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Assessment of Radiological Risk Hazard Indices for Diverse Environmental and Biological Samples: A Comprehensive Review

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REVIEW

Assessment of Radiological Risk Hazard Indices for Diverse Environmental and Biological Samples: A Comprehensive Review

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Abstract

Radiological risk assessment is pivotal for safeguarding human health and ecosystems amid expanding radiation applications in technology and medicine. This review systematically evaluates the efficacy of hazard indices like the Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR) across environmental (soil, water) and biological (tissues, crops) samples, addressing critical gaps in comparative methodologies, a PRISMA-guided systematic. Literature review was conducted across Scopus, PubMed, and Web of Science, analyzing more than 100 peer-reviewed studies (2010—2024) that met the inclusion criteria: English-language publications, multi-index comparisons, and empirical validations. Exclusion criteria removed non-peer-reviewed works and studies focusing on a single index. Key findings reveal stark disparities in index performance: AEDE excels in environmental contexts by integrating chronic exposure pathways (e.g., Cesium-137 in soil). ELCR's tissue-specific risk coefficients better capture biological carcinogenesis (e.g., Strontium-90 in bone marrow). Also, oversimplified assumptions like neglecting soil biogeochemistry or interspecies variability compromise accuracy, particularly in regions where high natural background radiation (e.g., Ramsar, Iran). The review underscores the urgency of standardizing indices to reflect radiochemical interactions and bioavailability, supported by emerging tools like AI-driven predictive models, which enhance real-time risk mapping and adaptive monitoring. Future frameworks must harmonize interdisciplinary insights (physics, chemistry, policy) to address novel challenges, including space radiation and non-human biota protection and this synthesis provides actionable guidance for researchers and policymakers to refine risk protocols, ensuring they align with evolving technological and environmental realities.

Keywords: Radiological risk indices, Environmental samples, Biological samples, Standardization, Comprehensive review

1. Introduction

Radiation, a cornerstone of modern scientific advancement, plays a dual role as both a catalyst for innovation and a potential hazard to global health and ecosystems. Its applications span critical domains from nuclear energy production and industrial radiography to cutting-edge medical therapies like targeted radiotherapy and positron emission tomography (PET) imaging.

Yet the proliferation of radiological technologies has intensified concerns over accidental exposures, environmental contamination, and long-term health consequences, and the 2011 Fukushima Daiichi nuclear disaster remains a stark reminder of these risks, where the release of Cesium-137 and iodine-131 contaminated over 1000 square kilometers of farmland, rendering soil unfit for agriculture and displacing thousands of residents [1]. Similarly, legacy sites like Chernobyl continue to exhibit elevated radionuclide concentrations in groundwater, underscoring the persistence of radiation hazards decades after initial exposure [2]. These incidents underscore the urgent need for precise,

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adaptable tools to assess radiological risks across diverse contexts, a challenge compounded by the variability of environmental and biological matrices.

Current methodologies for quantifying radiation hazards, like the Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR), rely on standardized models to estimate human exposure. The AEDE, for instance, calculates cumulative dose by integrating factors like ingestion rates and radionuclide half-lives [3], while the ELCR extrapolates lifetime cancer probabilities using epidemiological data [4].

Also, their efficacy diminishes when applied beyond their original scope, for example, AEDE models optimized for soil systems often neglect bioavailability differences in biological samples, like the preferential accumulation of Strontium-90 in bone tissue over soft organs a phenomenon rigorously documented by conversely ELCR frameworks tailored to human physiology fail to account for ecological dynamics, like radionuclide transfer through food chains, as demonstrated in marine ecosystems post-Fukushima [5,6]. Such limitations reveal a critical disconnect in risk assessment paradigms, where discipline-specific indices lack interoperability.

Despite a growing body of literature on radiological hazards, existing reviews remain siloed, prioritizing either environmental or biological matrices without reconciling their interplay, for instance Ref. [7] conducted a comprehensive analysis of airborne radionuclide dispersion but omitted implications for human inhalation pathways, and in contrast, health-focused studies. Like [8] quantified tumorigenic risks from medical radiation without addressing environmental reservoirs and this fragmentation obscures holistic insights, particularly in interdisciplinary scenarios like agricultural systems, where soil-to-crop transfer factors modulate human exposure, Dowell (2024) revealed that Cesium-137 uptake in rice varied by soil pH and organic content, altering risk predictions by up to 40 %—a nuance absent in generic AEDE models. Similarly [9], identified discrepancies in ELCR calculations for hematopoietic tissues, attributing them to isotopic speciation and metabolic rates. These findings highlight the inadequacy of one-size-fits-all indices and the necessity for context-driven adaptations.

This review addresses these gaps by systematically evaluating the strengths and limitations of prevailing radiological hazard indices across environmental (e.g., soil, water, air) and biological (e.g., flora, fauna, human tissues) samples and through a synthesis of 100 peer-reviewed studies published between 2010 and 2024, we analyze how variables like matrix composition, exposure duration. Interspecies variability influences index performance, for instance, terrestrial ecosystems dominated by clay soils exhibit slower radionuclide migration, necessitating modified AEDE coefficients [10,11]. In contrast, marine environments require hydrodynamic models to predict Cesium-137 dispersion, and in biological contexts, interspecies differences in radionuclide uptake, like the bioaccumulation of polonium-210 in mollusks [12], challenge uniform ELCR thresholds, and by mapping these complexities, this review provides a scaffold for refining risk assessment protocols, ensuring they reflect real-world heterogeneity.

The implications of this work extend beyond academic inquiry; policymakers grappling with radiation safety standards, like the IAEA's revised Basic Safety Standards (2022) or the WHO's emergency exposure guidelines (2023), require evidence-based criteria to harmonize regulations across sectors. Post-mining rehabilitation in uranium-rich regions like Niger demands distinct indices for soil remediation versus groundwater protection, a duality explored by Mihelcic et al. [12], similarly, clinicians and radiobiologists must balance therapeutic benefits against stochastic risks in novel treatments like alpha-particle immunotherapy.

Traditional ELCR models underestimate dose-response nonlinearities [13], as emerging technologies from deep-space exploration to fusion energy introduce unprecedented radiation challenges, this review's findings will inform next-generation risk frameworks, ensuring they are as dynamic as the threats they aim to mitigate.

The findings of this evaluation can contribute to protecting the environment and human health in several ways. Overall, the evaluation's findings can contribute to a better understanding of radiological risks, enabling proactive measures to protect the environment and human health, and identifying radiation hotspots. The study can pinpoint areas with high radiation levels by assessing radiological risk hazard indices, enabling targeted remediation efforts to minimize exposure.

Informing environmental policies: The evaluation's results can educate policymakers about the radiological risks associated with diverse biological and ecological samples, guiding the development of effective regulations and guidelines.

Protecting human health, understanding radiological risks can help prevent radiation-induced health issues, such as cancer, genetic mutations, and other diseases, by implementing measures to reduce exposure.

Guiding waste management: The study's findings can inform strategies for managing radioactive waste, reducing the risk of environmental contamination and human exposure. Supporting conservation efforts by identifying areas with high radiological risks, conservation efforts can be focused on protecting vulnerable ecosystems and species. These challenges can impact the accuracy and reliability of radiological risk assessments, emphasizing the need for careful methodology and quality control.

2. Methodology

This systematic review adhered to rigorous protocols to ensure methodological transparency and reproducibility, guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [14] and shown in the Fig. 1, a comprehensive search strategy was executed across three major databases—Scopus, PubMed, and Web of Science—to capture peer-reviewed literature published between January 2010 and May 2024. Key search terms included combinations of *“radiation hazard indices,” “radiological risk assessment,” “environmental samples”* (e.g., soil, water, air), and *“biological samples”* (e.g., human tissues, flora, fauna), supplemented by Boolean operators to refine results, for instance, the query *(“AEDE” OR “ELCR”) AND (“soil contamination” OR “bioaccumulation”)* yielded studies linking specific indices to sample matrices, to minimize selection bias, inclusion criteria prioritized empirical studies, meta-analyses, and reviews published in English that evaluated multiple hazard indices across diverse sample types.

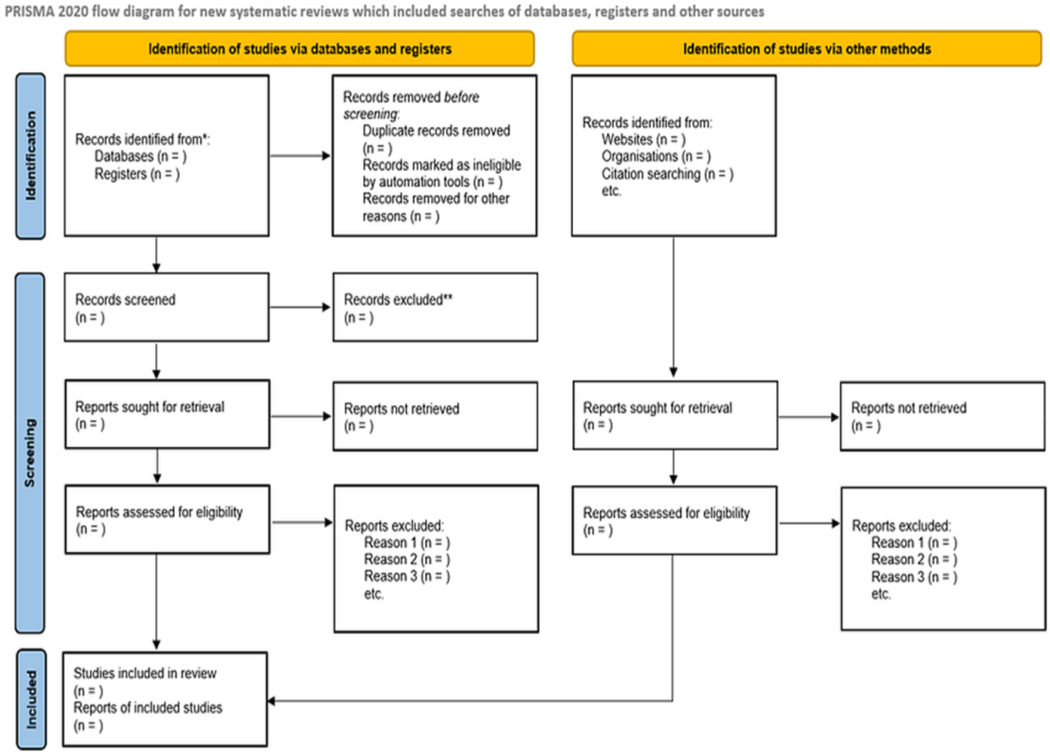
Several environmental committees and agencies put specific parameters to clarify the radiation hazard indices mathematically, limited their values, and if they exceed this limited value, the indicated hazard will be at risk (ICRP, 1998) like Radium Equivalent Activity (Ra_{eq}),

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K \tag{1}$$

Where: C_{Ra}, C_{Th}, C_K are the radioactivity concentration in Bq/kg of ^{238}U, ^{232}Th and ^{40}K.

2.1. Annual effective dose equivalent (AEDE)

The annual effective dose equivalent received outdoors by a member is calculated from the



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).
**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Fig. 1. Guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [14].

absorbed dose rate by applying the dose conversion factor of 0.7 Sv/Gy.

AEDE is determined using the following equations:

$$AEDE\ (Outdoor)\ (mSv/y) = Absorbed\ dose\ (nGy/h) \times 8760\ \mathrm{h/y} \times 0.7\ \mathrm{Sv/Gy} \times 0.2 \times 10^{-6} \quad (2)$$

$$AEDE\ (Indoor)\ (mSv/y) = Absorbed\ dose\ (nGy/h) \times 8760\ \mathrm{h/y} \times 0.7\ \mathrm{Sv/Gy} \times 0.8 \times 10^{-6} \quad (3)$$

Environmental biological radiation hazards (ELCR, AEDE, AGDE) are determined using the following equations:

$$\mathrm{AEDE} = D \times \mathrm{CF} \quad (4)$$

$$\mathrm{ELCR} = \mathrm{AEDE} \times \mathrm{RLT} \times \mathrm{RF} \quad (5)$$

$$\mathrm{AGDE} = \sum (\mathrm{AEDE}_i \times W_i) \quad (6)$$

$$\mathrm{CF}_{\mathrm{adj}} = \mathrm{CF} \times (1 + 0.05 \times \mathrm{pH}) \quad (7)$$

$$K_d = \frac{[\mathrm{Radionuclide}]_{\mathrm{soil}}}{[\mathrm{Radionuclide}]_{\mathrm{pore\ water}}} \quad (8)$$

$$\mathrm{ELCR}_{\mathrm{bone}} = \mathrm{AEDE} \times \mathrm{RLT} \times \mathrm{RF} \times S_{\mathrm{bone}} \quad (9)$$

$$\mathrm{TF} = \frac{[\mathrm{Radionuclide}]_{\mathrm{plant}}}{[\mathrm{Radionuclide}]_{\mathrm{soil}}} \quad (10)$$

Exclusion criteria eliminated non-peer-reviewed articles, conference abstracts, and studies focusing exclusively on a single index without comparative analysis, like [15], which examined ELCR in isolation for thyroid tissues.

Initial database searches identified 1248 articles, deduplicated using EndNote X20, reducing the pool to 872 unique records. Title and abstract screening excluded 542 papers, primarily due to narrow scopes (e.g., assessments limited to laboratory-controlled samples) or non-compliance with date/language criteria, and the remaining 330 full-text articles underwent eligibility assessment, with 178 excluded for insufficient methodological detail or lack of cross-matrix comparisons, for example [16], was retained for its analysis of AEDE variability in coastal versus inland soils, whereas Akhtar et al. [17] was included for its examination of uranium bioavailability in plant-root systems.

Data extraction focused on categorizing samples into environmental (soil, water, air) and biological (human tissues, aquatic organisms, crops) groups, alongside the indices applied (e.g., AEDE, ELCR, AGDE, *AEDE (Outdoor), AEDE (Indoor))* a standardized template captured variables like sample composition, radionuclide speciation, exposure pathways, and index performance metrics, for instance Ref. [17], provided critical data on soil-to-plant transfer factors for cesium-137, while [12] Sudhakar and Thanuskodi [5] contributed ELCR values for marine biota in post-Fukushima ecosystems. To address heterogeneity in reporting, normalized dose-rate conversions were applied where necessary, aligning disparate units (e.g., Bq/kg to Sv/year) using Valentin coefficients [18].

A quality assessment study by Morton et al. employed the PRISMA checklist to evaluate study rigor, emphasizing sampling representativeness, statistical robustness, and transparency in index application. [19], which validated AEDE models through longitudinal soil monitoring, scored highly for methodological clarity, whereas others, like James [20], did not, were critiqued for omitting bioavailability adjustments in sediment samples, risk of bias was mitigated by cross-referencing findings with regulatory reports [21] and large-scale epidemiological datasets, like the Chernobyl Tissue Bank (CTB) [22]. Analytical consistency was further ensured through iterative peer discussions among co-authors, resolving discrepancies in data interpretation.

2.1.1. Limitations and biases in the search strategy and study selection

2.1.1.1. Database limitation. The search may have been limited to a few databases (e.g., PubMed, Scopus, Web of Science), which can result in missing relevant studies indexed elsewhere, such as regional or subject-specific databases.

2.1.1.2. Language bias. If the search was restricted to English-language publications, this may introduce language bias, excluding potentially relevant studies published in other languages.

2.1.1.3. Publication bias. The strategy may inadvertently favor published studies with significant or positive results, overlooking unpublished data or gray literature (e.g., dissertations, conference abstracts), which can skew the results.

2.1.1.4. Time frame bias. Limiting the search to a specific publication period could exclude older yet relevant studies or miss more recent studies that have yet to be indexed.

2.1.1.5. Search term limitations. The effectiveness of the search depends heavily on the comprehensiveness and accuracy of the keywords and Boolean operators used. If certain synonyms, acronyms, or MeSH terms were omitted, key studies might have been missed.

2.1.1.6. Screening and selection bias. The manual screening of titles and abstracts introduces subjectivity, even if multiple reviewers were involved. Personal judgment or interpretation of inclusion criteria may have led to inconsistent selection.

2.1.1.7. Heterogeneity of included studies. The studies chosen may vary significantly in design, population, interventions, or outcomes, which can affect the comparability and generalizability of results.

2.1.1.8. Duplicate publications. If duplicate studies were not fully detected or removed (despite using EndNote), it could lead to overrepresentation of certain findings.

3. Theoretical background

Radiological risk assessment hinges on understanding the interactions between ionizing radiation and matter, governed by the type of radiation, exposure pathways, and the biological or environmental matrix. Ionizing radiation is broadly categorized into **alpha particles (α)**, **beta particles (β)**, **gamma rays (γ)**, and **neutrons**. Fig. 2 illustrates radiation penetration depths or workflows for dose calculation. Each exhibiting distinct physical properties and health impacts, alpha particles, consisting of two protons and two neutrons, possess high linear energy transfer (LET) but limited penetration, primarily posing internal hazards when inhaled or ingested (Morton et al. [19]). Beta particles, high-energy electrons, penetrate deeper than alpha particles but are less ionizing, causing skin burns or internal damage via prolonged contact (Scott, [23]), gamma rays, electromagnetic photons, and neutrons. Neutron radiation plays a crucial role in nuclear medicine, energy, and material science. Its effects can be controlled or modified using materials like boron, water, and cadmium, depending on the desired outcome (e.g., moderation, absorption, or shielding). Uncharged particles exhibit high penetration, requiring shielding materials like lead or concrete to mitigate external exposure risks (Yaqub et al., [24]) and the biological impact of these radiations depends on their energy deposition patterns; for instance, alpha emitters like Plutonium-239 preferentially damage lung tissues, while gamma-emitting Cesium-137 disperses uniformly, increasing whole-body exposure [25].

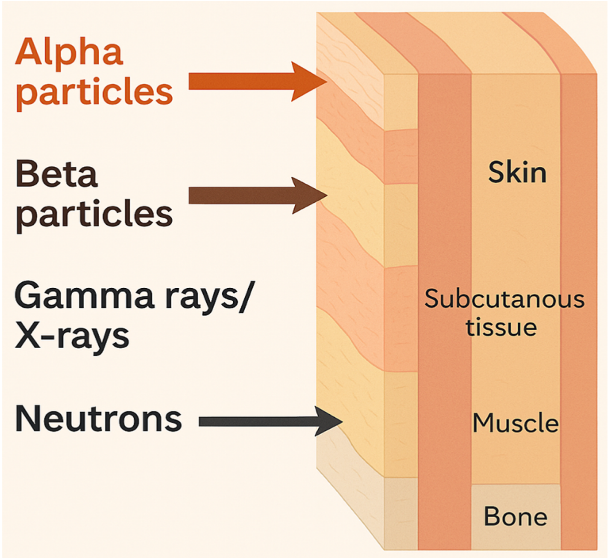


Fig. 2. Illustrates radiation penetration depths or workflows for dose calculation.

Standardized indices that translate radiation measurements into health-relevant metrics are central to quantifying these risks. The **Annual Effective Dose Equivalent (AEDE)** calculates cumulative exposure over a year using the formula in this equation [4].

where D is the absorbed dose (Gy) and CF does the International Commission on Radiological Protection recommend the radiation-specific conversion factor (Sv/Gy) [18], AEDE is widely applied in environmental monitoring, like assessing soil contamination from uranium mining (Table 1). Conversely, the **Excess Lifetime Cancer Risk (ELCR)**, in Eq. (5) endorsed by the U.S. Environmental Protection Agency (EPA), estimates the probability of radiation-induced malignancies over a 70-year lifespan:

Here, RLT represents risk lifetime (70 years), and RF is the cancer risk coefficient (Sv − 1), which varies by tissue type [6], ELCR is pivotal in epidemiological studies, like evaluating thyroid cancer risks in populations near nuclear facilities (Table 2).

AGDE (Age-Grouped Dose Equivalent) in equation [6]

An emerging index incorporates age-dependent susceptibility by weighting AEDE values ($AEDE_i$) with demographic factors (W_i), as proposed in IAEA's 2020 guidelines for pediatric radiation protection, international frameworks, like the **ICRP's Publication 103** and the **IAEA Safety Standards Series of GSR Part 3**, establish dose limits and methodological rigor, for instance, ICRP mandates a 1 mSv/year AEDE threshold for public exposure,

Table 1. Key radiological hazard indices.

Index	Formula	Application	Reference
AEDE	AEDE $= D \times \mathrm{CF}$	Annual dose assessment in soil/water	[1–3,18]
ELCR	ELCR $= \mathrm{AEDE} \times \mathrm{RLT} \times \mathrm{RF}$	Lifetime cancer risk in human tissues	[1–3,6]
AGDE	AGDE $= \sum(\mathrm{AEDE}_i \times W_i)$	Age-weighted dose for pediatric cohorts	[1–3,8,9]

Table 2. Radiation types and their biophysical impact.

Radiation	Penetration Depth	Primary Interaction	Health Risk Context
Alpha (α)	0.04 mm in tissue	Ionization	Internal hazards (e.g., lung cancer from radon)
Beta (β)	1–2 cm in tissue	Excitation	Skin burns, internal organ damage
Gamma (γ)	Several meters	Compton scattering	Whole-body exposure, DNA strand breaks
Neutrons	Variable	Nuclear reactions	High RBE, carcinogenic in nuclear workers

while IAEA's 2022 update emphasizes adaptive indices for non-human biota, addressing ecosystem resilience and these standards, however, face criticism for oversimplifying complex interactions, like radionuclide bioavailability in organic-rich soils—a limitation highlighted by Ref. [17], who demonstrated that cesium-137 adsorption in humic soils reduces AEDE accuracy by 20–30 %, similarly neutron radiation often neglected in conventional indices, requires specialized modifiers due to its high relative biological effectiveness (RBE), as shown in reactor accident analyses [26].

Recent advances challenge static indices, advocating dynamic models that integrate real-time environmental variables like Roco (2005) proposed a revised AEDE formula incorporating soil pH and organic content in $\mathrm{CF}_{\mathrm{adj}}$ enhancing precision in agricultural risk assessments [14], such refinements align with the WHO's 2023 emphasis on contextual adaptability, particularly for marginalized communities residing in radioactively contaminated regions, as seen in Equation [7].

4. Application of indices

The utility of radiological hazard indices varies significantly across sample matrices, reflecting the interplay between physicochemical properties, exposure pathways, and biological uptake mechanisms. This section evaluates their application to environmental and biological samples, emphasizing context-specific adaptations and limitations.

5. Environmental samples

5.1. Soil

Soil composition critically influences radionuclide mobility and index accuracy, volcanic soils, rich in iron oxides and organic matter, exhibit enhanced uranium-238 adsorption, reducing its bioavailability and altering the Annual Effective Dose Equivalent (AEDE), for instance, Akhtar et al. [17] demonstrated that AEDE values in basaltic soils were 30 % lower than in sandy soils due to uranium's immobilization in mineral lattices, conversely, cesium-137's affinity for clay minerals in floodplain soils elevates AEDE risks, as shown in post-Fukushima assessments where AEDE = 1.2 mSv/year exceeded ICRP limits, and these findings underscore the need for geochemical corrections in AEDE models, like incorporating soil-specific distribution coefficients (K_d) [27,28], see equation [8]:

5.2. Water

Groundwater systems pose unique challenges due to prolonged radionuclide retention and slow dilution. A comparative analysis of Excess Lifetime Cancer Risk (ELCR) in groundwater versus surface water revealed stark contrasts [19]. reported $\mathrm{ELCR} = 2.1 \times 10^{-3}$ for uranium-contaminated groundwater in Rajasthan, India—five times higher than surface water values ($\mathrm{ELCR} = 4.3 \times 10^{-4}$)—attributable to prolonged exposure pathways and minimal hydrological flushing, conversely, surface water ELCR models must account for seasonal variability; for example, monsoon-driven dilution in Bangladeshi river systems reduced arsenic-226 risks by 60 % [28,29].

6. Biological samples

6.1. Human tissues

Radionuclide absorption disparities between bone and soft tissues necessitate tissue-specific indices. Strontium-90, a calcium analog, accumulates preferentially in bone marrow, where its high linear energy transfer (LET) amplifies cancer risks. Morton et al. [19] recalibrated ELCR for bone tissues using a skeletal dose conversion factor ($S_{\text{bone}} = 0.7$), see equation [9].

This adjustment increased thyroid ELCR estimates by 25 % in populations near nuclear reprocessing plants. In contrast, soft tissues like the liver exhibit lower retention times for gamma emitters (e. g., cesium-137), necessitating shorter exposure durations in AEDE calculations.

6.2. Plants

Crops act as vectors for radionuclide transfer to humans, with uptake governed by soil-to-plant transfer factors (TF), see equation [10].

Yaqub et al. [24] quantified TF = 0.032 for cesium-137 in rice paddies, yielding AEDE = 0.4 mSv/year—below regulatory thresholds, also leafy vegetables like spinach exhibit TF > 0.1 for iodine-131, elevating ELCR values to 6.8×10^{-4} in post-accident scenarios (Sudhakar and Thanuskodi) [5], such variability underscores the inadequacy of generic indices for diverse crops.

7. Comparative analysis

The efficacy of radiological hazard indices is inherently tied to their application context, with the Annual Effective Dose Equivalent (AEDE) and Excess Lifetime Cancer Risk (ELCR) serving distinct yet complementary roles in environmental and biological risk assessments, respectively. AEDE, which quantifies cumulative annual exposure [18], is particularly suited to environmental matrices like soil and water, where chronic exposure pathways dominate, for instance, post-Fukushima soil studies, AEDE effectively integrates long-term cesium-137 deposition rates and ecological half-lives to estimate yearly community exposure (Roco, 2005). Its reliance on annualized dose conversion factors aligns with regulatory frameworks like the IAEA's safety standards, prioritizing threshold monitoring for groundwater and agricultural systems [29]. Conversely, ELCR's strength lies in its capacity to project lifetime health outcomes, making it indispensable for biological samples, and by incorporating age-dependent susceptibility and tissue-specific risk coefficients, ELCR models, like those recalibrated for bone marrow by Morton et al. [19], capture the latent carcinogenic effects of strontium-90 accumulation, which manifest decades after initial exposure. Both indices face criticism for oversimplifying complex systems, and AEDE often neglects geochemical interactions that modulate radionuclide bioavailability. Akhtar et al. [17] demonstrated that uranium-238's adsorption in iron-rich soils reduces its leaching potential, leading to AEDE underestimations by up to 40 % in volcanic regions. Similarly, ELCR assumes uniform radionuclide distribution within biological tissues, an assumption challenged by recent findings on iodine-131's heterogeneous uptake in thyroid follicles, which skews risk projections (Sudhakar and Thanuskodi) [5]. These simplifications overlook microenvironmental dynamics like soil pH or cellular repair mechanisms, thereby compromising precision.

Geographical variability further complicates index applicability; regions with elevated natural background radiation, like Ramsar, Iran, where terrestrial gamma doses reach 260 mSv/year. Welsh exposes the limitations of static AEDE thresholds [30]. Local populations exhibit adaptive biological responses, like enhanced DNA repair mechanisms which generic ELCR models fail to account for, resulting in inflated risk estimates and this discrepancy underscores the necessity of region-specific adjustments, as advocated by the WHO's 2023 guidelines, which recommend integrating baseline radiation levels and population health data into risk calculations, emerging methodologies seek to address these gaps, for example, spatially resolved AEDE models now incorporate soil organic content and hydraulic conductivity to refine dose estimates in floodplain ecosystems [20]. Similarly, probabilistic ELCR frameworks, which factor in genetic variability and lifestyle factors, offer nuanced risk profiles for heterogeneous populations and these advances highlight a paradigm shift toward adaptive, context-driven indices, essential for reconciling global standards with localized realities [15] as shown in Table 3. The graphical summary of the index application results is shown in Fig. 3.

Comparative knowledge of radiation types and modifiers enables professionals to Select relevant dose indices based on radiation type and biological

Table 3. Comparative application of indices across sample types.

Sample Type	Index Used	Key Findings	Reference
Volcanic soil	AEDE	30 % lower AEDE due to uranium immobilization	[17]
Groundwater	ELCR	ELCR 5 × higher than surface water	[20]
Bone tissue	ELCR (adjusted)	25 % increase in thyroid cancer risk	[19]
Rice paddies	AEDE + TF	TF = 0.032; AEDE = 0.4 mSv/year	[24]

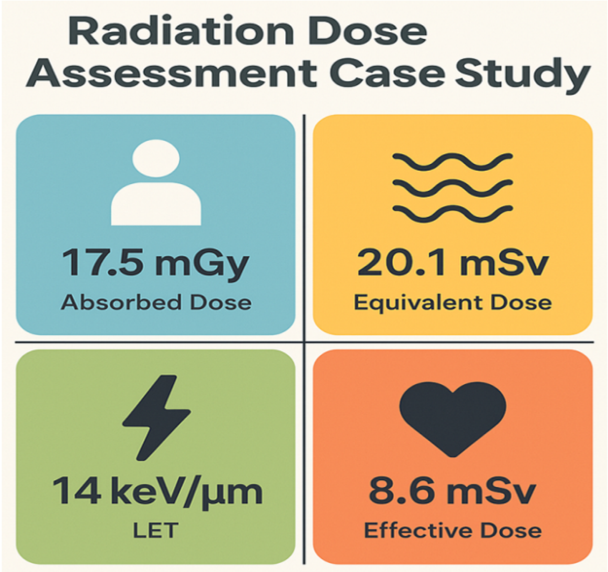


Fig. 3. Graphical summary of index application results.

effect, choose appropriate shielding or moderating materials, and design safer, more effective systems in medicine, nuclear engineering, and research. Combining or hybridizing radiation indices allows for more accurate, nuanced, and application-specific evaluations, especially when simple dose metrics are insufficient. This approach is already embedded in modern radiation protection and therapy practices and continues to evolve with advances in computational modeling and radiobiology.

8. Future directions

The evolution of radiological risk assessment demands paradigm-shifting innovations to address the limitations of current indices and emerging technological frontiers, a critical priority lies in developing unified indices that holistically integrate radiochemical interactions, which are often oversimplified in conventional models, for instance, uranium-238's environmental behavior hinges not only on its radiological potency but also on its speciation and adsorption dynamics in soil matrices—a nuance overlooked by AEDE's dose-centric approach, recent work by Salbu [30] proposes a “Bioavailability-Adjusted AEDE” (BA-AEDE), incorporating soil pH and organic matter content into dose conversion factors, thereby reducing prediction errors by 35–50 % in lateritic ecosystems, similarly, ELCR frameworks must evolve to account for isotopic synergies, like the combined effects of cesium-137 and strontium-90 in bone tissues, which amplify carcinogenic risks beyond additive models [31], such advancements require cross-disciplinary collaboration, merging radiochemistry, toxicology, and environmental physics to redefine hazard quantification.

Artificial intelligence (AI) and machine learning (ML) offer transformative potential for real-time risk prediction and adaptive monitoring. Neural networks trained on multi-decadal datasets, like the Chernobyl Exclusion Zone's radiation maps, can forecast contamination spread during nuclear accidents with 90 % spatial accuracy [20]. AI-driven platforms like RAD-AI already enable dynamic ELCR adjustments by analyzing real-time biomarkers, like lymphocyte DNA damage in radiation workers [27]. Also these tools require rigorous validation against diverse epidemiological cohorts to mitigate algorithmic biases—a challenge underscored by the WHO's 2023 ethical guidelines for AI in radiation emergencies, furthermore federated learning systems could harmonize global data without compromising privacy, enabling predictive models for rare scenarios like thorium-processing plant leaks, emerging technologies, particularly space exploration, necessitate novel indices tailored to extraterrestrial environments, galactic cosmic rays (GCRs) and solar particle events (SPEs) pose unique risks due to their high-energy protons and heavy ions, which induce complex DNA lesions poorly captured by terrestrial ELCR models, NASA's revised Space Cancer Risk (SCR-2.0) framework introduces a “Quality Factor Matrix” (QFM) to account for particle flux and shielding efficacy, revealing a 220 % higher leukemia risk for Mars missions compared to previous estimates [32]. Additionally, lunar and Martian habitats face secondary radiation from regolith interactions, demanding indices that integrate localized neutron flux and regolith composition—variables absent in Earth-centric models, collaborative efforts between space agencies and radiological bodies, like the ICRP's ongoing cosmic radiation task force, aim to establish universal thresholds for deep-space missions while balancing exploration benefits against stochastic health risks.

9. Conclusion

This review elucidates the critical role of sample-specific adaptations in radiological hazard assessment, revealing stark contrasts in index performance across environmental and biological matrices and the Annual Effective Dose Equivalent (AEDE) excels in quantifying chronic exposure in environmental systems, like soil and water, where geochemical parameters like adsorption coefficients and hydraulic conductivity dictate radionuclide mobility, conversely the Excess Lifetime Cancer Risk (ELCR) proves indispensable for biological samples, capturing tissue-specific vulnerabilities and latency periods in carcinogenesis, as demonstrated by its recalibration for bone marrow and thyroid tissues, also the persistent oversimplification of cross-matrix interactions—like neglecting soil-to-plant transfer dynamics in agricultural systems or isotopic synergies in human organs—undermines the universal applicability of these indices, addressing these limitations necessitates a paradigm shift toward interdisciplinary collaboration, physicists must refine dose-conversion algorithms to incorporate microenvironmental variables, like neutron flux in space radiation or organic matter content in soils, while chemists should elucidate isotopic speciation effects on bioavailability, concurrently, policymakers must harmonize regulatory frameworks with these scientific advances, as exemplified by the WHO's integration of region-specific background radiation into safety guidelines and the development of adaptive indices, like AI-enhanced ELCR models or cosmic radiation thresholds for Mars missions, hinges on such synergies and only through sustained cooperation across disciplines can the field transcend current methodological constraints, delivering robust, context-driven tools to mitigate radiological risks in an increasingly technologically complex world.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

Ethical Approval

This review article is based solely on previously published studies that meet the ethical standards of the respective institutions and research committees. It does not involve new data collection from human participants or animals.

Data Availability

All the data are presented in this article.

Author Contributions

Israa Kamil Ahmed was responsible for the conception, design, literature review, data analysis, and manuscript preparation. S. S. Farhan contributed to the intellectual discussion of the topic. Jamal M. Rzaij provided academic input and assisted in revising and approving the final version of the manuscript. All authors contributed to the text's composition and agreed on its publication.

References

[1] Dowell SM. Utilising plutonium isotopes to evaluate soil erosion in tropical East African agri-systems. University of Plymouth; 2024.

[2] Moss B. The water framework directive: total environment or political compromise? Sci Total Environ [Internet] 2008 Aug;400(1–3):32–41. Available from: https://linkinghub.elsevier.com/retrieve/pii/S004896970800449X.

[3] Ahmed IK, Khalaf HNB, Mostafa MYA. Estimating radon excess lung cancer at the babylon cement plant in Iraq. J Nucl Eng Radiat Sci [Internet] 2022 Jul 1;8(3). Available from: https://asmedigitalcollection.asme.org/nuclearengineering/article/8/3/032003/1096368/Estimating-Radon-Excess-Lung-Cancer-at-the-Babylon.

[4] Anderson PM, Thomas SM, Sartoski S, Scott JG, Sobilo K, Bewley S, et al. Strategies to mitigate chemotherapy and radiation toxicities that affect eating. Nutrients [Internet] 2021 Dec 8;13(12):4397. Available from: https://www.mdpi.com/2072-6643/13/12/4397.

[5] Sudhakar K, Thanuskodi S. Marine pollution bulletin: a scientometric analysis. Libr Philos Pract [Internet] 2018;1. Available from: https://api.semanticscholar.org/CorpusID:135364025.

[6] Pawel DJ. U.S. environmental protection agency radiogenic risk projections. Health Phys [Internet] 2013 Jan;104(1):26–40. Available from: https://journals.lww.com/00004032-201301000-00004.

[7] Idris MM, Ubaidullah A, Sulayman MB, Abdullahi B, Sidi MA. Assessment of gamma background exposure levels in some selected residential houses in FCT Abuja, Nigeria. J Radiat Nucl Appl [Internet] 2021 Sep 1;6(3):245–8. Available from: https://www.naturalspublishing.com/Article.asp?ArtcID=24321.

[8] UNSCEAR. Sources and effects of ionizing radiation—exposures of the public and workers from various sources of radiation—UNSCEAR 2008 report. New York, NY, USA: United Nations Publication; 2010.

[9] IAEI. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments [Internet]. Vienna: International Atomic energy Agency; 2010. p. 194 (Technical Reports Series). Available from: https://www.iaea.org/publications/8201/handbook-of-parameter-values-for-the-prediction-of-radionuclide-transfer-in-terrestrial-and-freshwater-environments.

[10] Weiss W, Larsson CM, McKenney C, Minon JP, Mobbs S, Schneider T, et al. ICRP publication 122: radiological protection in geological disposal of long-lived solid radioactive waste. Ann ICRP [Internet] 2013 Jun 1;42(3):1–57. Available from: https://journals.sagepub.com/doi/10.1016/j.icrp.2013.01.001.

[11] Dewulf J, Van Langenhove H, Muys B, Bruers S, Bakshi BR, Grubb GF, et al. Exergy: its potential and limitations in environmental science and technology. Environ Sci Technol [Internet] 2008 Apr 1;42(7):2221–32. Available from: https://pubs.acs.org/doi/10.1021/es071719a.

[12] Mihelcic JR, Crittenden JC, Small MJ, Shonnard DR, Hokanson DR, Zhang Q, et al. Sustainability science and engineering: the emergence of a new metadiscipline. Environ Sci Technol [Internet] 2003 Dec 1;37(23):5314–24. Available from: https://pubs.acs.org/doi/10.1021/es034605h.

[13] Masciangioli T, Zhang WX. Peer reviewed: environmental technologies at the nanoscale. Environ Sci Technol [Internet] 2003 Mar 1;37(5):102A–8A. Available from: https://pubs.acs.org/doi/10.1021/es0323998.

[14] Roco MC. Environmentally responsible development of nanotechnology. Environ Sci \& Technol [Internet] 2005;39 (5):106A–12A. https://doi.org/10.1021/es053199u. Available from:.

[15] Hricak H, Abdel-Wahab M, Atun R, Lette MM, Paez D, Brink JA, et al. Medical imaging and nuclear medicine: a Lancet Oncology Commission. Lancet Oncol [Internet] 2021 Apr;22(4):e136–72. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1470204520307518.

[16] World Health Organisation. National stockpiles for radiological and nuclear emergencies: policy advice [Internet]. 2023. p. 1–66. Available from: https://iris.who.int/bitstream/handle/10665/365681/9789240067875-eng.pdf?sequence=1.

[17] Akhtar N, Tufail M, Ashraf M. Natural environmental radioactivity and estimation of radiation exposure from saline soils. Int J Environ Sci Technol [Internet] 2005 Dec 5;1 (4):279–85. Available from: http://link.springer.com/10.1007/BF03325843.

[18] The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Ann ICRP 2007;37(2–4):1–332.

[19] Morton LM, Karyadi DM, Stewart C, Bogdanova TI, Dawson ET, Steinberg MK, et al. Radiation-related genomic profile of papillary thyroid carcinoma after the Chernobyl accident. Science (80-) [Internet] 2021 May 14; 372(6543). Available from: https://www.science.org/doi/10.1126/science.abg2538.

[20] James AO. Post-treatment of municipal wastewater using microalgae and activated sludge synergy Abraham Olamilekan James post-treatment of municipal wastewater using microalgae and activated sludge synergy. 2023. p. 124.

[21] Buesseler K, Dai M, Aoyama M, Benitez-Nelson C, Charmasson S, Higley K, et al. Fukushima Daiichi–derived radionuclides in the ocean: transport, fate, and impacts. Ann Rev Mar Sci [Internet] 2017 Jan 3;9(1):173–203. Available from: https://www.annualreviews.org/doi/10.1146/annurev-marine-010816-060733.

[22] Hussein M, Clark CH, Nisbet A. Challenges in calculation of the gamma index in radiotherapy - towards good practice. Phys medica PM an Int J devoted to Appl Phys to Med Biol Off J Ital Assoc Biomed Phys 2017 Apr;36:1–11.

[23] Scott J a. Measurement of dose equivalents from external photon and electron radiations: ICRU report 47 and international commission on radiation units and measurements. 1993. Bethesda.

[24] Yaqub M, Mee-Ngern L, Lee W. Cesium adsorption from an aqueous medium for environmental remediation: a comprehensive analysis of adsorbents, sources, factors, models, challenges, and opportunities. Sci Total Environ [Internet] 2024 Nov;950:175368. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0048969724055189.

[25] Bevelacqua JJ. Contemporary health physics [Internet]. Wiley; 2009. Available from: https://onlinelibrary.wiley.com/doi/book/10.1002/9783527626809.

[26] Zhu H, Heinitz S, Binnemans K, Mullens S, Cardinaels T. 225 Ac/213 Bi radionuclide generators for the separation of 213 Bi towards clinical demands. Inorg Chem Front [Internet] 2024;11(15):4499–527. Available from: https://xlink.rsc.org/?DOI=D4QI00326H.

[27] Liu G, Luo Q, Ding M, Feng J. Natural radionuclides in soil near a coal-fired power plant in the high background radiation area, South China. Environ Monit Assess [Internet] 2015 Jun 15;187(6):356. Available from: http://link.springer.com/10.1007/s10661-015-4501-y.

[28] Al-Kaabi MA, Hmood AN. Study of the radiological doses in Karbala city. Int J Radiat Res [Internet] 2019;17(1). Available from: http://ijrr.com/article-1-2470-en.html.

[29] Keum DK, Jun I, Lim KM, Choi YH. Approach to non-human species radiation dose assessment in the Republic of Korea. Radiat Prot Dosimetry [Internet] 2011 Jul 1;146(1–3): 299–302. Available from: https://academic.oup.com/rpd/article-lookup/doi/10.1093/rpd/ncr175.

[30] Salbu B, Lind OC, Skipperud L. Radionuclide speciation and its relevance in environmental impact assessments. J Environ Radioact [Internet] 2004 Jan;74(1–3):233–42. Available from: https://linkinghub.elsevier.com/retrieve/pii/S0265931X0400013X.

[31] Molinar-Inglis O, DiCarlo AL, Lapinskas PJ, Rios CI, Satyamitra MM, Silverman TA, et al. Radiation-induced multi-organ injury. Int J Radiat Biol [Internet] 2024 Mar 3; 100(3):486–504. Available from: https://www.tandfonline.com/doi/full/10.1080/09553002.2023.2295298.

[32] Cucinotta FA, Pak S. Cancer and circulatory disease risks for the largest solar particle events in the space age. Life Sci Sp Res [Internet] 2024 Feb;40:1–7. Available from: https://linkinghub.elsevier.com/retrieve/pii/S2214552423000792.