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# Annual Effective Dose and Excess Lifetime Cancer Risk Associated with Radon Exposure in Tap Water of Chiang Khan District, Loei Province, Thailand

(Dos Berkesan Tahunan dan Risiko Kanser Seumur Hidup Berlebihan Berkaitan dengan Pendedahan Radon dalam Air Paip Daerah Chiang Khan, Wilayah Loei, Thailand)

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ABSTRACT

Objectives of this study were to determine radon concentration in tap water and assess the annual effective dose (AED) and excess lifetime cancer risk (ELCR) associated with radon exposure in tap water in Chiang Khan District, Loei Province, Thailand. A total of 40 water samples were collected to determine radon concentration using the RAD7 radon detector and analyze the physical and chemical properties of the water using a multiparameter water quality meter. The results showed that radon concentrations in tap water were between 0.007 and 1.973 Bq/L with an average of 0.099 ± 0.307 Bq/L. The highest concentration was observed at one sampling location (1.973 Bq/L), although all measured values remained considerably below the World Health Organization (WHO) and U.S. Environmental Protection Agency (USEPA) recommended limits of radon levels in tap water. Radon concentration has a negative correlation with temperature. The AED and ELCR assessments showed that the infant group (0-1 years) had the highest risk compared to the children and adult groups due to the higher rate of water consumption per body mass. However, AED and ELCR values for all age groups were still low and did not exceed the levels that pose radiation risks to public health. This study provides the first baseline data on radon levels, associated radiological risks, and water quality parameters in tap water from Chiang Khan District, Loei Province.

Keywords: Annual effective dose; excess lifetime cancer risk; Chiang Khan District; radon; tap water

ABSTRAK

Objektif kajian ini adalah untuk menentukan kepekatan radon dalam air paip dan menilai dos berkesan tahunan (AED) dan risiko kanser seumur hidup berlebihan (ELCR) yang berkaitan dengan pendedahan radon dalam air paip di Daerah Chiang Khan, Wilayah Loei, Thailand. Sebanyak 40 sampel air telah dikumpulkan untuk menentukan kepekatan radon menggunakan pengesan radon RAD7 dan menganalisis sifat fizikal dan kimia air menggunakan meter kualiti air berbilang parameter. Keputusan menunjukkan bahawa kepekatan radon dalam air paip adalah antara 0.007 dan 1.973 Bq/L dengan purata 0.099 ± 0.307 Bq/L. Kepekatan tertinggi diperhatikan di satu lokasi persampelan (1.973 Bq/L), walaupun semua nilai yang diukur kekal jauh di bawah had tahap radon yang disyorkan oleh Pertubuhan Kesihatan Sedunia (WHO) dan Agensi Perlindungan Alam Sekitar A.S. (USEPA). Kepekatan radon mempunyai korelasi negatif dengan suhu. Penilaian AED dan ELCR menunjukkan bahawa kumpulan bayi (0-1 tahun) mempunyai risiko tertinggi berbanding kumpulan kanak-kanak dan dewasa disebabkan oleh kadar penggunaan air yang lebih tinggi bagi setiap jisim badan. Walau bagaimanapun, nilai AED dan ELCR untuk semua peringkat umur masih rendah dan tidak melebihi tahap yang menimbulkan risiko radiasi kepada kesihatan awam. Kajian ini menyediakan data asas pertama tentang tahap radon, risiko radiologi yang berkaitan dan parameter kualiti air dalam air paip dari Daerah Chiang Khan, Wilayah Loei.

Kata kunci: Air paip; Daerah Chiang Khan; dos berkesan tahunan; radon; risiko kanser sepanjang hayat berlebihan

## INTRODUCTION

Chiang Khan District, Loei Province, is one of the most favored tourist destinations in northeastern Thailand. It is well known as a cultural tourism area with unique natural features. Located next to the Mekong River, Chiang Khan has continuously developed with increasing numbers of hospitality facilities, restaurants, and tourist activities. The demand for tap water, therefore, has increased. The quality of the water affects the health of the locals and tourists, particularly through the contamination of natural radioactive substances or elements that could impact health in the future (World Health Organization 2021). The Provincial Waterworks Authority (PWA) of Chiang Khan showed that the tap water comes from the Mekong River. As a transboundary river, its water quality may be affected by anthropogenic activities within the watershed, which can cause changes in the physical, chemical, and natural radioactivity of the water sources. Geologically, Loei Province is located in an area where rocks and sediments of the Mekong River can affect the natural radioactivity of the water source, particularly radon gas (Singtuen et al. 2026). These characteristics make Chiang Khan District an interesting area for investigating the occurrence of radon in tap water and its potential radiological implications.

Radon ($^{222}$Rn) in tap water has become a growing public health concern worldwide because it is directly used in daily activities such as drinking, cooking, showering, and laundry, making it a concerning pathway of radon exposure for consumers. The evaluation of radon concentration and related health risks is particularly important in tourist destinations where tap water is used by local residents as well as tourists of all ages. Radon is a naturally occurring radioactive gas that is colorless, odorless, and flavorless. It is a decay product of radium ($^{226}$Ra) in the uranium ($^{238}$U) decay series and is commonly present in soil, rock, and groundwater. As an alpha-emitting radionuclide, making internal exposure through inhalation or ingestion a potential health concern (Dobrzyńska, Gajowik & Wieprzowski 2023). Radon can dissolve in water, especially in groundwater that flows through rock layers that contain uranium or radium (Faella et al. 2020). Although it is usually associated with groundwater, surface water may also contain radon depending on the geological conditions, sediment transport, and environmental factors (Al Hilal 2020). The concentration of radon in water is influenced by several factors, including geological formations, groundwater flow characteristics, and physicochemical conditions (Manawi et al. 2024). During household water use, dissolved radon can be transferred from water to indoor air through aeration and volatilization, contributing to inhalation exposure (Selala & Rathebe 2026). Radon can enter the human body through ingestion and inhalation during household water use. Prolonged exposure to radon can lead to cancer, particularly lung and stomach cancer (ICRP 2007; World Health Organization 2021). Currently, there has been much research on radon concentration in water in the fields of environmental science and public health, as water distribution systems and groundwater are utilized on a daily basis by most people. The World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) have both made recommendations regarding safe radon levels in water to prevent impacts on public health (US EPA 2003; WHO 2021). Measurement of radon concentration in combination with the assessment of the annual effective dose (AED) and excess lifetime cancer risk (ELCR) is important to evaluate water quality, estimate potential radiological health risks to consumers, and support local radiation risk assessment (Atyotha et al. 2026; Sittitanadol et al. 2026). In Thailand, radon in various water sources have already been investigated in many areas to evaluate water quality and radiation risk to public health. Titipornpun, Jirungnimitsakul and Sola (2025) and Titipornpun et al. (2021) studied radon concentrations in various water sources in Surat Thani Province and reported radon levels within the recommended safety limits, indicating a low radiological risk to the local population. Sola et al. (2017) investigated radon concentrations in air and tap water at the Thailand Institute of Nuclear Technology, Ongkharak, Nakhon Nayok Province, demonstrating the applicability of radon monitoring for radiation safety assessment. Meanwhile, Atyotha et al. (2026, 2023) studied radon concentrations in groundwater in Kantharawichai District, Maha Sarakham Province, and tap water in Khao Kho, Phetchabun Province, where variations in radon concentration were observed depending on water sources and geological conditions. These findings suggest that local environmental and geological characteristics may influence radon occurrence in water and highlight the importance of site-specific investigations. In addition, physical and chemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), salinity (S), and temperature could affect solubility and dispersion of radon in water (Titipornpun et al. 2021). The study of those parameters together with radon levels may better explain the behavior and distribution of radon in water.

Although there are studies on radon levels in certain areas of Thailand, information about radon levels in tap water in Chiang Khan District, Loei Province, is still limited. Because radon concentrations in water can vary depending on local geological and hydrogeological conditions, site-specific assessment is necessary for accurate risk evaluation. Furthermore, studies integrating radon levels with water quality and age-specific cancer risk assessment remain scarce. To the best of our knowledge, no previous study has comprehensively evaluated radon contamination and radiological risks associated with tap water in this area. This study therefore aims to measure radon levels in the tap water together with the physical and chemical parameters of the water and assess the annual effective dose (AED) and excess lifetime cancer risk (ELCR) for infants, children, and adults in Chiang Khan District, Loei Province, Thailand. The results can be used as baseline information for water quality surveillance and future radiation risk management.

## MATERIALS AND METHODS

### STUDY AREAS

The study area is Chiang Khan District, Loei Province, located in the northern part of Northeast Thailand. The total area covered by Chiang Khan District is 867 square kilometers, located along the Mekong River and adjacent to the Lao People's Democratic Republic. A total of 40 tap water samples were collected to ensure spatial coverage of high water-consumption areas, including residential communities and major tourist zones along the Mekong River where hotels, resorts, guesthouses, and homestays are concentrated. Samples were collected from various locations in Chiang Khan District and nearby areas of Khao Kaeo and Pak Tom during November and December. The coordinates of the sample collection points were recorded using the Global Positioning System (GPS), as shown in Figure 1.

### METHOD OF MEASUREMENTS

Tap water sampling was conducted by collecting water in 250 mL sealed bottles to prevent radon loss during transportation and storage. Prior to collection, tap water was allowed to run for approximately 5 min to ensure representative sampling. The radon concentration was then measured using the RAD7 radon detector with RAD $H_2O$ (Durridge Co., USA), calibrated annually by the manufacturer. Each water sample was measured once without duplication. Measurement of physical and chemical properties of water such as pH, electrical conductivity (EC), total dissolved solids (TDS), salinity (S), and temperature was done using a multiparameter water quality meter (HI 9829, HANNA Instruments) according to procedures described in an earlier publication (Sittitanadol et al. 2026).

### EVALUATION OF ANNUAL EFFECTIVE DOSE

The ingestion annual effective dose ($AED_{ing}$) resulting from radon exposure through tap water consumption was estimated to evaluate health risks. The calculation was performed using Equation (1) (Titipornpun, Jirungnimitsakul & Sola 2025).

$$AED_{ing} = C_{Rn} \times V \times EDC \tag{1}$$

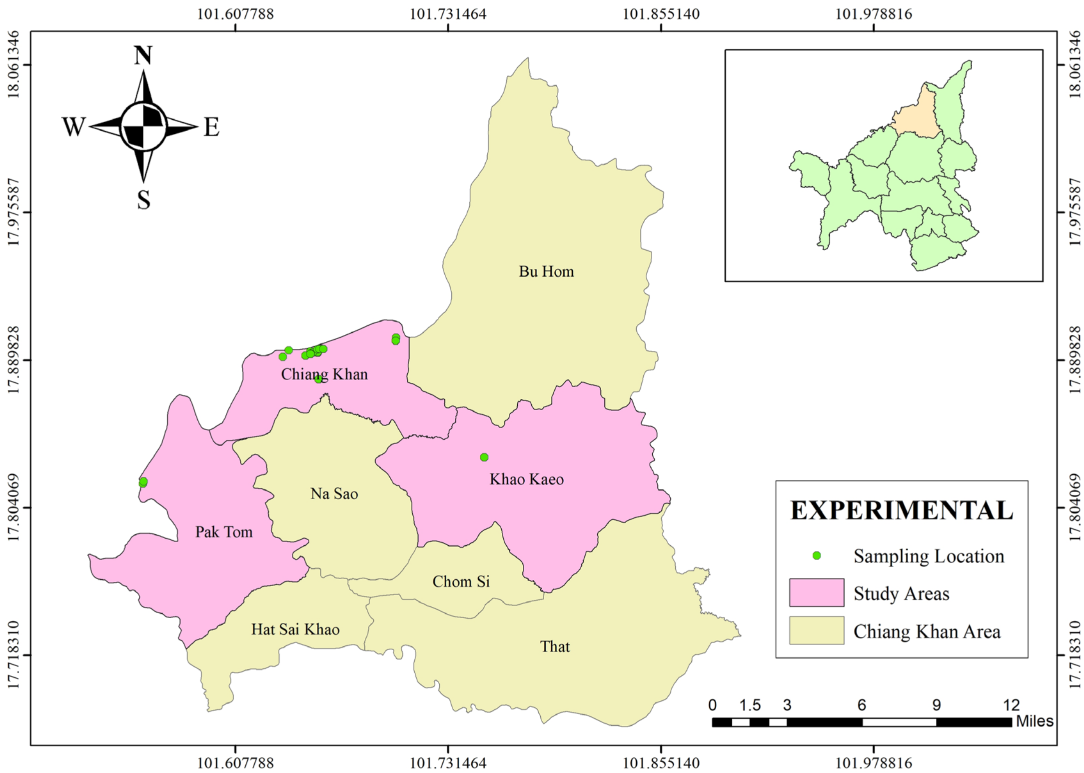



FIGURE 1. Study area and sampling locations in Chiang Khan District, Loei Province, Thailand

where $C_{Rn}$ represents the radon concentration in the tap water sample (Bq/L); $V$ represents the annual water consumption rate (L/y); and $EDC$ represents the ingestion effective dose coefficient (mSv/Bq). According to UNSCEAR recommendations, the annual water consumption rates for adults (>17 years), children (2-17 years), and infants (0-1 year) are estimated at 730, 330, and 230 L/y, respectively (Mamun & Alazmi 2022). The ingestion dose coefficients are $3.5\times10^{-6}$, $5.9\times10^{-6}$, and $2.3\times10^{-5}$ mSv/Bq for adults, children, and infants, respectively (UNSCEAR 2008).

The inhalation annual effective dose ($AED_{inh}$) resulting from radon released into the atmosphere was calculated using Equation (2) (Titipornpun, Jirungnimitsakul & Sola 2025).

$$AED_{inh} = C_{Rn} \times R \times DF \times EF_{inh} \times T \tag{2}$$

where $C_{Rn}$ represents the radon concentration (Bq/L); $R$ represents the transfer ratio of radon from water to air ($10^{-4}$); $DF$ represents the indoor equilibrium factor (0.4); $EF_{inh}$ represents the dose conversion factor recommended by UNSCEAR as $9\times10^{-9}$ Sv/(Bq h m$^{-3}$), and $T$ represents the average indoor occupancy time per year (7000 h/y) (Bem et al. 2014). In addition, the total annual effective dose ($AED_{total}$) was obtained using Equation (3) (Titipornpun, Jirungnimitsakul & Sola 2025).

$$AED_{total} = AED_{ing} + AED_{inh} \tag{3}$$

The annual effective dose due to radon dissolved in blood via inhalation ($AED_{di}$) was calculated using Equation (4) (Pyuskyulyan et al. 2024).

$$AED_{di} = C_{Rn} \times R \times T \times EF_{di} \tag{4}$$

where $C_{Rn}$ represents the radon concentration (Bq/L); $R$ represents the transfer ratio of radon from water to air ($10^{-4}$); $EF_{di}$ represents the dose conversion factor for radon dissolved in blood via inhalation, recommended by UNSCEAR as $0.17\times10^{-6}$ mSv/(Bq h m$^{-3}$) (UNSCEAR 2000).

### EVALUATION OF EXCESS LIFETIME CANCER RISK

The excess lifetime cancer risk (ELCR) associated with radon exposure through ingestion and inhalation from tap water was estimated using Equation (5) (Atyotha et al. 2023).

$$ELCR = AED_{total} \times AL \times RF \tag{5}$$

where $AED_{total}$ represents the total annual effective dose from radon exposure in tap water (Sv/y); $AL$ represents the average life expectancy, estimated at 77.74 years for the Thai population (Sittitanadol et al. 2026); and $RF$ represents the cancer risk factor per Sievert unit, recommended by ICRP as $5.5 \times 10^{-2}$ 1/Sv (ICRP 2007).

## RESULTS AND DISCUSSION

### RADON CONCENTRATIONS AND PHYSICOCHEMICAL PROPERTIES

The results of radon concentration and physicochemical properties of tap water from 40 samples collected in Chiang Khan District, Loei Province are given in Table 1. It was found that the radon concentration was in the range of 0.007-1.973 Bq/L with an average of 0.099 ± 0.307 Bq/L and a median value of 0.035 Bq/L. Almost all the samples possessed low values, the only exception being S40, which exhibited the highest level of 1.973 Bq/L, thus leading to a relatively high standard deviation in comparison to the average due to the uneven distribution of data across all sampling locations. However, the average radon concentration was lower than those reported in Khao Kho District, Thailand (0.30 Bq/L), Campson District, Thailand (0.56 Bq/L) (Atyotha et al. 2026), and Ongkharak District, Thailand (0.51 Bq/L) (Sola et al. 2017), as well as in Urumqi, Xinjiang, China (0.54 Bq/L) (Yong et al. 2021). These differences may be related to variations in geological settings, water sources, and local environmental conditions among the study areas.

When compared with the criteria recommended by the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA), which have set the recommended levels at 100 and 11 Bq/L, respectively (Pyuskyulyan et al. 2024), it becomes clear that all samples still have significantly lower levels than those recommended. This means that tap water in Chiang Khan District, Loei Province is safe regarding radiation risks to consumers. The generally low radon concentrations suggest limited radon accumulation in the local water supply system and provide useful baseline information for future environmental monitoring. Radon in water is generally derived from the natural decay of uranium and radium present in rocks and soils. Therefore, the radon concentrations observed in this study are likely influenced primarily by local geological conditions and groundwater characteristics.

The spatial distribution map of radon concentrations in tap water is presented in Figure 2. From the map, it is evident that radon concentrations are not evenly distributed in the study area, whereby most of the sampling locations in Chiang Khan District recorded concentrations lower than 0.1 Bq/L. However, a hotspot of radon concentration was found in the northern part of the study location, which corresponds to sampling location S40 that recorded the maximum concentration of 1.973 Bq/L. The occurrence of this hotspot may be associated with local

TABLE 1. Radon concentration and physicochemical parameters of tap water

| Sample | Coordinates (Latitude, Longitude) | Radon (Bq/L) | pH | EC (µS/cm) | TDS (ppm) | S (ppt) | T (°C) |
|---|---|---|---|---|---|---|---|
| S1 | 17.903137, 101.701194 | 0.018 | 5.30 | 270 | 135 | 0.01 | 24.20 |
| S2 | 17.906690, 101.701580 | 0.029 | 5.20 | 263 | 131 | 0.16 | 24.10 |
| S3 | 17.833370, 101.752385 | 0.016 | 6.01 | 242 | 121 | 0.18 | 24.40 |
| S4 | 17.839612, 101.762039 | 0.024 | 6.40 | 242 | 121 | 0.01 | 25.30 |
| S5 | 17.894297, 101.655739 | 0.070 | 7.45 | 60 | 33 | 0.11 | 27.50 |
| S6 | 17.894612, 101.655836 | 0.070 | 7.71 | 68 | 41 | 0.07 | 27.60 |
| S7 | 17.818178, 101.551281 | 0.210 | 7.15 | 73 | 45 | 0.02 | 27.70 |
| S8 | 17.892544, 101.648532 | 0.035 | 7.44 | 89 | 44 | 0.03 | 27.60 |
| S9 | 17.819508, 101.554500 | 0.070 | 7.94 | 119 | 59 | 0.01 | 27.20 |
| S10 | 17.893999, 101.651495 | 0.070 | 7.07 | 791 | 354 | 0.01 | 26.30 |
| S11 | 17.896584, 101.657303 | 0.007 | 6.89 | 180 | 95 | 0.61 | 27.80 |
| S12 | 17.895019, 101.651368 | 0.009 | 7.40 | 172 | 87 | 0.01 | 27.90 |
| S13 | 17.894376, 101.652920 | 0.035 | 7.44 | 168 | 88 | 0.01 | 27.60 |
| S14 | 17.896156, 101.655479 | 0.035 | 7.20 | 195 | 101 | 0.01 | 28.10 |
| S15 | 17.893676, 101.651635 | 0.070 | 7.28 | 174 | 87 | 0.01 | 28.20 |
| S16 | 17.893502, 101.651548 | 0.021 | 8.40 | 155 | 76 | 0.01 | 27.30 |
| S17 | 17.878737, 101.656295 | 0.014 | 7.86 | 169 | 83 | 0.01 | 27.70 |
| S18 | 17.901173, 101.701092 | 0.070 | 7.37 | 171 | 88 | 0.01 | 27.80 |
| S19 | 17.901248, 101.703176 | 0.070 | 7.58 | 199 | 89 | 0.01 | 26.70 |
| S20 | 17.896441, 101.656705 | 0.035 | 7.60 | 162 | 82 | 0.01 | 27.10 |
| S21 | 17.896450, 101.658907 | 0.035 | 7.58 | 193 | 112 | 0.01 | 27.30 |
| S22 | 17.894297, 101.655739 | 0.070 | 7.45 | 112 | 53 | 0.02 | 25.55 |
| S23 | 17.894612, 101.655836 | 0.070 | 7.71 | 234 | 119 | 0.04 | 25.68 |
| S24 | 17.892544, 101.648532 | 0.035 | 7.44 | 412 | 235 | 0.01 | 25.52 |
| S25 | 17.818178, 101.551281 | 0.210 | 7.15 | 365 | 159 | 0.02 | 25.66 |
| S26 | 17.819508, 101.554500 | 0.070 | 7.94 | 972 | 482 | 0.01 | 26.83 |
| S27 | 17.893999, 101.651495 | 0.070 | 7.07 | 790 | 320 | 0.01 | 25.86 |
| S28 | 17.896584, 101.657303 | 0.014 | 6.89 | 189 | 91 | 0.61 | 26.37 |
| S29 | 17.895020, 101.651369 | 0.011 | 7.40 | 175 | 89 | 0.01 | 26.34 |
| S30 | 17.894376, 101.652920 | 0.035 | 7.44 | 165 | 80 | 0.01 | 26.40 |
| S31 | 17.896156, 101.655479 | 0.035 | 7.20 | 193 | 103 | 0.01 | 26.32 |
| S32 | 17.893677, 101.651635 | 0.070 | 7.28 | 172 | 91 | 0.01 | 26.28 |
| S33 | 17.893502, 101.651548 | 0.009 | 8.40 | 156 | 81 | 0.01 | 26.50 |
| S34 | 17.489673, 101.278024 | 0.070 | 8.46 | 159 | 85 | 0.01 | 26.22 |
| S35 | 17.878737, 101.656295 | 0.013 | 7.86 | 166 | 88 | 0.04 | 26.28 |
| S36 | 17.901173, 101.701092 | 0.070 | 7.37 | 173 | 87 | 0.01 | 26.37 |
| S37 | 17.898429, 101.708637 | 0.070 | 7.58 | 197 | 101 | 0.01 | 26.21 |
| S38 | 17.896441, 101.656705 | 0.035 | 7.60 | 161 | 72 | 0.01 | 26.24 |
| S39 | 17.896450, 101.658907 | 0.035 | 7.58 | 192 | 96 | 0.03 | 26.27 |
| S40 | 17.891787, 101.635335 | 1.973 | 7.46 | 100 | 52 | 0.01 | 23.28 |
| Min | - | 0.007 | 5.20 | 60 | 33 | 0.01 | 23.28 |
| Max | - | 1.973 | 8.46 | 972 | 482 | 0.61 | 28.20 |
| Median | - | 0.035 | 7.44 | 173.50 | 88.50 | 0.01 | 26.37 |
| Mean ± SD | - | 0.099 ± 0.307 | 7.34 ± 0.67 | 230.95 ± 192.73 | 113.90 ± 87.90 | 0.06 ± 0.14 | 26.49 ± 1.16 |

geologic factors such as rock formations and aquifers that can influence radon accumulation in water (Ismail et al. 2021). Furthermore, low levels have been detected in the center and west portions of the district.

The physicochemical parameters of tap water showed that the pH was between 5.2 and 8.46 with an average of 7.34 ± 0.67, suggesting that most of the water was either neutral or mildly alkaline. Electrical conductivity (EC) and total dissolved solids (TDS) showed an average of 230.95 ± 192.73 μS/cm and 113.9 ± 87.9 ppm, respectively. Such results can be considered consistent since both parameters reflect the amount of dissolved substances in the water. However, some samples, for example, S26, showed much higher values of EC and TDS than others, which can be attributed to the accumulation of minerals or dissolved substances within the water distribution system in the study area. Both values were lower than the standards recommended by WHO (500-1500 μS/cm for EC and below 1000 ppm for TDS) (Titipornpun, Jirungnimitsakul & Sola 2025). Meanwhile, salinity (S) ranged from 0.01 to 0.61 ppt, with an average of 0.06 ± 0.14 ppt, showing that most of the tap water was freshwater with low salinity. The average temperature of the water was 26.49 ± 1.16 °C.

The results of the analysis of Pearson correlation coefficients between radon concentration and the physicochemical parameters of tap water are shown in Figure 3. It was found that the electrical conductivity (EC) has a high level of positive correlation with the total dissolved solids (TDS) value, which is consistent with the principles of water chemistry because both parameters reflect the amount of ionic solution in the water (Lucas Rego Barros, Thauara & Santiago 2020). Furthermore, radon concentration shows a negative correlation with temperature, which may be due to higher temperatures resulting in a decrease in the solubility of radon gas in water and an increase in the evaporation of radon from water into the atmosphere (Yong et al. 2021). While other parameters are associated with low levels of correlation with radon concentration, indicating that such physical and chemical parameters may not have a direct influence on changes in radon concentrations in the tap water of the study area.

## ANNUAL EFFECTIVE DOSE ASSESSMENT

Table 2 displays the results of the annual effective dose (AED) from exposure to radon in tap water, including the annual effective dose due to ingestion ($AED_{ing}$), inhalation ($AED_{inh}$), radon dissolved in blood via inhalation ($AED_{di}$), and the total annual effective dose ($AED_{total}$).

The results of the annual effective dose due to ingestion ($AED_{ing}$) showed that the highest average value, 0.526 ± 1.623 μSv/y, was found in the infant group aged 0-1 years, followed by the adult group (>17 years) and the children group (2-17 years), at 0.254 ± 0.784

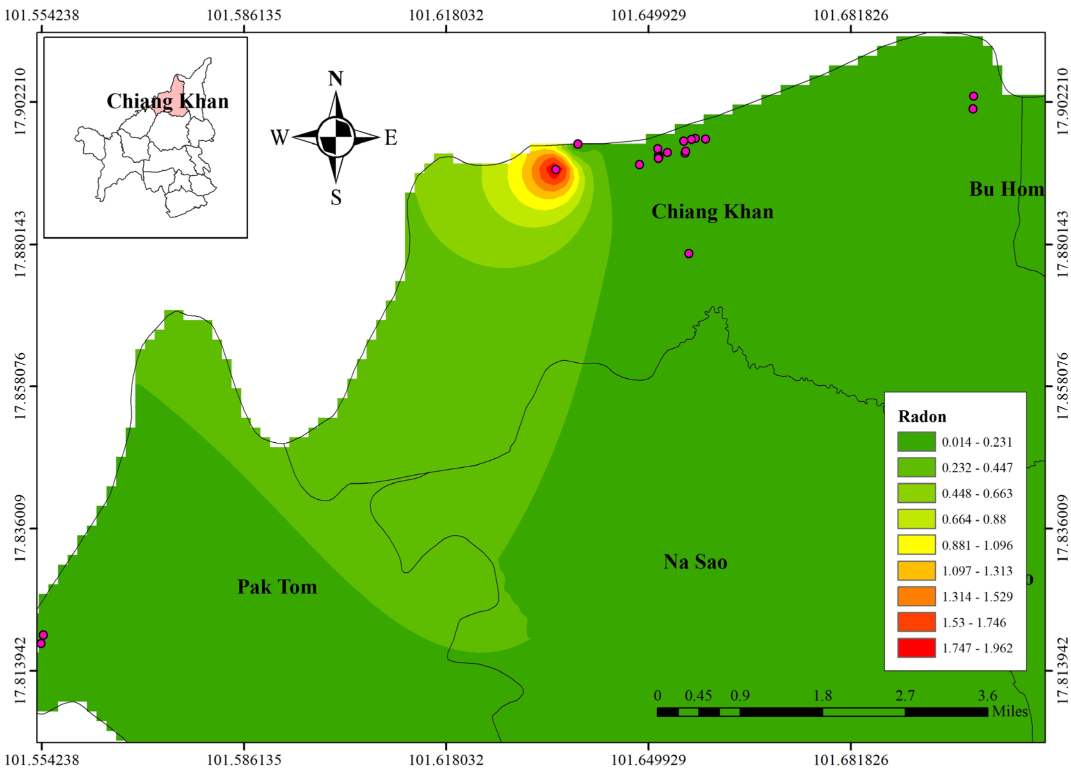
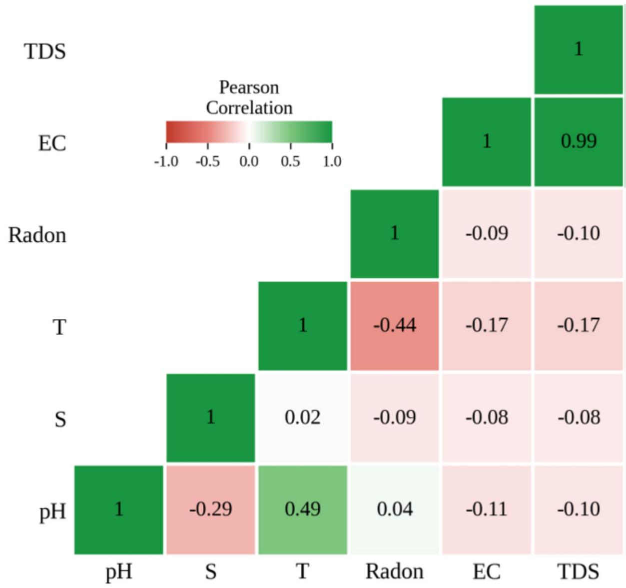



FIGURE 2. Spatial distribution of radon concentration in tap water samples




Correlation Matrix

| | pH | S | T | Radon | EC | TDS | |
|---|---|---|---|---|---|---|---|
| TDS | | | | | | - | Pearson's r |
| | | | | | | - | df |
| | | | | | | - | p-value |
| EC | | | | | - | 0.98996 | Pearson's r |
| | | | | | - | 38 | df |
| | | | | | - | 6.71e-34 | p-value |
| Radon | | | | - | -0.09365 | -0.10143 | Pearson's r |
| | | | | - | 38 | 38 | df |
| | | | | - | 0.565 | 0.533 | p-value |
| T | | | - | -0.43727 ** | -0.17330 | -0.16792 | Pearson's r |
| | | | - | 38 | 38 | 38 | df |
| | | | - | 0.00478 | 0.285 | 0.300 | p-value |
| S | | - | 0.02480 | -0.08706 | -0.08190 | -0.08025 | Pearson's r |
| | | - | 38 | 38 | 38 | 38 | df |
| | | - | 0.87925 | 0.59324 | 0.615 | 0.623 | p-value |
| pH | - | -0.28999 | 0.49321 ** | 0.03941 | -0.10659 | -0.09670 | Pearson's r |
| | - | 38 | 38 | 38 | 38 | 38 | df |
| | - | 0.0695 | 0.00122 | 0.80921 | 0.513 | 0.553 | p-value |

Note * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

FIGURE 3. Pearson correlation coefficients between radon concentration and physicochemical parameters of tap water, including statistical significance (p-values)

TABLE 2. Estimated annual effective dose and excess lifetime cancer risk from radon exposure in tap water for different age groups

| Age group | $AED_{ing}$ (μSv/y) | $AED_{inh}$ $\times10^{-3}$ (μSv/y) | $AED_{di}$ (μSv/y) | $AED_{total}$ (μSv/y) | ELCR $\times10^{-6}$ |
|---|---|---|---|---|---|
| Infant (0-1 yr) | 0.526 ± 1.623 | 0.250 ± 0.770 | 0.012 ± 0.037 | 0.526 ± 1.624 | 2.249 ± 6.946 |
| Children (2-17 yr) | 0.194 ± 0.598 | 0.250 ± 0.770 | 0.012 ± 0.037 | 0.194 ± 0.599 | 0.829 ± 2.559 |
| Adult (>17 yr) | 0.254 ± 0.784 | 0.250 ± 0.770 | 0.012 ± 0.037 | 0.254 ± 0.785 | 1.087 ± 3.357 |

The contribution of inhalation dose was negligible compared with ingestion dose; therefore, $AED_{total}$ values were approximately equal to $AED_{ing}$

and 0.194 ± 0.598 μSv/y, respectively. The results of this study show that infants are the group most affected by the consumption of radon-containing water compared to other age groups due to physiological factors, higher dose conversion factors, and age-specific water consumption assumptions. In addition, their smaller organs and lower metabolism increase the effect of radon (Faella et al. 2020; Leggett 2003). As a result, even if they are exposed to similar amounts of radon, the annual effective dose is higher. However, the $AED_{ing}$ values for all age groups were lower than the WHO-recommended reference level.

For the annual effective dose due to inhalation ($AED_{inh}$), it was found to be $0.25 \pm 0.77 \times 10^{-3}$ μSv/y, which is very low compared to $AED_{ing}$. This indicates that inhalation exposure to radon from tap water poses relatively low health risks. This may be due to the low concentration of radon in the water, as well as the low evaporation of radon from tap water into indoor air (Matsumoto et al. 2023).

For the annual effective dose due to radon dissolved in blood via inhalation ($AED_{di}$), it was found that the average value was 0.012 ± 0.037 μSv/y, which is higher than $AED_{inh}$ but significantly lower than $AED_{ing}$. This suggests that the main route of radiation exposure to radon in tap water is due to ingestion rather than inhalation of evaporated radon from water or radon dissolved in blood via inhalation, which is consistent with several studies reporting that radon exposure through ingestion is an important factor in assessing radiation risk from water (Atyotha et al. 2026; Sittitanadol et al. 2026; Titipornpun, Jirungnimitsakul & Sola 2025). These findings indicate that radon dissolved in blood via inhalation contributes minimally to radiation exposure and is unlikely to pose a significant public health concern.

For the total annual effective dose ($AED_{total}$), it was found that the infant group showed the highest average value, 0.526 ± 1.623 μSv/y, followed by the adult group and the children group, which were 0.254 ± 0.784 and 0.194 ± 0.598 μSv/y, respectively. This trend is consistent with the $AED_{ing}$ result and reflects the higher dose conversion factors and age-specific water consumption assumptions applied to the infant group. However, the $AED_{total}$ for all age groups was still very low compared to the World Health Organization (WHO) reference radiation dose value for drinking water, which is set at 100 μSv/y (Pyuskyulyan et al. 2024), as well as below the radiation dose limit for the general public of 1 mSv/y recommended by the International Commission on Radiological Protection (ICRP 2007). In addition, the estimated $AED_{total}$ values were lower than those reported in previous studies conducted in Surat Thani Province, Thailand (12.97 μSv/y) (Titipornpun, Jirungnimitsakul & Sola 2025), as well as in Ongkharak District, Thailand (0.20 mSv/y) (Sola et al. 2017). This indicates that the tap water in the studied region poses no significant risk of radiation to public health.

## EXCESS LIFETIME CANCER RISK ASSESSMENT

The excess lifetime cancer risk (ELCR) from exposure to radon in tap water of each age group is shown in Table 2. The results showed that the infant group had the highest ELCR value, with an average of 2.249 ± $6.946 \times 10^{-6}$, followed by the adult and children's groups, respectively, consistent with the $AED_{total}$ results due to the use of $AED_{total}$ in the ELCR evaluation. However, the ELCR for each age group was lower than the level recommended by ICRP (ELCR $\leq 10^{-4}$) (Atyotha et al. 2023). This is in agreement with the study of Omirou et al. (2024), who found that the cancer risk from radon in water is relatively low, particularly in areas with low water radon concentration. The ELCR values obtained in this study were also lower than those reported in Kantharawichai District, Thailand ($0.9 \times 10^{-4}$) (Atyotha et al. 2023), which is consistent with the relatively low AED values observed. This shows that radon exposure from tap water in the study area does not pose a significant lifetime cancer risk to the population. However, long-term exposure during a lifetime can still have potential biological effects, especially for sensitive groups, such as infants and those with a longer time of exposure. Therefore, continued monitoring of radon concentrations in drinking water is important for long-term surveillance of public health and radiation safety management (World Health Organization 2021).

It should be noted that the AED and ELCR estimates were calculated using standard dose conversion factors and water consumption rates recommended by international organizations. Therefore, some uncertainties may arise from variations in individual water consumption patterns, age-dependent exposure factors, and temporal fluctuations in radon concentrations.

## CONCLUSIONS

Forty tap water samples were collected from Chiang Khan District, Loei Province. The concentration of radon was determined by using the RAD7 apparatus while the physical and chemical properties were assessed for correlations with radon concentration. It was found that temperature had a negative correlation with radon concentrations, which might occur because high temperatures caused low radon solubility in water, resulting in increased loss of radon into the air. The average radon concentration of all tap water samples was lower than the USEPA recommended concentration level. The evaluation of AED showed that water ingestion is the main route of exposure to radon in tap water and is the major contributor to $AED_{total}$. However, all $AED_{total}$ values were lower than the WHO-recommended level. In addition, the ELCR values for all age groups were lower than the level recommended by the ICRP ($\leq 10^{-4}$), meaning that tap water in this study area is safe in terms of radiation and cancer risk. These results provide baseline data on radon in tap water in Chiang Khan District, as well as an assessment of radiation safety for drinking water in northeastern Thailand. Despite generally low radon activity, one sampling site contained higher amounts of radon compared to the other sampling points. Further investigation is needed to find out whether the presence of higher radon levels is due to local geology conditions or other environmental and anthropogenic factors. The present study was limited by the number of sampling locations and the sampling period. Therefore, long-term monitoring and seasonal investigations are recommended to improve understanding of radon variability and to support future water quality and radiation safety assessments.

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