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Meta analysis

Environmental Radiation Trends in Tamil Nadu (2000–2024): A Narrative Review of Natural and Anthropogenic Impacts

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ABSTRACT:

Environmental radiation represents a critical component of both public health and environmental risk assessment, arising from a combination of natural and anthropogenic sources. Tamil Nadu, located along the south-eastern coast of India, exhibits a uniquely complex radiation environment due to the presence of monazite-rich beach placer deposits, recognized high background radiation areas (HBRAs), and major nuclear installations including the Madras Atomic Power Station (MAPS) and the Kudankulam Nuclear Power Plant (KKNPP). This narrative review synthesizes peer-reviewed literature published between 2000 and 2024 to evaluate spatial and source-specific trends in environmental radiation across the region. Natural sources, particularly terrestrial radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K, dominate radiation exposure, especially along coastal belts such as Manavalakurichi and Kanyakumari. Anthropogenic contributions from nuclear facilities and medical radiation remain comparatively lower but are increasing in relevance. The review identifies significant gaps in long-term monitoring, radon mapping, and population-based dosimetry studies. Strengthening integrated monitoring frameworks and epidemiological research is essential for improved radiation risk assessment in Tamil Nadu.

Keywords:
MAPS, KKNPP, Environemntal Radiation, Risk Assessment, Anthropogenic

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1. Introduction

1.1 Global Significance of Environmental Radiation

Environmental radiation is a ubiquitous phenomenon originating from both natural and anthropogenic sources, contributing continuously to human exposure. Natural radiation sources include cosmic radiation, terrestrial radionuclides, and internal radionuclides incorporated through food and water. Among these, terrestrial radionuclides such as uranium (^{238}U series), thorium (^{232}Th), and potassium (^{40}K) are the principal contributors to external gamma radiation exposure due to their widespread occurrence in geological materials (Mehra, 2009; UNSCEAR, 2008). Radon (^{222}Rn), a decay product of radium, is a major contributor to internal exposure and is recognized as a leading cause of lung cancer after smoking (UNSCEAR, 2006).

Anthropogenic radiation sources have increased significantly due to nuclear energy production, industrial processes, and especially medical applications. Diagnostic imaging techniques such as computed tomography (CT) have become the dominant source of man-made radiation exposure globally (UNSCEAR, 2020). Historical nuclear accidents, including Chernobyl and Fukushima, have further emphasized the need for stringent environmental monitoring and risk communication (Ohtsuru et al., 2019).

1.2 Tamil Nadu as a Case Study

Tamil Nadu represents a significant case study in environmental radiation research due to its unique geological and industrial characteristics. The state's extensive coastline hosts monazite-bearing beach sands enriched with thorium and uranium, resulting in naturally elevated background radiation levels. Coastal regions such as Manavalakurichi, Kalpakkam, and Kanyakumari are recognized as high background radiation areas (HBRAs), where external gamma dose rates exceed global averages (Matsuda et al., 2011; Mohanty et al., 2004).

In addition to natural sources, Tamil Nadu hosts major nuclear installations, including MAPS and KKNPP, necessitating continuous environmental radiation monitoring. Baseline surveys conducted along the eastern coast have established reference levels for assessing potential anthropogenic contributions (Meenakshisundaram et al., 2005). The interaction between geological variability, coastal sediment dynamics, and human activities results in a heterogeneous radiation environment, making Tamil Nadu an important region for studying long-term low-dose radiation exposure.

1.3 Objectives

This review aims to synthesize peer-reviewed evidence on environmental radiation trends in Tamil Nadu between 2000 and 2024. Specific objectives include: (i) characterization of natural radiation sources and spatial variability, (ii) evaluation of anthropogenic contributions including nuclear and medical sources, (iii) assessment of potential health and environmental impacts, and (iv) identification of critical research gaps requiring future investigation.

2. Methodology

This study adopts a narrative review approach to integrate findings from diverse studies examining environmental radiation in Tamil Nadu and comparable regions. Literature was collected from peer-reviewed databases including Scopus, PubMed, and Google Scholar using keywords such as "Tamil Nadu," "environmental radioactivity," "monazite," and "HBRA." Inclusion criteria focused on studies reporting quantitative measurements of radionuclides, radiation dose rates, or health outcomes relevant to ionizing radiation. Studies lacking empirical data or focused solely on non-ionizing radiation were excluded. The collected literature was synthesized thematically based on radiation source (natural vs anthropogenic), geographic distribution, and associated health or environmental impacts.

3. Natural Radiation Trends in Tamil Nadu (2000–2024)

3.1 Terrestrial Radiation and Soil Radioactivity

Natural radioactivity in soils and sediments forms the primary component of environmental radiation in Tamil Nadu. The radionuclides ^{226}Ra, ^{232}Th, and ^{40}K are the dominant contributors to external gamma radiation and are intrinsically linked to the geological composition of the region. Elevated concentrations of these radionuclides are particularly associated with monazite-bearing beach placer deposits along the Tamil Nadu coastline, resulting in dose rates that often exceed global averages (Mehra, 2009; Mohanty et al., 2004).

Empirical studies across Tamil Nadu demonstrate significant spatial heterogeneity in radionuclide distribution. Investigations in inland districts such as Tiruchirappalli have reported moderate activity concentrations consistent with typical crustal values, whereas coastal regions exhibit substantially elevated levels due to thorium-rich mineralization (Sankaran Pillai et al., 2016). Baseline surveys along the east coast have further confirmed that natural radioactivity varies systematically with proximity to coastal sediment deposits and underlying geological formations (Meenakshisundaram et al., 2005). These findings underscore the importance of region-specific assessments rather than reliance on generalized national averages. The sources and characteristics of natural radiation in Tamil Nadu are summarized in Table 1.

Table 1. Major Natural Radiation Sources and Their Characteristics in Tamil Nadu

Radiation Source	Key Radionuclides	Origin	Spatial Distribution	Relative Contribution	Key References
Terrestrial (Soil/Sediment)	^{226}Ra, ^{232}Th, ^{40}K	Geological formations, monazite sands	High in coastal belts (Kanyakumari, Kalpakkam)	Dominant	Mehra (2009); Mohanty et al. (2004)
High Background Radiation Areas (HBRAs)	^{232}Th-rich monazite	Beach placer deposits	Southern coastal Tamil Nadu	Very High (localized)	Matsuda et al. (2011); Mohanty et al. (2004)
Radon Gas	^{222}Rn	Decay of ^{226}Ra in soil	Coastal + granitic inland regions	Moderate (internal exposure)	Mahur et al. (2009); UNSCEAR (2006)
Cosmic Radiation	Secondary cosmic particles	Atmospheric interactions	Uniform (slightly higher in elevated areas)	Low	UNSCEAR (2008)

3.2 High Background Radiation Areas (HBRAs)

High background radiation areas (HBRAs) along the Tamil Nadu coast are among the most extensively studied natural radiation environments in India. These regions, particularly Manavalakurichi, Kalpakkam, and the Kanyakumari coastal belt, are characterized by elevated external gamma dose rates resulting from high concentrations of thorium-bearing monazite sands (Matsuda et al., 2011; Mohanty et al., 2004).

Detailed field measurements using thermoluminescent dosimeters and gamma spectrometry have reported significantly elevated dose rates in localized hotspots within these regions. For example, Matsuda et al. (2011) documented external dose rates that are several times higher than global averages, confirming the classification of these areas as HBRAs. The distribution of radiation levels within these zones is highly heterogeneous, reflecting variations in sediment composition, coastal dynamics, and mineral concentration.

These HBRAs are of particular scientific interest because they provide natural laboratories for studying long-term exposure to low-dose radiation. Comparisons with other global HBRAs, such as those in Brazil and China, indicate that Tamil Nadu's coastal regions fall within the upper range of natural radiation environments worldwide (Møller & Mousseau, 2013; Mohanty et al., 2004).

3.3 Radon Emissions and Distribution

Radon (^{222}Rn) is a naturally occurring radioactive gas generated from the decay of ^{226}Ra in soils and rocks and constitutes a major pathway for internal radiation exposure. Its concentration in the environment is influenced by geological composition, soil permeability, and meteorological conditions. In Tamil Nadu, regions enriched with uranium and thorium-bearing minerals, particularly coastal HBRAs and granitic terrains, are expected to exhibit elevated radon exhalation rates.

Although systematic radon mapping in Tamil Nadu remains limited, studies from analogous high background radiation regions in India provide valuable insight. Investigations in monazite-rich coastal areas have demonstrated that radon exhalation rates can be significantly elevated in such environments, potentially impacting indoor air quality in nearby settlements (Mahur et al., 2009). Given the geological similarities, comparable conditions are likely in Tamil Nadu's coastal zones, although direct measurements are needed to confirm this.

The absence of comprehensive radon surveys across Tamil Nadu represents a critical gap in the current understanding of radiation exposure pathways, particularly considering the well-established link between radon inhalation and lung cancer risk (UNSCEAR, 2006).

3.4 Cosmic Radiation

Cosmic radiation contributes a relatively uniform component to natural background radiation and originates from interactions of high-energy particles with the Earth's atmosphere. Its intensity varies with altitude, latitude, and solar activity. In Tamil Nadu, which is largely at low elevation and near equatorial latitude, cosmic radiation contributes a smaller fraction of total background dose compared to terrestrial sources, particularly in coastal HBRAs where gamma radiation from monazite dominates.

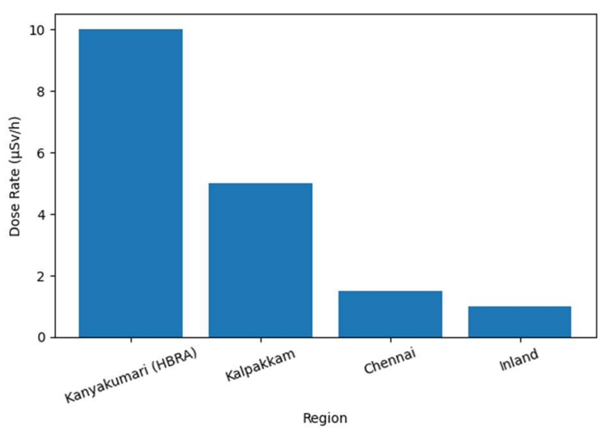
While no region-specific measurements of cosmic radiation trends in Tamil Nadu were identified, global models provide reliable estimates of its contribution to population dose (UNSCEAR, 2008). Populations residing in elevated terrains such as the Nilgiris may experience slightly higher exposure, although this remains minor compared to terrestrial radiation in HBRA zones.

3.5 Regional Variability and Environmental Controls

The distribution of natural radiation across Tamil Nadu is governed by geological structure, mineral composition, and sediment transport processes. Coastal regions, particularly in the southern districts, exhibit the highest radiation levels due to the accumulation of monazite-rich sands derived from the weathering of the Western Ghats (Mohanty et al., 2004). In contrast, inland and northeastern regions generally display lower activity concentrations closer to global background levels.

Environmental factors such as seasonal sediment redistribution, coastal erosion, and hydrodynamic processes influence the spatial variability of radionuclide concentrations. Although these processes can lead to localized fluctuations in radiation levels, long-term trends are primarily controlled by the stability of geological formations (Meenakshisundaram et al., 2005). The strong geological linkage between Tamil Nadu and Kerala coastal HBRAs further supports the role of regional mineralogical continuity in shaping radiation patterns. Representative regional variations in background radiation levels across Tamil Nadu are illustrated in Fig. 1 (Matsuda et al., 2011; Mohanty et al., 2004).

Figure 1. Representative background radiation dose rates in selected regions of Tamil Nadu



4. Anthropogenic Impacts on Radiation Levels

4.1 Nuclear Power Plants

Tamil Nadu hosts two major nuclear power facilities; the Madras Atomic Power Station (MAPS) at Kalpakkam and the Kudankulam Nuclear Power Plant (KKNPP) which necessitate continuous environmental radiation surveillance. Baseline studies conducted prior to and during the operation of these facilities indicate that natural background radiation dominates the regional radiation field, particularly along the coastal belt (Meenakshisundaram et al., 2005). Establishing such baselines is essential for distinguishing between natural and anthropogenic contributions in complex radiation environments.

Environmental monitoring around nuclear installations typically involves the measurement of radionuclide concentrations in soil, water, and biota, along with external dose rate assessments. Available evidence suggests that under normal operating conditions, nuclear power plants contribute minimally to ambient radiation levels when compared to natural sources (UNSCEAR, 2020). However, continuous monitoring remains critical to detect any deviations associated with operational changes or accidental releases.

International studies reinforce the importance of long-term surveillance. For instance, Ren et al. (2023) demonstrated the value of pre- and post-operational monitoring in assessing environmental radiation trends around nuclear facilities. Similarly, large-scale analyses have indicated that while occupational exposures in nuclear facilities may carry certain risks, environmental exposures for nearby populations remain generally low under regulated conditions (Lin et al., 2024). These findings are directly relevant to Tamil Nadu, where expanding nuclear infrastructure underscores the need for sustained monitoring and transparent reporting.

4.2 Industrial and Mining Activities

Industrial activities, particularly the extraction and processing of monazite-bearing heavy mineral sands, represent a localized anthropogenic source of radiation in Tamil Nadu. These activities are primarily associated with the recovery of rare earth elements and thorium, which are naturally present in elevated concentrations within coastal sediments. The mechanical processing and separation of these minerals can lead to the concentration of naturally occurring radioactive materials (NORM), potentially increasing radiation exposure in occupational settings and surrounding environments.

Studies from similar coastal mining regions in India have demonstrated that handling and processing of monazite sands can elevate radionuclide concentrations in waste streams and tailings, thereby requiring careful regulation and environmental monitoring (Mohanty et al., 2004). Although region-specific quantitative assessments in Tamil Nadu remain limited, the presence of mineral separation facilities along the coast highlights the need for systematic evaluation of industrial radiation exposure pathways.

The implementation of monitoring networks and adherence to radiation safety standards are essential to minimize risks associated with NORM industries. International frameworks emphasize the importance of integrating industrial radiation monitoring within broader environmental surveillance systems to ensure comprehensive risk management (UNSCEAR, 2008).

4.3 Medical Radiation Exposure

Medical radiation has emerged as the most significant anthropogenic source of radiation exposure globally and is increasingly relevant in Tamil Nadu due to the expansion of diagnostic imaging and radiotherapy services. Procedures such as computed tomography (CT), nuclear medicine imaging, and interventional radiology contribute substantially to patient dose, often exceeding exposures from other man-made sources (UNSCEAR, 2020).

A regional assessment conducted in Tamil Nadu highlighted a marked increase in the number of CT installations and emphasized the importance of establishing diagnostic reference levels (DRLs) to optimize patient doses (Livingstone & Dinakaran, 2011). While the clinical benefits of medical imaging are well established, inappropriate or excessive use can lead to unnecessary radiation exposure, necessitating strict adherence to radiation protection principles such as justification and optimization.

Globally, the rise in medical radiation exposure has prompted increased regulatory attention, with efforts focused on dose tracking, standardization, and technological improvements to reduce exposure without compromising diagnostic quality (UNSCEAR, 2020). In Tamil Nadu, strengthening regulatory oversight and promoting awareness among healthcare providers are essential for ensuring safe and effective use of ionizing radiation in medicine.

4.4 Radioactive Waste Management

The safe management of radioactive waste generated from nuclear power plants, research facilities, and medical institutions is a critical component of radiation protection in Tamil Nadu. Facilities such as the Indira Gandhi Centre for Atomic Research (IGCAR) at Kalpakkam are involved in advanced nuclear research and fuel cycle activities, necessitating robust waste handling and disposal systems.

International best practices emphasize the importance of containment, monitoring, and long-term storage of radioactive waste to prevent environmental contamination. Monitoring programs typically include periodic assessment of soil, groundwater, and marine environments surrounding nuclear facilities to ensure compliance with safety standards (UNSCEAR, 2008).

In addition to engineered solutions, emerging research on radiation-resistant microorganisms has highlighted potential applications in bioremediation of radioactive waste environments (Pal et al., 2024). Such approaches, while still under investigation, may complement traditional waste management strategies in the future.

4.5 Regulatory Framework and Monitoring

Radiation safety in India is governed by the Atomic Energy Regulatory Board (AERB), which establishes guidelines for environmental monitoring, occupational exposure, and waste management. These regulations are aligned with international standards set by organizations such as the International Atomic Energy Agency (IAEA) and UNSCEAR.

In Tamil Nadu, regulatory oversight encompasses nuclear facilities, industrial operations involving NORM, and medical radiation practices. The establishment of diagnostic reference levels for CT imaging represents a key step in standardizing radiation safety in healthcare (Livingstone & Dinakaran, 2011). Similarly, environmental monitoring programs around nuclear installations are designed to ensure that radiation levels remain within permissible limits.

Effective regulatory implementation requires not only technical monitoring but also transparency, public communication, and periodic review of safety protocols. International experience has demonstrated that proactive risk communication and data accessibility play a crucial role in maintaining public trust in nuclear and radiation-related activities.

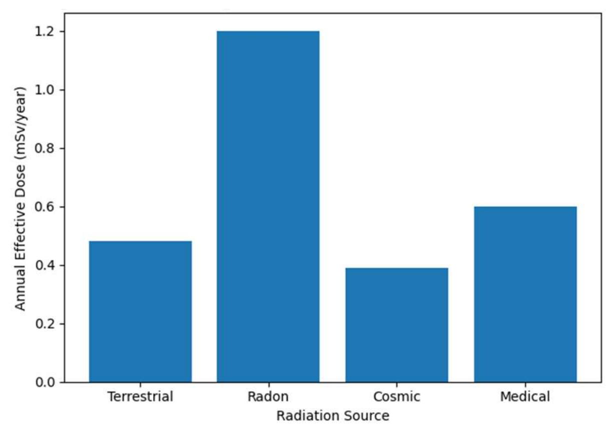
5. Comparative Assessment: Natural vs. Anthropogenic Radiation Sources

5.1 Relative Contributions to Population Dose

The comparative evaluation of radiation sources in Tamil Nadu clearly indicates that natural radiation dominates overall population exposure. Terrestrial gamma radiation arising from monazite-rich coastal sands constitutes the primary contributor, particularly in high background radiation areas (HBRAs) such as Manavalakurichi, Kalpakkam, and Kanyakumari (Matsuda et al., 2011; Mohanty et al., 2004). Measured external dose rates in these regions significantly exceed global averages, reinforcing the predominance of natural sources in shaping the regional radiation profile.

Global assessments consistently support this observation. According to UNSCEAR (2020), natural radiation accounts for the majority of human exposure worldwide, with terrestrial and radon contributions forming the largest components. In the context of Tamil Nadu, this dominance is further amplified due to the presence of thorium-rich coastal deposits. Baseline studies along the Tamil Nadu coast have demonstrated that natural variability in radiation levels is substantially greater than any incremental contributions from nuclear power plant operations under normal conditions (Meenakshisundaram et al., 2005). The relative contribution of major radiation sources based on global UNSCEAR estimates is shown on Figure 2 (UNSCEAR, 2008, 2020).

Figure 2. Global average radiation does make contributions by source (UNSCEAR-based estimates)



Anthropogenic sources, while comparatively smaller, are not negligible. Among these, medical radiation has emerged as the most significant contributor due to the rapid expansion of diagnostic imaging technologies. Regional studies have documented increasing utilization of CT scanners and associated radiation doses, highlighting the growing importance of medical exposure in the overall radiation budget (Livingstone & Dinakaran, 2011). In contrast, contributions from nuclear power plants remain minimal under standard operating conditions due to strict regulatory controls (UNSCEAR, 2020). A comparative summary of natural and anthropogenic radiation sources is presented in Table 2.

Table 2. Comparison of Natural and Anthropogenic Radiation Sources in Tamil Nadu

Category	Source Type	Examples	Exposure Pathway	Relative Contribution	Key References
Natural	Terrestrial Radiation	Monazite sands (^{232}Th)	External gamma exposure	Very High	Matsuda et al. (2011); Mohanty et al. (2004)
Natural	Radon	Soil gas (^{222}Rn)	Inhalation	Moderate	UNSCEAR (2006); Mahur et al. (2009)
Natural	Cosmic Radiation	Atmospheric particles	External exposure	Low	UNSCEAR (2008)
Anthropogenic	Nuclear Power Plants	MAPS, KKNPP	Environmental exposure	Low (regulated)	UNSCEAR (2020); Ren et al. (2023)
Anthropogenic	Medical Radiation	CT, radiotherapy	Patient exposure	Increasing (significant)	Livingstone & Dinakaran (2011); UNSCEAR (2020)
Anthropogenic	Industrial (NORM)	Monazite processing	Occupational/environmental	Localized	Mohanty et al. (2004)

5.2 Interaction Between Natural and Anthropogenic Sources

The interaction between natural and anthropogenic radiation sources in Tamil Nadu presents a complex analytical challenge, particularly in coastal HBRAs where natural background levels are inherently elevated. In such environments, distinguishing anthropogenic contributions from the dominant natural signal requires sensitive instrumentation and robust baseline datasets (Meenakshisundaram et al., 2005).

Gamma spectrometric techniques enable the identification of radionuclide signatures, allowing differentiation between naturally occurring radionuclides (e.g., ^232Th, ^238U series) and anthropogenic radionuclides (e.g., ^137Cs). However, in regions with high natural radioactivity, the detection of low-level anthropogenic signals becomes more difficult due to reduced signal-to-noise ratios. This underscores the importance of long-term baseline monitoring and advanced analytical methods.

Human activities can also influence the distribution of naturally occurring radioactive materials (NORM). Industrial processing of monazite sands, for example, may concentrate radionuclides in localized areas, thereby enhancing exposure risks beyond natural background levels (Mohanty et al., 2004). Conversely, effective regulatory controls and waste management practices can mitigate such impacts. The integration of natural and anthropogenic radiation assessments is therefore essential for accurate environmental risk evaluation.

5.3 Temporal Trends

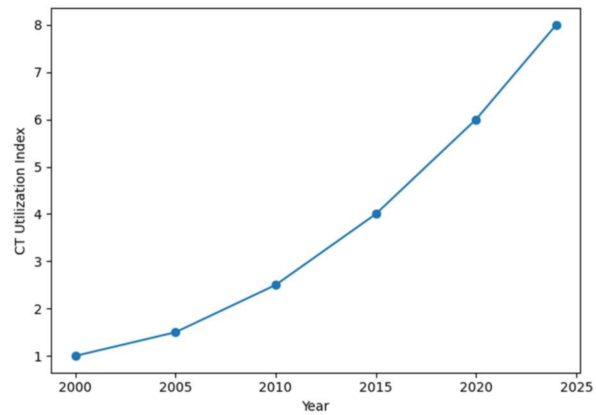
The evaluation of temporal trends in radiation levels across Tamil Nadu is constrained by the limited availability of long-term monitoring data. Natural radiation levels in coastal HBRAs are generally considered stable over geological timescales, as they are governed primarily by the distribution of monazite deposits and underlying geological formations (Matsuda et al., 2011). However, short-term fluctuations may occur due to seasonal variations in sediment transport, coastal erosion, and meteorological conditions.

In contrast, anthropogenic radiation trends are more dynamic and influenced by technological and infrastructural developments. The commissioning of the Kudankulam Nuclear Power Plant and the expansion of nuclear research activities represent notable changes in the regional radiation landscape. Nevertheless, available evidence suggests that environmental radiation levels around nuclear facilities have remained within regulatory limits under normal operating conditions (UNSCEAR, 2020; Ren et al., 2023).

Medical radiation exposure exhibits a clear upward trend, driven by increased access to advanced diagnostic and therapeutic technologies. This trend underscores the need for continuous monitoring and optimization of medical radiation practices to ensure patient safety (Livingstone & Dinakaran, 2011).

Overall, the absence of systematic, long-term monitoring networks in Tamil Nadu represents a significant limitation in understanding temporal variations in radiation exposure. Establishing such systems is essential for detecting trends, identifying emerging risks, and informing policy decisions. The increasing contribution of medical radiation exposure, driven by expanding diagnostic imaging, is illustrated in Figure 3 (Livingstone & Dinakaran, 2011; UNSCEAR, 2020).

Figure 3. Growth trend in medical imaging utilization as a proxy for radiation exposure (2000–2024)



6. Health and Environmental Impacts

6.1 Health Risks from Natural Radiation Exposure

Populations residing in high background radiation areas (HBRAs) of Tamil Nadu are chronically exposed to elevated levels of natural radiation, primarily from terrestrial gamma radiation and, to a lesser extent, radon inhalation. Coastal regions such as Manavalakurichi and Kanyakumari exhibit significantly higher external dose rates compared to global averages due to thorium-rich monazite deposits (Matsuda et al., 2011). Individual dosimetry studies conducted in these regions have provided important insights into actual exposure levels experienced by residents.

The health effects of long-term low-dose radiation exposure remain a subject of ongoing scientific investigation. The linear no-threshold (LNT) model, widely adopted in radiation protection, assumes that even low doses of ionizing radiation carry a proportional risk of cancer (ICRP, 2007; UNSCEAR, 2006). However, epidemiological evidence from HBRAs has not consistently demonstrated increased cancer incidence proportional to elevated background radiation levels, suggesting the need for region-specific long-term studies (Møller & Mousseau, 2013).

Despite these uncertainties, the potential contribution of radon exposure to lung cancer risk is well established globally. The absence of comprehensive radon mapping in Tamil Nadu limits accurate assessment of internal exposure pathways, highlighting a significant research gap (UNSCEAR, 2006).

6.2 Health Risks from Anthropogenic Radiation

Anthropogenic radiation exposure in Tamil Nadu arises primarily from medical applications and, to a lesser extent, from nuclear facilities. Among these, medical radiation represents the most significant contributor to population dose. The rapid expansion of computed tomography (CT) and other imaging modalities has led to increased radiation exposure among patients, necessitating careful dose optimization (Livingstone & Dinakaran, 2011; UNSCEAR, 2020).

Although nuclear power plants contribute minimally to environmental radiation under normal operating conditions, occupational exposure among workers and long-term low-level exposure in surrounding populations remain areas of scientific interest. Large-scale studies have reported associations between occupational exposure in nuclear facilities and certain cancer risks, although environmental exposure levels for nearby residents generally remain low (Lin et al., 2024).

Exposure to radionuclides through environmental pathways, including water and food, is another potential concern. UNSCEAR (2020) emphasizes that ingestion pathways can contribute to cumulative dose, particularly in regions with elevated natural or industrial radionuclide concentrations. Continuous monitoring and adherence to safety standards are therefore essential to minimize risks.

6.3 Vulnerable Populations

Certain population groups in Tamil Nadu are more susceptible to radiation exposure due to occupational, geographic, or physiological factors. Coastal communities residing in HBRAs experience higher external gamma exposure due to prolonged contact with monazite-rich sands (Matsuda et al., 2011). Workers in nuclear facilities, research centers, and mineral processing industries may receive additional occupational exposure, although such exposures are typically regulated and monitored.

Medical patients undergoing repeated diagnostic or therapeutic procedures represent another vulnerable group, particularly when exposure is cumulative. Children and pregnant women are generally considered more radiosensitive due to higher rates of cell division and developmental sensitivity, necessitating stricter dose control in medical settings (ICRP, 2007; Schmidt et al., 2021).

Understanding exposure patterns among these groups is essential for targeted risk assessment and the development of protective strategies.

6.4 Environmental Consequences

Elevated radiation levels in Tamil Nadu have implications not only for human health but also for ecological systems. In coastal HBRAs, organisms are exposed to chronic low-dose radiation, which may influence biological processes at cellular and population levels. Studies have identified radiation-resistant microbial communities in high radiation environments, suggesting adaptive mechanisms to prolonged exposure (Pal et al., 2024).

Environmental monitoring programs around nuclear facilities are designed to detect potential contamination in soil, water, and marine ecosystems. Under normal operating conditions, radionuclide releases are tightly controlled, and environmental concentrations remain within permissible limits (UNSCEAR, 2008). However, the potential for long-term accumulation and ecological transfer of radionuclides necessitates continued surveillance.

Understanding ecological responses to chronic radiation exposure is essential for comprehensive environmental risk assessment, particularly in regions where natural and anthropogenic sources coexist.

6.5 Risk Perception and Social Implications

Beyond physical health effects, radiation exposure is associated with psychological and social impacts, particularly in regions near nuclear facilities. Studies following major nuclear incidents have demonstrated that perceived radiation risk can significantly influence mental health, even in the absence of high exposure levels (Fukasawa et al., 2017; Murakami et al., 2017).

Although no major radiological accidents have been reported in Tamil Nadu, public perception of nuclear risk remains an important factor in community well-being. Effective risk communication, transparency in environmental monitoring, and community engagement are essential for building public trust and mitigating anxiety associated with radiation exposure.

Lessons from international experiences highlight the importance of integrating social and psychological dimensions into radiation risk management frameworks. The health and environmental impacts associated with radiation exposure are summarized in Table 3.

Table 3. Health and Environmental Impacts of Radiation Exposure in Tamil Nadu.

Impact Category	Exposure Type	Affected Population	Key Effects	Evidence Strength	Key References
Cancer Risk	Chronic low-dose natural radiation	Coastal HBRA residents	Uncertain increase; debated	Moderate	Møller & Mousseau (2013); UNSCEAR (2006)
Radon-related Lung Cancer	Internal exposure (^{222}Rn)	General population	Increased lung cancer risk	Strong	UNSCEAR (2006); Mahur et al. (2009)
Medical Exposure	CT, radiology	Patients	Increased cumulative dose	Strong	Livingstone & Dinakaran (2011); UNSCEAR (2020)
Occupational Exposure	Nuclear/industrial workers	Workers	Increased cancer risk (selected cases)	Moderate	Lin et al. (2024)
Psychological Impact	Perceived radiation risk	Communities near nuclear plants	Anxiety, stress	Strong	Fukasawa et al. (2017); Murakami et al. (2017)
Ecological Effects	Chronic environmental exposure	Microbial/ecosystems	Adaptive resistance mechanisms	Emerging	Pal et al. (2024)

7. Challenges and Future Directions

7.1 Gaps in Current Knowledge

Despite substantial research on environmental radiation in Tamil Nadu, several critical gaps remain. Most available studies are cross-sectional and localized, with limited long-term monitoring data available to assess temporal trends in radiation exposure. Baseline studies conducted along the Tamil Nadu coast have provided valuable reference points; however, continuous monitoring systems capable of detecting changes over time are largely absent (Meenakshisundaram et al., 2005).

Radon exposure represents another major gap. Although radon is globally recognized as a significant contributor to natural radiation dose, systematic radon surveys across Tamil Nadu—particularly in both coastal HBRAs and inland granitic regions—are lacking. This limits accurate assessment of internal exposure pathways and associated health risks (UNSCEAR, 2006; Mahur et al., 2009).

Furthermore, individual dosimetry data are scarce and largely restricted to specific coastal regions (Matsuda et al., 2011). There is a lack of comprehensive exposure data for key population groups, including nuclear workers, medical personnel, and residents in industrial zones. Additionally, epidemiological studies examining long-term health outcomes in Tamil Nadu populations exposed to elevated natural radiation are notably absent, in contrast to similar studies conducted in Kerala HBRAs.

7.2 Scientific and Operational Challenges (Rewritten)

The study of environmental radiation in Tamil Nadu is complicated by the coexistence of elevated natural background radiation and localized anthropogenic sources. In coastal HBRAs, distinguishing anthropogenic radionuclide contributions from naturally occurring radionuclides is technically challenging due to high baseline levels. This requires the use of sensitive analytical techniques and well-established baseline datasets (Meenakshisundaram et al., 2005).

Another challenge lies in the limited availability of high-resolution radiation monitoring infrastructure. Accurate detection of low-level radionuclides, particularly in environments with high natural background radiation, necessitates advanced instrumentation that is not uniformly accessible across research institutions.

Data accessibility and transparency also pose challenges. Environmental monitoring data from nuclear facilities are often not readily available for independent analysis, limiting opportunities for external validation. Additionally, the interdisciplinary nature of radiation research—spanning physics, environmental science, epidemiology, and public health—requires coordinated efforts that are not always effectively implemented.

8. Recommendations for Future Research and Policy

Addressing the identified gaps requires a coordinated and multidisciplinary approach. First, the establishment of a long-term environmental radiation monitoring network across Tamil Nadu is essential. Such a network should include coastal HBRAs, nuclear facility zones, and inland regions to capture spatial and temporal variability in radiation levels.

Second, comprehensive radon mapping programs should be implemented, particularly in regions with geological characteristics conducive to elevated radon emissions. This would enable better assessment of internal exposure risks and inform mitigation strategies.

Third, expanded individual dosimetry programs are needed to quantify actual exposure levels among different population groups, including residents of HBRAs, nuclear industry workers, and medical professionals. These data would provide a stronger foundation for epidemiological studies.

Fourth, large-scale epidemiological investigations should be conducted to evaluate long-term health outcomes associated with chronic low-dose radiation exposure in

Tamil Nadu. Such studies would be critical for validating risk models and informing radiation protection guidelines. Finally, regulatory frameworks should be strengthened through enhanced transparency, public communication, and adoption of advanced monitoring technologies, including real-time sensors and geospatial analysis tools. Lessons from international experiences highlight the importance of integrating scientific evidence with effective policy implementation (UNSCEAR, 2020).

9. Conclusion

Tamil Nadu presents a complex and heterogeneous radiation environment shaped predominantly by natural sources, particularly monazite-rich coastal deposits that give rise to high background radiation areas. These natural sources constitute the primary contributor to population radiation exposure, significantly exceeding anthropogenic contributions under normal conditions.

Anthropogenic radiation sources, including nuclear power generation and medical applications, remain important but comparatively smaller contributors. Among these, medical radiation is the most rapidly increasing component, reflecting broader global trends in diagnostic and therapeutic practices.

Despite extensive research, significant gaps persist in long-term monitoring, radon assessment, individual dosimetry, and epidemiological evaluation. Addressing these gaps is essential for improving radiation risk assessment and ensuring effective public health protection.

Tamil Nadu's unique combination of geological features and nuclear infrastructure offers a valuable opportunity for advancing the scientific understanding of chronic low-dose radiation exposure. Realizing this potential requires sustained investment in monitoring systems, interdisciplinary research, and evidence-based policy development.

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