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RADON CONCENTRATION MEASUREMENT AND EFFECTIVE DOSE ASSESSMENT IN TAP WATER OF TOURIST LOCATIONS FROM KHAO KHO, PHETCHABUN PROVINCE, THAILAND

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Abstract: Radon content in tap water at well-known tourist destinations in Khao Kho, Phetchabun Province, Thailand, was measured using a RAD7 radon gas detector. The average radon content in tap water from 19 samples in the Khao Kho Sub-district was 0.30 ± 0.27 Bq/L, with values ranging from 0.04 to 1.01 Bq/L. For the 20 samples collected from the Campson Sub-district, radon content ranged from 0.04 to 2.22 Bq/L, with an average of 0.56 ± 0.60 Bq/L. The health risks evaluated included the total annual effective dose (D_{total}), the annual effective dose from inhalation (D_{inh}) and ingestion (D_{ing}), and the annual effective dose to specific organs, such as the lungs (D_{lung}) and stomach ($D_{stomach}$). The radon content in all tap water samples was below the United States Environmental Protection Agency's permissible standard of 11.1 Bq/L, and the total average annual effective dose (D), calculated from the radon content in tap water, was below the 100 µSv/y recommended by the World Health Organization's regulatory level. Therefore, the tap water in these study areas does not pose a significant health risk based on current international guidelines.

Keywords: radon, annual effective dose, tap water, Khao Kho, Thailand

1. INTRODUCTION

Natural radioactive materials, also known as naturally occurring radioactive materials (NORM), are ubiquitous throughout the world. Natural radioactive materials decay in four series: the uranium series (U-238), the thorium series (Th-232), the actinium series (U-235), and the neptunium series (Np-237). Among the different types of nuclei, radon (Rn-222) is a radioactive material that comes from the uranium series (U-238), which is the most common form of uranium found in nature, making up about 99.3%. Therefore, the environment contains it, with the amount of radioactivity varying depending on the type of natural source (International Atomic Energy Agency, 2015; Pervin et al., 2020). For the reasons previously mentioned, various environments contain radon that decays from uranium. Radon sources include soil, rocks, water, plants, and food. Radon is typically present in low concentrations in the environment, but it can affect health if it accumulates in the body. Radon is one of the causes of cancer in various organs, such as the lungs and stomach (World Health Organization, 2021; Kim & Ha, 2023). When people breathe air contaminated with high levels of radon, it decays into alpha radiation, which damages lung tissue and causes lung cancer. Radon, after cigarettes, is the second leading cause of lung cancer. Research has shown that for every 1 Bq/m³ increase in air radon concentration (or 0.001 Bq/L in water), the risk of lung cancer increases by approximately 0.016% (Nilsson & Tong, 2020; Krewski et al., 2020). Radon can only build up in the body through breathing or ingestion, both of which can have health effects later on. According to the U.S. Environmental Protection Agency, approximately 21,000 people in the United States die from radon each year (Health Canada, 2019). There is still limited research on environmental radon in Thailand, especially at various tourist attractions, such as mountains and the sea, which are all sources of natural radon radiation. Consequently, there is a chance that radon can contaminate the environment, especially in the water sources that people regularly use and consume, which is tap water (the raw water sources used to produce tap water are mostly surface water and groundwater, which are sources of radon). As a result, the research team identified this issue and decided to investigate radon in the tap water of Khao Kho Sub-district and Campson Sub-district, Khao Kho District, Phetchabun Province. Over the past decade, these areas have become well-known tourist destinations, leading to a significant increase in water consumption by both tourists and local residents. To assess potential public health risks, the research team wanted to measure the concentration of radon in tap water using a radon-measuring device (RAD7 Electronic Radon Detector). The research results were used to assess the various risks that affect the health of people in the research area from the accumulated radon radiation in the body per year.

2. MATERIALS AND METHODS

2.1. STUDY AREAS

The study areas are located in Khao Kho Sub-district and Campson Sub-district, Khao Kho District, Phetchabun Province, Thailand. The research area is mostly forested and consists of large and small mountains, which are intricately similar to complex topography with elevations ranging from 500 to 1,600 meters above sea level. The geology is from the Cretaceous period and is predominantly composed of sedimentary rocks, including fine-grained red-brown sandstone, red-brown siltstone, and gray-white pebble sandstone containing rounded pebbles with medium-to-coarse grain size (Department of Mineral Resources, 2009). These lithological units, such as sandstone, siltstone, and pebbly sandstone, are known natural sources of radon due to their uranium content (Majumder et al., 2021; Li et al., 2022). The decay of uranium in these minerals, which are present in rocks in contact with groundwater and surface water sources, generates radon-222, a radioactive gas. As a noble gas, radon is chemically inert and can migrate through the surface of rocks and soils. From there, it can be released into both groundwater and surface water. Therefore, it is the reason why the research team wants to study the amount of radon in tap water because radon may leach from sandstone, siltstone, and gravel mixed with sandstone into surface water and groundwater, which serve as raw water sources for the production of tap water. Although surface water and groundwater were treated before being produced as tap water, there is no specific treatment for radon because there is no data on the amount of radon in water in each locality in Thailand. The increase in tourism has led to higher water consumption from local public supplies, raising concerns about potential exposure to radon. Water samples were collected three times from August to December 2023, during the winter season, when many people like to visit these study areas. Additionally, radon content tends to be higher in the winter, as the low temperature increases its solubility in water. During this season, the water level in the groundwater well and surface water, which are the raw water sources for producing tap water, has decreased. As a result, radon content levels have increased (Pervin et al., 2021; Divya & Prakash, 2022). In Table 1 and Figure 1, the GPS coordinates for collecting tap water samples in tourist areas in the research area are shown, namely, Khao Kho Sub-district (19 samples) and Campson Sub-district (20 samples).

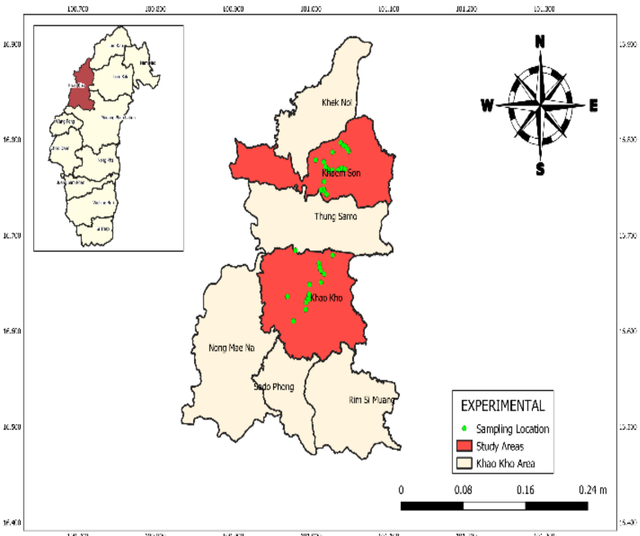

Figure 1. GPS coordinates of tap water sampling locations in the study areas.

2.2 RAD7: electronic-radon detector

RAD7 serves as a radon measuring device in this study. Within the structure of the alpha radiation chamber of RAD7, there is a semiconductor sensor for alpha radiation, which supplies an electric potential of 2 to 2.5 kV on the surface of the radiation sensor to create an electric field to induce positive ions. This is because alpha radiation from the decay of radioactive elements

Table 1. GPS locations of tap water sampling sites in the study areas.

Khao Kho Sub-district	
16.6846257,100.979938	16.6490042,100.9981104
16.6796228,101.0278564	16.6709591,101.0101696
16.634044,100.9979055	16.6671129,101.0108888
16.6108822,100.9773005	16.6634572,101.0124061
16.6340491,100.9957168	16.6598561,101.0168357
16.6330109,100.9948585	16.6378996,100.9973527
16.6302029,100.9940427	16.6376734,100.9976638
16.6228367,100.9932720	16.638777,100.9972904
16.6363970,100.9696059	16.777183,101.0164936
16.6512245,101.0128304	-
Campson Sub-district	
16.7470598,101.0148783	16.7705342,101.0393709
16.742980,101.0200895	16.7882226,101.0484582
16.7474954,101.0172249	16.7931426,101.0443812
16.748529,101.01599410	16.7945292,101.0413235
16.7565217,101.0168095	16.7973333,101.0381478
16.7675241,101.0227104	16.7686952,101.0275383
16.7693321,101.0212405	16.7689520,101.035188
16.7719927,101.0186334	16.7696505,101.0436638
16.7790497,101.0059305	16.7900063,101.0474919
16.7872866,101.0277803	16.74765870,101.012830

easily loses energy in the air. To measure alpha radiation energy correctly, the radioactive elements must be close to the surface of the radiation sensor in the case of a flowing air measurement chamber. Therefore, RAD7 measures radon (Rn-222) indirectly by detecting alpha radiation from its decay product, polonium-218 (Po-218) instead, because radon is an inert gas that has no charge, which does not interact directly with the electric field, and spreads out in the measurement chamber. However, after radon decays, Po-218 becomes a positively charged ion, which is attracted to the radiation sensor's surface by the electric field, and then it decays into alpha radiation, giving energy to the sensor. When RAD7 analyzes the alpha radiation spectrum, it will interpret the peak intensity of Po-218's radiation and adjust the value to represent the intensity of radon's radiation by using the properties and the principle of reaching radiation equilibrium. When considering the half-life of Po-218, it is equal to 3.05 minutes, resulting in the measurement of radon occurring instantaneously. RAD7 can measure radon in various samples, including water, soil, construction materials, and air. The measurement of radon in each sample requires different methods and accessories used with RAD7. In this research, we measure radon in tap water samples using the RAD H_2O method and accessories, as illustrated in Figure 2 (DURRIDGE Company, Inc., 2021).

2.3 Radon measurement in tap water samples (RAD H_2O)

RAD H_2O is a device used together with RAD7 to measure the amount of radon in water. The device functions by blowing water to create air bubbles, allowing its pump to extract radon from the water. This radon is then transferred into the RAD7 measuring device, which counts and displays the radiation level. Figure 2 displays the details. In this research, 250 ml of tap water samples were collected, and the measurement took approximately 30 minutes per sample (DURRIDGE Company, Inc., 2021).

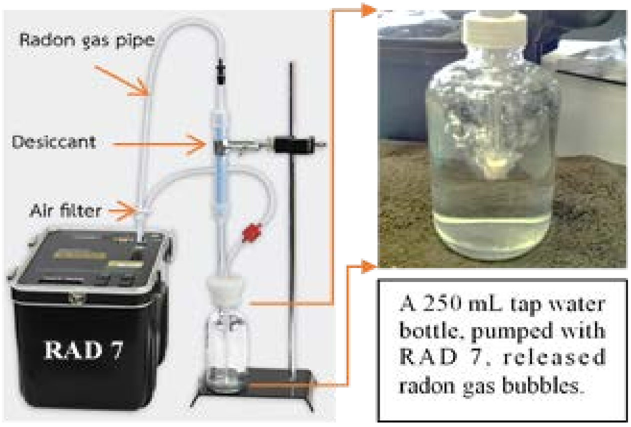

Figure 2. Radon gas measurement in tap water samples using RAD H_2O.

2.4 THE ANNUAL EFFECTIVE DOSE DUE TO INHALATION AND INGESTION

Assessment of D_{inh} and D_{ing} were calculated in accordance with the variable recommend by the UNSCEAR report (United Nations Scientific Committee on the Effects of Atomic Radiation, 2000) as shown in equations (1) and (2).

$$D_{inh}(\mu Sv/y) = C\ (Bq/L) \times 2.5\ (\mu Sv/(Bq/L)) \quad (1)$$

$$D_{ing}(\mu Sv/y) = C\ (Bq/L) \times 0.18\ (\mu Sv/(Bq/L)) \quad (2)$$

where C is Radon concentration in tap water (Bq/L)

2. 5. THE ANNUAL EFFECTIVE DOSE FOR LUNG AND STOMACH

The dose to the lungs and stomach was computed by multiplying the inhalation and ingestion doses by the respective tissue weighting factors. The resulting organ doses for the lung (D_{lung}) and stomach ($D_{stomach}$) were calculated using Equations (3) and (4) (Divya & Prakash, 2022; Kumar et al., 2022)

$$D_{lung}(\mu Sv/y) = D_{inh}(\mu Sv/y) \times W_R \times W_T \quad (3)$$

$$D_{stomach}(\mu Sv/y) = D_{ing}(\mu Sv/y) \times W_R \times W_T \quad (4)$$

Where D_{inh} and D_{ing} are the annual effective doses on account of inhalation and ingestion, respectively and W_R is the radiation weighting factor of α particles (20) and W_T is the tissue weighting factor of the lung and stomach (0.12), as recommended by the ICRP (International Commission on Radiological Protection, 1991).

3. RESULTS AND DISCUSSION

The results of radon measurements in tap water from the study areas are summarized in Table 2, including the maximum, minimum, and average values of radon content, pH, temperature (T), salinity, electrical conductivity (EC), and total dissolved solids (TDS). It was found that in the Khao Kho Sub-district, radon contents in 19 tap water samples ranged from 0.04 to 1.01 Bq/L. The properties of tap water were observed as follows: pH ranged from 6.51 to 8.50; T ranged from 23.20 to 32.10 °C; salinity ranged from 0.05 to 0.69 ppt; EC ranged from 107 to 1,780 µS/cm; and TDS ranged from 53 to 823 ppm. These values indicate that the tap water in Khao Kho Sub-district had a slightly alkaline pH and moderate EC and TDS levels.

In contrast, in the Camson Sub-district, radon contents in 20 tap water samples ranged from 0.04 to 2.22 Bq/L, showing a wider range than in Khao Kho Sub-district. The characteristics of tap water were observed as follows: pH ranged from 6.17 to 8.60; T ranged from 23.00 to 33.10°C; salinity ranged from 0.02 to 0.55 ppt; EC ranged from 44 to 1,280 µS/cm; and TDS ranged from 23 to 673 ppm. The pH and temperature were similar to those in Khao Kho Sub-district, while the salinity, EC, and TDS values were generally lower. The data indicate minor geographical variations in radon contents and water properties, perhaps driven by local geology or water supply sources. This is consistent with the study of Coțac et al. (2024), who found that the sediments and riverbed deposits in the Ditrău Massif area contain naturally occurring radionuclides (U-238, Th-232, and K-40) at levels higher than the global average of the Earth's crust, due to the geological and geophysical characteristics of the area, which influence the accumulation of these radionuclides.

Table 3 summarizes the results of radon exposure evaluations from tap water in the study areas. These include the annual effective dose from inhalation of radon released from tap water (D_{inh}), from ingestion (D_{ing}), the total annual effective dose ($D_{total} = D_{inh} + D_{ing}$), and the annual effective doses to specific organs such

Table 2. Radon content and various parameters in tap water of the study areas.

Site	Statistics data	Radon (Bq/L)	pH	(T ºC)	Salinity (ppt)	EC (µS/cm)	TDS (ppm)
1	Min	0.04	6.51	23.20	0.05	107.00	53.00
	Max	1.01	8.50	32.10	0.69	1,780.00	823.00
	Av. .±S.D.	0.30±0.27	7.59±0.58	26.64±2.37	0.26±0.20	583.81±529.54	289.25±242.03
2	Min	0.04	6.17	23.00	0.02	44.00	23.00
	Max	2.22	8.60	33.10	0.55	1280.00	673.00
	Av. .±S.D.	0.56±0.60	7.55±0.77	27.20±2.43	0.18±0.17	408.40±363.66	206.05±179.71
Av. .±S.D.		0.43±0.48	7.56±0.67	26.92±2.38	0.22±0.16	501.31±456.37	250.13±214.47

Table 3. Radon contents and estimated annual effective doses in tap water samples, including organ-specific doses in the study areas.

Site	Statistical factor	Radon (Bq/L)	D (µSv/y)			D on organs (µSv/y)	
			D_{inh}	D_{ing}	D_{total}	D_{lung}	$D_{stomach}$
1	Min	0.04	0.09	0.0065	0.097	0.22	0.016
	Max	1.01	2.52	0.18	2.70	6.04	0.44
	Av.±S.D.	0.30±0.27	0.74±0.68	0.053±0.050	0.79±0.73	1.78±1.64	0.13±0.12
2	Min	0.04	0.09	0.0065	0.097	0.22	0.016
	Max	2.22	5.55	0.40	5.95	13.32	0.96
	Av.±S.D.	0.56±0.60	1.40±1.49	0.10±0.10	1.50±1.60	3.35±3.58	0.24±0.26
Av.±S.D.		0.43±0.48	1.08±1.20	0.078±0.087	1.15±1.28	2.58±2.88	0.19±0.21

***Remark**: Site 1 = Khao Kho Sub-district, and Site 2 = Campson Sub-district as the lungs (D_{lung}) and stomach ($D_{stomach}$). It was found that in the Khao Kho Sub-district, D_{inh} ranged from 0.09 to 2.52 µSv/y, D_{ing} ranged from 0.065 to 0.18 µSv/y, D_{total} ranged from 0.097 to 2.70 µSv/y, D_{lung} ranged from 0.22 to 6.04 µSv/y, and $D_{stomach}$ ranged from 0.016 to 0.44 µSv/y.

In comparison, the Campson Sub-district showed a wider range of values. D_{inh} ranged from 0.09 to 5.55 µSv/y, D_{ing} ranged from 0.065 to 0.40 µSv/y, D_{total} ranged from 0.097 to 5.95 µSv/y, D_{lung} ranged from 0.22 to13.32 µSv/y, and $D_{stomach}$ ranged from 0.016 to 0.96 µSv/y.

Using the results from Table 2, a graph comparing the average radon levels to the US EPA's standard for radon in water, which should not exceed 11.1 Bq/L, as seen in Figure 3, was created, and it found that the radon content in the study areas ranged from 0.04 to 0.22 Bq/L, with an average of 0.43 ± 0.48 Bq/L, which is below the allowed limit. This shows that tap water in the study areas is safe from radon content, as supported by the data in Table 3. The results of the health risk assessment in various forms based on radon content measured in tap water found that the value of D_{inh} ranged from 0.09–5.55 µSv/y, with an average of 1.08 ± 1.20 µSv/y; D_{ing} ranged from 0.065–0.40 µSv/y, with an average of 0.078 ± 0.087 µSv/y; D_{total} ranged from 0.096–5.95 µSv/y, with an average of 1.15 ± 1.28 µSv/y; D_{lung} ranged from 0.22–13.32 µSv/y, with an average of 2.58 ± 2.88 µSv/y; and $D_{stomach}$ ranged from 0.19–0.21 µSv/y, with an average of 0.13 ± 0.12 µSv/y. When comparing all values with the standard criteria of the annual effective dose in water set by WHO, which should not exceed 100 µSv/y (World Health Organization, 2003), it was found that all values were below the specified standard criteria, indicating that tap water in the research area is safe from receiving cumulative radiation throughout the year from radon in tap water in the study area.

Correspondingly, a study of radon levels in tap water from Ongkharak, Nakhon Nayok, Thailand, found radon concentrations ranged from 0.10 to 2.89 Bq/L, with an average of 0.51 ± 0.55 Bq/L, and the average annual effective dose was 0.66 ± 0.04 mSv/y, which do not exceed the guidelines set by WHO and US EPA (Sola et al., 2017). Notably, the radon concentrations and annual effective dose values in this study are lower than those reported in the previous study in Thailand (Sola et al., 2017).

The information in Table 2 was used to create a graph that shows how different features of tap water, such as pH, temperature (T), salinity, electrical conductivity (EC), and total dissolved solids (TDS), are connected to radon levels, as shown in Figure 4. Although slight trends were observed, such as an inverse relationship between pH and radon, where radon levels increased as pH increased, with $R^2 = 0.0318$; and direct relationships between radon and T, where radon levels increased as temperature decreased, with $R^2 = 0.0031$; salinity, with $R^2 = 0.0355$; EC, with $R^2 = 0.0071$; and TDS, with $R^2 = 0.0055$, all R^2 values were very low, indicating that no statistically significant correlations were observed between radon levels and these water properties.

4. CONCLUSIONS

The radon content in tap water samples from tourist locations in Khao Kho Sub-district (19 samples) and Campson Sub-district (20 samples), Khao Kho District, Phetchabun Province, Thailand, was studied, totaling 39 tap water samples. The results of the radon

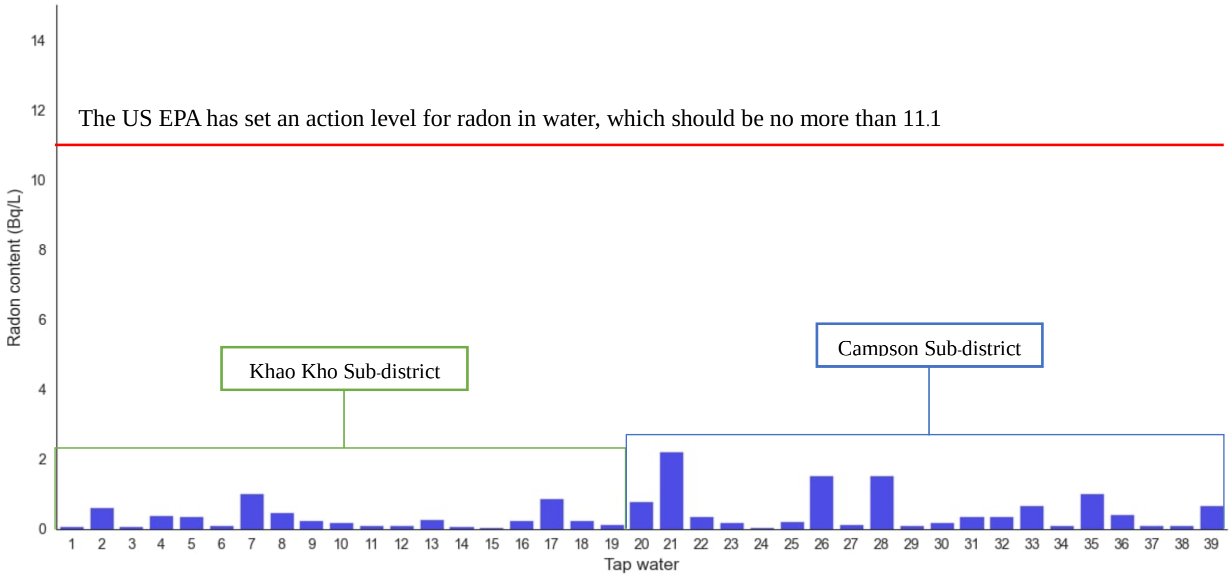

Figure 3. Graph showing the comparison between radon content and the US EPA standard.

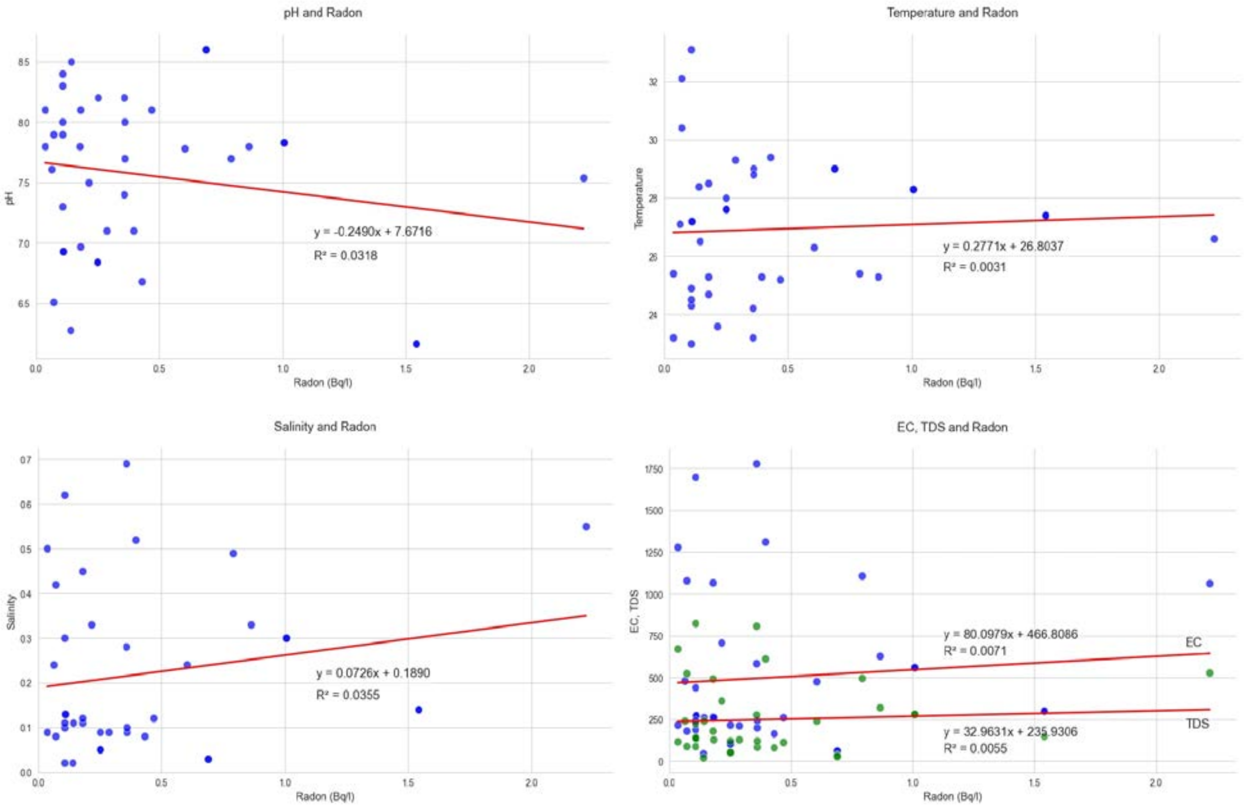

Figure 4. Graph showing the relationship between the properties of various water sources and radon concentration.

content measurements showed that all values were lower than the standard criteria set by the US EPA. In addition, the annual effective doses from radon in tap water via inhalation (D_{inh}) and ingestion (D_{ing}), the total annual effective dose (D_{total}), and the doses to specific organs, namely the lungs (D_{lung}) and stomach ($D_{stomach}$), were assessed, all of which were found to be below the standard criteria set by the WHO. Specifically, the average radon concentration in the study areas was 0.43 ± 0.48 Bq/L, which is below the US EPA limit of 11.1 Bq/L, and the calculated annual effective doses from inhalation and ingestion were 1.08 ± 1.20 and 0.078 ± 0.087 µSv/y, respectively, both significantly lower than the WHO reference dose of 100 µSv/y. These results indicate the safety of tap water used by local residents and tourists in the study areas. To the best of our knowledge, no previous studies have reported radon levels in tap water from these specific locations. Therefore, these findings provide baseline data that may be useful for future monitoring efforts of radon levels in tap water and for assessing risk values in various forms arising from possible future changes in radon levels in the study area.

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