± 3	519 ± 47
25	24°03′28.2″	89°03′44.04″	28 ± 2	41 ± 4	510 ± 47
26	24°03′22.32″	89°03′45.96″	28 ± 2	38 ± 3	490 ± 45
27	24°03′8.46″	89°03′44.34″	31 ± 3	40 ± 4	520 ± 47
28	24°02′53.94″	89°03′41.34″	28 ± 2	44 ± 4	500 ± 45
29	24°03′31.5″	89°03′46.92″	26 ± 2	34 ± 3	450 ± 41
30	24°03′38.46″	89°03′29.7″	32 ± 3	40 ± 4	550 ± 51
31	24°03′49.62″	89°03′48.78″	35 ± 3	49 ± 4	560 ± 51
32	24°03′52.92″	89°03′51″	26 ± 2	40 ± 4	390 ± 35
33	24°03′51.42″	89°03′53.88″	20 ± 2	29 ± 2	440 ± 41
34	24°03′49.68″	89°04′18″	31 ± 3	41 ± 4	530 ± 49
35	24°03′44.46″	89°04′15.66″	33 ± 3	43 ± 4	550 ± 51
36	24°03′27.84″	89°04′9.66″	28 ± 2	36 ± 3	530 ± 49
37	24°04′7.98″	89°04′21.24″	26 ± 2	36 ± 3	530 ± 49
38	24°04′26.34″	89°04′17.7″	24 ± 2	33 ± 3	490 ± 45
39	24°04′50.46″	89°04′24.36″	37 ± 3	51 ± 5	520 ± 47
40	24°04′52.44″	89°04′19.56″	22 ± 2	35 ± 3	450 ± 41
41	24°04′44.58″	89°04′14.58″	22 ± 2	30 ± 3	410 ± 37
42	24°04′42″	89°04′18.36″	27 ± 2	38 ± 3	420 ± 39
43	24°04′34.98″	89°04′9.66″	25 ± 2	39 ± 3	410 ± 37
44	24°04′34.2″	89°04′16.14″	24 ± 2	41 ± 4	400 ± 36
45	24°04′14.58″	89°02′58.86″	19 ± 1	31 ± 3	420 ± 37
46	24°03′16.26″	89°02′54.18″	29 ± 2	38 ± 3	490 ± 45
47	24°03′14.7″	89°02′27.06″	27 ± 2	40 ± 4	460 ± 42
48	24°03′46.14″	89°02′13.02″	26 ± 2	35 ± 3	410 ± 37
49	24°03′58.74″	89°02′48.9″	19 ± 1	25 ± 2	350 ± 31
50	24°04′3.6″	89°02′43.26″	19 ± 1	18 ± 1	360 ± 33
Maximum			38 ± 3	51 ± 5	560 ± 51
Minimum			18 ± 1	18 ± 1	310 ± 29
Average			27 ± 2	37 ± 3	499 ± 45

2.4.3. The annual effective dose

The annual effective doses of E_{in} and E_{out} can be determined by utilizing the correspondingly measured outdoor and interior exposures. Therefore, utilizing Equation (7) and Eq. (8), the annual effective doses E_{in} (mSv/y) and E_{out} (mSv/y) were calculated [1,49].

$$E_{in}\left(mSv/_{y}\right) = D_{in} \times (\,8760 \times 0.7 \times 0.8) \times 10^{-6} \tag{7}$$

$$E_{out}\left(mSv/_{y}\right) = D_{out} \times (\,8760 \times 0.7 \times 0.2) \times 10^{-6} \tag{8}$$

Worldwide, the average yearly effective dose of all indoor and outdoor terrestrial radiation is 0.48 mSv, per UNSCEAR 2000 [1]. The effective dosage limit for public exposure in planned exposure conditions is 1 mSv per year, as recommended by the ICRP [50],

Table 2
Concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in water sample.

Sl	Coordinates of water sample		Activity Concentration (Bqkg^{-1}) of water sample		
	Latitude (N)	Longitude (E)	Ra-226	Th-232	K-40
1	24°05′07.2″	88°49′08.9″	5.3 ± 0.5	3.9 ± 0.3	91 ± 9
2	24°04′57.9″	88°48′12.5″	4.5 ± 0.4	4.7 ± 0.4	93 ± 9
3	24°05′10.0″	88°48′31.9″	4.7 ± 0.4	4.5 ± 0.4	95 ± 9
4	24°10′18.2″	89°10′20.2″	3.5 ± 0.3	2.7 ± 0.2	73 ± 7
5	24°10′27.8″	88°48′37.5″	4.3 ± 0.4	3.1 ± 0.3	75 ± 7
6	24°11′11.3″	88°46′44.5″	3.7 ± 0.3	3.7 ± 0.3	77 ± 7
7	24°05′34.9″	88°53′30.3″	4.5 ± 0.4	3.3 ± 0.3	71 ± 7
8	24°06′33.9″	88°54′99.6″	4.3 ± 0.4	3.5 ± 0.3	73 ± 7
9	24°07′41.0″	88°54′42.5″	3.3 ± 0.3	3.3 ± 0.3	67 ± 6
10	24°06′84.8″	88°59′10.0″	3.1 ± 0.3	3.7 ± 0.3	81 ± 8
11	24°08′71.2″	89°01′62.1″	4.7 ± 0.4	3.3 ± 0.3	79 ± 7
12	24°07′75.6″	89°01′62.6″	2.5 ± 0.2	2.1 ± 0.2	75 ± 7
13	24°05′10.3″	89°10′32.2″	2.7 ± 0.2	3.1 ± 0.3	87 ± 8
14	24°05′86.9″	89°01′26.5″	3.7 ± 0.3	3.7 ± 0.3	81 ± 8
15	24°06′26.9″	89°01′67.1″	3.9 ± 0.3	2.7 ± 0.2	77 ± 7
16	24°03′97.1″	89°01′34.2″	3.5 ± 0.3	3.1 ± 0.3	85 ± 8
17	24°04′08.1″	89°01′77.6″	3.7 ± 0.3	4.9 ± 0.4	95 ± 9
18	24°04′21.8″	89°02′10.8″	2.7 ± 0.2	4.5 ± 0.4	87 ± 8
19	24°04′40.1″	89°02′11.5″	2.3 ± 0.2	3.9 ± 0.3	82 ± 8
20	24°03′40.0″	89°02′81.5″	2.5 ± 0.2	2.7 ± 0.2	69 ± 6
21	24°03′32.9″	89°01′25.7″	3.1 ± 0.3	3.5 ± 0.3	81 ± 8
22	24°03′15.9″	89°02′71.0″	2.1 ± 0.2	3.1 ± 0.3	69 ± 6
23	24°03′27.5″	89°02′33.3″	2.3 ± 0.2	2.7 ± 0.2	75 ± 7
24	24°03′22.0″	89°02′21.3″	2.7 ± 0.2	3.9 ± 0.3	93 ± 9
25	24°03′21.2″	89°02′32.1″	3.7 ± 0.3	4.1 ± 0.4	111 ± 10
26	24°02′45.4″	89°03′31.0″	2.8 ± 0.2	3.5 ± 0.3	77 ± 7
27	24°00′51.7″	89°01′47.5″	2.5 ± 0.2	3.7 ± 0.3	79 ± 7
28	24°00′65.2″	89°02′17.1″	2.7 ± 0.2	3.9 ± 0.3	83 ± 8
29	24°00′99.5″	89°02′19.9″	4.1 ± 0.4	4.1 ± 0.4	99 ± 9
30	23°50′05.0″	89°03′47.0″	3.3 ± 0.3	2.9 ± 0.2	69 ± 6
31	23°59′10.0″	89°03′95.4″	2.9 ± 0.2	3.5 ± 0.3	73 ± 7
32	23°59′31.0″	89°04′42.0″	3.9 ± 0.3	4.1 ± 0.4	87 ± 8
33	23°56′99.5″	89°07′02.9″	3.5 ± 0.3	3.7 ± 0.3	81 ± 8
34	23°56′11.2″	89°07′63.0″	5.1 ± 0.5	3.3 ± 0.3	83 ± 8
35	23°56′58.5″	89°09′38.6 ″	3.7 ± 0.3	4.1 ± 0.4	91 ± 9
36	23°57′30.0″	89°09′34.6″	2.7 ± 0.2	3.7 ± 0.3	73 ± 7
37	23°56′61.0″	89°11′12.0″	4.5 ± 0.4	2.7 ± 0.2	87 ± 8
38	23°54′08.4″	89°09′22.2″	5.1 ± 0.5	4.1 ± 0.4	99 ± 9
39	23°55′30.5″	89°14′27.0″	4.9 ± 0.4	3.7 ± 0.3	97 ± 9
40	23°55′54.5″	89°14′31.2″	6.1 ± 0.6	5.5 ± 0.5	115 ± 11
41	23°57′72.0″	89°14′40.0″	3.9 ± 0.3	3.9 ± 0.3	113 ± 11
42	23°55′10.5″	89°16′39.3″	3.5 ± 0.3	4.1 ± 0.4	87 ± 8
43	23°56′22.0″	89°17′55.5″	4.3 ± 0.4	4.6 ± 0.4	101 ± 10
44	23°56′45.2″	89°17′45.8″	5.3 ± 0.5	4.3 ± 0.4	95 ± 9
45	23°56′55.3″	89°17′55.8″	5.1 ± 0.5	4.7 ± 0.4	97 ± 9
46	23°57′10.3″	89°18′15.8″	4.7 ± 0.4	4.9 ± 0.4	99 ± 9
47	23°57′27.1″	89°18′29.8″	4.9 ± 0.4	4.5 ± 0.4	101 ± 10
48	23°57′45.3″	89°18′47.7″	5.3 ± 0.5	5.1 ± 0.5	97 ± 9
49	23°57′58.5″	89°18′57.5″	4.5 ± 0.4	5.3 ± 0.5	103 ± 10
50	23°58′25.3″	89°19′17.7″	5.1 ± 0.5	4.9 ± 0.4	95 ± 9
Maximum			6.1 ± 0.6	5.5 ± 0.5	115 ± 11
Minimum			2.1 ± 0.2	2.7 ± 0.2	67 ± 6
Average			3.8 ± 0.3	3.4 ± 0.3	86 ± 8

IAEA [1], and the Nuclear Safety and Radiation Control Rules-1997 of Bangladesh [51–55].

2.4.4. Hazard index

Hazard indices are essential for assessing the radiological concerns associated with soil radioactivity. They offer quantifiable indicators of possible radionuclide-related health risks, such as exposure to internal and external radiation. To decrease health risks while maintaining international radiation safety standards, these indicators are crucial in establishing rules and regulations that ensure safe application. To calculate the external hazard index (H_{ex}), equation (9) is used [56].

$$H_{ex} = \frac{S_{Ra}}{370} + \frac{S_{Th}}{259} + \frac{S_K}{4810} \tag{9}$$

Equation (10) yields the internal hazard index (H_{in}), a quantitative measure of the internal health danger resulting from radon exposure and the deposition of its byproducts on lung tissues [4].

$$H_{in} = \frac{S_{Ra}}{185} + \frac{S_{Th}}{259} + \frac{S_K}{4810} \tag{10}$$

2.4.5. Excess lifetime cancer risk (ELCR)

One crucial parameter utilized to evaluate the potential health consequences linked to carcinogenic agent exposure is excess lifetime cancer risk (ELCR). This statistic provides a quantitative assessment of the supplementary cancer risk associated with the exposure, beyond the pre-existing cancer risk. For the ELCR calculation, Equation (11) is utilized [2,57].

$$ELCR = E_{aed} \times A_{lf} \times R_f \tag{11}$$

Eaed, A_{lf}, and R_f represent, respectively, the equivalent annual effective dose, the average lifetime (72.6 years), and the fatal cancer risk factor [38]. ICRP recommends a risk factor of 0.05/Sv for stochastic consequences affecting the general public [58].

Table 3
Radiological measurements of ^{238}U, ^{232}Th, and ^{40}K in soil and water samples from areas surrounding nuclear power plants in various countries preceding commercial operation.

Sl	Region of Study	Type of sample	Range of Activity Concentration ((Bqkg^{-1})				Reference
			^{238}U (^{226}Ra)	^{232}Th	^{40}K	^{137}Cs	
01	Barakah NPP, UAE	Soil	5.33 ± 0.25–22.02 ± 0.52	2.23 ± 0.10 18.15 ± 0.43	141.35 ± 8.6–611.16 ± 14.9	–	[21]
02	Kudankulam NPP, India	Soil	8.5–453.7	21.0–2181.6	11.3–1713.1	–	[20]
03	Nuclear Power Plant IV, Gung-Liao, Taipei County, Taiwan	Soil	10.61 ± 3.78–44.73 ± 8.55	5.86 ± 1.92–66.97 ± 5.34	195.29 ± 20.44–640.04 ± 46.71	2.46 ± 0.55–12.13 ± 1.31	[23]
04	Potential site for nuclear power plant, Thailand	Soil	4 ±1–122 ± 1	6 ±1–170 ± 1	5 ±4–1422 ± 20	–	[68]
05	Nuclear Power Plant facility, Itu, Nigeria	Soil	23.21 ± 7–110.72 ± 14	13.92 ± 2 −68.44 ± 6	21.85 ± 3–84.20 ± 38	0.32 ± 0.1–2.97 ± 0.4	[69]
06	Al–Nigella site, north coast of Egypt	Soil	3.16 ± 0.04–36.28 ± 0.83	0.582 ± 0.01–33.35 ± 0.62	7.38 ± 0.18–477.64 ± 8.12	0.088 ± 0.002 3.98 ± 0.09	[22]
07	Proposed Mithivirdi Atomic Power Project Site, India	Soil	3.0–32.9	10.0–72.5	25.6–331.3	0.7–3.6	[70]
08	Proposed NPP Site, Southern Part of Bangladesh	Soil	12.65 ± 1.93–48.75 ± 4.09	10.35 ± 1.55–46.65 ± 4.26	126.05 ± 7.12–418.61 ± 34.53	–	[4]
09	RNPP, Bangladesh	Soil	20.9 ± 2.9–27.8 ± 6.8	22.87 ± 4.89–206.16 ± 10.70	411 ± 73.03–716 ± 95.07	–	[35]
10	RNPP, Bangladesh	Soil	25.52 ± 1.37–37.54 ± 2.28	32.89 ± 1.66–53.37 ± 2.00	313.19 ± 27.76–521.65 ± 28.35	–	[24]
11	RNPP, Bangladesh	Soil	3.52–28.5	4.18–34.5	84–345	–	[26]
12	RNPP, Bangladesh	Ground water	4.9 ± 1.24	1.71 ± 0.43	15.43 ± 3.08	–	[34]
13	RNPP, Bangladesh	Soil Surface water	11.1–34.5 0.111–0.214	19.5–42.6 0.130–0.303	289.1–511.1 0.300–0.468	– –	[71]
14	RNPP, Bangladesh	Soil River water	18±1–38 ± 3 2.1 ± 0.2–6.1 ± 0.6	18±1–51 ± 5 2.1 ± 0.2–5.5 ± 0.5	310 ± 29–560 ± 51 67±6–115 ± 11	– –	Current study

2.4.6. Gamma level index (I_γ)

Gamma level index refers to a tool utilized to assess the radiation hazard that a particular environment or area presents in the form of gamma radiation. The tool measures the magnitude of gamma radiation and provides an estimation of the possible radiation exposure for people in the vicinity. The gamma level index is calculated using Equation (12) [58].

$$I_\gamma = \frac{S_{Ra}}{150} + \frac{S_{Th}}{100} + \frac{S_K}{1500} \tag{12}$$

3. Results and discussion

Tables 1 and 2 delineates the concentrations of activity observed within both soil and water samples, providing a comprehensive

Table 4
Comprehensive insights into radiological hazard parameters across soil samples in the present study.

Sample ID	Ra_{eq} ($Bqkg^{-1}$)	D_{in} nGy/hr	H_{ex}	H_{in}	E_{in} mSv/yr	I_γ	ELCR × 10^{-3}
1	124.08	67.90	0.34	0.39	0.33	0.91	0.25
2	138.41	76.52	0.37	0.44	0.38	1.02	0.28
3	138.75	76.82	0.37	0.47	0.38	1.01	0.29
4	164.87	89.69	0.45	0.50	0.44	1.21	0.33
5	127.09	69.07	0.34	0.41	0.34	0.92	0.26
6	111.50	61.33	0.30	0.35	0.30	0.82	0.23
7	131.67	74.03	0.36	0.44	0.36	0.98	0.28
8	135.24	74.68	0.37	0.44	0.37	0.99	0.28
9	138.76	76.35	0.37	0.45	0.37	1.02	0.28
10	143.52	79.57	0.39	0.47	0.39	1.06	0.30
11	119.59	67.04	0.32	0.39	0.33	0.89	0.25
12	130.81	72.29	0.35	0.42	0.35	0.96	0.27
13	139.98	77.46	0.38	0.45	0.38	1.03	0.29
14	110.07	60.61	0.30	0.35	0.30	0.81	0.23
15	114.95	63.60	0.31	0.37	0.31	0.85	0.24
16	126.13	70.81	0.34	0.42	0.35	0.94	0.26
17	151.74	84.55	0.41	0.51	0.41	1.12	0.31
18	127.86	71.00	0.35	0.42	0.35	0.94	0.26
19	141.85	79.29	0.38	0.46	0.39	1.05	0.29
20	154.94	84.93	0.42	0.49	0.42	1.13	0.32
21	133.90	73.79	0.36	0.43	0.36	0.98	0.27
22	160.86	87.94	0.43	0.50	0.43	1.18	0.33
23	152.75	84.64	0.41	0.49	0.42	1.13	0.31
24	135.60	75.73	0.37	0.44	0.37	1.01	0.28
25	167.37	91.78	0.45	0.53	0.45	1.23	0.34
26	140.09	77.73	0.38	0.45	0.38	1.03	0.29
27	113.94	64.95	0.31	0.39	0.32	0.85	0.24
28	138.00	76.78	0.37	0.45	0.38	1.02	0.29
29	152.17	83.32	0.41	0.48	0.41	1.11	0.31
30	130.12	73.53	0.35	0.44	0.36	0.97	0.27
31	133.89	75.69	0.36	0.46	0.37	1.00	0.28
32	124.67	68.72	0.34	0.41	0.34	0.91	0.26
33	145.40	79.49	0.39	0.45	0.39	1.07	0.30
34	151.89	84.30	0.41	0.49	0.41	1.12	0.31
35	156.86	87.13	0.42	0.51	0.43	1.16	0.32
36	148.89	82.63	0.40	0.48	0.41	1.10	0.31
37	165.48	90.95	0.45	0.52	0.45	1.22	0.34
38	141.81	78.41	0.38	0.45	0.38	1.05	0.29
39	167.13	92.20	0.45	0.55	0.45	1.22	0.34
40	145.31	79.65	0.39	0.45	0.39	1.07	0.30
41	127.93	70.40	0.35	0.40	0.35	0.94	0.26
42	158.01	86.00	0.43	0.50	0.42	1.15	0.32
43	108.05	60.47	0.29	0.36	0.30	0.80	0.22
44	139.17	76.08	0.38	0.44	0.37	1.02	0.28
45	138.57	75.76	0.37	0.43	0.37	1.02	0.28
46	136.80	76.11	0.37	0.45	0.37	1.01	0.28
47	133.92	74.23	0.36	0.43	0.36	0.99	0.28
48	143.37	78.42	0.39	0.46	0.38	1.05	0.29
49	110.30	60.66	0.30	0.35	0.30	0.81	0.23
50	142.53	77.11	0.38	0.44	0.38	1.04	0.29
Maximum	167.37	92.20	0.45	0.55	0.45	1.23	0.34
Minimum	108.05	60.47	0.29	0.35	0.30	0.80	0.22
Average	138.33	76.44	0.37	0.45	0.37	1.02	0.28
Safety criteria (UNSCEAR, 2000)	370	84	<1	<1	0.41	<1	2.9

overview of the specific levels of interest in these environmental matrices.

A minority of the activity concentration values for ^{226}Ra, while the majority of the activity concentration values for ^{232}Th and ^{40}K exceed the respective world average values of 35, 30, and 400 Bqkg^{-1} [1] for ^{226}Ra, ^{232}Th, and ^{40}K in the soil samples under investigation. The findings show a wide range of activity concentrations and a diverse distribution. On the other hand, the gathered soil samples show no discernible ^{137}C activity, indicating that there has not been any buildup of fallout radiation from nuclear accidents like Chernobyl and Fukushima. It is essential to mention that the distinct topographical and geological features of every place on Earth have an impact on soil radioactivity [30,59–61]. The type of rock used in the creation of the soil affects the particular activity concentration values. When comparing sedimentary rocks to igneous rocks, such as granite, igneous rocks typically have greater NORMs [62–65]. It is clear from Table 1 that in the examined soils, the ^{232}Th chain exhibits higher activity levels than the ^{226}Ra chain. This result validates the theory that in the crust of the Earth, thorium (Th) is around 1.5 times more prevalent than uranium (U) [66]. Over muddy ground, ^{226}Ra tends to experience surface run-off due to its high-water solubility. As a result, ^{226}Ra is readily pushed away from its initial site by the water during rainfall or other water movement. On the other hand, because of its restricted geochemical mobility,

Table 5
Comprehensive insights into radiological hazard parameters across water samples in the present study.

Sample ID	Ra_{eq} (Bqkg^{-1})	D_{in} (nGy/hr)	H_{ex}	H_{in}	E_{in} (mSv/yr)	I_{γ}	ELCR × 10^{-3}
1	17.88	10.32	0.05	0.06	0.05	0.14	0.04
2	18.38	10.56	0.05	0.06	0.05	0.14	0.04
3	18.45	10.62	0.05	0.06	0.05	0.14	0.04
4	12.98	7.55	0.04	0.04	0.04	0.10	0.03
5	14.51	8.38	0.04	0.05	0.04	0.11	0.03
6	14.92	8.59	0.04	0.05	0.04	0.11	0.03
7	14.69	8.44	0.04	0.05	0.04	0.11	0.03
8	14.93	8.57	0.04	0.05	0.04	0.11	0.03
9	13.18	7.57	0.04	0.04	0.04	0.10	0.03
10	14.63	8.45	0.04	0.05	0.04	0.11	0.03
11	15.50	8.95	0.04	0.05	0.04	0.12	0.03
12	11.28	6.66	0.03	0.04	0.03	0.09	0.02
13	13.83	8.10	0.04	0.04	0.04	0.11	0.03
14	15.23	8.79	0.04	0.05	0.04	0.12	0.03
15	13.69	7.97	0.04	0.05	0.04	0.10	0.03
16	14.48	8.44	0.04	0.05	0.04	0.11	0.03
17	18.02	10.36	0.05	0.06	0.05	0.14	0.04
18	15.83	9.11	0.04	0.05	0.04	0.12	0.03
19	14.19	8.21	0.04	0.04	0.04	0.11	0.03
20	11.67	6.80	0.03	0.04	0.03	0.09	0.03
21	14.34	8.31	0.04	0.05	0.04	0.11	0.03
22	11.85	6.86	0.03	0.04	0.03	0.09	0.03
23	11.94	6.99	0.03	0.04	0.03	0.09	0.03
24	15.44	8.98	0.04	0.05	0.04	0.12	0.03
25	18.11	10.58	0.05	0.06	0.05	0.14	0.04
26	13.73	7.94	0.04	0.04	0.04	0.11	0.03
27	13.87	8.02	0.04	0.04	0.04	0.11	0.03
28	14.67	8.48	0.04	0.05	0.04	0.11	0.03
29	17.59	10.20	0.05	0.06	0.05	0.13	0.04
30	12.76	7.38	0.03	0.04	0.04	0.10	0.03
31	13.53	7.80	0.04	0.04	0.04	0.10	0.03
32	16.46	9.49	0.04	0.06	0.05	0.13	0.04
33	15.03	8.68	0.04	0.05	0.04	0.11	0.03
34	16.21	9.37	0.04	0.06	0.05	0.12	0.03
35	16.57	9.58	0.04	0.05	0.05	0.13	0.04
36	13.61	7.83	0.04	0.04	0.04	0.10	0.03
37	15.06	8.81	0.04	0.05	0.04	0.12	0.03
38	18.59	10.75	0.05	0.06	0.05	0.14	0.04
39	17.66	10.25	0.05	0.06	0.05	0.13	0.04
40	22.82	13.12	0.06	0.08	0.06	0.17	0.05
41	18.18	10.64	0.05	0.06	0.05	0.14	0.04
42	16.06	9.27	0.04	0.05	0.05	0.12	0.03
43	18.66	10.77	0.05	0.06	0.05	0.14	0.04
44	18.76	10.81	0.05	0.07	0.05	0.14	0.04
45	19.29	11.09	0.05	0.07	0.05	0.15	0.04
46	19.33	11.11	0.05	0.06	0.05	0.15	0.04
47	19.11	11.03	0.05	0.06	0.05	0.15	0.04
48	20.06	11.49	0.05	0.07	0.06	0.15	0.04
49	20.01	11.49	0.05	0.07	0.06	0.15	0.04
50	19.42	11.13	0.05	0.07	0.05	0.15	0.04
Maximum	22.82	13.12	0.06	0.08	0.06	0.17	0.05
Minimum	11.28.	6.66.	0.03	0.04	0.03	0.09	0.02
Average	15.94	9.21	0.04	0.05	0.05	0.12	0.03

^{232}Th has a tendency to stick to the soil more firmly. Because of this property, it is less likely to be transported by water and is more likely to stay in the soil where it was first deposited [67]. In the soil samples under examination, the depleted levels of ^{226}Ra can be attributed to the absence of minerals rich in uranium, such as apatite and zircon. This indicates a scarcity of specific uranium-containing minerals in the soil composition, contributing to the observed lower values of ^{226}Ra in the collected samples. It is evident from Table 1 that there is a conspicuous elevation in the concentration of ^{40}K across all examined soil samples when juxtaposed with the reference values provided by UNSCEAR 2000. This heightened presence of ^{40}K could be attributed to prevalent agricultural practices, notably the substantial application of chemical fertilizers, including NPK (nitrogen, phosphorus, potassium), TSP (triple superphosphate), and SSP (single superphosphate), aimed at enhancing crop productivity. Given that agricultural fertilizers encompass trace amounts of various elements, including uranium, thorium, and potassium, the application of these fertilizers introduces additional quantities of these elements into the soil. Consequently, this fertilization process may lead to an augmentation in the concentrations of radionuclides, specifically ^{40}K, in the soil matrix. The intricate interplay between agricultural practices, fertilization choices, and subsequent radionuclide concentrations underscores the complex dynamics influencing the radioactivity profile of the soil under examination. Table 3 displays the radiological assessments of ^{238}U, ^{232}Th, and ^{40}K in soil and water samples obtained from regions adjacent to nuclear power plants across different countries before the commencement of commercial operations.

As shown in Table 3, elevated levels of ^{226}Ra, ^{232}Th, and ^{40}K were discovered close to the locations of proposed nuclear power plants in southern Thailand [68] and Tirunelveli District, India [20]. The authors [20] suggest that the presence of opaque minerals with different compositions, such as zircon, monazite, tourmaline, apatite, and rutile, may be the cause of the elevated levels of NORMS in soil samples collected in the vicinity of the Kudankulam nuclear power project in the Tirunelveli District of India. Leaching of fertilizers containing potassium from agricultural lands is also considered to be a major factor. According to the scientists, the presence of igneous rocks in the southern region of Thailand may have contributed to elevated values of ^{226}Ra, ^{232}Th, and ^{40}K at potential sites for nuclear power facilities [68]. These results are particularly consistent with international studies, including those conducted at Gung-Liao Nuclear Power Plant, Taipei County, Taiwan [23] and the Proposed Mithivirdi Atomic Power Project Site, Bhavnagar District, Gujarat, India [70]. Furthermore, soil samples from the vicinity of planned nuclear power facilities in Nigeria [69], Taiwan [23] and India [70] showed lower concentrations of the artificial radionuclide ^{137}Cs. Scrap metal recycling factory [69], previous open-air atomic bomb testing carried out by several nations before the ban on such tests, and radioactive fallout from nuclear accidents such as Chernobyl and Fukushima [22,23,70] are all potential origins of this pollution. The discrepancies between our findings and those of previous studies in the same region could stem from several factors. Variations in soil sample collection methods, locations, and depths can lead to different radiometric readings. Additionally, radiometric levels in soil can fluctuate over time due to environmental changes, such as precipitation, dust deposition, and natural radioactivity variations, which might differ from the temporal context of the cited studies. Differences in analytical techniques, including calibration procedures, detection limits, and measurement methods, could also contribute to variations in reported results. Finally, local factors such as geological formations and anthropogenic activities may influence radiometric levels in soil differently from other studies.

The computed values for the different hazard characteristics connected to the soil and water samples are displayed in Tables 4 and 5, while the spatial distributions of effective dose are depicted in Figs. 2 and 3.

Radiological hazard parameters, such as radium equivalent activity, annual effective dose, external and internal hazard indices, and lifetime carcinogenic risk, for both soil and water samples consistently fall below the safe thresholds set by various international organizations, even though the majority of outdoor absorbed dose rate, outdoor effective dose, and gamma representative level index values linked to soil samples exceed the global average of 59 nGy/h, 0.07 mSvyr^{-1}, and the recommended limit of 1 [1,72]. This

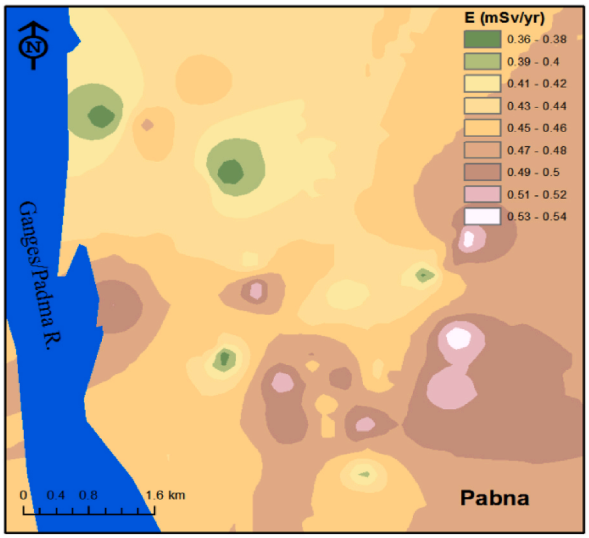

Fig. 2. Spatial distributions of effective dose associated with soil samples.

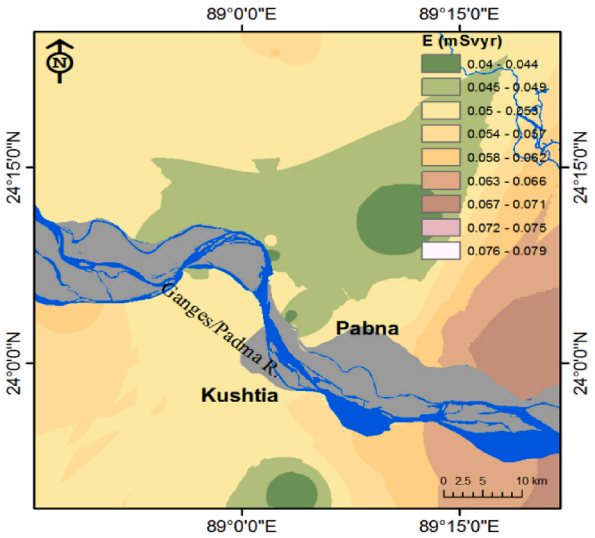

Fig. 3. Spatial distribution of effective dose associated with water samples.

suggests that there is no discernible radioactive risk to the local community or ecosystem from the soil and water samples collected from the RNPP area. All of the tested samples' analyses confirm that they are suitable for a range of uses, including construction of buildings and agriculture, without posing a serious risk to the environment or public health.

4. Conclusion

In this investigation, an assessment was conducted to determine the concentrations of primordial radionuclides, specifically ^{226}Ra, ^{232}Th, and ^{40}K, in soil and water samples collected from the vicinity of the Rooppur Nuclear Power Plant in Rooppur, Pabna district, Bangladesh. Notably, the analysis revealed the absence of any artificial radionuclides in the examined samples. It is important to acknowledge that the absence of ^{137}Cs may be due to the limitations of the gamma spectrometer used in this study, which may not have been sensitive enough to detect this radionuclide at low levels. While most of the outdoor absorbed dose rate, outdoor effective dose, and gamma representative level index values associated with soil samples surpassed the global average, it is crucial to highlight that other key radiological hazard parameters for both soil and water samples consistently remained below the established safety thresholds defined by various international organizations. The results suggest that the soil and water samples collected from the RNPP area do not pose a significant radiological hazard to the neighbouring population and the ecosystem. The significance of these findings lies in the establishment of a comprehensive understanding of the radiological landscape in the Rooppur Nuclear Power Plant's adjacent area. Notably, the data presented in this study, being the most recent available, can serve as vital baseline information for ongoing and future assessments of the region's environmental radioactivity. Furthermore, the results contribute valuable insights for monitoring potential fluctuations in background radioactivity within the surroundings of the RNPP following its operational phase.

Consent to participate

This study included neither experimental animals nor people as subjects.

CRediT authorship contribution statement

S. Yeasmin: Writing – original draft, Investigation, Conceptualization. **S.K. Das:** Supervision. **M.M. Mahfuz Siraz:** Writing – original draft, Methodology, Investigation, Data curation. **A.F.M. Mizanur Rahman:** Investigation, Data curation. **M.S. Rahman:** Supervision.

Statements and declarations

No funds, grants, or other support was received.

Statements and declarations

"All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors".

Data availability

The datasets created and/or examined for this study are not publicly accessible, however they can be obtained from the corresponding author upon justifiable request.

Funding

This work was carried out without any financing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] UNSCEAR, Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation,Report to the General Assembly with Scientific Annexes, Annex B, 2000. United Nations, New York.
[2] R. Ravisankar, et al., Assessments of radioactivity concentration of natural radionuclides and radiological hazard indices in sediment samples from the East coast of Tamilnadu, India with statistical approach, Mar. Pollut. Bull. 97 (1–2) (2015) 419–430, https://doi.org/10.1016/j.marpolbul.2015.05.058.
[3] S. Yeasmin, S.K. Das, M.M.M. Siraz, M.S. Rahman, Assessing radioactivity and hazards: analysis of soil, water, and coal samples near a coal-fired thermal power plant and their implications for human health and the environment, Int. J. Environ. Anal. Chem. (Oct. 2023) 1–18, https://doi.org/10.1080/03067319.2023.2267995.
[4] M.M.M. Siraz, et al., Baseline radioactivity in the five candidate sites for the second nuclear power plant in Bangladesh and concomitant hazards assessment, Int. J. Environ. Anal. Chem. (May 2023) 1–16, https://doi.org/10.1080/03067319.2023.2207470.
[5] M. Tanha, et al., Environmental radioactivity studies in Kabul and northern Afghanistan, J. Radioanal. Nucl. Chem. 318 (3) (2018) 2425–2433, https://doi.org/10.1007/s10967-018-6242-1.
[6] M.A.M. Uosif, Z.A. Alrowaili, R. Elsaman, A.M.A. Mostafa, SOIL–SOYBEAN TRANSFER FACTOR of NATURAL RADIONUCLIDES in DIFFERENT SOIL TEXTURES and the ASSESSMENT of COMMITTED EFFECTIVE DOSE, Radiat. Protect. Dosim. 188 (4) (2020) 529–535, https://doi.org/10.1093/rpd/ncaa005.
[7] B. Jananee, A. Rajalakshmi, V. Thangam, K.M. Bharath, V. Sathish, Natural radioactivity in soils of Elephant hills, Tamilnadu, India, J. Radioanal. Nucl. Chem. 329 (3) (2021) 1261–1268, https://doi.org/10.1007/s10967-021-07886-7.
[8] O.O. Adewoyin, O. Maxwell, S.A. Akinwumi, T.A. Adagunodo, Z. Embong, M.A. Saeed, Estimation of activity concentrations of radionuclides and their hazard indices in coastal plain sand region of Ogun state, Sci. Rep. 12 (1) (2022) 1–8, https://doi.org/10.1038/s41598-022-06064-3.
[9] M. Ghiassi-Nejad, S.M.J. Mortazavi, J.R. Cameron, A. Niroomand-Rad, P.A. Karam, Very high background radiation areas of Ramsar, Iran: preliminary biological studies, Health Phys. 82 (1) (2002) 87–93, https://doi.org/10.1097/00004032-200201000-00011.
[10] L. Wei, T. Sugahara, An introductory overview of the epidemiological study on the population at the high background radiation areas in Yangjiang, China, J. Radiat. Res. 41 (2000) 1–7, https://doi.org/10.1269/jrr.41.S1. Suppl, no. 2000.
[11] A.C. Paul, P.M.B. Pillai, P.P. Haridasan, S. Radhakrishnan, S. Krishnamony, Population exposure to airborne thorium at the high natural radiation areas in India, J. Environ. Radioact. 40 (3) (1998) 251–259, https://doi.org/10.1016/S0265-931X(97)00087-8.
[12] A.K. Mohanty, D. Sengupta, S.K. Das, S.K. Saha, K.V. Van, Natural radioactivity and radiation exposure in the high background area at Chhatrapur beach placer deposit of Orissa, India, J. Environ. Radioact. 75 (1) (2004) 15–33, https://doi.org/10.1016/j.jenvrad.2003.09.004.
[13] B. Santhanabharathi, et al., Source, fate and transfer of primordial radionuclides as potential contaminants in environmental matrices of high and low background radiation areas–a critical review, Int. J. Environ. Anal. Chem. 00 (00) (2023) 1–27, https://doi.org/10.1080/03067319.2023.2277891.
[14] M. SureshGandhi, R. Ravisankar, A. Rajalakshmi, S. Sivakumar, A. Chandrasekaran, D. Pream Anand, Measurements of natural gamma radiation in beach sediments of north east coast of Tamilnadu, India by gamma ray spectrometry with multivariate statistical approach, J. Radiat. Res. Appl. Sci. 7 (1) (2014) 7–17, https://doi.org/10.1016/j.jrras.2013.11.001.
[15] M.M.M. Siraz, et al., Evaluation of radioactivity in soil and rock samples from an undiscovered sea beach in the southeastern coastline of Bangladesh and associated health risk, Environ. Monit. Assess. 195 (9) (2023) 1–15, https://doi.org/10.1007/s10661-023-11636-5.
[16] D. Balakrishnan, P.J. Jojo, M.U. Khandaker, Inhalation dose in the indoor environment of Eloor industrial area, Kerala, India, Radiat. Phys. Chem. 188 (April) (2021) 109655, https://doi.org/10.1016/j.radphyschem.2021.109655.
[17] P.J. JoJo, et al., Study of certain congenital malformations due to low-level radiation exposures from high background radiation areas, J. King Saud Univ. Sci. 34 (6) (2022), https://doi.org/10.1016/j.jksus.2022.102166.
[18] H.N. Singh, D. Shanker, V.N. Neelakandan, V.P. Singh, Distribution patterns of natural radioactivity and delineation of anomalous radioactive zones using in situ radiation observations in Southern Tamil Nadu, India, J. Hazard Mater. 141 (1) (Mar. 2007) 264–272, https://doi.org/10.1016/J.JHAZMAT.2006.06.118.
[19] IAEA Nuclear Energy Series No. NG-T-3.11, Managing Environmental Impact Assessment for Construction and Operation in New Nuclear Power Programmes, 2014. Vienna, Austria.
[20] G.M. Brahmanandhan, S. Selvasekarapandian, J. Malathi, D. Khanna, M.P. Rajan, A.G. Hegde, Natural radioactivity in the soil samples in and around Kudankulam nuclear power plant site, J. Radioanal. Nucl. Chem. 274 (2) (2007) 361–366, https://doi.org/10.1007/s10967-007-1123-z.
[21] M.R. Al Rashdi, W. El Mowafi, S. Alaabed, M. El Tokhi, A.A. Arabi, Radiological baseline around the Barakah nuclear power plant, UAE, Arab. J. Chem. 14 (5) (2021) 103125, https://doi.org/10.1016/j.arabjc.2021.103125.
[22] A.N. Shabaka, A. Omar, S.A. El-Mongy, A.F. Tawfic, Analysis of natural radionuclides and 137Cs using HPGe spectrometer and radiological hazards assessment for Al-Nigella site, Egypt, Int. J. Environ. Anal. Chem. 102 (2) (2022) 575–588, https://doi.org/10.1080/03067319.2020.1724985.
[23] T.L. Tsai, C.C. Lin, T.W. Wang, T.C. Chu, Radioactivity concentrations and dose assessment for soil samples around nuclear power plant IV in Taiwan, J. Radiol. Prot. 28 (3) (2008) 347–360, https://doi.org/10.1088/0952-4746/28/3/005.
[24] J. Ferdous, A. Begum, A. Islam, Radioactivity of soil at proposed Rooppur nuclear power plant site in Bangladesh, Int. J. Radiat. Res. 13 (2) (2015) 135–142.
[25] M.A. Haydar, et al., The status of NORMs in natural environment adjacent to the Rooppur nuclear power plant of Bangladesh, Nucl. Eng. Technol. 53 (12) (Dec. 2021) 4114–4121, https://doi.org/10.1016/j.net.2021.06.025.
[26] Samiul, et al., THE ACTIVITY CONCENTRATION OF RADIONUCLIDES (226 Ra , 232 Th AND 40 K) IN SOIL SAMPLES AND ASSOCIATED HEALTH HAZARDS IN NATORE , KUSHTIA AND, J. Bangladesh Acad. Sci. 43 (2) (2019) 169–180.
[27] M.A. Haydar, et al., Natural radioactivity around Rooppur nuclear power plant before commissioning, J. Phys. Conf. Ser. 1701 (1) (2022) 786–796, https://doi.org/10.1088/1742-6596/1701/1/012009.
[28] A.S.M. Sayam, M.A. Islam, M.R. Ali, M.M. Hossain Khan, M.F. Ishrak, Neutron activation analysis of sediments of the Padma River adjacent to Rooppur nuclear power plant: elemental and multivariate statistical approach, Appl. Radiat. Isot. 196 (October 2022) (Jun. 2023) 110784, https://doi.org/10.1016/j.apradiso.2023.110784.

[29] I.V.G.R.A. Mikailova, D.N. Kurbakov, E.V. Sidorova, A.V.P.N.V. Andreeva, Yu V. Sorokin, Comprehensive RADIOECOLOGICAL monitoring of freshwater ecosystems in the vicinity of rooppur NPP (PEOPLE'S republic of Bangladesh), Mar. Biol. J. 5 (3) (Sep. 2020) 30–54, https://doi.org/10.21072/mbj.2020.05.3.04.

[30] M.M.M. Siraz, et al., The presence of carcinogenic radon in the Padma River water, adjacent to the Rooppur nuclear power plant, Nucl. Eng. Technol. 55 (8) (Aug. 2023) 3046–3053, https://doi.org/10.1016/j.net.2023.04.038.

[31] A. Valerievich Panov, N. Nizametdinovich Isamov, P. Nikolaevich Tsygvintsev, I. Viktorovna Geshel, E. Valentinovna Sidorova, Comprehensive radioecological monitoring of terrestrial ecosystems in the vicinity of the Rooppur nuclear power plant (People's Republic of Bangladesh), Environ. Nanotechnology, Monit. Manag. 17 (November 2021) (May 2022) 100623, https://doi.org/10.1016/j.enmm.2021.100623.

[32] Y.V. Sorokin, A.V. Panov, Ichthyofauna of the Padma River in the area of the Rooppur nuclear power plant (People's Republic of Bangladesh), J. Ichthyol. 62 (5) (Oct. 2022) 786–796, https://doi.org/10.1134/S0032945222050186.

[33] S. Pervin, et al., Measurement of 222Rn in ground water and NORMs in top soil in the environs of Rooppur Nuclear Power Plant site and associated health hazard, J. Radioanal. Nucl. Chem. (Aug. 2023) 0123456789, https://doi.org/10.1007/s10967-023-09083-0.

[34] T.R. Choudhury, J. Ferdous, M.M. Haque, M.M. Rahman, S.B. Quraishi, M.S. Rahman, Assessment of heavy metals and radionuclides in groundwater and associated human health risk appraisal in the vicinity of Rooppur nuclear power plant, Bangladesh, J. Contam. Hydrol. 251 (Dec. 2022) 104072, https://doi.org/10.1016/j.jconhyd.2022.104072.

[35] M.A. Haydar, et al., The status of NORMs in natural environment adjacent to the Rooppur nuclear power plant of Bangladesh, Nucl. Eng. Technol. 53 (12) (2021) 4114–4121, https://doi.org/10.1016/j.net.2021.06.025.

[36] A.V. Panov, N.N. Isamov, P.N. Tsygvintsev, I.V. Geshel, E.V. Sidorova, Radiation monitoring of foodstuffs and drinking water in the vicinity of the Rooppur Nuclear Power Plant (People's Republic of Bangladesh), J. Food Compos. Anal. 114 (April) (Dec. 2022) 104732, https://doi.org/10.1016/j.jfca.2022.104732.

[37] S.T. Islam, A. Paul, Geography in Bangladesh : Niche of the discipline in the context of global change, Geogr. Bangladesh (Apr. 2019) 1–7, https://doi.org/10.4324/9780429263354-1.

[38] BBS, "BANGLADESH BUREAU OF STATISTICS (BBS) Statistics and Informatics Division (SID) Ministry of Planning, Rep. Agric. Rural Stat 23 (2019).

[39] M.B. Rashid, M.A. Habib, R. Khan, A.R.M.T. Islam, Land transform and its consequences due to the route change of the Brahmaputra River in Bangladesh, Int. J. River Basin Manag. (Jun. 2021) 1–13, https://doi.org/10.1080/15715124.2021.1938095.

[40] IAEA, Guidelines on soil and vegetation sampling for radiological monitoring, Tech. Reports Ser. No. 486 (2019) 486.

[41] S. Amatullah, R. Rahman, J. Ferdous, M.M.M. Siraz, M.U. Khandaker, S.F. Mahal, Assessment of radiometric standard and potential health risks from building materials used in Bangladeshi dwellings, Int. J. Environ. Anal. Chem. (2021) 1–13, https://doi.org/10.1080/03067319.2021.1907361.

[42] A. Rahim, S. Ms, J. Ferdous, A. Begum, I. Ma, A Study of Activity Concentrations in Water Samples from Kurigram , Bangladesh, J. Environ. Pollut. Manag. 1 (1) (2018) 1–7.

[43] M.M.M. Siraz, et al., Assessment of radionuclides from coal-fired brick kilns on the outskirts of Dhaka city and the consequent hazards on human health and the environment, Nucl. Eng. Technol. (May 2023), https://doi.org/10.1016/J.NET.2023.04.045.

[44] M.M.M. Siraz, et al., Risk assessment of naturally occurring radioactivity in soil adjacent to a coal-fired brick kiln, Radiat. Phys. Chem. 209 (March) (Aug. 2023) 110985, https://doi.org/10.1016/j.radphyschem.2023.110985.

[45] S. Yeasmin, S. Karmaker, A.M. Rahman, M.M.M. Siraz, M.S. Sultana, Measurement of Radioactvity in Soil and Vegetable Samples in the Northern Area of Madhupur Upzila At Tangail District in Bangladesh and Assessment of Assiociated Radological, Bangladesh J. Phys. 16 (2014) 49–58. March 2017.

[46] M.N. Aktar, S.K. Das, S. Yeasmin, M.M. Siraz, A.M. Rahman, Measurement of Radioactivity And Assessment of Radiological Hazard of Tea Samples Collected From Local Market In Bangladesh, J. Bangladesh Acad. Sci. 42 (2) (2018) 171–176, https://doi.org/10.3329/jbas.v42i2.40049.

[47] M.S.D. Sarker, R. Rahman, M.M.M. Siraz, M.U. Khandaker, S. Yeasmin, The presence of primordial radionuclides in powdered milk and estimation of the concomitant ingestion dose, Radiat. Phys. Chem. 188 (March) (Nov. 2021) 109597, https://doi.org/10.1016/j.radphyschem.2021.109597.

[48] M. Siraz, D. Roy, J. Dewan, B. Rashid, M.U. Khandaker, "Vertical distributions of radionuclides along the tourist - attractive Marayon Tong Hill, in: The Bandarban District of Bangladesh, 2023, https://doi.org/10.1007/s10661-023-10921-7.

[49] J. Al Mahmud, et al., A pioneering study of the radiological mapping in the world ' s largest mangrove forest (the Sundarbans) and implications for the public and environment, Mar. Pollut. Bull. 202 (2024) 116349. September 2023.

[50] International Commission on Radiological Protection, Ann. ICRP (2007), https://doi.org/10.1016/j.icrp.2004.12.002.

[51] R. Khan, A. Begum, A. Hoque, M.M.M. Siraz, Occupational Dose From External Ionizing Radiation in Interventional Cardiology, Bangladesh J. Phys. 14 (2013) 17–22.

[52] M.M.M. Siraz, A. Begum, R. Khan, A. Hoque, A. Begum, Measurement of effective dose to patient during interventional cardiac procedure, J. Asiat. Soc. Bangladesh, Sci. 40 (1) (2014) 1–7, https://doi.org/10.3329/jasbs.v40i1.31728.

[53] M.S. Rahman, A. Begum, A. Hoque, R.K. Khan, M.M.M. Siraz, Assessment of whole-body Occupational radiation exposures in nuclear medicine practices of Bangladesh during 2010-2014, Iran. J. Nucl. Med. 24 (1) (2016) 51–58.

[54] M.S. Rahman, A. Begum, M.R.K. Khan, M.A. Hoque, M.M.M. Siraz, Occupational Exposure to Ionizing Radiation in Interventional Cardiology Practices in Bangladesh during 2010-2014, Malaysian J. Med. Biol. Res. 3 (2) (Dec. 2016) 63–68, https://doi.org/10.18034/mjmbr.v3i2.407.

[55] M.S. Rahman, A. Begum, A. Hoque, R.K. Khan, M.M.M. Siraz, Assessment of whole-body occupational radiation exposure in industrial radiography practices in Bangladesh during 2010-2014, Brazilian J. Radiat. Sci. 4 (2) (Nov. 2016), https://doi.org/10.15392/bjrs.v4i2.187.

[56] M.M.M. Siraz, et al., Evaluation of radioactivity in soil and rock samples from an undiscovered sea beach in the southeastern coastline of Bangladesh and associated health risk, Environ. Monit. Assess. 195 (9) (Sep. 2023) 1028, https://doi.org/10.1007/s10661-023-11636-5.

[57] M.T. Kolo, S.A.B.A. Aziz, M.U. Khandaker, K. Asaduzzaman, Y.M. Amin, Evaluation of radiological risks due to natural radioactivity around Lynas Advanced Material Plant environment, Kuantan, Pahang, Malaysia, Environ. Sci. Pollut. Res. 22 (17) (Sep. 2015) 13127–13136, https://doi.org/10.1007/S11356-015-4577-5.

[58] M.U. Khandaker, K. Asaduzzaman, A.F. Bin Sulaiman, D.A. Bradley, M.O. Isinkaye, Elevated concentrations of naturally occurring radionuclides in heavy mineral-rich beach sands of Langkawi Island, Malaysia, Mar. Pollut. Bull. 127 (2018) 654–663, https://doi.org/10.1016/j.marpolbul.2017.12.055. December 2017.

[59] J. Al Mahmud, et al., A study into the long-overlooked carcinogenic radon in bottled water and deep well water in Dhaka, Bangladesh, Int. J. Environ. Anal. Chem. (Jan. 2023) 1–13, https://doi.org/10.1080/03067319.2022.2163895.

[60] M.S. Alam, et al., A study on measuring the 222Rn in the Buriganga River and tap water of the megacity Dhaka, PLoS One 18 (5) (May 2023) e0286267, https://doi.org/10.1371/journal.pone.0286267.

[61] M.M.M. Siraz, et al., Assessment of radioactivity level and associated radiological hazard in fertilizer from Dhaka, Environ. Monit. Assess. 196 (2) (Feb. 2024) 192, https://doi.org/10.1007/s10661-024-12328-4.

[62] A. Faanu, et al., Natural radioactivity levels in soils, rocks and water at a mining concession of Perseus gold mine and surrounding towns in Central Region of Ghana, SpringerPlus 5 (1) (2016) 1–16, https://doi.org/10.1186/s40064-016-1716-5.

[63] E. Kapdan, N. Altinsoy, G. Karahan, A. Yuksel, Outdoor radioactivity and health risk assessment for capital city Ankara, Turkey, J. Radioanal. Nucl. Chem. 318 (2) (2018) 1033–1042, https://doi.org/10.1007/s10967-018-6060-5.

[64] K. Manisa, et al., Assessment of natural radioactivity level of soil and water in the region of Çorlu (Turkey), J. Radioanal. Nucl. Chem. 329 (3) (2021) 1213–1221, https://doi.org/10.1007/s10967-021-07906-6.

[65] K.U. Reddy, C. Ningappa, J. Sannappa, Natural radioactivity level in soils around Kolar Gold Fields, Kolar district, Karnataka, India, J. Radioanal. Nucl. Chem. 314 (3) (2017) 2037–2045, https://doi.org/10.1007/s10967-017-5545-y.

[66] M.U. Khandaker, et al., Evaluation of radionuclides transfer from soil-to-edible flora and estimation of radiological dose to the Malaysian populace, Chemosphere 154 (2016) 528–536, https://doi.org/10.1016/j.chemosphere.2016.03.121.

[67] G. Suresh, V. Ramasamy, V. Meenakshisundaram, R. Venkatachalapathy, V. Ponnusamy, Influence of mineralogical and heavy metal composition on natural radionuclide concentrations in the river sediments, Appl. Radiat. Isot. 69 (10) (2011) 1466–1474, https://doi.org/10.1016/j.apradiso.2011.05.020.
[68] R. Kritsananuwat, H. Arae, M. Fukushi, S.K. Sahoo, S. Chanyotha, Natural radioactivity survey on soils originated from southern part of Thailand as potential sites for nuclear power plants from radiological viewpoint and risk assessment, J. Radioanal. Nucl. Chem. 305 (2) (2015) 487–499, https://doi.org/10.1007/s10967-015-3994-8.
[69] G.B. Ekong, T.C. Akpa, I. Umaru, M.A. Akpaowo, S.D. Yusuf, N.U. Benson, Baseline radioactivity and associated radiological hazards in soils around a proposed nuclear power plant facility, South-South Nigeria, J. African Earth Sci. 182 (May) (2021) 104289, https://doi.org/10.1016/j.jafrearsci.2021.104289.
[70] A. Patra, T. Jaison, S. Wagh, M. Jha, I. Saradhi, Av Kumar, Studies on natural and fallout radioactivity mapping of the proposed Mithivirdi Atomic Power Project Site in Bhavnagar District, Gujarat, India, Radiat. Prot. Environ. 44 (1) (2021) 12, https://doi.org/10.4103/rpe.rpe_5_21.
[71] A.S. Mollah, S.R. Chakraborty, "Radioactivity and Radiation Levels in and Around the Proposed Nuclear Power Plant Site at Rooppur,", 2009.
[72] NEA-OECD, "Exposure to Radiation from Natural Radioactivity in Building Materials, Report by NEA group of Experts, OECD (1979). Paris, France.