Report

Short-term Variations of Indoor and Outdoor Airborne Particulate Matter (PM$_{2.5}$ and PM$_{10}$) and Radon Concentrations during the Highest Burning Season in Chiang Mai, Thailand

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This study investigated radon, PM$_{2.5}$, and PM$_{10}$ concentrations in two residences in Chiang Mai, Thailand, during the highest burning period to assess their potential impacts on public health. The selected houses represented contrasting scenarios: House 1 (H1) was associated with a reported case of lung cancer, while House 2 (H2) had no such reported history. Measurements revealed that the indoor radon concentration at H1 (52 ± 23 Bq m^{-3}) exceeded the global average of 40 Bq m^{-3}, although it remained below the World Health Organization's recommended limit of 100 Bq m^{-3}. In contrast, H2 exhibited a lower radon concentration (21 ± 14 Bq m^{-3}). Significantly higher concentrations of both indoor and outdoor PM$_{2.5}$ and PM$_{10}$ were observed at H1 compared to H2, potentially attributable to factors such as building materials, ventilation practices, and proximity to pollution sources. A strong positive correlation between PM$_{2.5}$ and PM$_{10}$ concentrations was observed in both houses, suggesting that these may originate from similar sources. These findings underscore the importance of continuous monitoring and targeted interventions to mitigate potential health risks associated with exposure to radon and airborne particulates in specific locations.

Key words: Radon, Lung Cancer, Chiang Mai, PM$_{2.5}$, PM$_{10}$

1. Introduction

Lung cancer is one of the leading causes of cancer-related deaths worldwide, affecting individuals across all genders and ages[1-3]. It is widely recognized that smoking greatly increases the risk of lung cancer. The link between smoking and lung cancer is well-documented and remains the most significant risk factor, with smokers facing a substantially higher risk of developing the disease compared to non-smokers. However, a growing body of research has highlighted a troubling trend: an increasing number of lung cancer cases are being diagnosed in individuals who have never smoked[4-7]. Studies show that lung cancer rates are rising faster in young women who have never smoked compared to young men[8, 9]. This has drawn attention to other potential causes, such as

environmental exposures to radon gas and air pollutants, which may be contributing to the increase in lung cancer cases[10-12]. The growing incidence of lung cancer in non-smokers underscores the need for increased awareness, early detection efforts, and further research into the diverse range of factors that may be influencing this trend. Understanding these factors is crucial for developing targeted prevention strategies and improving outcomes for all individuals at risk of lung cancer, regardless of their smoking history.

To address the rising concern of lung cancer among non-smokers, researchers are delving deeper into various environmental and genetic factors that may contribute to this alarming trend. The role of air pollution, particularly in urban areas with high levels of industrial emissions and vehicular exhaust, has been a significant focus of study. Fine particulate matter ($PM_{2.5}$) and other pollutants have been linked to respiratory diseases, including lung cancer, suggesting a need for stricter air quality regulations to mitigate these risks[13, 14]. Additionally, indoor air quality is another area of concern. Many households and workplaces may have elevated levels of radon, a naturally occurring radioactive gas that can seep into buildings through cracks in floors and walls. Long-term exposure to high radon levels has been proven to increase the risk of lung cancer, prompting health authorities to recommend regular radon testing and mitigation measures in affected areas[15, 16].

Parallel monitoring of radon and particulate matter (PM) is increasingly seen as crucial since both may contribute to lung cancer. Some decay products of radon, such as the radioactive metals, especially the short-lived alpha particles-emitter polonium (^{214}Po and ^{218}Po), can attach to airborne PM. These PMs include both PM_{10} (particles with an aerodynamic diameter of ≤ 10 μm) and $PM_{2.5}$ (particles with an aerodynamic diameter of ≤ 2.5 μm) types found in pollutants like smoke and dust[17, 18]. Both $PM_{2.5}$ and PM_{10} can penetrate the respiratory system, causing a range of health issues from respiratory infections to cardiovascular diseases. The attachment of radon decay products to fine particles is particularly concerning, as their size distribution significantly impacts respiratory deposition patterns[19]. Indoor radon exposure is a greater concern because radon can easily accumulate in enclosed spaces, and most people spend the majority of their time indoors over their lifetime[20]. However, air pollution can affect human health both indoors and outdoors, as outdoor air pollutants, including radon and PM, can infiltrate indoor spaces. To provide a context for understanding these pollutants, Table 1 summarizes the World Health Organization's (WHO) recommended thresholds for $PM_{2.5}$, PM_{10}, and radon concentrations.

In Thailand, lung cancer is the second leading cause of death, particularly prevalent in the northern region[21, 22].

Chiang Mai, the largest city in northern Thailand, shows a concerning trend with high rates of new lung cancer cases and a high mortality rate from the disease[22, 23]. Additionally, there is an increasing number of lung cancer cases among the younger population in Thailand, with recent diagnoses often being at an advanced stage, and slightly higher incidence in females compared to males[24]. Over the past few decades, Chiang Mai has been severely impacted by health risks from ambient air pollution, including lung cancer. During the burning season, PM_{10} levels frequently exceeded 200 μg m^{-3}, surpassing the Environmental Protection Agency's (EPA) recommended limit of 150 μg m^{-3} [25]. Moreover, radon concentrations in Chiang Mai have been found to be five times higher than the global average (40 Bq m^{-3})[26].

Although numerous studies have examined factors linked to lung cancer incidence in northern Thailand, such as genetic mutations, gender, patient behaviour, and environmental hazards like PM and exposure to radioactive material[21, 22, 27, 28], there is a lack of simultaneous monitoring data on radon and PM concentrations in Chiang Mai's ambient air during the burning season. This study investigated short-term variations in indoor and outdoor $PM_{2.5}$, PM_{10}, and radon concentrations during the burning season in two residences, one with a reported lung cancer case and one without. Combining short-term radon monitoring with real-time airborne $PM_{2.5}$ and PM_{10} measurements provided a detailed and dynamic assessment of environmental exposure, enhancing data robustness and offering new insights into radon concentration patterns and air quality. This study reports these concentrations, comparing them with measurements from other regions to assess associated risks. By analyzing these variations, the research highlights air quality deterioration during the burning season and its potential public health impact, providing insights into the effectiveness of current mitigation measures and informing future strategies for improved air quality in Chiang Mai and similar regions.

Table 1. WHO's recommended thresholds for $PM_{2.5}$, PM_{10}, and radon in indoor air

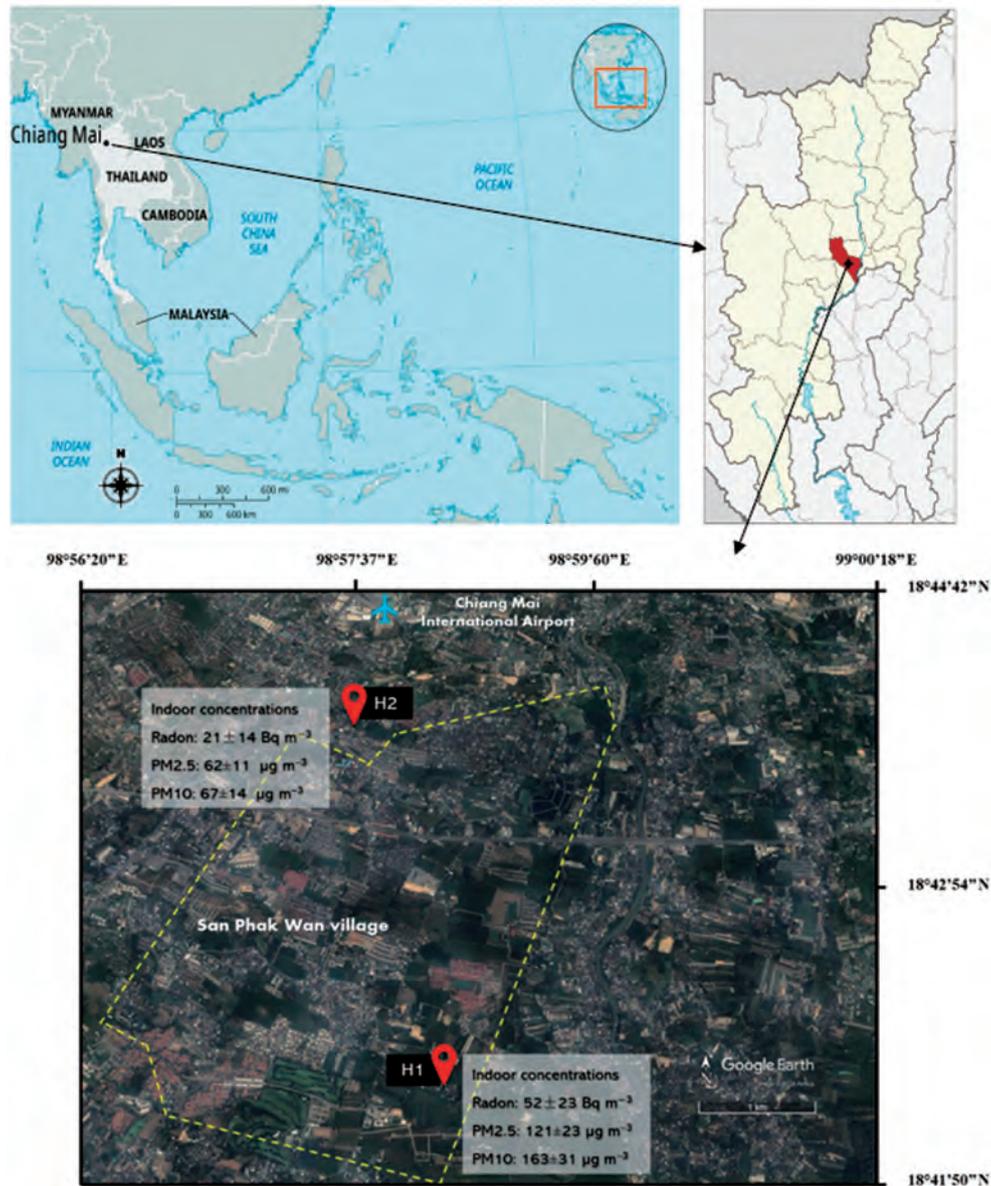| Pollutant	WHO's recommended threshold	Reference
$PM_{2.5}$	24-hour average : 15 μg m^{-3} Annual average : 5 μg m^{-3}	29)
PM_{10}	24-hour average : 45 μg m^{-3} Annual average : 15 μg m^{-3}	
Radon	100 Bq m^{-3}	16)

Fig. 1. Map of sampling locations in Chiang Mai city, Thailand. This map was created using Google Earth Pro software (version 7.1).

2. Materials and Methods

2.1 Study area

Chiang Mai is the second-largest city in Thailand and the largest city in the Upper Northern region of Thailand. It is situated on the Mae Ping River and is surrounded by mountains, predominantly composed of granitic rock, which contributes to a high background radiation area. The city enjoys a tropical climate with three distinct seasons: winter (November–February), summer (March–May), and rainy (June–October). One of the most critical periods for air quality in Chiang Mai is the burning season, which typically occurs between February and April, peaking in March. During this time, the city experiences severe air pollution due to widespread agricultural burning and forest fires.

2.2 Sampling locations

Two typical residences within Chiang Mai city were chosen for field measurements of short-term variations of radon, $PM_{2.5}$ and PM_{10} concentrations using active devices both indoors and outdoors. The first residence (House 1: H1) was selected due to a reported case of lung cancer among its occupants, while the second residence (House 2: H2) served as a general house with no lung cancer cases reported among its residents. H1 and H2 are located about 6.9 km away from each other, and situated in San Phak Wan village, an urban area within

Chiang Mai city. The primary construction material for both houses is concrete. Figure 1 illustrates the sampling locations for H1 and H2, situated in San Phak Wan village of Chiang Mai city area. The field measurements at these residences were conducted in March 2023, during a period of consistently hot weather and clear skies, which provided a stable environment for the study. By comparing data from these two houses, the study aims to understand the impact of indoor and outdoor air quality on health, particularly concerning the incidence of lung cancer. Additionally, long-term measurements of radon and thoron concentrations were conducted in San Phak Wan village (an urban area in Chiang Mai Province) and Nong Kaeo village (a rural area in Chiang Mai Province) using passive alpha track detectors known as RADUET (Radosys Ltd., Hungary).

2.3 Data collection and analysis

Data collection focused on both indoor and outdoor environments at the two sampling locations, H1 and H2. To measure atmospheric radon concentrations, a pulse-type ionization chamber detector, commercially known as the AlphaGUARD detector (model PQ2000PRO, Genitron Instruments GmbH, Germany), was employed both indoors in the middle of the main living room on the first floor and outdoors, 2 meters away from the houses. This device recorded radon levels at 1-hour intervals throughout each measurement cycle. The instrument's measurement range extends from 2 Bq m⁻³ to 2×10^6 Bq m⁻³. For accurate measurements, the detector was positioned on a stand approximately 1 and 2 meters above the ground and far from the wall, respectively at each sampling site. Data were collected continuously over approximately two weeks for each location.

To provide a long-term comparison of radon concentrations in the vicinity, passive alpha track detectors (RADUET, Radosys Ltd., Hungary) were used. These detectors consist of two diffusion chambers with different air-exchange rates. The chamber with a high air exchange rate allows both radon and thoron to enter, while the chamber with a low air exchange rate has a hidden air gap that acts as a barrier, making it difficult for thoron to enter. This combination of chambers helps minimize thoron interference, leading to a more accurate estimation of radon concentration[30]. The detectors were placed in 26 houses in San Phak Wan village and 25 houses in Nong Kaeo village. Most houses in these regions are constructed from cement and wood. The detectors were deployed for approximately four months, from February to June 2023, to calculate the annual average radon concentration, following the recommendations of the World Health Organization (WHO) air quality guidelines for Europe[31]. After exposure, the detectors were processed and analysed

at the Institute of Radiation Emergency Medicine of Hirosaki University, Japan. The analysis process of CR-39 detectors from RADUET is chemically etched in a concentrated base solution of 6.25 M NaOH solution at 90℃ for 6 h[32]. After that, the tracks formed on CR-39 are counted with an automatic reading system. To obtain the radon and thoron concentrations, the track densities are replaced into the equations, which are mentioned in Kranrod *et al.*[32] and ISO16641[33]. This broader dataset helps to contextualize the radon levels found in H1 and H2 within the local environment, offering insights into potential variations and long-term exposure risks.

Airborne $PM_{2.5}$ and PM_{10} concentrations were assessed using a portable air quality monitor, specifically the Aeroqual Series 500 (Aeroqual Inc., New Zealand) at the nearby position of the AlphaGUARD detector at each location. This handheld, battery-operated device provides real-time aerosol mass readings and is designed for accurate, on-the-go surveying of common pollutants such as $PM_{2.5}$ and PM_{10}. The Aeroqual particulate matter sensor head employs a laser and optical counter to measure light scattered by particles traversing the laser beam. The optical sensor converts scattered light into electrical signals, which are subsequently processed to yield mass measurements of $PM_{2.5}$ and PM_{10}. This sensor concurrently measures PM_{10} and $PM_{2.5}$ within a range of 0.001 to 1.000 mg m⁻³, with a resolution of 0.001 mg m⁻³ and an accuracy of ± (0.005 mg m⁻³ or 15% of the reading value). The Aeroqual Series 500 exhibits a response time of 5 seconds. During the measurements, the monitor was held approximately 1 meter above the ground, with each sampling period set at 30 minutes per cycle. The $PM_{2.5}$ and PM_{10} measurements were carried out concurrently with the radon measurements. Data were recorded directly on the monitor and subsequently downloaded to a laptop via Aeroqual software after the completion of the measurement period. This approach ensured comprehensive and precise monitoring of particulate matter levels, complementing the radon concentration data collected during the same timeframe.

By the way, indoor and outdoor aerosol particle concentrations are affected by many factors[34], including room size, ventilation, indoor activities, outdoor conditions, building construction, window and door quality, climate, and environmental parameters, which have to be considered in the detailed study in the future.

3. Results and Discussion

3.1 Radon concentration

The average radon concentrations measured both indoors and outdoors at the sampling locations H1 and H2 are summarized in Table 2. When comparing the average indoor radon concentration at H1 (52 ± 23 Bq m⁻³)

Table 2. Average radon concentrations observed in Chiang Mai

Reference	Sampling locations [Detector: number of samples or data]	Measurement period	Average radon concentration (Bq m^{-3}) ± SD	
			Indoor	**Outdoor**
This study	**San Phak Wan village, Chiang Mai**			
	House 1 [AlphaGUARD: 334 data]	2nd to 16th March 2023	52 ± 23	44 ± 29
	[RADUET: 1 sample]	Feb. to Jun. 2023	52 ± 3	-
	House 2 [AlphaGUARD: 330 data]	16th to 29th March 2023	21 ± 14	22 ± 19
	[RADUET: 1 sample]	Feb. to Jun. 2023	45 ± 3	-
	[RADUET: 26 samples]	Feb. to Jun. 2023	68 ± 25	-
	Nong Kaeo village, Chiang Mai [RADUET: 25 samples]	Feb. to Jun. 2023	59 ± 17	-
Thumvijit *et al.* [43]	**Pa Miang, Chiang Mai** [RADUETt: 60 samples]	-	53 ± 15	52 ± 10
Sriburee *et al.* [44]	**Bann Pang Fan, Chiang Mai** [RADUET: 118 samples]	Feb. to Jun. 2017	54 ± 29	-

Noted: all values reported in the table and across the manuscript are (mean ± sd).

with previous studies conducted in Chiang Mai, the results are consistent, showing similar values (Table 2). Additionally, the radon concentration at H1, San Phak Wan village, and Nong Kaeo village were found to be higher than both the global average of 40 Bq m^{-3} [35] and the value observed at H2 (21 ± 14 Bq m^{-3}). The fact that the radon concentration in these areas exceeds the global average indicates that this location may have specific conditions such as soil composition (Chiang Mai is located in a high radon potential zone[36] and lies in a basin of granitic rock[37], which is rich in uranium and radium, releases significantly high radon), building materials (Some building materials can release radon such as brick, marble, granite, and cement), or ventilation (Poor ventilation or very tightly sealed buildings can increase radon levels) that contribute to higher radon levels. However, the radon levels recorded in this study are still below WHO's recommended maximum of 100 Bq m^{-3} for indoor environments[16], indicating that, while elevated, the radon concentration does not yet pose a significant health risk according to international standards. The difference in radon levels between H1 and H2 highlights the importance of site-specific factors that may influence radon accumulation. Further research could explore the underlying causes of these differences, potentially leading to targeted interventions to reduce radon exposure in areas with higher concentrations.

Combining the box plots of indoor and outdoor radon concentrations as shown in Figure 2, it can be seen that the variation of radon concentrations indoors and outdoors are similar. Furthermore, F-tests were performed on the measured radon concentration at indoor and outdoor areas, revealing that there is no significant difference (p >
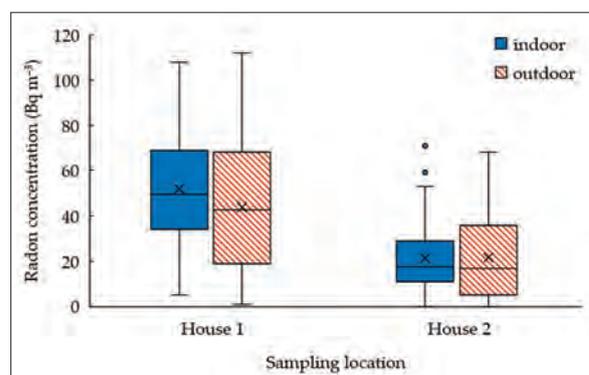

Fig. 2. Box plots of variations in radon concentration indoors and outdoors measured using the AlphaGUARD detector.

0.05) between radon concentration at indoor and outdoor for both sampling locations. This result suggests that indoor radon levels may be influenced by a combination of factors. The use of cement in the construction of both H1 and H2 may contribute to radon emissions from building materials. Furthermore, reduced ventilation due to air conditioner usage during the burning and summer seasons likely exacerbates indoor radon concentrations. Notably, H1, being an older house (20 years), may have structural cracks in its foundation or walls, facilitating the entry of radon from the surrounding outdoor environment. Typically, radon gas is released into the atmosphere from ground formation and considerably contributes to indoor air quality through a variety of phenomenon such as diffusion from the soil through cracks and pore space, and radon entry into the building
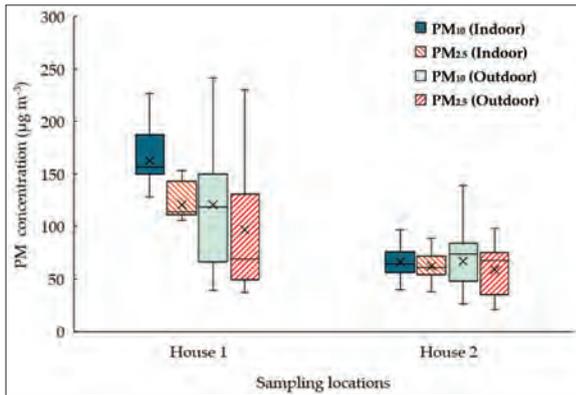
Fig. 3. Box plots of variations in $PM_{2.5}$ and PM_{10} concentrations indoors and outdoors.

Fig. 4. Correlation between PM_{10} and $PM_{2.5}$ concentrations at H1.

from outdoor air[38, 39]. Future research efforts should prioritize the identification of the primary source of indoor radon within this study area to enhance our understanding of the phenomenon.

3.2 $PM_{2.5}$ and PM_{10} concentrations

Figure 3 presents box plots illustrating the variations in $PM_{2.5}$ and PM_{10} concentrations, both indoors and outdoors, for H1 and H2. The average indoor and outdoor PM_{10} concentrations in H1 were observed around 163 ± 31 μg m^{-3} and 120 ± 63 μg m^{-3}, respectively. While the indoor and outdoor $PM_{2.5}$ concentrations in H1 were observed around 121 ± 23 μg m^{-3} and 97 ± 65 μg m^{-3}, respectively. For H2, the average indoor and outdoor PM_{10} concentrations were observed around 67 ± 14 μg m^{-3} and 67 ± 23 μg m^{-3}, respectively. While the indoor and outdoor $PM_{2.5}$ concentrations were observed around 62 ± 11 μg m^{-3} and 59 ± 22 μg m^{-3}, respectively. It can be seen that H1 exhibits higher PM concentrations for both PM_{10} and $PM_{2.5}$ compared to H2, both indoors and outdoors. This could be due to a variety of factors, including differences in sources that may contribute to indoor environments directly (e.g., emissions from consumer products, building materials, equipment, and combustion sources, as well as infiltration of outdoor pollutants) or indirectly (i.e., through convective flows (e.g., ventilation, open doors and windows) or diffusional flows/infiltration (e.g., cracks and fissures)[40]. The high levels of PM_{10} and $PM_{2.5}$ in H1, especially indoors, could pose significant health risks to the occupants. $PM_{2.5}$ is particularly concerning because it can penetrate deep into the lungs and even enter the bloodstream, leading to respiratory and cardiovascular issues[41].

Moreover, it can be seen that PM_{10} levels tend to be higher than $PM_{2.5}$, both indoors and outdoors. Figure 4 shows the correlation between PM_{10} and $PM_{2.5}$ concentrations at H1. The data points are represented by
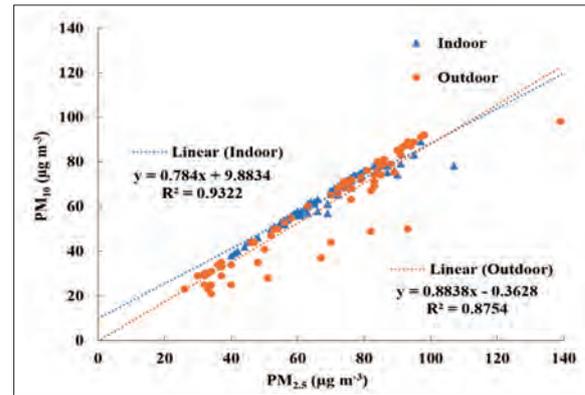
blue triangles (indoor data) and orange circles (outdoor data), each corresponding to different measurements or sampling times. The plot includes trend lines (dotted and dashed) that represent the relationship between PM_{10} and $PM_{2.5}$ for the data collected. The data points are clustered closely along the trend lines, indicating a strong positive correlation between PM_{10} and $PM_{2.5}$ levels. This suggests that as PM_{10} concentrations increase, $PM_{2.5}$ concentrations also tend to rise, likely because PM_{10} includes $PM_{2.5}$ particles. The strong correlation observed between PM_{10} and $PM_{2.5}$ concentrations, both indoors and outdoors, within this study area, suggests a shared origin for these particulate matter types. Potential sources include indoor activities such as cooking, smoking, cleaning, heating, and the operation of appliances with motors, as well as outdoor sources like combustion processes, traffic emissions, and natural occurrences. However, during the burning season in Chiang Mai (February to April), a significant contributor to outdoor PM levels is attributed to biomass burning, specifically the open burning of agricultural waste and forest fires[42]. Therefore, understanding this correlation is important for air quality management because high levels of both PM_{10} and $PM_{2.5}$ are associated with adverse health effects. Since $PM_{2.5}$ can penetrate deeper into the lungs, monitoring its levels in relation to PM_{10} can help assess health risks more accurately.

4. Conclusion

This preliminary study of radon, PM_{10}, and $PM_{2.5}$ concentrations in Chiang Mai highlights the importance of these pollutants for public health. While some areas, notably H1, San Phak Wan, and Nong Kaeo, exhibited average radon levels exceeding the global average, all measurements remained below the WHO guideline of 100 Bq m^{-3} [16], suggesting a potential but not yet critical

health risk. Site-specific factors like soil composition, building materials, and ventilation appear to influence radon accumulation, warranting further investigation. Elevated PM_{10} and $PM_{2.5}$ levels at H1, likely due to building materials, ventilation, and pollution sources, coupled with a strong PM_{10}-$PM_{2.5}$ correlation (especially at H1), emphasize the need to monitor and control both pollutants, particularly the more hazardous $PM_{2.5}$. Continuous monitoring and targeted research are crucial for understanding the dynamics of radon and PM in specific locations to effectively mitigate exposure and protect public health.

Conflicts of Interest

All the authors declare that there are no personal or financial conflicts of interest.

Author Contributions

The authors confirm contribution to the paper as follows: Conceptualization, S.T. and C.K.; Methodology, R.Y., C.K., Formal analysis, C.K., and W.P; Investigation, R.Y., C.K., T.T., S.S., S.S., K.R., and S.T; Data acquisition and interpretation, C.K. and W.P; Supervision, C.K. and S.T; Validation, C.K. and S.T; Writing-original draft, C.K., and W.P; Writing-review and editing, C.K., W.P, M.J., and S.T; Funding acquisition, T.T. and S.T. All authors have read and agreed to the published version of the manuscript.

Highlight: This study presented radon levels along with $PM_{2.5}$ and PM_{10} concentrations and compared these findings with data from other areas to better understand the risks associated with radon and PM levels.

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