

REVIEW ARTICLE

Radiation Exposure in Malaysian Communities: A Narrative Review of Sources, Health Risks and Mitigation Strategies.

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Abstract

Radiation exposure in Malaysia arises from natural and anthropogenic sources. Granite and Silurian-Triassic-Devonian geological backgrounds showed the highest radioactivity concentrations and terrestrial gamma radiation dose rate (TGDR) with Ipoh, Perak recording the highest mean value of 295 ± 1 nGy/h. Atmospheric conditions and variations in monsoon wind patterns also contributed to the amount of natural background radiation in Malaysia communities. Other than radiation exposure from medical devices, some Malaysian communities are also exposed to radiation from tin-tailing processing plants and radiological hazards associated with the rare earth element (REE) industry, especially for workers and communities living in industrial areas. At the Lynas Advanced Material Plant, thorium activity in water leach purification residue (6,727.64 Bq/kg) was reported to be 6.7 times the IAEA safety threshold for radioactive waste (1000 Bq/kg), with approximately 1.2 million metric tons of residue generated between 2012 and 2023. The well-being of Malaysian communities is potentially at risk if adequate control and safety measures are not strictly implemented. This includes continuous accurate monitoring, consistent application of protective measures and personal dosimeters, as well as adherence to established safety guidelines. Awareness activities and risk communication to Malaysian communities are also important, especially in reaching the indigenous groups and those with low proficiency in the Malay language. In mitigating these risks, various approaches can be implemented by taking into consideration the safety of any individual involved, cost-effectiveness, advances in current technology, and current guidelines and regulations. This is essential to promote sustainable communities and the environment, hence enhancing overall Malaysian well-being and quality of life.

Keywords: Background radiation, health risks, mitigation, radiation awareness, radiation exposure, radiation sources.



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Introduction

International policy on radiation handling and exposure was established by the International Commission on Radiological Protection (ICRP) based on the radiation protection framework of justification, optimisation, and dose limitation, while also considering socio-economic and environmental factors and implementing the linear-no-threshold (LNT) model for low-dose radiation exposure risk assessment [1]. Although there are scientific arguments about LNT reliability, especially in terms of carcinogenic mutational responses towards low radiation doses, international bodies still retain the model because of insufficient scientific justification to substitute LNT [2]. Malaysia established radiation protection regulations through the Radiation Protection (Licensing) Regulations 1986, which specifically relate to licensing and authorisation processes [3], and the Atomic Licensing Act 1984 that governs radioactive material handling [4].

Many studies have been conducted related to radiation in Malaysia; these include radiation sources and safety in the medical sector [5], building materials [6], geological formations [7], fodder [8], coal power plants [9], rare earth element (REE) industries [10] and many more. Therefore, this study will narratively review the various sources existing in Malaysian settings, the risks to human health and the environment, and the mitigation strategies to reduce radiation exposure and risks.

Methodology

This narrative review focuses on studies published from 2020 to 2026 through Scopus, Google Scholar, PubMed, and the Directory of Open Access Journals (DOAJ) using appropriate search strings. However, older publications were also included to cite seminal works, review historical perspectives, and address the current lack of publications on certain issues. Potentially relevant studies were identified through titles and abstracts, followed by evaluating eligibility based

on the inclusion and exclusion criteria. The search string, inclusion and exclusion criteria are summarised in Table 1. The data extracted were based on the key themes of this study, which include: (i) Natural radiation sources and geographic hotspots in Malaysia, (ii) anthropogenic radiation in medical and industrial expansion, (iii) health risks due to radiation exposure, (iv) occupational exposure and worker safety, (v) community awareness and risk communication, and (vi) mitigation strategies. In total, 3020 articles were identified, and 94 were selected after deduplication and screening procedures.

Discussion

Natural radiation sources and geographic hotspots in Malaysia

A study has established an activity concentration map for thoron (Rn-220) in soil gas in Perak, Malaysia. It reveals a wide range of values and clear correlations between radon levels and specific geological formations and soil types, with higher concentrations noted in the central part of the state, which is a granite-rich region. At the same time, most other areas fall into low to medium risk categories [11]. The activity concentration of Rn-220 in the soil ranged from undetectable levels up to 563 kBq/m³. The mean value observed was 38 ± 11 kBq/m³. Meanwhile, elevated Rn-220 activity was observed in granite and Triassic-Jurassic formations in the region. Conversely, low Rn-222 values were revealed in Quaternary and Silurian formations. High Rn-220 activity concentrations were specifically identified in peat, riverine, and granite source soils. In contrast, marine and other soil types exhibited low activity concentrations. A primary map of Rn-220 in the soil gas was developed based on a geogenic impact assessment, indicating a greater Rn-220 activity concentration in the central part of the Malaysian state of Perak. Correspondingly, this study utilised a RAD7 radon detector and the THORON protocol for in-

situ measurements to establish the activity concentration map for Rn-220 in soil gas.

A study by Nuhu et al. [12] revealed that the regions with high radon risk are predominantly concentrated in the central and southern parts of Perak state. These high-risk areas are primarily composed of soils derived from granite rocks. Based on the Geogenic Radon Potential (GRP) classification, low Rn-222 (also known as radon) values were observed in the southeastern and northern-central sectors of the study area. These areas with low Rn-222 values are characterised by medium soil permeability. The radon risk index for Perak state, derived from the GRP classification, indicates that the area is mostly at low risk. However, there are specific areas within the state that exhibit medium radon risk, and some isolated locations demonstrate high GRP values. In summary, while most of Perak state is at low radon risk, specific granite-rich areas in the central and southern regions are identified as high-risk zones [12].

A comprehensive study conducted by Nazaruddin et al. [13] on urban soil across 13 major cities in Peninsular Malaysia that combined terrestrial gamma radiation (TGR) and variations of Uranium-238 (U-238), Thorium-232 (Th-232), and Potassium-40 (K-40) was reported in 2025. It involved a total of 9754 TGR measurements across all involved cities. Table 2 shows the details on the mean terrestrial gamma dose rate (TGDR), range of TGDR, and the geological background of the involved cities, as reported in the study. Overall, the range of TGDR was found within 42 – 371 nGy/h, where Kuala Terengganu, Terengganu and Ipoh, Perak showed the lowest and highest values, respectively. The highest mean TGDR was recorded in Ipoh, Perak (295 ± 1 nGy/h) and the lowest was Kuala Terengganu (146 ± 1 nGy/h). The mean TGDR of all involved cities was notably higher compared to Malaysian mean value (92 nGy/h) based on the UNSCEAR 2000 Report [14]. In contrast, a study conducted by Seow et al. [7] on TGR in East Malaysia

involving Labuan and Miri, Sarawak showed mean TGDR below the Malaysian mean value with 81.1 nGy/h and 91.4 nGy/h respectively. These findings are also in agreement with those of Nuhu et al. [11] where cities with granite terrain and/or Paleozoic metasedimentary units (Silurian-Triassic-Devonian) showed high TGDR compared to Carboniferous formations and Quaternary deposits.

Nazaruddin et al. [13] in the same study also reported on the three main primordial radionuclides (Uranium-238 (U-238), Thorium-232 (Th-232) decay series, and Potassium-40 (K-40)) concentration in soils of the selected cities in Peninsular Malaysia. 120 soil samples were taken across the selected cities where the concentration of U-238, Th-232 decay series, and K-40 ranged from 27 – 347 Bq/kg, 27 – 590 Bq/kg, and 61 – 1857 Bq/kg respectively. The maximum value for each radionuclide activity concentration was notably more than four times higher than the global median or mean value (Table 3). A study [15] conducted in Lahad Datu, Sabah also showed high mean concentration compared to the global median or mean value, where the mean values for U-238, Th-232, and K-40 concentration were 42.6 Bq/kg, 77.7 Bq/kg, and 810.9 Bq/kg respectively. The maximum value for each radionuclide activity concentration was between 1.5 – 3 times the global median or mean value (Table 3). To authors' knowledge, no available exact data was found regarding the geological background of Lahad Datu.

A study [17] to map anthropogenic radionuclide concentrations, specifically americium-241 (Am-241), caesium-137 (Cs-137), strontium-90 (Sr-90), and plutonium isotopes (Pu-239 and Pu-240) fallout in the Malaysia-South China Sea region was conducted due to concerns about atmospheric conditions and international community safety after nuclear activities and accidents in the Asia Pacific region. The study concluded that caesium-137 (Cs-137) was the only relevant anthropogenic radionuclide detected in the Malaysia-South

China Sea region more than three years after the Fukushima incident. This is based on the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) database. The study indicates that the Northeast Monsoon had a noticeable influence on radionuclide movement, leading to slightly elevated concentrations of Cs-137 in the Malaysian environment, as observed in the 2014 pattern. The latest study conducted by Haris et al. [18] also agrees that the monsoon significantly influences atmospheric radionuclide transport, where the concentrations of beryllium-7 (Be-7) showed predictive relationships with Northeast Monsoon surges with 2-11 day lags. Atmospheric factors such as humidity, precipitation, and wind patterns [18], and changes in temperature and intense weather like typhoons [19], were reported to influence radionuclide concentrations and distributions in the environment.

In conclusion, the diverse geological background in different regions in Malaysia affects the amount of radionuclide concentration in soils, with granite and Silurian-Triassic-Devonian types contributing to the highest concentration compared to Quaternary and Carboniferous. Other external factors such as atmospheric conditions and variations in monsoon wind patterns also contributed to the amount of natural background radiation in Malaysia.

Anthropogenic radiation in medical and industrial expansion

Anthropogenic radiation, defined as ionising radiation originating from human activities rather than natural sources [20] includes medical radiation applications, nuclear incidents, nuclear weapon testing fallout, industrial usage, and waste [21–23]. Moreover, global studies revealed a notable growth in anthropogenic radiation across the medical and industrial sectors. Accordingly, 4.2 billion radiological examinations were reported to be performed annually, yielding 0.57 mSv effective dose per capita [24,25]. Meanwhile, 24 million workers

are exposed to radiation sources, and 52% of these involve natural radiation sources [25].

The national and international recommended annual dose limit, which includes external and internal exposure, is 20 mSv/year for workers [26] and 1 mSv/year for the public [27]. There is no set patient dose limit for justified diagnostic imaging examinations. However, Diagnostic Reference Levels (DRLs) are used to optimise the exposure while maintaining the image quality for accurate diagnosis [28], and they may vary in different examinations, equipment, protocols, patient population, and country [29,30].

In Malaysia, radiation exposure from the medical sector arises mainly from diagnostic imaging, interventional radiology, nuclear medicine, and radiotherapy [5,26,31,32]. The primary concerns in the medical sector revolve around two key areas, which are internal exposure from unsealed sources in nuclear medicine [26], and increasing radiation doses from Computed Tomography (CT) scans, as evidenced by Dose-Length Product (DLP) values exceeding the 75th percentile of national DRL (450 mGy.cm) [33].

In contrast, the radiation exposure from the industrial sector in Malaysia arises from various sources. The tin-tailing processing plant was reported to produce radiological hazards that exceeded the regulatory limit, as well as water effluent contamination with heavy metals [34]. Rodzi et al. [34] reported (refer to Table 4) that the Ra-226 and Ra-228 in seven Perak tin-tailings exceeded regulatory control limits in water (5 Bq/L for Ra-226 and 10 Bq/L for Ra-228) with 2.4 - 34.9 Bq/L and 0.8 - 14.7 Bq/L, respectively. The average estimated annual effective dose from accidental water ingestion (1.43 ± 0.67 mSv/year) is over 14 times higher than the WHO guideline of 0.1 mSv/year, and the average total annual effective dose for external exposure (1.71 ± 0.79 mSv/year) exceeds the public safety limit of 1 mSv/year. A review by Kristanti et al. [35] reported that genetic mutations and reproduction issues were observed among population

consuming drinking water containing high concentrations of Ra-226 due to long-term exposure to the radiation source, while uranium may cause kidney damage due to chemical toxicity. However, Rodzi et al. [34] also reported that the mean indoor and outdoor air absorbed dose rates (30.76 nGy/h and 15.91 nGy/h, respectively) due to the tin-tailing activities remain below the global background average of 55 nGy/h, and worker dermal health risks are well within safe thresholds (dermal hazard index of < 1) and an acceptable lifetime cancer risk. Therefore, these findings indicate the critical need for effective wastewater treatment before discharge to prevent long-term radionuclide and heavy metal accumulation in the local water environment.

The radiological hazards associated with the rare earth element (REE) industry also raise concerns about environmental issues such as radioactive hazards, increased radiotoxicity, and ionic radiation, as reported by a study conducted at Malaysia's Lynas Advanced Material Plant (LAMP) [10]. The study also reported that thorium activity in water leach purification (WLP) is 6.7 times higher (6,727.64 Bq/kg) than the IAEA safety standard threshold for radioactive waste (1000 Bq/kg), with approximately 1.2 million metric tons of WLP residue generated between 2012 and 2023. Due to that, this has raised concern about the long-term radiation hazards to community well-being and the local environment, as locals need to deal with the massive accumulation of WLP residue, transportation risks, and environmental and food chain contamination.

Significant regulatory gaps have been noted in both the medical and industrial sectors by some studies. A study revealed that some industrial workers received radiation exposure five times higher than the 20 mSv/year recommended annual dose limit [36]. This is possibly due to the 1994 exemption order for tin-tailing processing industries from the Atomic Licensing Act 1984

[4]. Although the exemption order has been revoked in 2021, a study by Rahmat et al. [37] suggested that site remediation and waste management aspects need to be emphasised especially transition guidance from unlicensed to licensing of the tin-tailing processing industry. This is crucial to ensure the safety of the workers and the environment. Findings of the study also revealed a lack of improvement in terms of managing the processing residues compared to past decades' data, which henceforth led to the finding that the radium equivalent activity (Ra_{eq}) values (mean $\pm$ SD for individual samples ranging from 596.64 ± 488.04 Bq/kg to 20881.72 ± 7979.43 Bq/kg) exceeded the permissible value (370 Bq/kg) and also increased the cancer occurrence potential, especially among the workers.

The advancement of technologies and the demand to utilise radiation bring opportunities and risks. This includes both medical and industrial sectors [38]. Consequently, radiation protection systems are required to control and minimise radiation exposure, especially through safer technological solutions [39].

Health risks due to radiation exposure

Radon has been reported [12,35] to cause cellular damage and free radical formation, especially when inhaled and ingested, as radon decay releases alpha particles. Radon also is recognised by the International Agency for Research on Cancer (IARC) to be the second leading cause of lung cancer after tobacco smoke [35]. It was estimated that 89% of an individual's total cancer risk was associated with inhalation of radon released by water supplies [35]. Thus, high concentrations in water supplies will directly expose the lung and gastrointestinal tract lining to radiation dose and increase the potential risks of lung and gastrointestinal cancers. Due to that, monitoring of radon levels in water supplies is crucial to minimise health effects by strictly following the WHO recommended reference concentration of ≤ 100 Bq/L in drinking water

with individual annual effective dose criterion of 0.1 mSv/year from water consumption.

Although the most well-documented consequence of long-term radiation exposure is still cancer, non-cancerous effects are becoming more widely acknowledged. Cumulative lens absorbed doses as low as 0.5 Gy have been connected to opacities, indicating that cataract formation in medical radiation workers is a dose-dependent effect [40]. In line with this, monitoring eye exposure during fluoroscopic and interventional procedures is crucial as the eye lens is among the most radiosensitive organs, and higher workload among the staff may increase the risks of exceeding the revised equivalent dose limit for staff eye lens as recommended by ICRP which is 20 mSv/year, and further increase other risks such as vision loss, and blindness [41]. Malaysia, on the other hand, as stated in the Atomic Energy Licensing (Basic Safety Radiation Protection) Regulations 2010 [42], the equivalent dose limit to the eye lens of a worker shall be 150 mSv/year [42], which is higher than the ICRP recommendation. This may lead to more radiation exposure as well as more radiation hazards to the workers' eye lens. In addition to ocular effects, international findings, as reported in meta-analyses and systematic review studies on chromosomal aberrations, revealed a higher incidence among the radiation workers population exposed to ionising radiation compared to the unexposed workers population [43,44] and higher levels of DNA damage among the e-waste workers population [45].

Additionally, the unregulated handling of radioactive residues and dust inhalation pose risks to workers in the mining and quarry industries, as well as informal e-waste recyclers [4]. Studies have revealed that long-term health risks are increased for these types of workers. This includes lung cancer and chronic lung disease among the mining and quarry workers due to the inhalation of alpha particles and contaminated dust [46], and high levels of toxic elements such

as lead and mercury among the e-waste recyclers [47,48].

Occupational exposure and worker safety

Research on occupational exposure to ionising radiation in industry and healthcare workers has emerged as a critical area of inquiry due to the widespread use of ionising radiation in medical and industrial applications, as well as the associated health risks to workers [25,49]. Since the discovery of X-rays and radioactivity in the late 19th century, technological advances have led to an expansion in the use of radiation. This, in turn, increases concerns about occupational exposure [50,51]. Globally, millions of workers are exposed to ionising radiation, with medical workers accounting for over 50% of artificial radiation exposure [25,44]. The practical significance lies in preventing adverse health effects such as cancer, genetic damage, and cardiovascular complications, underscoring the need for effective dose monitoring and safety protocols [52–54].

The ICRP Publication 103 [55] recommends that the effective dose limit to a worker should not exceed 20 mSv/year averaged over five consecutive years and should not exceed 50 mSv in any year. ICRP also recommends equivalent dose limits of 500 mSv/year for the skin and extremities and 20 mSv/year for the eye lens. Malaysia's Atomic Energy Licensing (Basic Safety Radiation Protection) Regulations 2010 [42] align with these ICRP effective dose limits (20 mSv/year averaged over five years, with no single year exceeding 50 mSv). However, the Malaysian equivalent dose limit to the eye lens is 150 mSv/year [42], which is substantially higher than the ICRP recommendation of 20 mSv/year.

The practical significance of this research is underscored by data indicating that certain healthcare professionals, such as nuclear medicine technologists and interventional radiology staff, may receive extremity doses approaching or exceeding regulatory limits, with

some reports documenting annual skin doses up to 573 mSv/year [56,57]. Similarly, industrial workers exposed to mixed radiation fields require accurate monitoring to ensure compliance with dose constraints and to mitigate long-term health effects [58,59].

Studies provide extensive dose assessments across diverse occupational groups, suggesting that doses generally remain below regulatory limits in both healthcare and industrial environments [58,60–62]. In addition, comparative analyses highlight the higher extremity doses associated with manual handling tasks and the benefits of automated systems in reducing doses [57,63,64]. Moreover, the use of dose conversion factors from equipment parameters aids rapid dose estimation in interventional radiology [65].

The establishment of centralised dose registries is an important strategy for managing complex occupational radiation data and ensuring robust regulatory compliance in high-risk sectors like healthcare and industry [62,66]. These registries facilitate evidence-based policies and safety benchmarking [67]. However, their effectiveness depends on improving adherence to dosimeter protocols to ensure that exposure data remains a reliable foundation for worker safety [68].

Several studies have investigated compliance with Personal Protective Equipment (PPE) protocols as a key component of radiation protection in clinical practice. Andini et al. [69] strongly indicated that adhering to PPE guidelines positively impacts work safety for health workers, leading to a recommendation for targeted training [31] to enhance this compliance. Similarly, Ahmad et al. [70] concluded that while healthcare workers face significant risks from scattered radiation, these risks can be minimised through the consistent application of protective measures and adherence to established safety guidelines.

Despite established guidelines, PPE compliance for radiation protection remains inconsistent. Issues of inconsistent use of dosimeters, especially in terms of forgetfulness and the fear of losing the monitoring devices, should be highlighted in each working setting. This is crucial in ensuring that accurate radiation doses are measured for further health risk monitoring [53].

Community awareness and risk communication

In the Malaysian setting, official materials released by organisations like the Ministry of Health and the Malaysian Atomic Energy Department have mostly used *Bahasa Melayu* in public radiation safety initiatives. However, especially outside of major cities, translated materials in Chinese and Tamil have been less visible. Many studies in diverse fields have concluded that cultural and linguistic differences are the primary factors in communication challenges [71–73]. Therefore, community awareness programmes are suggested to use language specific to the targeted minority community to ensure effective communication [74].

Strong cultural practices, oral knowledge systems, and a dependence on traditional healers, such as shamans or ‘*dukuns*,’ for health interventions are all maintained by indigenous groups, including the Temuan, Jah Hut, Senoi, and others. A study [75] observed that measles vaccination campaigns among Batek Orang Asli in Kelantan demonstrated low engagement when health messaging was imposed without cultural relevance. The study also concluded that indigenous preventive behaviour was ingrained in cultural decision-making and trust networks. Hence, involving leaders and elders of the community as intermediaries has been proven to build trust and assist in conveying messages effectively [76–78].

Many studies have been conducted to assess the population's awareness of radon and the risks it may pose. Studies conducted in Italy, Russia, and Bulgaria indicated that most respondents have a significant lack of awareness, especially in the context of health risks [79–81]. Previous studies have generally concluded that a lack of radon awareness is globally evident. However, to date, no published study has been identified on radon-specific awareness programmes among the Malaysian population. Therefore, an effective continuous awareness programme for Malaysian communities is crucial to mitigate the health risks posed by background radiation exposure.

Mitigation strategies: cost-effective and health risks

Mapping of ionising radiation using drones and radiation detectors has been successfully delivered, yielding promising outcomes while ensuring the safety of researchers and remaining cost-effective [82]. Remote sensing has also been widely used with an accuracy rate of 80% to 91% in mapping radioactive materials in high-background radiation areas [83]. Another cost-effective method for mapping ionising radiation was the use of the Gaussian Process (Kriging) approach [84]. At the same time, an unmanned vehicle was also reported to be utilised in radiological and nuclear events [85]. GIS has also been proven to be an efficient and cost-effective method for radiometric and radon potential assessment, as well as planning, using data obtained from multiple approaches [86]. From our point of view, by considering the landscape of Perak state, which is vast with limestone terrain, we believe using drones and radiation detectors is more efficient and cost-effective in mapping the background radiation distribution, especially in remote areas.

Engineering controls, such as radon-resistant construction techniques, including passive soil depressurisation systems, sealed vapor barriers, and multiple layers of wallpaper, have been reported to be cost-effective in mitigation

strategies [87–90]. Although applying layers of wallpaper looks less convincing, a study showed that this technique can reduce radon levels by up to 98% [90]. Therefore, we would suggest that residents in areas with high background radiation levels apply the wallpaper method as it is cheap and easy to install.

Reducing radiation dose in medical settings should be based on radiation protection principles, including justification-optimisation-dose limitation, time-distance-shielding, and the As Low As Reasonably Achievable (ALARA) principle [91,92]. Some studies also suggested utilising digital radiography and Automated Exposure Control (AEC) to reduce the radiation exposure dose [93]. The need for more stringent regulatory guidelines in industries with high radiation levels is suggested [4,36]. Studies conducted on radiation protection knowledge, adherence, and practice among industrial personnel and medical workers have reported inconsistencies in the use of radioprotective garments and insufficient radiation protection knowledge [5,36]. Recommendations for continuous training were reported as an effort to mitigate the health risks associated with radiation exposure [5,31,94].

Study limitations

This study is acknowledged to have some limitations due to its format as a narrative review, which is unlike a systematic literature review or meta-analysis. Therefore, this study did not employ international standard guidelines such as the PRISMA protocol or a study registration protocol, and did not employ the formal quality appraisal tools for risk of bias assessment. It is subject to biases during the selection process and data interpretation, as it is intended to provide a broader context regarding radiation exposure in Malaysian communities.

Conclusion

Radiation exposure in Malaysian communities primarily arises from natural sources, including radionuclides in soil, rocks, and cosmic rays, with additional contributions from agricultural, industrial, and medical applications. Industrial growth and medical expansion can cause regional public-radiation risks, especially where tin-tailings and rare-earth processing sectors produce naturally occurring radioactive materials (NORM). However, studies that have been conducted were site-specific, thus lacking evidence to propose long-term health effects for the Malaysian population. Therefore, a large-scale study that could encompass the nation would be beneficial.

To support sustainable communities and well-being, we recommend that policymakers ensure effective implementation of the post-2021 licensing framework for the tin-tailing processing industry, prioritise site remediation and waste management, and provide clear transition guidance from unlicensed to licensed operations [37]. This is important, as findings by Rahmat et al. [37] indicate that the annual effective dose among the workers was estimated at 0.7 – 207.6 mSv/year, which exceeds the recommended ICRP annual dose limit, and that excess lifetime cancer risks also exceeded the limit established by the local regulatory body.

We would also like to recommend that the authority bodies or related institutions develop and implement multilingual, culturally tailored radon awareness campaigns, particularly in high-risk areas like Perak. As shown by many studies [76–78] engaging community leaders such as 'dukuns' and village heads as the main partners in risk communication for *Orang Asli* communities could bridge the communication gap, build trust, and assist in conveying messages effectively.

Due to the lack of published studies related to surveys on public radon awareness, future

researchers are encouraged to conduct a nationwide survey and establish long-term cohort studies in high-background areas to better understand low-dose health risks. Barriers to PPE compliance were also identified [5] as an area requiring future investigation to design effective interventions.

From the author's point of view, there remains room for improvement in the regulations, controls, interventions, and awareness in Malaysian settings to promote a sustainable community and the environment, hence enhancing overall Malaysian well-being and quality of life.

Authors contributions

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Statement on conflict of interest

The authors declare no conflict of interest.

Table 1. Summary of the search strategy.

Items	Details
Date of search	1 June 2025 – 20 October 2026
Publication period	2021 – 2026 (approximately 93% of the total articles)
Database	Scopus, Google Scholar, PubMed, and the Directory of Open Access Journals (DOAJ)
Search string	("background radiation" OR "radiation exposure" OR "radiation dose" OR "occupational dose" OR "radiation sources" OR "medical sources" OR "industrial sources" OR "anthropogenic sources") AND ("health risks" OR "health effects") AND ("mitigation strategy") AND ("Malaysia")
Inclusion criteria	(i) Original publications, and review articles; (ii) data from Malaysia or other countries that are relevant to this study direction; (iii) no restriction in terms of language if translation version are available.
Exclusion criteria	(i) Opinion pieces; (ii) editorials; (iii) studies not related to ionising radiation.

Table 2. The TGDR and geological background data in major cities of Peninsular Malaysia.

Region/Cities	TGDR (nGy/h)		Geological Background			
	Range	Mean	G	Q	C	S
Malaysia [14]	-	92	-	-	-	-
West Peninsular Malaysia [13]						
Johor Bahru (Johor)	67 – 281	157 ± 1	Y	Y	-	Y
Melaka	103 – 307	244 ± 2	-	-	-	Y
Seremban (Negeri Sembilan)	135 – 334	254 ± 1	Y	-	-	Y
Lembah Klang (Selangor)	79 – 360	218 ± 2	Y	Y	Y	Y
Kuala Lumpur	105 – 302	210 ± 1	Y	-	Y	Y
Putrajaya	116 – 292	200 ± 3	-	Y	Y	-
Ipoh (Perak)	81 – 371	295 ± 1	Y	-	-	Y
Pulau Pinang	82 – 326	220 ± 3	Y	Y	-	-
Alor Setar (Kedah)	65 – 263	161 ± 2	Y	Y	-	-
Kangar (Perlis)	46 – 270	93 ± 1	-	Y	-	-
East Peninsular Malaysia [13]						
Kota Bharu	89 – 279	181 ± 1	-	Y	-	-
Kuala Terengganu	42 – 217	146 ± 1	-	Y	-	-
Kuantan	55 – 259	178 ± 1	Y	Y	-	-
Overall	42 – 371	202 ± 1				
East Malaysia [7,16]						
Labuan	No data	81.1	-	Y	-	-
Miri, Sarawak	No data	91.4	-	Y	-	-

Notes: G – Granite (igneous rock), Q – Quaternary, C – Carboniferous, S – Silurian-Triassic-Devonian, Y – yes. A city may overlie more than one geological unit; multiple "Y" entries indicate that the listed geological backgrounds all underlie or occur within the city's catchment area.

Table 3. The mean activity concentration of U-238, Th-232 decay series, and K-40, and the geological background data in selected cities in Peninsular Malaysia [13–15].

City / region	Mean activity concentration and range			Geology background
	U-238 (Bq/kg)	Th-232 (Bq/kg)	K-40 (Bq/kg)	
World mean/median	Median: 35 (16 – 110)	Mean: 30 (11 – 64)	Mean: 400 (140 – 850)	Various
Ipoh (Perak)	308.3 ± 15.2 (278.5 – 338.1)	341.3 ± 45.6 (250.6 – 432.0)	506.5 ± 95.7 (318.1 – 695.0)	Granite, Silurian
Selangor & Kuala Lumpur	167.3 ± 21.1 (125.7 – 208.9)	160.0 ± 15.7 (128.9 – 191.1)	537.9 ± 72.3 (395.0 – 680.8)	Carboniferous, Silurian
Seremban (Negeri Sembilan)	161.4 ± 26.1 (108.2 – 214.6)	127.5 ± 14.6 (97.7 – 157.3)	940.3 ± 152.6 (641.3 – 1239.3)	Silurian
Kuala Terengganu (Terengganu)	181.4 ± 16.9 (148.2 – 214.6)	186.0 ± 20.7 (145.3 – 226.7)	301.5 ± 35.5 (232.0 – 371.0)	Quaternary, Carboniferous
Kangar (Perlis)	212.3 ± 32.5 (146.7 – 277.9)	228.8 ± 71.3 (82.5 – 375.1)	390.3 ± 151.7 (65.5 – 715.1)	Quaternary
Alor Setar (Kedah)	154.8 ± 22.1 (110.7 – 198.9)	122.0 ± 11.3 (99.2 – 144.8)	372.8 ± 49.8 (274.6 – 471.0)	Quaternary
Pulau Pinang	140.7 ± 29.9 (79.3 – 202.1)	188.6 ± 18.1 (151.7 – 225.5)	533.3 ± 79.9 (375.9 – 690.7)	Granite, Quaternary
Kota Bharu (Kelantan)	137.3 ± 21.3 (95.3 – 179.3)	124.5 ± 16.4 (91.5 – 157.5)	333.7 ± 36.0 (263.2 – 404.2)	Quaternary
Kuantan (Pahang)	125.1 ± 21.7 (81.2 – 169.0)	149.1 ± 27.9 (92.3 – 205.9)	619.0 ± 103.8 (414.5 – 823.5)	Quaternary, Granite
Melaka	101.2 ± 15.4 (68.7 – 133.7)	152.0 ± 15.1 (120.3 – 183.7)	616.5 ± 170.2 (279.9 – 953.1)	Devonian
Johor Bahru (Johor)	91.1 ± 12.2 (66.9 – 115.3)	139.0 ± 18.3 (102.9 – 175.1)	472.2 ± 111.8 (252.0 – 692.4)	Quaternary
Lahad Datu (Sabah)	42.6 (18.7 – 58.1)	77.7 (34.0 – 110.7)	810.9 (426 – 1225.7)	No data

Note: The "World mean/median" row reports UNSCEAR reference values; for U-238 a median is given, while for Th-232 and K-40 means are given. Geology background classifications follow the scheme in Table 2.

Table 4. The radiological impact assessment associated with water effluents from Malaysian tin-tailing processing plants [34].

Assessment Aspects	Findings	Guideline Value (GV)/Global Mean Value (GMV)	References
Radionuclide concentration in effluent water:			
- Ra-226	2.4 to 34.9 Bq/L Mean = 16.1 ± 7.4 Bq/L	GV: ≤ 5 Bq/L	AELB Act 1984 / AELB 2010
- Ra-228	0.8 to 14.7 Bq/L Mean = 6.8 ± 3.22 Bq/L	GV: ≤ 10 Bq/L	AELB Act 1984 / AELB 2010
	19.5 to 299.4 Bq/L		
- K-40	Mean = 104.1 ± 52.2 Bq/L	Not Stated	ANZECC & ARMCANZ 2000
Annual effective dose due to water ingestion	0.73 to 2.61 mSv/year Mean = 1.43 ± 0.67 mSv/year	GV: ≤ 0.1 mSv/year	WHO 2006 (Guidelines for Drinking-Water Quality)
Gamma radiation absorbed dose rates (measured 1 metre above ground):			
- Indoor absorbed dose rate	13.80 to 54.81 nGy/h Mean = 30.76 ± 14.22 nGy/h	GMV: 55 nGy/h	UNSCEAR 2000
- Outdoor absorbed dose rate	7.19 to 28.38 nGy/h Mean = 15.91 ± 7.35 nGy/h	GMV: 55 nGy/h	UNSCEAR 2000
Total annual effective dose (AED)	0.77-3.04 mSV/year; Mean = 1.71 ± 0.79 mSv/year	GV: ≤ 1 mSv/year	UNSCEAR 2000

Notes: AELB - Atomic Energy Licensing Board; ANZECC - Australian and New Zealand Environment and Conservation Council; ARMCANZ - Agriculture and Resource Management Council of Australia and New Zealand; WHO - World Health Organization; UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation.

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