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Research article

Transfer factors of naturally occurring radionuclides from soil-to-rice cultivated in Bangladesh and associated health implications

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ABSTRACT

This study investigates the uptake of naturally occurring radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) from soil by rice plants in extensively cultivated regions in Bangladesh. It also evaluates the potential radiation risks associated with rice consumption by the Bangladeshi populace. High purity germanium (HPGe) gamma-ray spectrometry was employed to measure the concentrations of radionuclides in both soil and rice samples. For ^{40}K, our results agree with the International Atomic Energy Agency's (IAEA) published value; however, the transfer factors (TF) for the other two radionuclides differ considerably. Despite the fact that the IAEA based its publication of TFs for ^{226}Ra and ^{232}Th on clay soil, the majority of the soil profile in the present study was silty clay with a little alkalinity. Moreover, the data obtained may have been impacted by the growing seasons, cultivation methods, and soil fertility. Additionally, the annual effective dose due to the ingestion of radioactivity resulting from rice consumption was evaluated and the results agree with UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000. With a few exceptions, the excess lifetime cancer risk (ELCR) values for ^{226}Ra, ^{232}Th, and ^{40}K were below the globally average permissible level (1×10^{-3}). In light of this, the current study indicates that consuming rice does not pose an immediate health risk to the general public. By studying TFs among various rice varieties and geographical areas, scientists can develop models to forecast the possible radiation exposure from rice consumption and pinpoint activities or areas that require additional attention.

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1. Introduction

It is crucial to comprehend how natural radionuclides behave in the environment (including their distribution pathways, mobility, and transfers), as this knowledge can be used to create models, test them, and determine the right parameter values for the evaluations of radiological performance [1]. The soil contains natural radionuclides, which are taken up by plants and eventually find their way into food and water. Similar behavior is seen in man-made radionuclides, and over the past half-century, food chains all over the world have been tainted by radionuclides that were discharged into the atmosphere during nuclear weapons testing [2]. ^{238}U, ^{232}Th, and their decay products, as well as ^{40}K, are the most regularly observed radionuclides. Finding the source of contamination with any degree of accuracy is extremely difficult, if not impossible. Numerous types of research on environmental radioactivity in foodstuffs and its transmission or route mechanisms to plants, animals, and people have been published so far [3–6]. To quantify the transmission of radionuclides to the food chain in radioecological research, a metric known as the soil-to-plant transfer factor (TF) is frequently utilized. This statistic is crucial for determining the human ingestion doses given the potential for radiological toxicity. Now, this TF can differ considerably based on the element types and ecological factors such as soil and plant types, frequency of rain, intensity of sunlight, temperature or seasonal variation etc. [7–9]. Along with these, there are additional human influences that have a big impact like agricultural methods or practices. Since each of the above features depends on the climatic zone, it is normal to predict that the same element would have various TF values for a given plant (and plant portion/section) that is located in a different climatic zone [10, 11]. Therefore, it is advised to utilize site-specific or local data to estimate radiation hazards since the absorption of radionuclides from soil to plants varies depending on the above-mentioned parameters.

Due to varying farming practices, methods, irrigation infrastructure, farmer attitudes, etc. in various regions of the nation, Bangladesh's overall agricultural development masks significant regional disparities. Various environmental conditions, such as downpours, humidity, temperature, as well as agroecological factors are mainly responsible for the geographical variations in agricultural production [12]. The main staple food in Bangladesh is rice (*Oryza sativa* L.) and rice productivity has increased significantly over the past 50 years as a result of significant research efforts and farming innovations. According to the Food and Agriculture Organization (FAO) of the United Nations, national rice output expanded dramatically throughout this period, rising by an astounding 2.5 times, from 15 million tons in 1971 to 37.8 million tons in 2021. With a 38.3-million-ton production in 2022, Bangladesh now holds the 3rd position globally in rice production [13].

The Jashore area is crucial to Bangladeshi agriculture. The area provides a range of crops all year long such as rice, mustard, pulse, jute, wheat, pumpkin, lentil, sesame, sugarcane, vegetables, etc. Among them, rice is mainly produced in most parts of the cultivable land of this area. Once more, crops raised in various settings and cropping regimes had diverse reactions to fertilizer nutrients. The entire nutritional balance of intensive cropping systems depends heavily on the inputs of mineral fertilizers [12,14]. However, due to intense cropping with current cultivars, inappropriate and imbalanced application of fertilizer and manure, soil fertility and production are heading towards a negative direction in this area [15]. Hence, a detailed study regarding the TF values of soil-to-rice and other hazard parameters is essential for this region which is missing in the current literature. Moreover, Bangladesh is establishing its first-ever nuclear power plant (2400 MW) at Rooppur, Pabna which is approximately 120 km away from the Jashore area [16]. The power plant is expected to start up in the latter half of 2024. Therefore, establishing a baseline radiological data is necessary before the commissioning of the power plant.

In this study, we have tried to depict the radiological data (^{226}Ra, ^{232}Th, and ^{40}K) and corresponding TF values of soil-to-rice of the Jashore area and assessed various radiation hazard indices to give an idea of the current situation. It is important to understand these transfer variables for several reasons. First of all, it enables scientists to develop precise models that forecast radiation exposure levels for populations in various areas according to local soil parameters and rice consumption patterns. This information identifies regions that may be more vulnerable, allowing for more focused treatments and risk-reduction techniques. Second, selecting safer cultivars for agriculture can reduce overall population exposure by evaluating TFs among different kinds of rice. Furthermore, transfer factors data is an essential component of risk assessments required by international agencies such as the IAEA, providing guidance for public health policy and food safety legislation. Finally, determining TFs is not just a scholarly endeavor; it enables preventative actions to protect the health of millions of people who depend on rice.

2. Materials and methods

2.1. Study area

The study was carried out in the Jashore district of Bangladesh, which is 10.89 m (35.73 feet) above sea level and has a tropical wet and dry or savanna climate (classification: Aw) according to Köppen-Geiger climate classification [17]. The temperature ranges from 15.4 to 34.6 °C yearly, which is 0.6 % higher than Bangladesh's norms. With 115.8 wet days (31.73 % of the time), the annual average precipitation is 1651 mm (64.9 inches). The average wind speed varies from 4.9 to 9.1 mph, while the humidity is between 35 and 76 % per year [18]. Jashore is primarily highland and medium highland and is situated in the western part of the Ganges River floodplain. In the upper portions of floodplain ridges, there is a general distribution of olive-brown silt loams and silty clay loams, and on ridge sites and in basins, there is a general distribution of dark grey mottled brown, primarily clay soils [19]. There exists mild alkalinity in these soils while the overall fertility rate is low. In general, this area is conducive to cultivating crops, particularly vegetables and cereals. That's why the level of farming is significantly higher than in any other area of the country. Meanwhile, a general constraint on contemporary Boro rice growing in the area is low water holding capacity whereas in some places, water stagnation is a barrier as well.

Table 1
Details of sample collection sites.

Area of Study	Location No.	Sampling locations	Lattitude	Longitude	Sample code	
					Soil	Rice
Chawgacha thana	1	Narayanpur	23°20’52.79″N	88°60’12.39″E	S - 01	R - 01
	2	Hakimpur	23°19’25.39″N	89°03’27.94″E	S – 02	R – 02
	3	Jagadishpur	23°17’57.02″N	89°4’8.79″E	S – 03	R – 03
	4	Patibila	23°17’56.46″N	89°2’4.77″E	S – 04	R – 04
	5	Chawgacha	23°15’47.53″N	89°1’13.16″E	S – 05	R – 05
	6	Swarupdaha	23°14’52.79″N	88°58’12.39″E	S – 06	R – 06
	7	Phulsara	23°14’55.33″N	89°5’5.26″E	S – 07	R – 07
	8	Singhajhuli	23°13’50.52″N	89°3’39.34″E	S – 08	R – 08
	9	Dhuliani	23°12’25.39″N	89°1’27.94″E	S – 09	R – 09
	10	Pashapole	23°11’42.3″N	89°4’48.08″E	S – 10	R – 10
Jhikargachha thana	11	Ganganandapur	23°10’15.31″N	89°1’21.77″E	S – 11	R – 11
	12	Magura	23°10’7.68″N	89°04’11.39″E	S – 12	R – 12
	13	Shimulia	23°6’19.4″N	89°1’41.78″E	S – 13	R – 13
	14	Jhikargachha	23°5’59.67″N	89°5’56.79″E	S – 14	R – 14
	15	Gadkhali	23°4’50.39″N	89°3’30.03″E	S – 15	R – 15
	16	Navaron	23°3’38.51″N	89°0’55.95″E	S – 16	R – 16
	17	Panisara	23°3’29.28″N	89°5’5.26″E	S – 17	R – 17
	18	Nirbaskhola	23°1’10.08″N	89°1’14.01″E	S – 18	R – 18
	19	Hajirbag	22°59’11.16″N	89°2’47.77″E	S – 19	R – 19
	20	Shankarpur	22°57’44.54″N	89°0’30.14″E	S - 20	R - 20
Jashore Sadar thana	21	Hoibatpur	23°16’1.44″N	89°10’31.3″E	S – 21	R – 21
	22	Churamonkati	23°13’25.82″N	89°9’52.73″E	S – 22	R – 22
	23	Noapara	23°12’57.41″N	89°23’33.39″E	S - 23	R - 23
	24	Kashimpur	23°12’1.44″N	89°12’31.3″E	S – 24	R – 24
	25	Basundia	23°10’58.32″N	89°22’53.8″E	S – 25	R – 25
	26	Arabpur	23°9’38.48″N	89°10’53.3″E	S – 26	R – 26
	27	Ramnagar	23°7’55.34″N	89°16’0.89″E	S – 27	R – 27
	28	Narendrapur	23°7’32.9″N	89°17’23.49″E	S – 28	R – 28
	29	Chanchra	23°06’58.32″N	89°10’53.8″E	S – 29	R – 29
	30	Deara	22°55’16.75″N	89°7’5.47″E	S - 30	R - 30

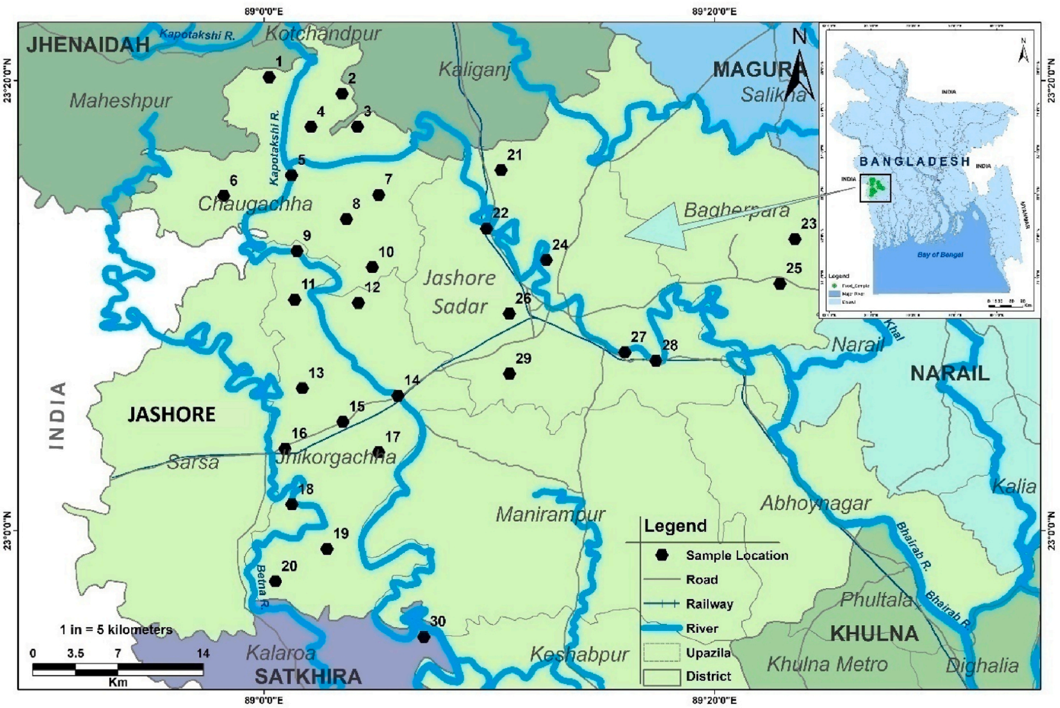

Fig. 1. Soil and rice sample collection sites in Jashore, Bangladesh.

2.2. Sample collection and processing

From the aforementioned study areas, a total of 60 samples (30 rice samples and 30 soil samples) were collected from 30 different locations. The locations were chosen based on the availability of paddy fields in that particular region. Throughout the study area, an attempt was made to guarantee that a sufficient number of representative samples were collected. The approximately 40 square meters rice harvesting fields were divided into smaller sections, each about 8 square meters. In each study location, fully grown rice plants were randomly picked during harvesting time and positioned in an X-shape, with one plant collected from each sub-unit at each corner and in the center [5]. From each location, one representative rice sample and one representative soil sample were prepared. As we know, in contrast to other plants, rice has a root system that only penetrates the top few inches of the soil [5]. So, the soil samples were collected down to a depth of 5 cm from each location which coincides with the rooting zone of the rice plant. All the collected samples were properly marked and identified by their location using Global Positioning System (GPS). The details of the marking and GPS coordinates are given in Table 1 and sample collection sites are also depicted in Fig. 1.

After separating the rice grain from the plant's inedible parts, the samples were sieved to exclude any extraneous material. To create a representative sample, around 1 kg of rice grains were extracted, and they were dried in an oven for 24 h at temperatures below 80 °C to remove moisture and keep a steady dry weight. Following that, the samples were ground into a fine powder and filtered through a 2 mm sieve for homogeneity. Later, a Marinelli beaker was filled with 500 g of rice powder from each sampling location for subsequent analysis.

A representative soil sample was prepared by removing the non-representative components, such as portions of stone, pebbles, leaves, and roots, and then measuring the mass of the sample after it had dried for a few days at room temperature and attained a steady mass. A portion of the soil from this representative sample weighing around 1 kg was dried in an oven for 24 h at 100 °C to achieve a uniform dry weight. The samples were then ground into a fine powder and homogenized using a 2 mm sieve. For further analysis, 500 g of soil sample was transferred to a Marinelli beaker.

Prior to the radioactive analysis using a gamma-ray detector, all the sample containers were sealed tightly, wrapped with thick vinyl tape around the screw necks and stored for a time span of 4–5 weeks to achieve secular equilibrium between the ^{238}U and ^{232}Th and their progenies [5].

2.3. Gamma ray spectrometry system

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, in the samples were determined using a p-type high purity germanium (HPGe) (NATS GCD-30185, Baltic Scientific Instruments, Riga, Latvia) gamma-ray spectrometer (59.4 mm crystal diameter, 56.6 mm thickness, +2700 V operating bias voltage). The low background detector has a relative efficiency of 30% and an energy resolution of 1.67 keV full width at half maximum (FWHM) at the 1332 keV peak of ^{60}Co. The counting system was connected to a 16k multi-channel analyzer (MCA 527, GBS Elektronik GmbH) with associated electronics for data acquisition of photo-peak areas. A SpectraLine GP© software was used to analyze the gamma-ray counts received from the samples. Energy calibration and the absolute photo-peak efficiency assessment were performed using standard reference material (Code: 8501-EG-SVE, Eckert and Ziegler Analytics), diluted with a multi-nuclide gamma-ray source (^{242}Am, ^{109}Cd, ^{57}Co, ^{139}Ce, ^{113}Sn, ^{85}Sr, ^{137}Cs, ^{88}Y, ^{60}Co) having equivalently distributed activity, and maintaining the same geometry and density as the Marinelli beaker containing the samples. To minimize the statistical counting error, the samples were counted for a period of 20,000 s. An empty container was also counted under the same conditions to determine the background counts. To calculate the specific activities, the background counts for the same counting situation were deducted from the counts of each sample to achieve the net counts. For spectrum analyses, the single conversion gamma-ray line 1460.822 keV was used to find out the activity concentrations of ^{40}K. The gamma-ray photo-peaks of 295.221 keV and 351.922 keV from ^{214}Pb, and 609.320 keV, 1120.310 keV and 1764.551 keV from ^{214}Bi were used to verify the activity concentrations of ^{226}Ra. The activity concentrations of ^{232}Th were determined using the net counts under the 238.630 keV and 300.087 keV photo-peaks from ^{221}Pb, 911.205 keV and 968.970 keV photo peaks from ^{228}Ac, and 583.190 keV and 2614.533 keV from ^{208}Tl. For the appraisal of ^{226}Ra and ^{232}Th activity, a weighted mean approach was applied using the aforementioned gamma lines [20]. Much care was taken to avoid contagion during the research.

2.4. Calculation of radioactivity

The minimum detectable activity (MDA) concentration was calculated by using the following equation [21].

$$MDA = \frac{2.71 + 4.65\sqrt{N_B}}{\varepsilon \times I_\gamma \times m \times T} \tag{1}$$

where, MDA is given in Bqkg^{-1}, N_B = net background counts for corresponding photo-peak, ε = counting efficiency corresponding to specific gamma-ray, I_γ = absolute transition probability of the specific gamma-ray, m = mass of the sample in kg, and T = counting time in second. The MDA for the radionuclides of interest was calculated using equation (1) as 0.5 Bqkg^{-1} for ^{226}Ra, 0.6 Bqkg^{-1} for ^{232}Th and 2.2 Bqkg^{-1} for ^{40}K.

After subtracting background counts from the acquired counts, the activity concentration of radionuclides in the samples was determined using the relation expressed as

Table 2
Activity concentrations of radionuclides in soil and rice and corresponding transfer factors (soil-to-rice) from three thanas of Jashore district in Bangladesh.

Activity concentration in Soil ($Bqkg^{-1}$)				Activity concentration in Rice ($Bqkg^{-1}$)				TFs		
Sample ID	^{226}Ra	^{232}Th	^{40}K	Sample ID	^{226}Ra	^{232}Th	^{40}K	^{226}Ra	^{232}Th	^{40}K
S - 01	37.4 ± 0.1	40.5 ± 0.1	381.2 ± 0.7	R - 01	28.0 ± 0.2	36.±0.1	97.6 ± 0.6	0.75	0.89	0.26
S – 02	37.3 ± 0.1	55.9 ± 0.2	439.8 ± 0.7	R – 02	30.1 ± 0.2	7.0 ± 0.1	63.9 ± 0.5	0.81	0.12	0.15
S – 03	28.8 ± 0.1	34.7 ± 0.1	360.3 ± 0.7	R – 03	13.8 ± 0.1	12.3 ± 0.1	58.5 ± 0.5	0.48	0.35	0.16
S – 04	28.4 ± 0.1	31.1 ± 0.1	216.6 ± 0.5	R – 04	23.8 ± 0.2	6.9 ± 0.1	40.7 ± 0.5	0.84	0.22	0.19
S – 05	30.5 ± 0.1	31.9 ± 0.1	250.5 ± 0.6	R – 05	8.8 ± 0.1	7.8 ± 0.1	24.7 ± 0.5	0.29	0.24	0.10
S – 06	28.5 ± 0.1	37.1 ± 0.1	234.2 ± 0.5	R – 06	6.5 ± 0.1	8.7 ± 0.1	47.6 ± 0.5	0.23	0.23	0.20
S – 07	25.6 ± 0.1	45.1 ± 0.1	314.5 ± 0.7	R – 07	8.1 ± 0.1	11.6 ± 0.1	11.7 ± 0.4	0.32	0.29	0.04
S – 08	18.5 ± 0.1	36.9 ± 0.1	263.9 ± 0.5	R – 08	9.7 ± 0.1	12.8 ± 0.1	63.8 ± 0.5	0.53	0.35	0.24
S – 09	29.4 ± 0.1	29.9 ± 0.1	215.7 ± 0.6	R – 09	3.9 ± 0.1	7.8 ± 0.1	24.7 ± 0.5	0.13	0.26	0.11
S – 10	28.8 ± 0.1	30.7 ± 0.1	222.5 ± 0.6	R – 10	4.0 ± 0.1	6.1 ± 0.1	68.9 ± 0.7	0.14	0.20	0.31
S – 11	24.8 ± 0.1	31.2 ± 0.1	311.2 ± 0.4	R – 11	5.5 ± 0.1	7.5 ± 0.2	41.2 ± 0.4	0.22	0.24	0.13
S – 12	29.5 ± 0.1	29.9 ± 0.1	175.6 ± 0.6	R – 12	3.9 ± 0.1	9.0 ± 0.1	11.7 ± 0.4	0.13	0.30	0.07
S – 13	35.7 ± 0.1	36.5 ± 0.1	132.7 ± 0.5	R – 13	18.0 ± 0.2	6.0 ± 0.1	99.0 ± 0.4	0.50	0.16	0.75
S – 14	39.1 ± 0.1	34.8 ± 0.1	324.8 ± 0.8	R – 14	8.1 ± 01	9.8 ± 0.1	30.5 ± 0.4	0.21	0.28	0.09
S – 15	40.1 ± 0.2	41.3 ± 0.2	437.1 ± 0.9	R – 15	6.8 ± 0.1	4.2 ± 0.1	39.0 ± 0.4	0.17	0.10	0.09
S – 16	39.1 ± 0.1	49.4 ± 0.2	412.9 ± 0.7	R – 16	14.1 ± 0.1	9.5 ± 0.1	10.6 ± 0.4	0.36	0.19	0.03
S – 17	38.7 ± 0.1	41.5 ± 0.1	318.0 ± 0.3	R – 17	18.4 ± 0.2	10.7 ± 0.1	52.0 ± 0.6	0.48	0.26	0.16
S – 18	32.0 ± 0.1	32.7 ± 0.1	308.4 ± 0.6	R – 18	13.9 ± 0.1	6.4 ± 0.1	35.1 ± 0.5	0.44	0.19	0.11
S – 19	28.3 ± 0.1	42.9 ± 0.1	250.5 ± 0.6	R – 19	8.2 ± 0.1	10.4 ± 0.1	93.7 ± 0.6	0.29	0.24	0.37
S - 20	36.7 ± 0.1	44.0 ± 0.1	345.1 ± 0.7	R - 20	4.4 ± 0.1	2.8 ± 0.1	106.4 ± 0.6	0.12	0.06	0.31
S – 21	51.1 ± 0.2	52.6 ± 0.2	578.5 ± 0.9	R – 21	5.0 ± 0.1	2.8 ± 0.1	85.2 ± 0.6	0.10	0.05	0.15
S – 22	49.5 ± 0.2	47.7 ± 0.2	508.5 ± 0.9	R – 22	3.1 ± 0.1	8.2 ± 0.1	100.4 ± 0.6	0.06	0.17	0.20
S - 23	34.2 ± 0.1	29.7 ± 0.1	291.1 ± 0.7	R - 23	5.5 ± 0.1	6.5 ± 0.1	122.2 ± 0.6	0.16	0.22	0.42
S – 24	34.8 ± 0.1	41.2 ± 0.1	311.2 ± 0.4	R – 24	13.4 ± 0.2	11.2 ± 0.1	128.8 ± 0.7	0.38	0.27	0.41
S – 25	29.0 ± 0.1	43.3 ± 0.1	341.2 ± 0.7	R – 25	4.3 ± 0.1	6.6 ± 0.1	23.4 ± 0.5	0.15	0.15	0.07
S – 26	37.9 ± 0.1	39.7 ± 0.1	376.1 ± 0.8	R – 26	3.4 ± 0.1	13.6 ± 0.1	57.1 ± 0.5	0.09	0.34	0.15
S – 27	53.9 ± 0.2	35.0 ± 0.1	596.8 ± 1.0	R – 27	5.5 ± 0.1	10.0 ± 0.1	98.6 ± 0.7	0.10	0.29	0.17
S – 28	36.4 ± 0.1	54.9 ± 0.2	518.5 ± 1.0	R – 28	1.0 ± 0.1	6.1 ± 0.1	33.2 ± 0.5	0.03	0.11	0.06
S – 29	38.9 ± 0.2	43.7 ± 0.2	368.0 ± 0.8	R – 29	2.0 ± 0.1	8.2 ± 0.1	91.1 ± 0.7	0.05	0.19	0.25
S - 30	33.1 ± 0.1	41.0 ± 0.1	246.2 ± 0.6	R - 30	5.1 ± 0.1	10.4 ± 0.1	11.2 ± 0.4	0.15	0.25	0.04
Range	18.5–53.9	29.7–55.9	132.7–596.8		1.0–30.1	2.8–36.0	10.6–128.8	0.03–0.84	0.05–0.89	0.03–0.75
[a]**GM**	33.7	38.9	316.8		7.2	8.2	47.0	0.21	0.21	0.15
[b]**GSD**	1.3	1.2	1.4		2.2	1.6	2.1	2.3	1.7	2.1

[a] GM – Geometric mean.
[b] GSD - Geometric standard deviation factor.

$$A = \frac{N}{\varepsilon \times I_\gamma \times m \times T} \tag{2}$$

where, A = activity concentration of the radionuclide in the sample given in $Bqkg^{-1}$, N = net counts for corresponding photo-peak, ε = counting efficiency corresponding to specific gamma-ray, I_γ = absolute transition probability of the specific gamma-ray, m = mass of the sample in kg, and T = counting time in second [22].

The combined standard uncertainty of the measured activity concentration of the radionuclides (ΔA) was calculated using the uncertainty propagation law of the pertinent values illustrated by Eq. (2). The formula for determining the radioactivity concentration's uncertainty is mathematically represented in equation (3) [22].

$$\Delta A = A \times \sqrt{\left(\frac{u(N)}{N}\right)^2 + \left(\frac{u(\varepsilon)}{\varepsilon}\right)^2 + \left(\frac{u(I_\gamma)}{I_\gamma}\right)^2 + \left(\frac{u(m)}{m}\right)^2 + \left(\frac{u(T)}{T}\right)^2} \tag{3}$$

where, N, ε, I_γ, m, and T have the same meanings as in Eq. (2).

2.5. *Calculation of transfer factor (TF)*

Using the measured activity concentrations of radionuclides, the soil-to-plant transfer factor for rice was computed using the relationship shown below [23,24].

$$TF = \frac{A_i^p}{A_i^s} \tag{4}$$

where, A_i^p = activity concentration of a radionuclide in a plant or plant part (in our case rice), and A_i^s = activity concentration of that radionuclide in the soil within the rooting zone.

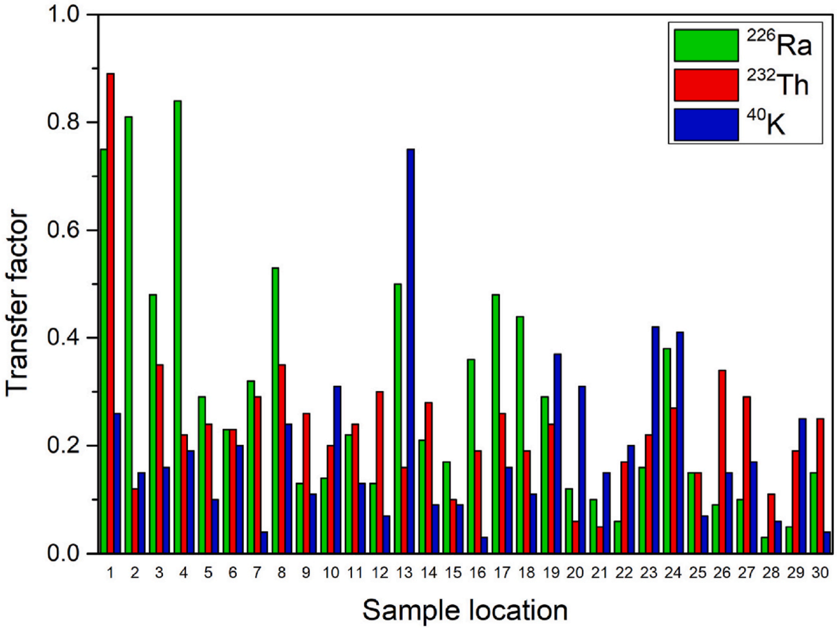

Fig. 2. Transfer factor from soil-to-rice plants for the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in three thanas of Jashore district in Bangladesh.

3. Results and discussion

3.1. Radionuclides activity concentrations

Table 2 presents the soil and rice samples activity concentrations (using equation (2)) and corresponding TF values (using equation (4)) for the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K that were obtained from each of the investigated spots. It reveals that the average activity concentration for ^{226}Ra in the soil was found 29.3 Bqkg^{-1}, 34.4 Bqkg^{-1} and 39.9 Bqkg^{-1} while for the rice samples the average activity concentration was 13.7 Bqkg^{-1}, 10.1 Bqkg^{-1} and 4.8 Bqkg^{-1} for Chawgacha thana, Jhikargachha thana and Jashore Sadar thana, respectively. Radium concentration in rice is typically governed by the metabolic traits of the rice plant species, the amount of radium present in the soil and the amount accessible to the rice plant [25]. Out of all the sites that were examined, the Jashore Sadar thana had the greatest average activity concentration of ^{226}Ra in the soil, despite the fact that the comparable rice samples from that area had the lowest average activity concentration. A possible explanation for this might be variations in the species of rice plants and their radium uptake characteristics [25].

For the ^{232}Th, the average activity concentration for soil samples were found to be 37.4 Bqkg^{-1}, 38.4 Bqkg^{-1}, and 42.9 Bqkg^{-1} while for the rice samples the values were 11.7 Bqkg^{-1}, 7.6 Bqkg^{-1} and 8.4 Bqkg^{-1} for Chawgacha thana, Jhikargachha thana and Jashore Sadar thana, respectively. It is evident that the lowest average activity concentration for soil samples was found for the Chawgacha thana, however, the highest average activity concentration for rice samples was found for the same region. Since the accumulation of ^{232}Th in each species of rice plant is unique, the diversity of rice plants might have again affected the activity concentration of ^{232}Th in rice samples. It was also seen that the ^{232}Th buildup is little greater than ^{226}Ra in the soil samples. Usually, ^{226}Ra is quickly retrieved and migrates with soil water, while ^{232}Th undergoes a significant erosion process and absorbs in the soil on the spot [26]. This might be one of the causes of the aforementioned behavior.

^{40}K has the greatest concentration across all locations in soil and rice samples. For soil samples, the ^{40}K average activity concentration was determined to be 289.9 Bqkg^{-1}, 301.6 Bqkg^{-1} and 413.6 Bqkg^{-1}; for rice samples, the values were 50.2 Bqkg^{-1}, 51.9 Bqkg^{-1} and 75.1 Bqkg^{-1} for Chawgacha thana, Jhikargachha thana and Jashore Sadar thana, respectively. In this case, the highest average activity concentration for the soil and rice samples was found for the Jashore Sadar thana, meanwhile, the lowest average activity concentration for the soil and rice samples was found for the Chawgacha thana. The pH and type of soil have an impact on the accumulation of ^{40}K in the majority of the studied locations.

For ^{226}Ra, ^{232}Th, and ^{40}K, the range of activity concentrations in soil were from 18.5 $\pm$ 0.1 to 53.9 $\pm$ 0.2 Bqkg^{-1}, 29.7 $\pm$ 0.1 to 55.9 $\pm$ 0.2 Bqkg^{-1} and 132.7 $\pm$ 0.5 to 596.8 $\pm$ 1.0 Bqkg^{-1}, respectively. Likewise, the activity concentrations in rice plants ranged from 1.0 $\pm$ 0.1 to 30.1 $\pm$ 0.2 Bqkg^{-1}, 2.8 $\pm$ 0.1 to 36.0 $\pm$ 0.1 Bqkg^{-1}, and 10.6 $\pm$ 0.4 to 128.8 $\pm$ 0.7 Bqkg^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively. In both the soil and rice samples, as well as the analyzed sites, Table 2 shows some notable variations in the activity concentrations of the radionuclides under study. Possible explanations for this might include variations in soil composition and physical characteristics, differences in climate and quantity, and different types of fertilizers used to the soil to improve crop yield [27].

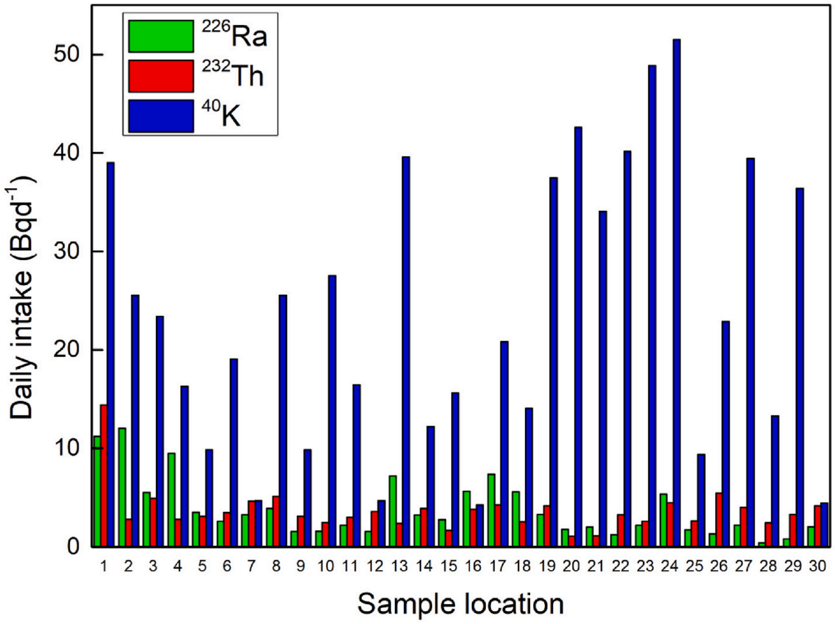

Fig. 3. Daily intake of radionuclides for rice consumption from three thanas of Jashore district in Bangladesh.

3.2. Transfer factor from soil-to-rice

The corresponding TF values for all the radionuclides are calculated using Eq. (4) and are presented in Fig. 2. For ^{226}Ra, the average TF values were calculated to be 0.45, 0.29 and 0.13 for Chawgacha thana, Jhikargachha thana and Jashore Sadar thana, respectively. In contrast to Jashore Sadar thana, it is evident that Chawgacha thana has an average TF value that is over three times higher, but Jhikargachha thana's average TF value is over two times higher for ^{226}Ra. Meanwhile for ^{226}Ra, the overall range for TF was found to be 0.03–0.84 for all the investigated samples with a geometric mean of 0.21. Our results differ significantly from the International Atomic Energy Agency's (IAEA) published TF value for clay soil-to-rice for ^{226}Ra (0.00025–0.0029, average: 0.00057) [23]. However, the values are comparable to the nearby regions studies [28–31].

For ^{232}Th, the average TF values were found as 0.32, 0.2 and 0.2 for Chawgacha thana, Jhikargachha thana and Jashore Sadar thana, respectively. In this case, the average TF values for ^{232}Th are similar for Jhikargachha thana and Jashore Sadar thana, however, it is nearly 1.5 times higher for Chawgacha thana. For every sample that was examined for ^{232}Th, there was an overall range of 0.05–0.89, with a geometric mean of 0.21. Comparing these values with IAEA's data for ^{232}Th (0.000026–0.00083, average: 0.00014), our investigated values are far away from the range [23]. The findings, meanwhile, are in line with research from neighboring locations [28–31].

Both crop fertilization and the plant's capacity to respond to environmental stresses depend heavily on potassium. Nevertheless, plants may readily adjust to potassium since it is a remnant of their homeostatic symmetry [32]. The average TF values for ^{40}K were 0.18, 0.21 and 0.19 for Chawgacha thana, Jhikargachha thana and Jashore Sadar thana, respectively. Across all the regions under investigation, it is evident that the average TF values for ^{40}K are comparable to one another. In this instance, a geometric mean of 0.15 was achieved with a range of 0.03–0.75. The results obtained were found to be compatible with the IAEA's stated statistics for ^{40}K (0.087–0.78, average: 0.22) and other studies, in contrast to earlier readings for ^{226}Ra and ^{232}Th [23,28–31].

Plant's radionuclide concentrations ought to correspond with soil concentrations, based on the principles of concentration ratios. This may not always be the case, though, as sorption on soil reduces the radionuclide's availability for absorption. Similar chemical features allow radionuclides to be selectively absorbed or excluded [25]. This study demonstrates that radioactive buildup in farmlands varies slightly depending on the kind of soil. The variations between TFs and farmlands for different soil types might be caused by the features of the soil, including its pH, organic matter concentration, granulometric and mineralogical composition, and hydrological circumstances. A large portion of the anomaly in TFs is probably caused by the biological diversity that exists naturally in plants as well as the differences between various types and species. Additional factors that affected TFs were soil potency, crop farming techniques, growth period length, and features of root dispersal in the soil. The previously mentioned variables might alter the characteristics of the soil or cause radionuclides to be redistributed in the root zone, which would alter how crops absorb these radionuclides [33]. It was noted that the IAEA data and our studied TF values for ^{226}Ra and ^{232}Th differed from one another. While the IAEA published TFs for ^{226}Ra and ^{232}Th on the basis of the clay soil, the soil profile in the current examined regions was primarily silty clay with slight alkalinity. The farming practices in the nations where the IAEA gathered the data, as well as the farms we analyzed, may differ in terms of soil fertility, growing season length, and cultivation methods.

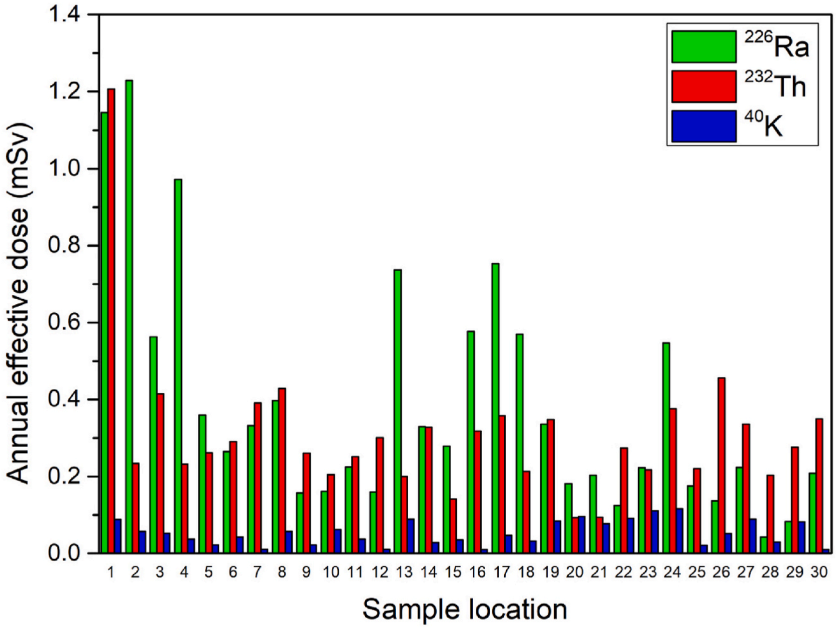

Fig. 4. Annual effective dose for rice consumption from three thanas of Jashore district in Bangladesh.

3.3. Radiological impacts

3.3.1. Daily intake

The daily intake of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) by individuals due to the rice diet has been approximated using the formula below [34].

$$D_i = A_i^p \times R_c \quad (5)$$

Where, D_i = daily intake of radionuclides by individuals in Bqd^{-1}, A_i^p = activity concentration of a radionuclide in rice in Bqkg^{-1}, and R_c = per capita consumption of rice in kgd^{-1}. According to a 2019 survey, Bangladeshi people's daily rice consumption per capita is approximately 0.4 kg [35]. The corresponding daily intake of radionuclides for rice was calculated by using equation (5) and is depicted in Fig. 3.

Based on the computation, the average daily intake of ^{226}Ra was found to be 3.8 Bqd^{-1}, with a range of 0.4–12.0 Bqd^{-1}. The average for ^{232}Th was found to be 3.7 Bqd^{-1}, with a range of 1.1–14.4 Bqd^{-1}. With an average of 23.6 Bqd^{-1}, it ranged from 4.3 to 51.5 Bqd^{-1} for ^{40}K. Evidently, every study site exhibits a notably greater daily consumption of ^{40}K than the other radionuclides.

3.3.2. Annual effective dose

The annual effective dose for the intake of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) from rice consumption by an individual is calculated by the following formula (equation (6)) [34] and presented in Fig. 4.

$$E = D_i \times D_{cf} \times 365 \text{ days} \quad (6)$$

Where, E = annual effective dose in Svy^{-1}, and D_{cf} = ingestion dose conversion factor for the radionuclides of interest in SvBq^{-1}. The values for D_{cf} are reported as 2.8×10^{-7} SvBq^{-1} for ^{226}Ra, 2.3×10^{-7} SvBq^{-1} for ^{232}Th and 6.2×10^{-9} SvBq^{-1} for ^{40}K [36].

In comparison to ^{40}K, the yearly effective dose for ^{226}Ra and ^{232}Th was found to be greater for all the locations under investigation. With an average of 0.39 mSvy^{-1}, it varied from 0.04 to 1.23 mSvy^{-1} for ^{226}Ra. An average of 0.31 mSvy^{-1} was discovered for ^{232}Th, with a range of 0.09–1.21 mSvy^{-1}. Conversely, an average yearly effective dose of 0.05 mSvy^{-1} was determined for ^{40}K, with a variation between 0.01 and 0.12 mSvy^{-1}. Ingestion of uranium and thorium series had an average global effective dose of 0.12 mSvy^{-1}; for ^{40}K, the reported effective dose was 0.17 mSvy^{-1}, resulting in a total ingestion exposure of 0.29 mSvy^{-1}. The total annual effective dose was reported to vary within a typical range of 0.2–0.8 mSvy^{-1} by UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), 2000 [37]. Our study revealed that the average total annual effective dose was 0.75 mSvy^{-1} for the ingestion of ^{226}Ra, ^{232}Th, and ^{40}K for the studied locations.

3.3.3. Excess lifetime cancer risk

Cancer is now referred to as a life-threatening illness, and for a variety of reasons, its prevalence is rising globally. An estimated 1.5 million people in Bangladesh suffer from cancer, and about 110,000 of them pass away each year, according to a recent World Health

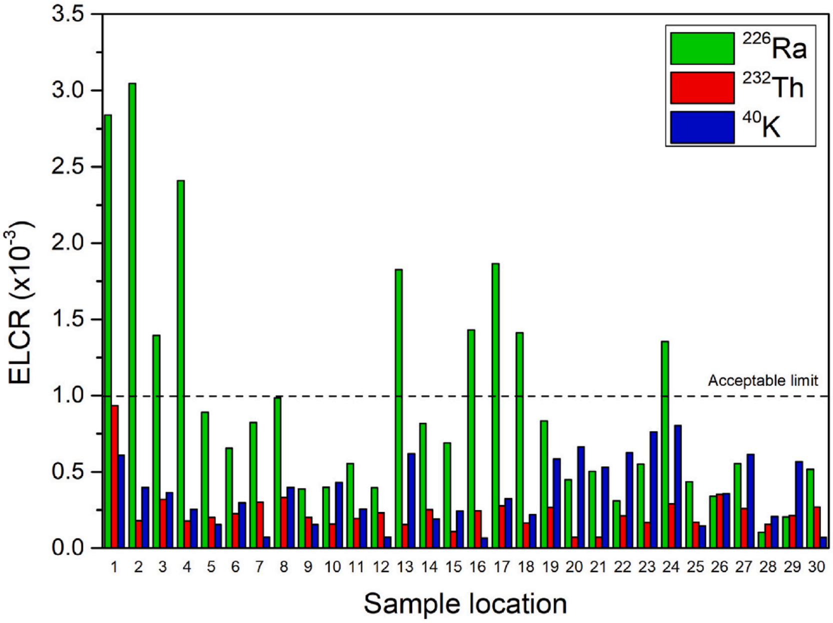

Fig. 5. Excess lifetime cancer risk (ELCR) for rice consumption from three thanas of Jashore district in Bangladesh.

Organization (WHO) report [38]. According to the data, cancer strikes around 160,000 individuals annually. The impact of radiation on biological cells is thought to be one of the causes of cancer, despite the fact that the exact cause is yet unknown. For this reason, an attempt was undertaken to determine the excess lifetime cancer risk (ELCR) associated with rice intake using the United States Environmental Protection Agency's (US EPA) recommended methodology [39]. Fig. 5 shows the results of calculating the mortality cancer risk using the following equation (7) [40].

$$ELCR = D_i \times 365\ days \times A_{lf} \times M_{rc} \tag{7}$$

Where, A_{lf} = average life span in years, and M_{rc} = mortality risk coefficient for the ingestion of food in Bq^{-1}. The average life expectancy for Bangladeshi people is 72.59 years [41]. The ingestion mortality cancer risk coefficients are 9.56×10^{-9} Bq^{-1}, 2.45×10^{-9} Bq^{-1}, and 5.89×10^{-10} Bq^{-1} for ^{226}Ra, ^{232}Th, and ^{40}K, respectively [39].

The average ELCR varied between 1.1×10^{-4} – 3.05×10^{-3} for ^{226}Ra, 7.0×10^{-5} – 9.3×10^{-4} for ^{232}Th, and 7.0×10^{-5} – 8.0×10^{-4} for ^{40}K. In general, the acceptable limit of ELCR for radiological risk is 1×10^{-3} [40]. It is evident from Fig. 5 that the ELCR was found lower in all the studied locations for ^{232}Th and ^{40}K. However, the ELCR crossed the acceptable limit for ^{226}Ra in some of the locations (location no. 1, 2, 3, 4, 13, 16, 17, 18, and 24). Thus, the present study suggests that there is no immediate concern for the public's health from consuming rice grains due to their radioactive content. However, policymakers should take into consideration about the fact and take necessary steps for the future. We hope that the results of this study will aid in creating a baseline database of TFs and radioactive exposure that the general public encounters from consuming rice.

4. Limitations of this study

Notably, the current investigation was limited to three thanas in Jashore area of Bangladesh. Therefore, in order to obtain the district's entire situation, future research may incorporate the other five thanas. In order to determine the TFs of more plants and radiation dangers, additional food kinds could be included in the future study as well.

5. Conclusion

In this study, the uptake of naturally occurring radionuclides by rice plants in Bangladesh is examined and the potential health implications associated with rice consumption is evaluated. It was found that the TFs of ^{226}Ra, ^{232}Th, and ^{40}K from soil-to-rice plants varied between 0.03 and 0.84, 0.05–0.89, and 0.03–0.75, respectively. The computed annual effective dose lies within UNSCEAR-established worldwide safety limits even though the transfer factors for ^{226}Ra and ^{232}Th deviated from international reference values. The biological variety found naturally in plants and variations among different kinds and species are likely responsible for a significant percentage of the anomaly in TFs. Aside from these variables, crop farming practices, soil potency, growth period length, and characteristics of root dissemination in the soil all had an impact on TFs. Further research is necessary even if the current findings do not indicate any immediate health risks. This reassurance is crucial for the Bangladeshi population, considering the staple nature of rice in their diet.

The implications of this study extend beyond immediate health concerns. The construction of prediction models, which may identify regions or agricultural practices in need of closer monitoring and mitigation methods, can be facilitated by studying transfer factors across a range of rice types and geographical locations. This study helps to ensure the long-term health and safety of rice-consuming populace in Bangladesh by proactively studying the factors driving radionuclide uptake in rice.

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Data availability statement

All data are presented within the manuscript.

CRediT authorship contribution statement

Shahadat Hossain: Writing – original draft, Formal analysis. **Shikha Pervin:** Writing – review & editing, Formal analysis, Conceptualization. **Laisee Lubna:** Formal analysis. **Shanjib Karmaker:** Formal analysis. **Selina Yeasmin:** Writing – review & editing, Supervision. **Mayeen Uddin Khandaker:** Writing – review & editing.

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.

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