

# Environmental Consequences of Nuclear Accidents and Radiation Leaks: A Narrative Synthesis of Global Impact

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*Abstract- Nuclear accidents and radiation leaks present profound risks to environmental integrity, public health, and global security. However, nuclear technology provides essential benefits in energy production, medicine, agriculture, and scientific innovation. Accidental radiation releases have posed major environmental and public health challenges. This narrative review synthesizes global evidence on the environmental consequences of nuclear accidents and radiation leaks. Over the past decades, major incidents such as Chernobyl and Fukushima have highlighted the need for intensive international monitoring and regulatory systems capable of detecting radiological releases rapidly and coordinating an effective response. This paper also examines the effectiveness and limitations of global monitoring networks and regulatory frameworks governing nuclear safety. The review concludes that global monitoring and regulatory structures have improved significantly; continued advancement is needed to ensure rapid detection, harmonized communication, and effective environmental protection in the face of evolving nuclear technologies and geopolitical risks.*

*Index Terms- Radiation, Nuclear Accidents, Radiation Leaks, Radiation Leaks, Chernobyl, Fukushima*

## I. INTRODUCTION

Radiations are energetic particles that are components of both natural and anthropogenic environments. Radiations play a dual role in human life and ecological systems. On one hand, ionizing radiation is widely utilized for beneficial purposes, including medical imaging, cancer therapy, sterilization of medical instruments, and various industrial processes [1, 2]. These advantages contribute significantly to scientific progress and societal development.

However, uncontrolled or excessive exposure to radiation, either from nuclear accidents, radiological incidents, or naturally occurring high-background radiation areas, poses severe threats to ecosystems, human health, and biodiversity [3, 4]. This dual

nature highlights the importance of understanding radiation not only for its applications but also for its environmental and health risks.

The environmental consequences of radiation leaks have emerged as a critical area of research, particularly in the context of nuclear power and energy production. Catastrophic events such as the Chernobyl accident in 1986 and the Fukushima Daiichi disaster in 2011 illustrated the far-reaching ecological impacts of radioactive contamination [5, 6]. The impact includes the deposition of radionuclides in soil, contamination of water systems, and disruption of agricultural activities [7, 8]. Moreover, these accidents highlighted the vulnerability of wildlife, microbial communities, and ecosystem services to radiation exposure, with effects persisting for decades in affected regions [9, 10]. Beyond nuclear accidents, studies in regions with naturally elevated background radiation, such as Indonesia and Vietnam, have demonstrated the importance of dose assessment and continuous monitoring to understand long-term ecological and human exposure risks [3, 11].

The study of the environmental consequences of radiation is essential for multiple reasons. It informs risk assessment, environmental management, and disaster preparedness strategies, while also guiding regulatory frameworks for nuclear safety and radiation protection. Insights gained from both historical accidents and ongoing environmental monitoring provide critical evidence for designing remediation measures, developing public health policies, and implementing sustainable land and water management practices.

This review aims to synthesize global evidence on the environmental impacts of nuclear accidents and radiation leaks. By integrating findings from major historical events, naturally high-background radiation

areas, and contemporary research on ecological and human exposure. Hence, this narrative synthesis seeks to provide a comprehensive understanding of radiation's consequences, highlights strategies for sustainable environmental protection, disaster preparedness, and effective regulatory oversight in the context of both natural and anthropogenic radiation hazards.

## II. RADIATION AND THE ENVIRONMENT: CONCEPTUAL OVERVIEW

Abdulahman, et al. [4] study emphasizes that while natural radiation is ever-present, the introduction of human-made radioactive materials significantly alters environmental exposure levels, particularly in the vicinity of nuclear facilities. They highlight multiple environmental exposure pathways, including the release of radioactive gases into the air, leakage or improper disposal of contaminated water into aquatic systems, and deposition of radionuclides into soil, all of which enable radiation to infiltrate the food chain through plant absorption and bioaccumulation in animals. The authors note that short-term environmental impacts frequently manifest as acute contamination events, which can harm local ecosystems. In contrast, long-term consequences include persistent soil and water contamination, ecological imbalances, reduced biodiversity, and potential genetic mutations in exposed species.

Aba, et al. [1] reports that radiation in the environment arises from both natural and anthropogenic sources, each contributing differently to ecosystem exposure and ecological health. Natural sources, such as cosmic rays, terrestrial radionuclides, and naturally occurring radioactive materials in soil and water, represent persistent background radiation, whereas anthropogenic sources, including nuclear power generation, medical applications, and industrial activities, introduce localized, often higher-intensity radiation hazards [1]. Radiation enters ecosystems through multiple pathways, including air, soil, and water, ultimately accumulating in the food chain and posing risks to both flora and fauna. Exposure through these pathways may result in short-term ecological impacts, such as immediate mortality or reduced

reproductive success, as well as long-term consequences, including genetic mutations, bioaccumulation of radionuclides, and persistent disruptions to ecosystem functioning.

Bonacic, et al. [10] established that while natural radiation forms part of normal ecosystem functioning, anthropogenic leaks introduce concentrated radionuclides that disrupt environmental stability. The authors describe multiple exposure pathways, including atmospheric fallout, soil deposition, and contamination of surface and groundwater systems, which enable radionuclides to move through the food chain, leading to bioaccumulation and biomagnification across trophic levels. From their perspective, short-term ecological impacts often manifest as acute physiological stress, reduced reproductive output, and mortality in sensitive species. At the same time, long-term effects extend to genetic mutations, population declines, altered species interactions, and shifts in ecosystem structure and function.

Patel, et al. [12] assessment shows that variations in soil composition, mineral deposits, and geological structures influence the release of naturally occurring radioactive materials into air, soil, and water, creating pathways through which radiation becomes integrated into local ecosystems. These radionuclides subsequently enter the food chain through the absorption of plants and the transfer of radionuclides from soil to crops. This emphasizes the importance of continuous environmental monitoring.

Van Dung, et al. [11] examine a region in Vietnam with naturally high background radiation originating from rare earth element deposits. Their investigation highlighted how geological factors significantly influence environmental radiation exposure. The study demonstrates that naturally occurring radionuclides are released into air, soil, and water, creating pathways through which radiation can enter ecosystems and subsequently the food chain via plant uptake and animal consumption. The authors note that in such high natural radiation areas, short-term ecological impacts are generally minimal due to the adaptation of local flora and fauna, but long-term effects remain relevant, including chronic exposure

risks, potential bioaccumulation, and genetic alterations over successive generations.

Kurilovská and Mullerova [5] describe how failures in containment during accidents allow radionuclides to disperse through airborne release, soil contamination, and water infiltration, creating complex pathways through which radiation spreads across ecosystems. These contaminants subsequently infiltrate the food chain as plants absorb radioactive particles from soil and water, while animals accumulate them through feeding, thereby magnifying ecological exposure.

Nugraha, et al. [3] found that elevated natural radiation in Indonesia primarily arises from geological formations rich in thorium and uranium, which contribute to continuous radiation release into air, soil, and water. These radionuclides enter the food chain through plant uptake and soil-to-crop transfer, offering insight into how ecosystems adapt to long-term, naturally elevated radiation levels. The authors note that short-term ecological impacts are often minimal in such environments, as species may develop tolerance to persistent low-dose exposure. However, long-term effects remain important, particularly regarding cumulative doses, potential genetic mutations, and altered ecological interactions.

Lee, et al. [13] study shows that the failure of the containment systems of the particle accelerator can disperse radiation through airborne smoke plumes, runoff water, and soil deposition, creating multiple environmental exposure pathways that extend far beyond the facility itself. These radionuclides subsequently wattle in the food chain, contaminating vegetation, agricultural soil, and aquatic life, thereby increasing exposure risks for both wildlife and human populations. The authors highlight that short-term ecological impacts may include acute contamination of local water bodies, disruption of microhabitats, and immediate physiological stress on exposed organisms. Meanwhile, long-term effects arise from the persistence of deposited radionuclides, which may lead to chronic exposure, bioaccumulation, genetic changes, and slow ecosystem degradation.

Ishikawa [14] study explains that radionuclides are dispersed through airborne emissions, contaminated soil particles, and polluted water systems, creating

multiple routes through which radiation enters local ecosystems. These pathways facilitated the movement of radioactive isotopes into the food chain, contaminating crops, livestock, and aquatic organisms, thereby extending ecological exposure beyond the initial release period. The author notes that short-term environmental impacts included rapid accumulation of radionuclides in soil and vegetation, disruptions in agricultural activities, and immediate threats to wildlife populations. In contrast, long-term impacts were characterized by sustained environmental contamination due to long-lived isotopes such as cesium-137, leading to chronic exposure risks, potential genetic alterations in biota, and protracted ecosystem recovery timelines.

Hasegawa, et al. [7] examine the environmental and health consequences following major nuclear accidents, with particular focus on the Fukushima event. They illustrate how natural background radiation differs significantly from the high-level anthropogenic radiation released during such disasters. They describe how radionuclides disseminate through airborne plumes, soil contamination, and water transport, forming interconnected pathways that introduce radioactive particles into terrestrial and aquatic ecosystems. The authors distinguish between short-term ecological effects, including contamination of agricultural land, disruption of wildlife habitats, and immediate declines in biodiversity, and long-term impacts, such as persistent radionuclide deposition, genetic alterations in exposed species, and prolonged ecosystem destabilization.

Yamada [8] addresses the environmental impacts and health effects resulting from major nuclear accidents at Three Mile Island, Chernobyl, and Fukushima Daiichi. He emphasizes the distinction between natural background radiation and the elevated anthropogenic radiation released during these events. The study outlines multiple pathways of exposure, including airborne radionuclide dispersal, soil deposition, and water contamination, which enable radioactive materials to enter the food chain through crops, livestock, and aquatic organisms. According to Yamada, short-term ecological impacts include immediate habitat contamination, acute physiological stress in exposed organisms, and disruption of local

biodiversity, while long-term effects involve persistent radionuclide accumulation, chronic ecological exposure, genetic mutations, and long-lasting alterations to ecosystem structure and function.

Wehrden, et al. [9] analyze the ecological consequences of nuclear accidents on biodiversity and ecosystem services, highlighting the stark contrast between background natural radiation and the concentrated anthropogenic radiation released during such events. They describe multiple pathways of exposure, including airborne dispersion of radionuclides, soil contamination, and waterborne transport, which allow radiation to infiltrate ecosystems and the food chain, impacting both plants and animals. The study emphasizes that short-term ecological impacts often manifest as acute mortality, disruption of reproductive cycles, and immediate loss of habitat, while long-term consequences include persistent radionuclide contamination, reductions in species richness, altered community composition, and degradation of ecosystem services such as soil fertility and water purification.

### III. CRITICAL EVALUATION OF THE IMPACT OF NUCLEAR ACCIDENTS ON THE ENVIRONMENT

Nuclear accidents represent some of the most severe anthropogenic disruptions to natural ecosystems, with consequences that span decades and cross geographic, ecological, and political boundaries. A critical evaluation of their environmental impacts reveals a complex interplay between radionuclide behavior, ecosystem vulnerability, emergency management failures, and long-term socio-ecological repercussions. Events such as Chernobyl (1986) and Fukushima Daiichi (2011) remain the most extensively studied due to their scale and severity [6, 8]. Smaller nuclear incidents, including Three Mile Island (1979) and accidental releases from research or industrial facilities, collectively demonstrate that even low-level radiation events can exert measurable ecological pressure when containment systems fail [10, 13].

Studies consistently show that radioactive materials released during accidents contaminate the environment through atmospheric deposition, soil infiltration, water transport, and bioaccumulation across trophic levels [4, 10]. However, the degree of environmental impact varies significantly depending on accident mechanics, radionuclide composition, and local ecological characteristics. For example, Chernobyl's graphite fire propelled large quantities of volatile isotopes into the atmosphere, causing widespread terrestrial contamination, whereas Fukushima's marine discharge resulted in unprecedented coastal and marine pollution [5, 6, 13]. These differences expose a core limitation in environmental risk assessments: many models assume uniform radionuclide behavior despite clear evidence that environmental transport and toxicity depend heavily on chemical form, solubility, and ecosystem type.

Studies such as Lee, et al. [13] broaden the discourse by examining radioactive releases from non-reactor facilities like particle accelerators. While the scale of release is significantly smaller than in Chernobyl or Fukushima, their findings demonstrate that unplanned radiation releases, regardless of origin, can mimic key ecological pathways seen in major accidents, such as airborne dispersion, soil deposition, and food chain accumulation.

However, the ecological impacts in this context are largely inferential, as the magnitude of contamination and long-term consequences are not comparable to reactor-scale disasters. In contrast, Sihver and Yasuda [6] provide one of the most technically detailed comparisons of the Chernobyl and Fukushima accidents, clearly outlining differences in accident mechanisms, radionuclide release magnitudes, and spatial distribution of fallout. Their contribution is strong on radiological and mechanistic grounds, though ecological interpretations remain underdeveloped, particularly regarding how contaminated landscapes and marine environments responded over time.

Basically, short-term impacts are characterized by acute mortality, physiological stress, and reproductive disruption, particularly in intensively monitored zones. Yet the most contentious debate

arises from evaluating long-term, chronic ecological effects. While some researchers argue that biodiversity rebounds in exclusion zones indicate resilience and partial ecosystem recovery, others highlight persistent genetic damage, altered species composition, behavioral abnormalities, and ecosystem restructuring.

The apparent “rewilding” of Chernobyl, often cited as an example of ecological recovery, is increasingly critiqued as being superficial. Many species show reduced reproductive success, suppressed immune function, and decreased population viability due to chronic exposure [4]. These inconsistencies highlight a methodological shortcoming, which is a long-term monitoring is fragmented and lacks standardized indicators, making cross-study comparisons unreliable. Kurilovská and Mullerova [5] complement this perspective by focusing on crisis management and the environmental risks arising from containment failures. They offer a more operational view of how radionuclides travel through ecological systems. Although their analysis highlights critical short- and long-term ecological threats, it tends to remain procedural rather than ecological, with limited discussion of biological responses or ecosystem-specific vulnerabilities.

More ecologically centered perspectives emerge from Ishikawa [14] and Hasegawa, et al. [7] both of whom analyze the environmental consequences of Fukushima with attention to exposure pathways and dose assessments. Ishikawa highlights the significant marine contamination following Fukushima, detailing how radionuclides entered fisheries, sediments, and coastal ecosystems. While this expands understanding of marine vulnerability, the study provides limited discussion of terrestrial ecosystem responses. Hasegawa et al. bridge ecological and human health dimensions by examining how soil contamination, bioaccumulation, and chronic exposure shaped long-term risks in both wildlife and agricultural systems. Their comparison with Chernobyl identifies similar patterns of soil deposition and ecosystem disruption, though the analysis remains more descriptive than integrative, with limited synthesis of cross-ecosystem differences.

Yamada [8] offers the broadest comparative perspective by including Three Mile Island (TMI) alongside Chernobyl and Fukushima. His work highlights how containment success at TMI minimized ecological impacts, in contrast to the extensive fallout and ecosystem disruption documented in Chernobyl, and the mixed terrestrial–marine contamination patterns characteristic of Fukushima. While valuable for framing differences in accident severity and emergency response effectiveness, Yamada’s narrative lacks the mechanistic ecological detail found in more recent studies, relying instead on generalized descriptions of exposure and contamination.

A critical environmental risk understated in earlier assessments is the interaction between contamination and broader ecological factors. Radiation rarely acts alone; wildfire events in contaminated forests, flooding, erosion, and agricultural activities can remobilize radionuclides decades after the initial accident. This secondary redistribution complicates remediation and perpetuates environmental exposure, reinforcing that nuclear accidents initiate a prolonged contamination cycle rather than a single-point event. Furthermore, the term of persistent radionuclides such as cesium-137 and strontium-90 continues to affect soil fertility, food safety, and water quality long after initial cleanup efforts have ended [4, 10].

Additionally, emergency response and crisis management efforts also warrant rigorous critique. Comparative analyses reveal that environmental damage is often amplified not merely by the accident itself but by delays in containment, inadequate monitoring, and insufficient environmental risk communication. In Fukushima, for example, the failure to prevent contaminated water from reaching the ocean was partly attributed to inadequate infrastructure and delayed decision-making, while Chernobyl’s widespread fallout stemmed from both reactor design flaws and delayed hazard acknowledgment [6, 8, 13, 14]. These cases underline the systemic vulnerability of nuclear facilities to natural disasters, human error, and institutional shortcomings.

Conclusively, the studies illustrate that the scale and nature of radionuclide release fundamentally shape

ecological settings, with Chernobyl representing catastrophic terrestrial contamination. Also, Fukushima demonstrated significant marine and coastal impacts, and TMI offered a case where effective containment limited environmental consequences.

#### IV. GLOBAL MONITORING AND REGULATORY RESPONSES ON NUCLEAR ACCIDENTS AND RADIATION LEAKS

Global monitoring and regulatory frameworks for nuclear accidents and radiation leaks have evolved significantly in response to catastrophic events such as Chernobyl (1986) and Fukushima Daiichi (2011). These incidents exposed major weaknesses in early-warning systems, international communication networks, and emergency coordination. This prompted the development of more effective radiation surveillance and regulatory protocols.

One of the principal actors in global monitoring is the International Atomic Energy Agency (IAEA), whose mandate includes facilitating radiation detection, establishing safety standards, and ensuring that member states report nuclear events transparently [15]. Furthermore, the IAEA's Incident and Emergency Centre (IEC) operates 24/7 to coordinate global responses [16]. However, compliance still varies widely by country, and reporting remains influenced by political and economic considerations. This variability in adherence underscores the current challenge, that is, global monitoring systems depend heavily on national approval to share data [17].

Regulatory responses at the global level have advanced in parallel with monitoring efforts, though gaps remain. After Chernobyl, the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency were established, aiming to create legally binding frameworks for timely communication and international support [18].

However, these conventions rely on national self-reporting, and the Fukushima accident revealed their limitations when initial delays and incomplete information hindered international protective actions.

As a result, regulatory bodies have increasingly emphasized harmonized safety standards, peer-review mechanisms, and stress tests to evaluate the resilience of nuclear facilities against natural disasters, system failures, and human error [4, 10].

The European Union's post-Fukushima stress tests, for example, revealed significant weaknesses in reactor safety protocols across multiple countries, prompting new regulatory reforms [19, 20]. Still, regulatory enforcement remains inconsistent globally, particularly in regions where nuclear governance infrastructure is weak.

In addition to international bodies, national regulatory agencies play a central role in enforcing safety standards and coordinating emergency responses. Agencies such as the U.S. Nuclear Regulatory Commission (NRC), the Japanese Nuclear Regulation Authority (NRA), and the French Autorité de Sûreté Nucléaire (ASN) have strengthened reactor safety requirements, improved public communication protocols, and introduced mandatory risk assessments. Yet a critical evaluation reveals persistent systemic challenges: regulatory capture, political pressure to maintain nuclear capacity, and unequal resourcing limit the independence and effectiveness of many agencies.

Technological advancements have significantly strengthened global monitoring capabilities. The International Monitoring System (IMS), originally designed under the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to detect clandestine nuclear tests, has become a crucial tool in tracking radiation releases from accidental events [21-23]. With networks of radionuclide stations, seismic arrays, infrasound sensors, and hydroacoustic detectors, the IMS provides a near-real-time global radiological picture [24]. Its ability to detect Fukushima's radioactive plumes as they circled the globe demonstrated both the effectiveness and necessity of independent verification systems [21, 22].

Nonetheless, the IMS is not explicitly designed for environmental monitoring, and access to its full dataset is limited to member states, leaving gaps in broader scientific and public-health applications. This highlights the tension between national security

interests and the need for transparency in global radiation surveillance.

Despite these advancements, the global system still lacks a fully integrated, standardized, and enforceable regulatory architecture. Fragmentation across jurisdictions leads to inconsistencies in safety standards, emergency preparedness, and long-term environmental monitoring. Furthermore, radiation monitoring networks often focus on acute fallout events but inadequately address long-term ecological contamination, radionuclide migration, and cumulative exposure risks. Climate change adds another layer of complexity, as extreme weather events increasingly threaten nuclear facilities and radioactive waste repositories, highlighting the need for adaptive regulatory frameworks that account for evolving environmental hazards.

In conclusion, global monitoring and regulatory responses to nuclear accidents have strengthened considerably since the major disasters of the late 20th and early 21st centuries. Technological innovations, expanded surveillance networks, and more comprehensive regulatory frameworks contribute to improved detection, communication, and risk mitigation. However, significant challenges persist, including uneven national compliance, limited transparency, insufficient long-term monitoring, and the absence of a unified global enforcement mechanism.

#### V. FUTURE DIRECTIONS IN GLOBAL MONITORING AND REGULATORY MANAGEMENT OF NUCLEAR ACCIDENTS

Future efforts to strengthen global monitoring and regulatory responses to nuclear accidents must focus on addressing the persistent gaps in transparency, coordination, and long-term environmental surveillance. One critical priority is the development of a fully integrated international monitoring architecture that allows for real-time sharing of radiological data across borders.

Although networks such as the IAEA's Unified System for Information Exchange (USIE) and the CTBTO's International Monitoring System (IMS) provide essential capabilities, they remain

fragmented and largely dependent on voluntary compliance [4, 23]. A more unified, automated global platform, equipped with publicly accessible datasets and satellite-based radiation detection technologies, will effectively improve early warning accuracy, reduce delays in reporting, and enable faster international mobilization during emergencies.

Another key future direction involves enhancing regulatory independence and harmonizing global safety standards. Many nuclear regulatory bodies still face political and economic pressures that compromise their ability to enforce safety protocols, as revealed by the Fukushima accident. The establishment of legally binding international benchmarks for reactor design, ageing management, seismic resilience, cybersecurity, and emergency preparedness would create a more consistent global safety culture.

Additionally, periodic peer reviews, cross-national audits, and mandatory stress tests should be institutionalized through expanded IAEA authority to ensure that safety standards do not vary widely between countries [5, 16]. Strengthening regulatory oversight for emerging reactor technologies, including small modular reactors (SMRs) and advanced Generation IV designs, is also essential as the future nuclear landscape diversifies.

Long-term environmental monitoring represents another foundational area for future improvement. Most radiation surveillance systems emphasize acute, short-term fallout, but long-term ecological recovery, radionuclide migration in soil and water, bioaccumulation, and chronic low-dose exposure remain insufficiently studied. Future research must focus on improving ecological risk models, integrating biological indicators (e.g., genetic biomarkers, bioaccumulation patterns), and expanding ocean-based monitoring networks, particularly in regions vulnerable to marine transport of radionuclides.

Also, investment in autonomous drones, sensor arrays, and machine-learning models capable of predicting dispersion pathways will aid both scientific understanding and emergency planning.

Finally, future directions must consider the geopolitical dimensions of nuclear safety. The establishment of multilateral rapid-response teams under the IAEA is highly recommended, and improvement in access to international assistance resources will create an equitable and resilient global safety system.

## VI. CONCLUSION

Global monitoring and regulatory responses to nuclear accidents and radiation leaks have evolved significantly over the past several decades, driven by lessons learned from major events such as Chernobyl, Fukushima, and the Three Mile Island incident. Furthermore, international frameworks anchored by the IAEA's safety standards, real-time radiological monitoring networks, and regional early-warning systems provide the backbone for coordinated detection, reporting, and mitigation of radiological hazards. These systems have strengthened transparency, improved emergency preparedness, and supported standardized communication among nations.

However, despite these advancements, substantial challenges remain. Monitoring capabilities are unevenly distributed, with developing regions lacking adequate real-time sensors, trained personnel, and effective regulatory infrastructure. At the global level, reporting mechanisms still rely heavily on voluntary disclosure, leaving gaps during politically sensitive or rapidly evolving crises. Furthermore, the increasing complexity of modern nuclear technologies, the emergence of small modular reactors, and the risks posed by geopolitical conflicts underscore the need for more adaptive, resilient, and technologically integrated monitoring regimes.

In conclusion, while substantial progress has been made in global surveillance and regulation of nuclear accidents and radiation leaks, sustaining long-term environmental and public health protection requires continuous improvement. Strengthening international cooperation, expanding sensor networks, harmonizing regulatory frameworks, and investing in advanced detection technologies are essential steps. Ultimately, the global community must embrace a proactive, science-driven, and transparent approach

to ensure that future nuclear incidents are detected early, communicated responsibly, and managed effectively to safeguard both human and ecological systems.

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