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Research article

Radon Contamination in Various Water Sources and Indoor Air in Buildings in the Coastal Region of Surat Thani Province, Southern Thailand

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Abstract

The coastal region of Kanchanadit District, Surat Thani Province, is known for aquaculture and mining activities, and may be environmentally contaminated with radon. Therefore, this work was aimed at studying the physical properties and measuring the radon concentrations in water and indoor air within buildings. In addition, health risks from radon exposure were evaluated. One hundred and fifty six samples were collected from various water sources, including groundwater, tap water, shallow wells, canals, and coastal areas, using a RAD7 device for radon measurement. Additionally, 58 CR-39 detectors were installed in buildings to monitor radon levels in indoor air for 90 days. The average background radiation doses, total dissolved solids, electrical conductivity, and pH of water were found to be 0.94±0.29 mSv/y, 0.88±2.10 g/L, 0.17±0.39 S/m, and 6.84±0.47, respectively. The radon levels in water ranged from 0.18 to 50.03 Bq/L with a mean of 4.75±10.81 Bq/L. The average annual effective dose for radon contamination in water was 12.97±29.51 μSv/y. It was only in groundwater that the average values of radon level of 40.53±8.53 Bq/L and annual effective dose of 110.65±23.28 μSv/y were higher than the maximum contaminant level for drinking water (11.1 Bq/L) and the reference level (100 μSv/y), respectively. Additionally, the indoor radon concentration levels ranged from 17.86 to 266.74 Bq/m^3 with an average of 84.75±45.68 Bq/m^3, while the average annual effective dose for indoor radon exposure was 2.14±1.15 mSv/y, which did not exceed the reference levels of 100 Bq/m^3 and 2.5 mSv/y, respectively.

Keywords: radon in water; indoor radon; health risks; RAD7; CR-39

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1. Introduction

Radon-222 (Rn-222) is a radioactive inert gas that cannot be detected by human senses. It is produced from the decay of uranium-238 and subsequently radium-226 is found as contaminant in rocks, water, soil, and sand (Roy et al., 2022; EL-Araby et al., 2024). During the decay of radon gas, alpha particles are emitted. These particles are also emitted in the decay of radon's shorted-lived daughters. Radon daughters can cause internal radiation exposure and pose a health risk to humans (ICRP, 1987; WHO, 2010). It is estimated that radon is responsible for thousands of deaths each year in the United States (US EPA, 2016). Radon may pose a problem in dwellings and workplaces in certain areas of Surat Thani province, as some studies indicated that radon gas concentrations were high in areas with elevated uranium levels at the ground surface (Titipornpun et al., 2015; 2016; 2017). The acceptable levels for indoor radon levels vary by region and country, with the United States Environmental Protection Agency (US EPA) defining 148 Bq/m³ as the action level in homes (US EPA, 1993). The World Health Organization (WHO, 2009) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) defined the reference level of radon gas in homes at 100 Bq/m³. The effective dose of 2.5 mSv per year was also proposed by the UNSCEAR (2000) for indoor radon exposure. In addition, the International Commission on Radiological Protection (ICRP) defined an annual effective dose of about 3-10 mSv per year for people spending 7000 h at home (ICRP, 1993). Radon levels in water such as groundwater from private wells or public water systems present a bigger problem for household water users, while surface water usually does not pose a concern (US EPA, 2016). It was reported that uranium concentration in aquifers and the surface area of the rocks contributed to the high concentration of radon in groundwater (Torgersen et al., 1990). Drinking water contaminated with radon could contribute to human internal exposure. The radon activity ratio of water to air was typically about 10^{-4}, with 10 Bq/L in water implying a level of 0.001 Bq/L in air. The average radon level in water worldwide was found to be 10 Bq/L (UNSCEAR, 1993). Radon in water can pose health risks through inhalation, which may increase lung cancer risk. The US EPA reported that about 1-2% of indoor radon came from drinking water (US EPA, 2014). Additionally, drinking water containing dissolved radon may pose a risk for stomach cancer (National Research Council, 1999; US EPA, 1999; 2014). Radon exposure from water may occur during showering, washing kitchenware, cooking, and drinking. For this reason, the US EPA has defined national regulations for a maximum contaminant level (MCL) and an alternative maximum contaminant level (AMCL) of radon in drinking water at 11.1 Bq/L and 148 Bq/L, respectively (US EPA, 1999). Moreover, the recommended radon concentrations in drinking water were defined in the range of 100 Bq/L to 1,000 Bq/L by the European Union (Catão et al., 2022), while the WHO recommended a reference level of 100 Bq/L (WHO, 2011). An effective dose of 0.1 mSv per year (100 μSv/y) was proposed by the WHO (2004), while the ICRP set 1 mSv per year as a limitation for the public (ICRP, 2007). However, there is no known safe level of radon, so measuring radon concentration is necessary to keep it under control.

The coastal region of Kanchanadit District, Surat Thani Province, located along the Gulf of Thailand, serves as a receiving area for water from many large and small canals, leading to sedimentation at the estuary, which is an important food source for aquatic animals and contributes to the diversity of the ecosystem. It is often replaced by coastal aquaculture farms, which pose environmental and coastal ecosystem crises. Wastewater from shrimp farms, coastal industries, and shellfish ponds is discharged into the sea causing the ecosystem to deteriorate and seriously affecting sea creatures (Suanthong &

Thinbangtieo, 2019). Moreover, these activities may contribute to radionuclide contamination in the coastal environment. The process of groundwater salinization was indicated to affect the distribution of radon activity found in the Upper Gulf of Thailand (Wang et al., 2022). Additionally, a review of indoor radon studies in the Asia-Pacific region found that indoor radon measurements per million inhabitants increased following the rise in the human development index (Janik et al., 2023). Moreover, previous research conducted in Surat Thani province focused only on indoor radon concentrations, and did not provide data to assess the risks of radon gas contamination in both water and air, particularly in the study area of this research. Therefore, this study was focused on the physical properties of water for consumption and the levels of radon in water and indoor air in the buildings located in the coastal region of the Kanchanadit District. In addition, the effective doses due to radon in water and indoor air were evaluated for health risk impacts.

2. Materials and Methods

2.1 Study of the physical properties and measurement of radon concentration in water

The study area was located in the coastal region of Kanchanadit District, Surat Thani Province. The sampling points were located in an area bound by northern latitudes from 9.14332 N to 9.68244 N and eastern longitudes from 99.38101 E to 99.56863 E, covering five sub-districts, namely Tha Thong, Tha Thong Mai, Phlai Wat, Kadae, and Takhian Thong, as shown in Figure 1. The study area for water sampling was near the coastal community, which may be at risk of radionuclide contamination in water due to shrimp farming, shellfish ponds, and the disposal of waste from seafood restaurants or the coastal community. Moreover, indoor air samples were collected from dwellings in the coastal area, which were found to be at risk for indoor radon concentrations due to ground surface-equivalent uranium levels exceeding 3 ppm eU (Duval, 1988). The samples were classified into five types: groundwater, tap water, shallow well water, canal water, and coastal water. A total of 156 samples were collected from 52 sampling sites, with 3 samples per sampling site. The majority of people in the study areas used public tap water for household consumption, with only a small minority using private groundwater and shallow well water. Samples were collected in 250 mL glass vials. Before collecting the samples, it was necessary to let the water flow for 10-15 min to ensure fresh water when sampling groundwater, tap water, and shallow well water. In canal and coastal water cases, the samples were obtained from the water at about 1 m depth from the surface. The vial was carefully filled with water without bubbles and then tightened with a cap.

To study the physical properties of the water samples, the background radiation dose (BG), total dissolved solids (TDS), electrical conductivity (EC), and pH were measured. A Ranger Survey Meter (model CE0197BG) was used for the BG level measurement, while the TDS, EC, and pH were measured using a Hach HQ40D portable multimeter. A RAD7-H_2O device was used for radon level measurement in water, following the manual of the Durridge Company Inc. (2020). For measuring the radon concentration, it took approximately no more than 4 days after sample collection. During the measurement, radon levels continued to decline due to radioactive decay. Therefore, the initial radon concentration in water at sampling time (C_w) was calculated using equation (1) (Ravikumar & Somashekar, 2014; Titipornpun et al., 2021):

$$C = C_w e^{-\lambda t} \tag{1}$$

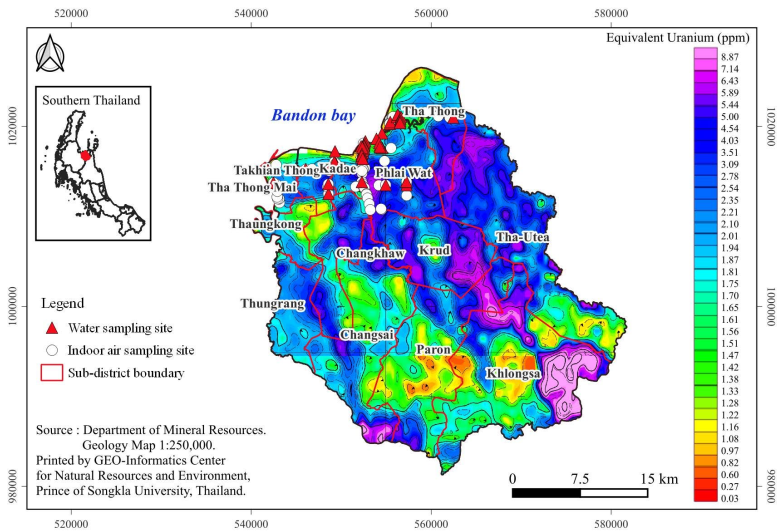

Figure 1. A map showing the relationship between the equivalent uranium in the ground surface and the water sampling sites (triangle symbol) and indoor air sampling sites (circle symbol) in Kanchanadit District, Surat Thani Province

where C stands for radon activity concentration at the time of measurement, λ represents the decay constant for radon with a value of 2.1×10^{-6} s^{-1} (McPherson, 1993), and t is the decay time (s).

2.2 Assessment of annual effective dose due to radon-contaminated in water

The annual effective dose for radon-contaminated water ingestion (AE_{ing}) was assessed for health risk estimation. It can be calculated by equation (2) as follows (UNSCEAR, 2000; Ismail et al., 2021):

$$AE_{ing}(Sv/y) = C_w \text{ x } ED \text{ x } V \quad (2)$$

where ED and V stand for the effective dose intake for water consumption (3.5×10^{-9} Sv/Bq), and the estimated volume consumption of tap water per year (60 L/y), respectively (UNSCEAR, 2000). The annual effective dose for radon inhalation (AE_{inh}) can be calculated as in equation (3) below (UNSCEAR, 2000; Ismail et al., 2021):

$$AE_{inh}(Sv/y) = C_w \text{ x } R \text{ x } DF \text{ x } EF \text{ x } T \quad (3)$$

where R, DF, and EF stand for the ratio of air-water concentration (10^{-4}), the dose conversion factor of 9 μSv (Bq h/L)$^{-1}$, and the equilibrium factor of 0.4 for indoors, respectively. The parameter T represents the indoor occupancy of 7,000 h/y. Moreover, the total annual effective dose (AE_t) was obtained (Mamun & Alazmi, 2022):

$$AE_t(Sv/y) = AE_{ing} + AE_{inh} \quad (4)$$

2.3 Indoor radon concentration measurement and risk assessment

The calibration of CR-39 detectors (Track Analysis Systems Ltd, UK) for indoor radon concentrations was conducted at the Thailand Institute of Nuclear Technology (Public Organization), Nakhon Nayok Province, Thailand. A total of 30 detectors in closed plastic cups were classified into three experimental sets of radon concentration levels and one set of control. The radon concentration levels were obtained at 634.33, 885.15, and 1182.38 Bq/m^3. Seven detectors at each radon concentration level were installed in the ionization chamber of an AlphaGUARD portable radon detector with 0.1137 m^3 in volume. The exposure time was carried out within 72 h. After that, all detectors were chemically etched using a LAUDA A100 water bath following the method reported by Titipornpun et al. (2016; 2017) conducted at Suratthani Rajabhat University. Then, the alpha track densities were counted under a Primo Star Carl Zeiss optical microscope with a magnification of 100x. The calibration curve was plotted as shown in Figure 2.

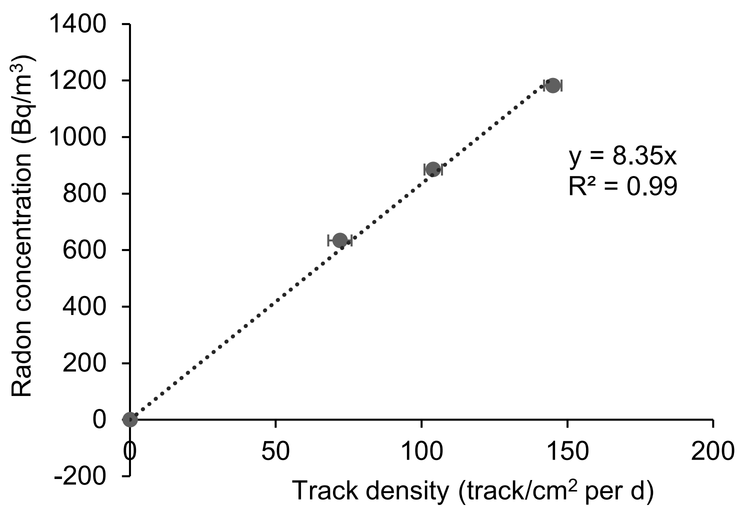

Figure 2. The plot of the relationship between radon concentration and track density obtained from the calibration of the CR-39 detectors

The relationship between radon concentration and track density in a linear curve, as shown in Figure 2, allowed for the derivation of a mathematical equation that could be converted to calculate the radon concentration in indoor air (C_a) as follows:

$$C_a = \frac{kD}{t} \quad (5)$$

where D and t represent the alpha track density (tracks/cm^2) corrected for the background radiation, and the exposure time of 90 days for CR-39 detectors installed in buildings, respectively, and k stands for the calibration factor of 8.35 Bq/m^3 per (track/cm^2 per d) obtained from the slope of the regression line (Figure 2).

For indoor radon measurement in the study area, 58 concrete buildings were randomly selected from six sub-districts located in the coastal region of the Kanchanadit District, Surat Thani Province (Figure 1). The CR-39 detectors used for indoor radon concentration measurements were prepared in the same way as the calibration detectors. The CR-39 detectors were installed on the first floor in bedrooms and living rooms of 30 dwellings and in the workrooms of 28 workplaces for 90 days of exposure time. The chemical etching of alpha tracks was done in the same condition as per the calibration experiment. The alpha track densities were counted under an optical microscope (Primo Star Carl Zeiss). The track densities were substituted into equation (5) to calculate the radon concentration in the indoor air in the buildings. The annual effective dose for indoor radon exposure (AE_a) was calculated as per the following equation (UNSCEAR, 2000):

$$\mathrm{AE}_a(\mathrm{Sv/y}) = \mathrm{C}_a \mathrm{\ x\ DF\ x\ EF\ x\ T} \quad (6)$$

3. Results and Discussion

A total of 156 water samples collected from the coastal region of the Kanchanadit District, Surat Thani Province were classified into five types: groundwater (GW), tap water (TW), shallow well water (SW), canal water (CN), and coastal water (CW). The average values of BG, TDS, EC, and pH were found to be 0.94±0.29 mSv/y, 0.88±2.10 g/L, 0.17±0.39 S/m, and 6.84±0.47, respectively (Table 1). The average BG levels for groundwater (1.23 ± 0.08 mSv/y) and shallow well water (1.32±0.17 mSv/y) were found not to differ significantly (Tukey HSD, p>0.05), and neither did the average BG for canal water (0.76±0.18 mSv/y) and coastal water (0.77±0.26 mSv/y). The average values of BG for groundwater, tap water, and shallow well water were higher than a limitation of 1 mSv/y (ICRP, 2007). However, all water sources were found to have BG averages below the global average value of 2.4 mSv/y (UNSCEAR, 2000). It was observed that the TDS of coastal water had a higher average level (6.00±2.66 g/L) compared to other types of water, with lower averages found in canal water (0.67±1.85 g/L), groundwater (0.46±0.01 g/L), shallow well water (0.34±0.01 g/L), and tap water (0.12±0.09 g/L), respectively. This showed that canal water with a TDS level exceeding 0.5 g/L, was considered unsuitable for drinking, while coastal water, exceeding 1.5 g/l, was also considered undrinkable (WHO, 2004). The EC of coastal water (1.16±0.0.44 S/m) was significantly higher than other types of water (Tukey HSD, p<0.05) and exceeded the reference level for drinking water (0.05-0.15 S/m) recommended by the WHO (2004). The study results indicated that the EC and TDS of coastal water were relatively high due to brackish water caused by the intrusion of seawater from the Gulf of Thailand. Specifically, the average pH values of groundwater (7.58±0.06) and shallow well water (7.51±0.08) were higher compared to other types of water with a significant difference (Tukey HSD, p < 0.05). However, all data of pH values were within the standard range of 6.5-8.5 (WHO, 2004).

The distribution of radon concentrations in the 156 water samples showed a right-skewed pattern in a Kolmogorov-Smirnov normality test at the 0.05 level, as shown in Figure 3(a), while the distribution of indoor radon concentrations in buildings from 58 samples followed a normal curve, as shown in Figure 3(b). The average radon concentrations in water and indoor radon concentrations were 4.75±10.81 Bq/L and84.75±45.68 Bq/m^3, respectively. Figure 3(c) shows that most radon concentrations in water samples were distributed below 10 Bq/L (144 samples, 92.31 %). However, some

Table 1. Physical properties of various types of water in the coastal region of the Kanchanadit District, Surat Thani Province

Water Types	n		Physical Properties of Water			
			BG (mSv/y)	TDS (g/L)	EC (S/m)	pH
GW	12	Range	1.14-1.31	0.45-0.48	0.08-0.10	7.51-7.68
		Mean	1.23±0.08^{c}	0.46±0.01^{a}	0.08±0.01^{a}	7.58±0.06^{b}
TW	45	Range	0.88-1.40	0.04-0.30	0.01-0.06	5.38-7.66
		Mean	1.10±0.21^{b}	0.12±0.09^{a}	0.03±0.02^{a}	6.83±0.58^{a}
SW	12	Range	1.14-1.58	0.33-0.35	0.05-0.07	7.42-7.72
		Mean	1.32±0.17^{c}	0.34±0.01^{a}	0.06±0.01^{a}	7.51±0.08^{b}
CN	75	Range	0.44-1.14	0.08-9.58	0.01-1.69	6.10-7.32
		Mean	0.76±0.18^{a}	0.67±1.85^{a}	0.13±0.33^{a}	6.63±0.24^{a}
CW	12	Range	0.44-1.05	3.33-10.95	0.63-1.91	6.61-7.13
		Mean	0.77±0.26^{a}	6.00±2.66^{b}	1.16±0.44^{b}	6.80±0.13^{a}
Total	156	Range	0.44-1.58	0.04-10.95	0.01-1.91	5.38-7.72
		Mean	0.94±0.29	0.88±2.10	0.17±0.39	6.84±0.47

Note: Different superscript letters (e.g., a, b, c) within each column indicate that the data differ significantly (Tukey HSD, $p < 0.05$).

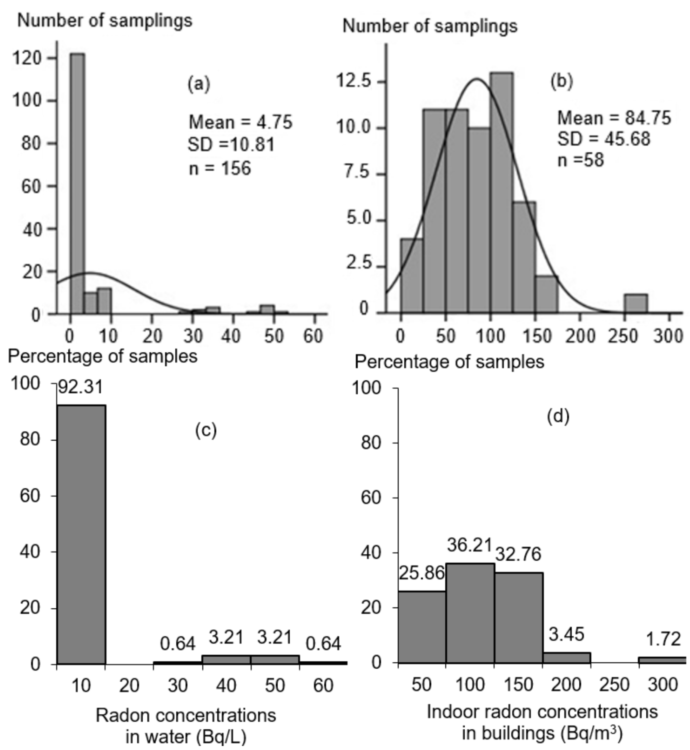

Figure 3. Distribution histograms of the number of samples for radon concentrations in water (a) and indoor radon concentrations in buildings (b), including the percentages of water samples (c) and indoor air samples (d) in the Kanchanadit District, Surat Thani Province

samples found in groundwater were in the range of 30-60 Bq/L (12 samples, 7.69%), which was above the MCL for drinking water (11.1 Bq/L) (US EPA, 1999). Most samples of indoor radon concentrations shown in Figure 3(d) ranged from 50 to 100 Bq/m^3 (21 samples, 36.21%), followed by those in the range of 100-150 Bq/m^3 (19 samples, 32.76%). Only 3 samples (5.17%) of buildings were more than 150 Bq/m^3. These results indicated that 37.93% (22 samples) had indoor radon concentrations exceeding the reference level of 100 Bq/m^3 (UNSCEAR, 2000; WHO, 2009).

The radon concentration levels in water ranged from 0.18 to 50.03 Bq/L with a mean value of 4.75±10.81 Bq/L, as shown in Table 2. The average radon concentration in groundwater of 40.53±8.53 Bq/L, which exceeded the MCL, was significantly higher than the levels in other types of water sources (Turkey HSD, p<0.05). However, the average radon concentrations in tap, canal, and coastal water were not significantly different (Tukey HSD, p>0.05). It was possible that groundwater had higher radon concentrations than surface water sources because it was pumped from underground sources (US EPA, 2014). In addition, the study area was located in an area with high uranium levels at the ground surface, which may result in higher radon concentrations in groundwater. When comparing radon levels in water with other studies, the average radon level in groundwater was higher than in the Southwest Coastal Region of Peninsular Malaysia (32.36±1.8 Bq/L) (Ismail et al., 2021), but lower than in the Ría de Vigo coastal basin located in the largest radon-prone area of the northwestern coast of the Iberian Peninsula (121.1 Bq/L) (Ibánhez et al., 2023). However, it was slightly higher than the limit of 40 Bq/L recommended by the UNSCEAR (2008). In tap water, an average radon level of 1.65±1.96 Bq/L was lower than in the Southwest Coastal Region of Peninsular Malaysia at 1.95±0.61 Bq/L (Ismail et al., 2021). In comparison, the average radon level in the shallow wells of this study (6.88±0.57 Bq/L) was lower than in the Namom district, Songkhla province, Southern Thailand (32.0±9.2 Bq/L) (Pisapak & Bhongsuwan, 2017) and the Ekiti State, Nigeria at 19.5±12.5 Bq/L (Isinkaye & Ajiboye, 2017). Moreover, the means of radon levels found in canals (1.12±1.42 Bq/L) and coastal regions (1.17±0.30 Bq/L) in this study were higher than in the Tapi River near the Tapi Estuary of Bandon Bay, Muang District, Surat Thani Province (0.37±0.18 Bq/L) (Titipornpun et al., 2021) and in Padma River located around the Rooppur Nuclear Power Plant of Bangladesh (0.228±0.140 Bq/L) (Sultana et al., 2024). However, our results were in agreement with the average radon level (1.17±1.70 Bq/L) found in Nam Phong River, Khon Kaen Province (Atyotha et al., 2024). Moreover, the results showed that the average annual effective dose due to radon contamination in groundwater of 110.65±23.28 mSv/y exceeded the reference level of 100 mSv/y (WHO, 2004).

Indoor radon levels in dwellings and workplaces and annual effective doses for indoor radon exposure surveyed from the coastal region of 5 sub-districts in Kanchanadit District, Surat Thani Province, namely Tha Thong, Tha Thong Mai, Phlai Wat, Kadae, and Takhian Thong, were statistically analyzed as shown in Table 3.

Table 3 shows that the indoor radon concentrations for all surveyed locations ranged from 17.86 to 266.74 Bq/m^3. The minimum and maximum values were found in the workplaces of the Kadae sub-district and the dwellings of the Tha Thong Mai sub-district, respectively. Moreover, the maximum value (104.84 Bq/m^3) found in a workplace was the Tha Thong sub-district. The highest levels detected in the dwellings of the Tha Thong Mai sub-district and the workplaces of the Tha Thong sub-district were associated with poorly ventilated rooms. This findings corresponded with the WHO (2009) and the US EPA (2016) reports, which indicated that inadequate ventilation contributed to elevated indoor radon concentrations. For all measurements, the average indoor radon concentration was 84.75±45.68 Bq/m^3, which was below the reference levels (UNSCEAR, 2000; WHO, 2009).

Table 2. Radon levels and annual effective doses due to radon contamination in various water types

Water Types (n)	C_w (Bq/L)			AE_{ing}	AE_{inh}	AE_t
	Min	Max	Mean		(μSv/y)	
GW (12)	27.26	50.03	40.53±8.53^c	8.51±0.79^c	102.13±21.49^c	110.65±23.28^c
TW (45)	0.18	8.19	1.65±1.96^a	0.35±0.41^a	4.16±4.94^a	4.51±5.35^a
SW (12)	6.09	7.73	6.88±0.57^b	1.44±0.12^b	17.34±1.44^b	18.79±1.56^b
CN (75)	0.23	8.28	1.12±1.42^a	0.24±0.30^a	2.82±3.57^a	3.05±3.87^a
CW (12)	0.89	1.92	1.17±0.30^a	0.25±0.06^a	2.96±0.76^a	3.21±0.82^a
Total (156)	0.18	50.03	4.75±10.81	1.00±2.27	11.97±27.24	12.97±29.51

Note: Different superscript letters (a, b, and c) in the same column indicate that the data differ significantly (Tukey HSD, p < 0.05).

Table 3. Indoor radon levels and annual effective doses in various building types

Building Types	Sub-districts (n)	C_a (Bq/m^3)			AE_a (mSv/y)
		Min	Max	Mean	
Dwellings	Tha Thong (5)	67.03	124.55	108.87±23.82^{ns}	2.74±0.60^{ns}
	Tha Thong Mai (4)	124.79	266.74	170.42±65.89^{ns}	4.29±1.66^{ns}
	Phlai Wat (5)	84.20	110.87	97.32±11.34^{ns}	2.45±0.29^{ns}
	Kadae (7)	66.10	157.49	112.13±30.80^{ns}	2.83±0.78^{ns}
	Takhian Thong (9)	67.03	149.84	111.13±26.53^{ns}	2.80±0.67^{ns}
	Total (30)	66.10	266.74	116.59±37.73^a	2.94±0.95^a
Workplaces	Tha Thong (4)	36.65	104.84	71.03±32.11^{ns}	1.79±0.81^{ns}
	Tha Thong Mai (4)	41.29	85.59	68.43±20.54^{ns}	1.72±0.52^{ns}
	Phlai Wat (4)	30.85	80.72	60.66±21.71^{ns}	1.53±0.55^{ns}
	Kadae (10)	17.86	64.71	42.70±15.79^{ns}	1.08±0.40^{ns}
	Takhian Thong (6)	18.09	42.91	31.70±10.13^{ns}	0.80±0.26^{ns}
	Total (28)	17.86	104.84	50.63±23.29^b	1.28±0.59^b
	Overall (58)	17.86	266.74	84.75±45.68	2.14±1.15

Note: Different superscript letters (a, b, and c) within each column indicate that the data are significantly different (Independent samples t-test, p<0.05) and ns shows a non-significant difference (One-way ANOVA, p>0.05).

The annual effective doses for indoor radon exposure ranged from 0.45 to 6.72 mSv/y, with a mean of 2.14±1.15 mSv/y, which was lower than the reference level of 2.5 mSv/y but higher than the worldwide average (1.2 mSv/y) for internal exposure from radon inhalation

(UNSCEAR, 2000). Moreover, the means of the indoor radon level and annual effective doses in dwellings of the Tha Thong Mai sub-district were the highest at 170.42±65.89 Bq/m^3, and 4.29±1.66 mSv/y, respectively. The average values of indoor radon levels and annual effective doses for indoor radon exposure in dwellings were 116.59±37.73 Bq/m^3 and 2.94±0.95 mSv/y, respectively, which were significantly higher than in the workplaces, which were 50.63±23.29 Bq/m^3 and 1.28±0.59 mSv/y, respectively (Independent samples t-test, $p<0.05$). However, indoor radon concentrations in different sub-districts showed a non-significant difference (One-way ANOVA, $p>0.05$). These results showed that the mean values of radon level and annual effective dose in dwellings in the study area exceeded the reference levels (US EPA, 1993; UNSCEAR, 2000; WHO, 2009).

When compared with other areas of Surat Thani Province, the overall mean of the indoor radon levels in buildings in this work (84.75±45.68 Bq/m^3) was higher than the geometric mean of indoor radon levels in the Chiya and Tha Chana Districts (28±2 Bq/m^3; Titipornpun et al., 2015), in the Phanom and Ko Pha-ngan Districts (34±2 Bq/m^3; Titipornpun et al., 2016), in the Ko Samui District (32.6±1.65 Bq/m^3) located in Surat Thani Province (Titipornpun et al., 2017), and the average of some surveys in Thailand (36 Bq/m^3; Janik et al., 2023). Moreover, it was higher than the average indoor radon at some measurement points in some countries of the Asia-Pacific Region such as India (32 Bq/m^3), Myanmar (17 Bq/m^3), Vietnam (79 Bq/m^3), Taiwan (11 Bq/m^3), China (37 Bq/m^3), Japan (18 Bq/m^3), Malaysia (22 Bq/m^3), Singapore (15 Bq/m^3), and Australia (12 Bq/m^3), while it was lower than in Bangladesh (113 Bq/m^3), Nepal (123 Bq/m^3), Korea (91 Bq/m^3), and Hong Kong (155 Bq/m^3) (Janik et al., 2023).

The variations of indoor radon levels and annual effective doses for indoor radon exposure in different rooms of the buildings located in the study areas are shown in Figure 4. A total of 58 samples collected from 58 rooms were classified into three types. The bedrooms (13 samples) and living rooms (17 samples) were collected from dwellings, while workrooms (28 samples) were collected from workplaces. Figure 4(a) shows that the lowest average indoor radon concentration of 50.63±23.29 Bq/m^3 and the highest value of 127.02±48.88 Bq/m^3 were found in workrooms and bedrooms, respectively. However, a significant difference was not found (Turkey HSD, $p>0.05$) compared to the average indoor radon concentration levels in the bedrooms (127.02±48.88 Bq/m^3) and living rooms (108.62±25.15 Bq/m^3). However, they were significantly higher than in workrooms (Turkey HSD, $p<0.05$) and higher than the reference level (100 Bq/m^3). The means of annual effective doses in bedrooms (3.20±1.23 mSv/y) and living rooms (2.74±0.63 mSv/y) were not significantly different (Turkey HSD, $p>0.05$), while workrooms (1.28±0.59 mSv/y) was lower than other room types at significant differences (Turkey HSD, $p<0.05$). The average values of annual effective doses in bedrooms and living rooms were higher than the reference level of 2.5 mSv/y (UNSCEAR, 2000). These findings showed that most workrooms were retail stores with windows and doors open during the day, which may reduce the accumulation of radon gas in the building compared to residential homes, especially bedrooms, and living rooms, which had the highest values, and were more likely to be enclosed throughout the day.

To consider the effect of building construction age on indoor radon levels and annual effective doses due to indoor radon exposure, the building types were classified into four groups including those constructed less than 10 years (<10), between 10 and 20 years, between 20 and 30 years, and between 30 and 50 years (Figure 5). Figure 5(a)

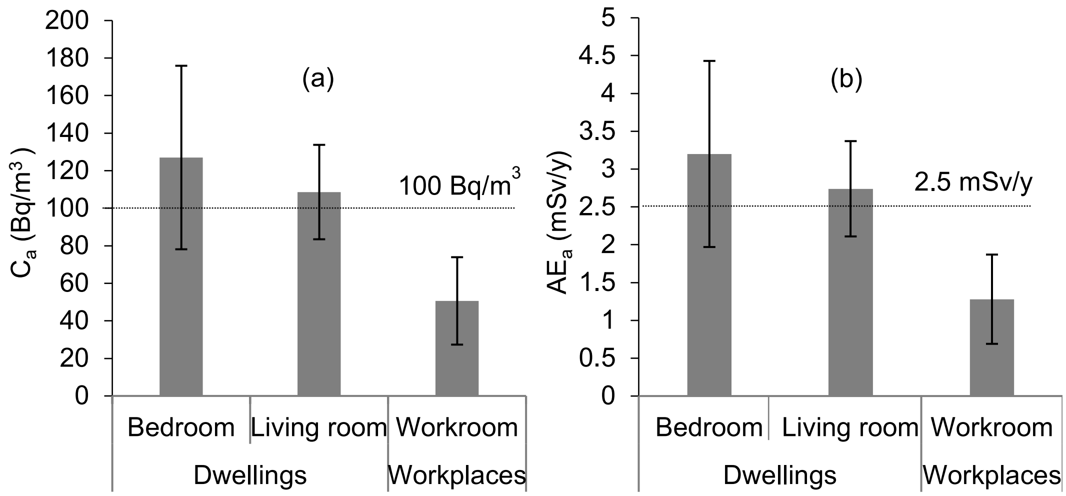

Figure 4. Indoor radon levels (a) and annual effective doses for indoor radon exposure (b) in dwellings and workplaces as a function of different rooms

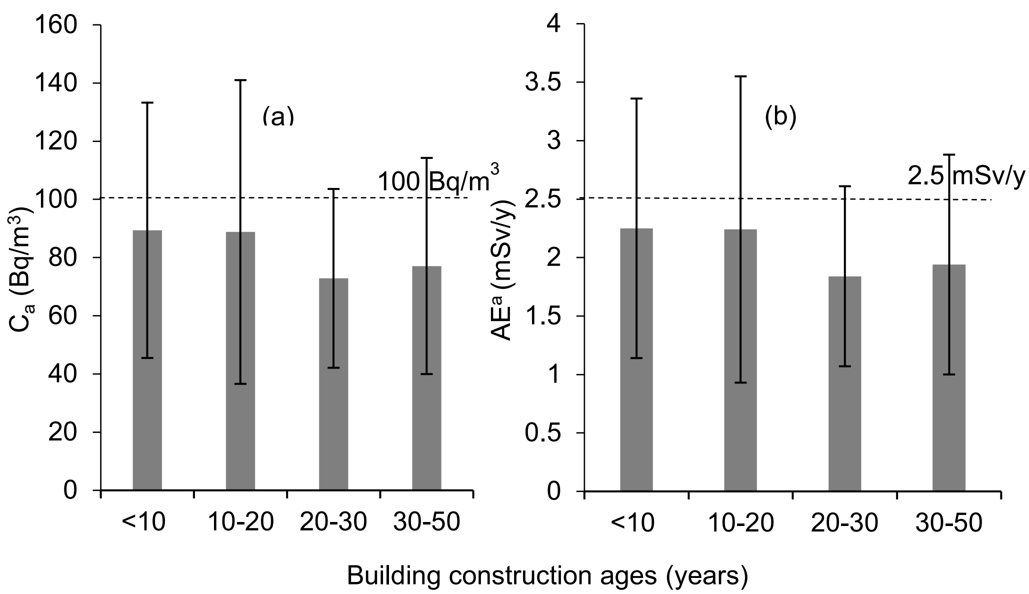

Figure 5. Indoor radon levels (a) and annual effective doses for indoor radon exposure (b) as a function of building construction ages

shows the average indoor radon levels in buildings constructed less than 10 years (89.3±43.88 Bq/m^3), between 10 and 20 years (88.80±52.20 Bq/m^3), between 20 and 30 years (72.86±30.73 Bq/m^3) and between 30 and 50 years (77.11±37.15 Bq/m^3), and the differences were not significant (One-way ANOVA, p>0.05). Analogous to annual effective doses shown in Figure 5(b), the average values in the buildings constructed less than 10 years (2.25±1.11 mSv/y), between 10 and 20 years (2.24±1.32 mSv/y), between 20 and 30 years (1.84±0.77 mSv/y), and between 30 and 50 years (1.94±0.94 mSv/y) showed non-significant differences (One-way ANOVA, p>0.05). Moreover, indoor radon levels and annual effective doses in buildings of different construction ages did not exceed the reference levels of 100 Bq/m^3 (UNSCEAR, 2000; WHO, 2009) and 2.5 mSv/y (UNSCEAR, 2000), respectively. However, the results of this study corresponded to the research of Kolovou et al. (2023), which was reported that houses built before 1960 (60 years or more) tended to have higher indoor radon concentrations compared to those built after that year, while houses built less than 50 years ago showed no differences in indoor radon levels. Moreover, old houses may have a higher concentration of radon gas, possibly due to deteriorated conditions with cracks, gaps, and joints in the plumbing, or because the design of ventilation systems in the past may have been inferior to modern standards (US EPA, 2016; Kolovou et al., 2023).

This study suggests that indoor radon levels may depend more on the room atmosphere or other factors rather than being caused by water used for household consumption. Moreover, the study areas were located near gypsum, anhydrite, and dolomite mines, which may potentially lead to radon contamination in the indoor air (Abo-Elmagd et al., 2018).

4. Conclusions

From the results, it can be concluded that the total dissolved solids and electrical conductivity of the coastal water exceeded the standard values for drinking water, while the physical parameters of groundwater, tap water, shallow well water, and canal water were found within the standard value range. Radon concentrations in water varied from 0.18 to 50.03 Bq/L. The overall mean of 4.75±10.81 Bq/L was below the MCL (11.1 Bq/L), while the average radon level in groundwater of 40.53±8.53 Bq/L exceeded the MCL. This study suggests that groundwater should not be consumed without prior treatment. Indoor radon concentrations ranged from 17.86 to 266.74 Bq/m^3. The average indoor radon level was 84.75±45.68 Bq/m^3, which was below the reference level of 100 Bq/m^3. However, the average indoor radon levels in the bedrooms (127.02±48.88 Bq/m^3) and living rooms (108.62±25.15 Bq/m^3) were higher than the reference level of 100 Bq/m^3 but lower than the action level of 148 Bq/m^3. These results suggest that rooms with poor ventilation had high indoor radon levels. The mean values of annual effective doses for radon contamination in water and indoor air in buildings in the study areas were 12.97±29.51 μSv/y, and 2.14±1.15 mSv/y, respectively. These were below the reference levels of 100 μSv/y and 2.5 mSv/y, respectively. However, these values were within the action level range of 3 to 10 mSv/y. Additionally, the indoor radon levels in households were not related to radon levels in water. Households using groundwater with open systems in the rooms had lower indoor radon levels compared to those using tap water with closed systems.

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6. Authors' Contributions

Kanokka Titipornpun: designed research, performed research, analyzed data, coordinated research, and wrote the paper. Sumit Jirungnimitsakul: shared some discussion. Pachirarat Sola: calibrated the CR-39 detectors for indoor radon concentration measurement.

7. Conflicts of Interest

The authors declare no conflict of interest.

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