

Environmental Impacts of Ionizing Radiation: Sources, Pathways, and Environmental Consequences

Yunus Tawana^{1*}, Prof. Rajab Ali khawari², Prof. Ihsanullah saqib³

^{1,2}Department of Nuclear and Atomic Physics, Faculty of Physics, Kabul University, Kabul, Afghanistan.

³Department of Nuclear and Atomic Physics, Faculty of Physics, Nangarhar University, Nangarhar, Afghanistan.

ABSTRACT: Ionizing radiation is a significant physical factor that, in cases of improper exposure or the release of radioactive materials into the environment, can impact environmental quality, the health of living organisms, and ecosystem balance. These radiations originate from natural sources such as cosmic rays, radionuclides in the Earth's crust, and radon gas as well as artificial sources resulting from medical, industrial, and nuclear activities. This article aims to examine the environmental impacts of ionizing radiation, emphasizing the fundamentals of nuclear physics and the pathways of radionuclide transport within the environment. Conducted using a literature review and a descriptive-analytical approach, the study focuses on concepts such as radioactive decay, half-life, radionuclide activity, radiation type and energy, and radiation-matter interaction. Furthermore, it investigates the dispersion and transport pathways of radioactive materials in air, water, soil, and sediments, as well as their entry into plants, animals, and the food chain. Analysis of the literature indicates that the persistence and transport of radionuclides in the environment depend not solely on their radioactive activity but also on factors such as half-life, chemical properties, soil composition, climatic conditions, and bioavailability. Additionally, exposure to ionizing radiation may, under certain conditions, cause cellular damage and biological alterations in living organisms; however, the nature and severity of these consequences depend on the absorbed dose, dose rate, type of radiation, and the biological sensitivity of the organisms. Consequently, understanding the fundamentals of nuclear physics and simultaneously examining radionuclide transport pathways is essential for a better understanding of the environmental impacts of ionizing radiation. This study can provide the necessary scientific foundation for future field research on radioactive contamination across various environmental compartments.

KEYWORDS: environmental transport, food chain, Ionizing radiation, nuclear physics, radionuclides, radioactive contamination,

1. INTRODUCTION

Ionizing radiation refers to electromagnetic waves or particles possessing sufficient energy (typically around 30 electron-volts or more in living tissue) to detach electrons from atoms or molecules, thereby creating positive ion-free electron pairs. These radiations exist either within the electromagnetic spectrum or as high-speed particles (Gruppen, 2010). Ionizing radiation includes alpha (α), beta (β), and gamma (γ) radiation, X-rays, and positrons; these forms of radiation possess sufficient energy to eject electrons from atoms. As they pass through matter, energy transfer, ionization, and excitation occur—processes that can induce chemical changes and biological damage (Turner, 2007). In contrast, non-ionizing radiation—such as radio waves, visible light, or ultraviolet radiation—does not possess this energy (UNEP, 2016). The use of radiation in medical diagnosis and treatment, industry, and research is beneficial; however, inadequate source control, nuclear accidents, and improper waste management can lead to environmental contamination and unintended exposure (United Nations Environment Programme [UNEP], 2016). The environmental significance of the issue extends beyond direct radiation exposure; radioactive materials may deposit in soil or water, be taken up by plants, transfer to livestock, and ultimately reach humans through the food chain or the inhalation of dust (IAEA, 2006). Consequently, understanding these impacts requires a grasp of fundamental nuclear physics concepts, such as radioactive decay, nuclear activity, radiation type and energy, radiation-matter interaction, absorbed dose, and dose rate (Kai et al., 2020). Ionizing radiation is a significant nuclear phenomenon observed in both natural settings and human activities; according to the standards of the International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA), sources of ionizing radiation are categorized into two main groups: natural and artificial (man-made).

2. METHODOLOGY

2.1. Study Design

In terms of objective, this research is applied in nature; regarding its execution method, it is a review study employing a descriptive-analytical approach. This study examines scientific literature concerning the environmental impacts of ionizing radiation to analyse the nature of such radiation, its nuclear-physical characteristics, and the mechanisms of radioactive material dispersion and transport within the environment. The study relies on published sources and does not involve new experiments or field measurements.

2.2. Theoretical Framework

The research's theoretical framework is grounded in the principles of nuclear physics and concepts regarding the behavior of radioactive materials in the environment. Key concepts include radioactive decay, half-life, radionuclide activity, radiation-matter interaction, and the transport of radionuclides through air, water, and soil. Additionally, the study examines the transfer of radioactive materials from the environment to plants, animals, and the food chain, as well as the potential consequences for living organisms. This framework facilitates an analysis of the relationships between the physical properties of radioactive materials, their release rates, and their environmental impacts.

2.3. Data Sources and Extraction

Research data are gathered from secondary sources, including scientific research articles, specialized nuclear physics texts, scientific reports, and documents from reputable international organizations concerned with radioactive materials and the environment. Keywords such as ionizing radiation, environmental effects of radiation, radionuclides, transport of radioactive materials, and half-life are used to locate these sources.

Relevant information is extracted from the selected sources and categorized according to themes such as radiation sources, nuclear properties, environmental transport pathways, and biological and ecological consequences. Criteria for source selection include topical relevance, scientific credibility, and the clarity of the information.

2.4. Data Analysis Method

The collected data are examined using a descriptive-analytical approach. First, the concepts and scientific findings from the sources are outlined; subsequently, the similarities, differences, and relationships among them are compared. The analysis focuses on the pathways of radionuclide dispersion and transport across various environmental compartments, as well as the roles of factors such as half-life, radionuclide activity, radiation type, and environmental characteristics. Finally, the findings are synthesized thematically to provide a clear understanding of the factors influencing the environmental impacts of ionizing radiation.

2.5. Research Scope and Limitations

Research Scope: This study focuses on the environmental impacts of ionizing radiation, emphasizing the fundamentals of nuclear physics. The environments under investigation include air, water, and soil; additionally, subject to the availability of relevant sources, the transfer of radionuclides to plants, animals, and the food chain is examined. The primary focus is on the scientific analysis of published literature.

Research Limitations: Potential limitations of this study include restricted access to the full text of certain articles, variations in measurement and reporting methods across studies, a scarcity of local environmental data, and differences in the geographical and climatic conditions of the regions studied. Furthermore, as the research relies on secondary sources, its findings do not substitute for direct field or laboratory measurements.

3. RESULTS

3.1. Fundamentals of Ionizing Radiation

Ionizing radiation refers to radiation possessing sufficient energy to remove electrons from atoms or molecules, thereby creating ions. Such radiation is categorized into two general groups:

- Particulate radiation: such as alpha particles, beta particles, and neutrons.
- Electromagnetic radiation: such as gamma rays and X-rays.

These types of radiation differ in their ionizing capability, ability to penetrate matter, and the amount of energy transferred to the medium. Consequently, one type of radiation may have limited penetration in air or tissue, whereas another may travel a greater distance or require thicker shielding (Knoll, 2010); Turner, 2007).

3.2. Radioactive Decay, Half-Life, and Activity

Unstable nuclei transform into a more stable state or into another nucleus by emitting particles or photons. This process is called radioactive decay, and the number of remaining nuclei after time t is expressed by the following relationship:

$$(1) \quad N(t) = N_0 e^{-\lambda t}$$

Half-life is the time it takes for the number of radioactive nuclei to decrease to half of the initial amount:

$$(2) \quad T_{1/2} = \frac{\ln 2}{\lambda}$$

Short-lived radionuclides may lose the bulk of their activity within a relatively short period, whereas long-lived radionuclides can persist in the environment for much longer. However, half-life alone does not determine the level of risk; initial activity, radiation type, energy, environmental mobility, and chemical toxicity are also significant factors.

Activity is the number of nuclear decays per unit time; the relationship between activity and the number of remaining nuclei is as follows:

$$(3) \quad A(T) = \lambda N(t)$$

In the assessment of environmental contamination, activity concentration is also significant. For instance, the activity of a radionuclide per kilogram of soil or per liter of water can be used to compare environmental samples. However, high activity does not automatically equate to a high absorbed dose, as factors such as the type of radiation, exposure geometry, energy, and duration of contact must also be taken into account.

4. SOURCES OF IONIZING RADIATION

4.1. Natural Sources

Natural ionizing radiation is part of the Earth's environment, and humans are constantly exposed to it:

Cosmic Radiation: Includes primary cosmic rays (mainly high-energy protons emitted from the sun and galactic space) and secondary cosmic rays (such as neutrons, muons, electrons, positrons, and photons) produced by the interaction of primary rays with the Earth's atmosphere. Cosmic radiation exposure increases with altitude (e.g., during air travel) and at polar latitudes (Lindell, n.d.; Lochard et al., 2016).

Terrestrial Sources: Primordial radionuclides present in the Earth's crust, soil, and rocks—including uranium (^{238}U and ^{235}U), thorium (^{232}Th), and potassium (^{40}K)—and their decay products (Lochard et al., 2016).

Internal Exposure & Radon: The entry of natural radionuclides into the body through the inhalation of air and the consumption of water and food. Radon gas (^{222}Rn) and its decay products, which accumulate in enclosed spaces and homes, account for approximately half of the annual natural radiation dose received by individuals (EUROPEAN COMMISSION et al., 2014).

4.2. Artificial and Man-made Sources

Artificial sources result from human achievements, technologies, and activities (IAEA, 2011). Medical equipment and applications (Medical Sources) account for the largest share of artificial radiation exposure among human populations. These sources include radiation-generating devices (such as X-ray and CT scanners) and radiopharmaceuticals or radiation sources used in radiology, nuclear medicine, and radiotherapy (EUROPEAN COMMISSION et al., 2014).

Radiation generators and accelerators: Electrical devices—such as X-ray tubes, accelerators (cyclotrons and synchrotrons), and neutron generators—that do not contain radioactive material and produce radiation only when connected to an electrical power supply (Valentin, 2005).

Industrial and research radiation sources: Sealed and unsealed sources containing radioisotopes such as ^{60}Co , ^{137}Cs , ^{192}Ir , ^{252}Cf , and ^{241}Am , used in industrial radiography, control gauges, oil well logging, and sterilization equipment (Valentin, 2005).

Nuclear facilities and fuel cycle: Nuclear reactors, nuclear power plants, spent fuel, and the radioactive waste derived from them (EUROPEAN COMMISSION et al., 2014).

Naturally Occurring Radioactive Material (NORM) and radioactive contaminants: Industrial activities such as extraction and mining, construction materials, as well as deposits and residues resulting from past nuclear accidents or nuclear weapon tests (Clement, 2018).

5. CLASSIFICATION OF IONIZING RADIATION

5.1. Directly Ionizing Radiation (Charged Particles)

Alpha (α) particles: These consist of helium nuclei (two protons and two neutrons) with a +2 charge and high mass; their energy typically ranges from 4 to 6 MeV, and they possess high ionizing power. However, they have a very short range (a few centimeters in air) and are stopped by a sheet of paper or the outer layer of the skin; nevertheless, their entry into the body via inhalation or ingestion is highly dangerous (Gruppen, 2010). Heavy charged particles are used in hadron therapy for cancerous tissues due to the presence of the Bragg peak at the end of their range (Colombo, 2019)

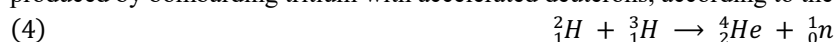
Beta (β) particles: These are high-speed electrons or positrons emitted from the nuclei of unstable atoms, characterized by very low mass and a unit electric charge. They exhibit a continuous energy spectrum and greater penetrating power than alpha particles (penetrating a few millimeters into tissue), yet they can be stopped by thin layers of plastic or aluminium (Gruppen, 2010).

5.2. Indirectly Ionizing Radiation (Photons and Neutral Particles)

Gamma and X-rays: These are forms of electromagnetic radiation (photon waves)—possessing neither mass nor charge—characterized by very short wavelengths, extremely high frequencies, and high energy (typically in the mega-electron-volt range for gamma rays, which are emitted during nuclear transitions) (Knoll, 2010). Unlike charged particles (such as alpha and beta particles), these rays do not directly ionize matter; instead, their interaction with matter (via phenomena such as the photoelectric effect, Compton scattering, and pair production) releases high-energy secondary electrons, which subsequently cause ionization in the medium (Sabol, 2023). Due to their lack of electric charge and mass, gamma rays exhibit a very long range and high penetrating power in matter and living tissues. Attenuation and shielding against gamma rays require dense, thick layers of materials with high atomic numbers (such as lead, concrete, or steel) (Naji et al., 2026). X-rays are electromagnetic waves similar to gamma rays, but they originate from electronic transitions within the atom or from the deceleration of high-speed electrons upon striking a metal target (a process known as *Bremsstrahlung*) (Gruppen, 2010).

5.3. Neutrons (n)

Nuclear reactors are the most prolific sources of neutrons; the energy spectrum of neutrons resulting from the fission of ^{235}U spans a range from a few keV to over 10 MeV. The mean energy of this distribution is approximately 2 MeV. Research reactors often feature ports through which neutron beams are directed to experimental areas outside the reactor's primary shielding; the energy of these neutrons is typically reduced as they pass through the reactor core, coolant, and structural materials (Prussin, 2007). Particle accelerators can also be used to generate a variety of neutron beams through different reactions. For instance, neutrons can be produced by bombarding tritium with accelerated deuterons, according to the following reaction:



Neutrons are electrically neutral particles that do not cause direct ionization; instead, they generate secondary charged particles through collisions with atomic nuclei. Hydrogen-rich materials, such as water and paraffin, are the most effective neutron moderators (Turner, 2007).

6. PATHWAYS OF RADIONUCLIDE ENTRY INTO THE ENVIRONMENT

The transfer of radionuclides among air, water, soil, and living organisms is a primary determinant of environmental impacts. Major pathways include:

- Release of radioactive particles or gases into the air;
- Deposition of radioactive materials onto soil, vegetation, and surfaces;
- Transfer to surface waters via precipitation and runoff;
- Infiltration into groundwater;
- Uptake through plant roots;
- Transfer to animals via food and water;
- Entry into the human body through inhalation, ingestion, or, in certain situations, through wounds.

Radionuclide transfer depends on more than just radioactivity levels. Key factors include:

- Nuclear properties: Half-life, decay mode, and radiation energy.
- Chemical properties: Solubility, oxidation state, and affinity for binding with minerals or organic matter.

- Soil properties: Mineral type, pH, organic matter content, and moisture.
- Climatic conditions: Precipitation, wind, temperature, and runoff.
- Biological characteristics: Plant type, root depth, animal feeding habits, and rates of bodily excretion.

For instance, two radionuclides with similar initial activity levels may exhibit vastly different behaviors in soil and the food chain due to differences in solubility and bioavailability (IAEA, 2014; Reisz et al., 2014).

6.1. Impact on Water

Water contamination with radioactive materials is a major environmental and health challenge, as water serves as the primary pathway for radionuclides to enter the human body and the food chain. Through the weathering of rocks, rainfall can wash natural radioactive elements—such as uranium, radium, and thorium—into groundwater, rivers, and oceans (Grupen, 2010). Aquatic organisms (such as shellfish and fish) accumulate suspended radioactive particles in their tissues through filter feeding. The concentration of cesium-137 in the tissue of shellfish has been recorded to be significantly higher than that in the dissolved phase of seawater, indicating biomagnification and transport in the marine food chain (Hosoda et al., 2026). Drinking contaminated water and consuming seafood are the main routes of internal human exposure. The entry of radionuclides into the body triggers the ionization of intracellular water molecules (radiolysis), generating free radicals and substances such as hydrogen peroxide that attack vital cellular structures; chronic exposure via drinking water significantly increases the risk of developing various cancers (including gastrointestinal and thyroid cancers) and leukemia (Taha et al., 2025).

6.2. Impact on Soil

Radioactive soil contamination is a central topic in radioecology and environmental radiation protection. Soil naturally contains primordial radionuclides such as potassium-40 (^{40}K), uranium-238 (^{238}U), thorium-232 (^{232}Th), and radium-226 (^{226}Ra); additionally, radon gas—a product of radium decay—accumulates within soil pores (Clement et al., 2014).

Atmospheric release and deposition of radionuclides such as cesium-137 (^{137}Cs), cesium-134 (^{134}Cs), strontium-90 (^{90}Sr), and iodine-131 (^{131}I) during accidents like Chernobyl and Fukushima result in widespread surface soil contamination. Furthermore, the interaction of high-energy neutron flux with the atoms constituting the soil (such as silicon, oxygen, iron, and manganese) in the vicinity of nuclear facilities or accelerators leads to the production of secondary radionuclides within the soil—a process known as soil activation (Kai et al., 2020).

6.3. Impact on Air

Air contamination by radioactive materials and ionizing radiation is a fundamental topic in radiation health and protection. Radioactive materials in the atmosphere can exist as gases, vapors, aerosols, or suspended particulates. Radon gas (^{222}Rn) and its progeny—the most significant natural source, resulting from the decay of radium (^{226}Ra) in the natural uranium series—emanate from soil and rock into the air. While radon itself is an inert gas that does not accumulate in the body, its short-lived solid progeny (such as ^{218}Po and ^{214}Po) attach to airborne dust and suspended particulates; inhaling these radon progeny accounts for over 50% of the total natural equivalent dose received by humans (approximately 1.2 mSv per year) (Turner, 2007). Regarding cosmogenic radionuclides, the interaction of cosmic rays with atmospheric gases generates radioisotopes such as carbon-14 (^{14}C)—via the $^{14}\text{N}(\text{n,p})^{14}\text{C}$ reaction—tritium (^3H), beryllium-7 (^7Be), and sodium-22 (^{22}Na) in the air (Turner, 2007). Atmospheric nuclear tests and nuclear accidents (such as the Chernobyl disaster) have resulted in the dispersal of fission products like cesium-137 (^{137}Cs) and strontium-90 (^{90}Sr) into the atmosphere; nuclear weapon tests in the atmosphere have caused the release of fallout... radioactive material (fallout) and hazardous isotopes—such as Cesium-137 (^{137}Cs) and Iodine-131 (^{131}I)—are released into the atmosphere, subsequently being washed out by rain or settling onto the ground (Grupen, 2010).

Coal-fired power plants—or the combustion of coal for electricity generation—release large quantities of naturally occurring radioactive materials (including approximately 800 tons of uranium annually in a country like the United States) into the air through their stacks; without adequate filtration, these emissions can exceed those resulting from the normal operation of nuclear power plants (Grupen, 2010).

6.4. Impact on Plants and the Food Chain

Plants are exposed to radiation via two primary pathways: external exposure—involving the direct deposition of radioactive materials onto leaf and stem surfaces and exposure to radiation from contaminated soil and surrounding air—and internal exposure,

which entails the uptake of radionuclides (such as Cesium-137 and Strontium-90) through roots from contaminated soil and water, or direct absorption from the water column by algae and aquatic plants (Kai et al., 2020).

Plants may be exposed to radiation externally or absorb radionuclides from soil and water; the deposition of radioactive substances on leaves and stems also constitutes an exposure pathway. Subsequently, the absorbed materials may be transferred to livestock via forage and to humans through milk, meat, agricultural produce, fruits, or fungi. The inhalation of contaminated dust rising from the soil is another potential exposure route (Kai et al., 2020). The rate of transfer depends on the type of radionuclide, the plant or animal species, and environmental conditions; therefore, applying a single, constant transfer value across all ecosystems is inappropriate.

6.5. Effects on Animals and Ecosystems

Animals may be exposed to radiation through external irradiation or the intake of radioactive materials via water and food. Consequences can range from cellular changes to impacts on growth, survival, and reproduction; however, the nature of the effect and the likelihood of its occurrence depend on the dose, dose rate, type of radiation, and species sensitivity (International Commission on Radiological Protection, 2014). At the ecosystem level, assessments should not focus solely on a single organism. Food web interactions, population dynamics, material cycling, habitat quality, and the potential transfer of radionuclides among environmental components must also be considered. Environmental protection assessments require methods that reflect differences between species and ecological conditions (International Commission on Radiological Protection, 2023 ICRP, 2014).

6.6. Effects on humans

Prolonged exposure to high levels of radiation can lead to a wide range of health problems, including cancer, damage to the hematopoietic system, thyroid dysfunction, liver impairment, damage to the lens of the eye, and immune system disorders (Chen, 2026).

Humans may encounter radiation via two primary pathways:

1. External exposure: The radiation source is located outside the body.
2. Internal exposure: Radioactive material enters the body through inhalation, ingestion, or other routes.

By transferring energy to tissues, ionizing radiation can induce ionization and chemical reactions, thereby damaging biological molecules, including DNA. The consequences depend on the dose, radiation type, dose rate, exposed tissue, and cellular repair capacity. In radiation protection, effects involving tissue thresholds are distinguished from potential carcinogenic risks; therefore, it cannot be claimed that any level of exposure necessarily leads to observable disease (Valentin & International Commission on Radiological Protection, 2007).

7. FACTORS DETERMINING THE SEVERITY OF THE EFFECT

According to the literature, the severity of an environmental effect does not depend solely on the presence of radioactive material. The most important factors are: (1) the type of radiation and its energy; (2) the type of radionuclide and its half-life; (3) the activity concentration in air, water, soil, or tissue; (4) the absorbed dose and dose rate; (5) the duration and pathway of exposure; (6) bioavailability and transferability; and (7) species sensitivity and developmental stage. Consequently, the mere presence of a radionuclide in the environment is insufficient to draw conclusions regarding the extent of damage; the dose and exposure pathways must also be evaluated.

8. DISCUSSION AND ANALYSIS

8.1. The Role of Nuclear Physics Principles in Explaining the Environmental Effects of Ionizing Radiation

Findings from the reviewed literature indicate that understanding the environmental effects of ionizing radiation is impossible without grasping the physical properties of nuclei and the interaction of radiation with matter. Unstable nuclei transition to more stable states through radioactive decay, a process that may involve the emission of alpha particles, beta particles, or gamma photons. The rate of this process is linked to the radionuclide's decay constant and half-life; consequently, long-lived radionuclides can persist in the environment for extended periods, whereas short-lived radionuclides may lose the bulk of their activity in a relatively short time (Knoll, 2010; Turner, 2007).

Regarding interactions with matter, the distinctions between alpha, beta, gamma, X-ray, and neutron radiations are of particular importance. Alpha particles possess high ionizing power but limited penetration in matter; thus, the entry of alpha-emitting materials

into the body via inhalation or ingestion poses significant radiological protection concerns. Beta particles have greater penetrating power than alpha particles, while gamma photons and X-rays—due to their higher penetrability—require appropriate shielding measures. Neutrons, too, can transfer energy to matter through nuclear interactions and the production of secondary particles. Consequently, the choice of protection method should be based on the type of radiation and the characteristics of the source, rather than applying a uniform method to all forms of radiation (Gruppen, 2010; Knoll, 2010; Turner, 2007).

8.2. Analysis of Radionuclide Transport Pathways in the Environment

A fundamental finding of source characterization is that the environmental impacts of radioactive materials cannot be assessed solely based on the initial release location. Following atmospheric release, radionuclides may deposit onto the ground and vegetation, be transported to surface waters via precipitation, remain in the soil, or gradually infiltrate groundwater. The resuspension of contaminated particles from the soil surface into the air can also create a new exposure pathway. Therefore, assessments of environmental contamination must consider the interconnections between air, water, soil, and living organisms (Kai et al., 2020).

The behavior of a radionuclide in the environment depends on its nuclear and chemical properties; half-life and decay mode influence its radiological persistence, whereas solubility, chemical state, particle size, and the substance's affinity for binding with minerals or organic matter can alter its transport in water and soil. Furthermore, factors such as soil acidity, moisture, precipitation, temperature, vegetation type, and the activity of living organisms influence the mobility and bioavailability of radionuclides. Consequently, two environments with similar initial contamination levels may yield different outcomes regarding the transport of radioactive materials and the extent of exposure for living organisms (IAEA, 2014; Kai et al., 2020).

This analysis demonstrates that measuring radiation at a single point is insufficient for an accurate assessment of environmental risk. It is essential that sampling of relevant environmental components—such as soil, water, sediments, and food products—be accompanied by the identification of radionuclides and an assessment of potential transmission pathways. Such an approach can help identify sources of contamination, pinpoint critical areas, and select appropriate measures to mitigate release and exposure.

8.3. Transfer of Radionuclides to Plants, Animals, and the Food Chain

Plants play a fundamental role in the interaction between soil, water, and animals. Radionuclides may deposit directly onto plant leaves and stems or be absorbed from soil and water through the roots. Under certain conditions, these substances can be transferred to animals via forage and crops, and subsequently to humans through milk, meat, fruits, and other food products. However, the extent of this transfer depends on the type of radionuclide, soil and water characteristics, the plant or animal species, and environmental conditions; therefore, applying a uniform transfer rate across all ecosystems is scientifically inappropriate (IAEA, 2014; Kai et al., 2020).

From the perspectives of nuclear physics and radioecology, a distinction must be made between the presence of a radioactive substance in the environment and its concentration within the tissues of a living organism. A radionuclide may be present in the environment yet exhibit limited bioavailability; conversely, under specific conditions, its transfer and accumulation within certain segments of the food chain may become significant. Consequently, risk assessment must consider not only environmental activity measurements but also pathways of entry into the body and potential exposure levels.

8.4. Biological Consequences for Humans and Ecosystems

When ionizing radiation interacts with living tissue, it can ionize atoms and molecules and trigger chemical reactions. This process may damage biological molecules, including DNA. The ultimate outcome depends on the absorbed dose, the type of radiation, the dose rate, the exposed tissue, and the capacity for cellular repair. Therefore, it should not be assumed that any level of exposure necessarily leads to observable disease; risk assessment must be based on scientific evidence and actual exposure levels (ICRP, 2007).

At the ecosystem level, the potential effects of radiation exposure can range from cellular changes to possible impacts on growth, survival, and reproduction. However, drawing conclusions regarding population-level effects or lasting ecological changes requires data on dose, duration of exposure, species sensitivity, and environmental conditions. An appropriate environmental assessment must account for inter-species differences and their relationships within food webs, rather than relying on a single organism or a limited indicator (IAEA, 2008; ICRP, 2014).

Accordingly, nuclear physics provides the necessary framework for understanding the source, radiation type, decay, and energy transfer, while radioecology and radiation protection are employed to examine environmental consequences and design control measures. Integrating these fields enables the assessment of radiation risks based on the actual characteristics of the source and exposure pathways.

9. LIMITATIONS OF THE ANALYSIS

This article is based on a review and analysis of scientific literature and existing thesis material; consequently, its findings represent a conceptual and theoretical synthesis of the subject and should not be interpreted as the result of an experiment or direct environmental assessment. No new measurements of radionuclide activity, contamination concentrations in environmental samples, or actual radiation doses received by specific populations were conducted for this article. Therefore, determining the precise level of risk in a given area—such as regions within Afghanistan—requires field studies, valid sampling, appropriate measurement equipment, and local data regarding sources and exposure pathways.

10. CONCLUSION

Ionizing radiation is of particular importance from the perspectives of nuclear physics and environmental protection due to its ability to ionize atoms and molecules. A review of scientific literature indicates that the environmental effects of such radiation are not limited merely to the presence of a radioactive source; rather, factors such as the nuclear properties of radionuclides, the type and energy of radiation, half-life, activity, mode of interaction with matter, and environmental conditions all play a role in determining potential consequences.

While radioactive decay and half-life explain the persistence of radioactive materials, risk assessment requires evaluating absorbed dose, dose rate, and exposure pathways alongside radioactivity levels. This demonstrates that high radionuclide activity does not automatically equate to greater biological damage; consequently, the interpretation of measurement results must account for the physical, chemical, and biological characteristics of the sample (Knoll, 2010; Turner, 2007).

Furthermore, the transfer of radionuclides across air, water, soil, flora, and fauna is a fundamental determinant of environmental risk. The persistence and mobility of radioactive materials depend on factors such as half-life, solubility, soil properties, climatic conditions, and the rate of biological uptake. Therefore, assessing environmental contamination requires the simultaneous examination of multiple environmental compartments and the identification of pathways leading into the food chain (IAEA, 2014; Kai et al., 2020).

From a biological standpoint, ionizing radiation can cause molecular and cellular damage if sufficient energy is transferred to tissues; However, the likelihood and severity of the consequences depend on exposure conditions and biological sensitivity. At the ecosystem level, potential impacts on various species and their ecological relationships must also be examined, rather than limiting the assessment solely to human health (Valentin & International Commission on Radiological Protection, 2007, 2008).

Ultimately, it can be concluded that mitigating the environmental risks associated with ionizing radiation requires integrating knowledge of nuclear physics, environmental monitoring, the safe management of radioactive sources, and the implementation of radiation protection principles. Key measures in this regard include preventing the release of radioactive materials, timely detection of contamination, controlling transport pathways, and adhering to the ALARA principle. Given the review nature of this article, determining the actual contamination status or risk level in a specific area requires the collection of field data and scientific measurements.

11. RECOMMENDATIONS

1. Establishing or strengthening radionuclide monitoring programs for air, water, soil, and food products, particularly near potential sources of contamination.
2. Reporting activity concentrations, ambient doses, and measurement uncertainties separately to enable valid comparisons across studies.
3. Investigating radionuclide transfer pathways from soil and water to plants, livestock, and food products through field studies.

- Utilizing established frameworks from the IAEA, ICRP, and UNSCEAR for sampling design, dose assessment, and environmental protection.

REFERENCES

- Clement, C. H. (Ed.). (2018). Proceedings of the Fourth International Symposium on the System of Radiological Protection. SAGE. International Symposium on the System of Radiological Protection.
- Clement, C. H., Hamada, N., & Lecomte, J.-F. (2014). Radiological protection against radon exposure. SAGE.
- Colombo, L. (2019). Atomic and Molecular Physics: A primer. IOP Publishing. <https://doi.org/10.1088/2053-2563/ab2df2>
- European commission, food and agriculture organization of the united nations, international atomic energy agency, international labour organization, oecd nuclear energy agency, pan american health organization, united nations environment programme, & world health organization. (2014). Radiation protection and safety of radiation sources: international basic safety standards. International atomic energy agency. <https://doi.org/10.61092/iaea.u2pu-60vm>
- Gruppen, C. (2010). Introduction to radiation protection: Practical knowledge for handling radioactive sources. Springer.
- Hosoda, M., Anderson, D., Yamada, R., Fujishima, Y., Tanaka, K., Kudo, H., Omori, Y., Kranrod, C., Tazoe, H., Akata, N., Itaki, C., Miura, T., Kashiwakura, I., & Tokonami, S. (2026). Radiation research at Hirosaki University after the Fukushima accident: Contributions to public health, education, and community resilience. *Radiation Medicine and Protection*, 7(3), 124–136. <https://doi.org/10.1016/j.radmp.2026.05.001>
- International Commission on Radiological Protection (Ed.). (2014). Protection of the environment under different exposure situations. Elsevier.
- International Commission on Radiological Protection (Ed.). (2023). Proceedings of the Sixth International Symposium on the System of Radiological Protection. International Symposium on the System of Radiological Protection.
- Internationale Atomenergie-Organisation. (2006). Fundamental safety principles: Safety fundamentals.
- Internationale Atomenergie-Organisation (Ed.). (2008). Radiation protection in newer medical imaging techniques: CT Colonography. International Atomic Energy Agency.
- Internationale Atomenergie-Organisation. (2011). Radiation protection and safety of radiation sources: International basic safety standards; general safety requirements (Interim ed). International Atomic Energy Agency.
- Kai, M., Homma, T., Lochard, J., Schneider, T., Lecomte, J. F., Nisbet, A., Shinkarev, S., Averin, V., & Lazo, T. (2020). Radiological protection of people and the environment in the event of a large nuclear accident. SAGE.
- Knoll, G. F. (2010). Radiation detection and measurement (4th ed). John Wiley.
- Lindell, P. B. (n.d.). Editor: F. D. SOWBY ICRP, Sutton, Surrey.
- Lochard, J., Bartlett, D. T., Rühm, W., Yasuda, H., & Bottolier-Depois, J.-F. (with International Commission on Radiological Protection). (2016). Radiological protection from cosmic radiation in aviation. Sage.
- Naji, A. T., Alhelali, M. A., & Abu-hadi, T. M. (2026). Assessment of knowledge, attitudes, and practices about radiation protection and safety among radiology and operating room personnel. *Radiation Medicine and Protection*, 7(2), 106–113. <https://doi.org/10.1016/j.radmp.2026.03.005>
- Prussin, S. G. (2007). Nuclear physics for applications: A model approach. Wiley-VCH-Verlag.
- Reisz, J. A., Bansal, N., Qian, J., Zhao, W., & Furdui, C. M. (2014). Effects of Ionizing Radiation on Biological Molecules—Mechanisms of Damage and Emerging Methods of Detection. *Antioxidants & Redox Signaling*, 21(2), 260–292. <https://doi.org/10.1089/ars.2013.5489>
- Sabol, J. (2023). Basic Radiation Protection for the Safe Use of Radiation and Nuclear Technologies. In T. J. FitzGerald (Ed.), *Radiation Therapy*. IntechOpen. <https://doi.org/10.5772/intechopen.108379>
- Taha, A., Zgair, I. A., Hussein, A. A., Hussein, N. N., Jamil, T. N., Hasan, T. H., & Mohammed, K. A. (2025). Biological Effects of Ionizing and Non-Ionizing Radiation: A Comprehensive Review of Health and Environmental Impacts. *International Journal of Design & Nature and Ecodynamics*, 20(4). <https://doi.org/10.18280/ij dne.200417>
- Turner, J. E. (2007). Atoms, radiation, and radiation protection (3rd completely rev. and enl. ed). Wiley-VCH.
- UNEP (Ed.). (2016). Radiation effects and sources: What is radiation? What does radiation do to us? Where does radiation come from? UNEP.



-
23. Valentin, J. (Ed.). (2005). Protecting people against radiation exposure in the event of a radiological attack. Elsevier.
 24. Valentin, J. & International Commission on Radiological Protection (Eds.). (2007). The 2007 recommendations of the International Commission on Radiological Protection. Elsevier.