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Environmental Chemistry of Radioactive Waste Management

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Abstract: *The safe and effective management of radioactive waste is a global priority, essential for protecting both human health and the environment. This work synthesizes the complexities of nuclear waste management, drawing on lessons from major nuclear incidents such as the Chernobyl and Fukushima Daiichi accidents to underscore the long-term environmental impacts of radionuclide release. It examines the fundamental principles and modern practices of radioactive waste management, from the classification of waste types and the regulatory frameworks established by international bodies like the IAEA, to advanced treatment and immobilization techniques. A significant portion of the analysis is dedicated to the long-term disposal of high-level radioactive waste and spent nuclear fuel, with a focus on the development and safety of deep geologic repositories. The work also delves into the specific behavior of key radionuclides like Cesium-137 and Iodine-129, exploring their transport in the environment and the scientific approaches to their containment. By integrating historical context, contemporary research, and evolving safety standards, this research provides a comprehensive overview of the challenges and solutions in securing a safe future for nuclear energy and its byproducts.*

Keywords: *Radioactive waste management, Environmental radioactivity, Geologic disposal, Radionuclide, Waste immobilization*

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1.0 Introduction

The management of radioactive waste is one of the most severe and complex challenges associated with the peaceful applications of nuclear science and technology in various sectors, especially power generation. Arising from the arrival of technologies that led to nuclear power generation in the mid-20th century, large quantities of radioactive waste are been consistently generated from diverse sources, such as nuclear power plants, research reactors, medical facilities, industrial applications, and military programs. Nuclear wastes contain radionuclides that emit ionizing radiation and can remain hazardous for periods ranging from a few hours to millions of years, depending on their half-lives and chemical forms. The environmental chemistry of radioactive waste is central to understanding how these radionuclides interact with various environmental media such as soil, water, and air, and to predicting their mobility, transformation, and potential pathways of human and ecological exposure. As a multidisciplinary field, it draws on radiochemistry, geochemistry, environmental engineering, and toxicology to inform waste treatment, storage, and disposal strategies that minimize environmental and public health risks. For example, some studies have demonstrated the sorption behaviour of actinides on clay minerals, redox transformations of uranium and technetium under varying geochemical conditions, and the performance of vitrified waste forms over geological timescales. Field experiences from sites such as the Hanford Nuclear Reservation in the United States, the Sellafield reprocessing plant in the United Kingdom, and the Onkalo deep geological repository in Finland have provided valuable insights into the long-term stability of storage systems and the environmental consequences of leaks or failures. In addition, environmental monitoring after nuclear accidents such as Chernobyl in 1986 and Fukushima Daiichi in 2011 has contributed to our understanding of radionuclide dispersion, deposition, and bioaccumulation in ecosystems (Steinhauser *et al.,* 2014). These studies collectively underscore the importance of integrating environmental chemistry principles into nuclear waste management practices.

Despite this body of knowledge, significant gaps remain. Many studies have focused on the immediate radiological hazards without sufficient attention to the coupled chemical and physical processes that govern radionuclide behavior over extended timescales. The long-term performance of multi-barrier disposal systems under the influence of climate change, seismic activity, and evolving groundwater chemistry is still not fully understood. Moreover, there is limited field data on the environmental behavior of certain long-lived fission products and actinides in complex, heterogeneous geological settings. Emerging waste streams from advanced nuclear fuel cycles and innovative reactor designs are currently providing new chemical challenges to the existing radionuclides waste management frameworks, indicating that it may not adequately address. There is therefore a pressing need for a more comprehensive and chemistry-driven approach to radioactive waste management that bridges the gap between laboratory research, field observations, and predictive modelling.

This study aims to examine the environmental chemistry of radioactive waste management, focusing on how the chemical properties and environmental interactions of radionuclides influence treatment, immobilization, and disposal strategies. The study seeks to analyse recent knowledge on radionuclide waste classification, sources, chemical behavior, and containment technologies while highlighting case studies that illustrate successes and failures in real-world contexts. By integrating fundamental chemical principles with applied waste management practices, the study aspires to provide a framework that supports safe, sustainable, and scientifically robust solutions for radioactive waste handling.

The significance of this work lies in its potential to enhance the safety and sustainability of nuclear technology by ensuring that waste management decisions are informed by a deep understanding of environmental chemistry. Such an approach will not only minimize environmental contamination and human exposure but also improve public confidence in nuclear energy and its applications. In an era of growing interest in nuclear power as a low-carbon energy source, addressing radioactive waste challenges with scientifically sound and environmentally responsible strategies is imperative. This study contributes to that effort by providing a detailed, chemistry-focused perspective on one of the most critical environmental issues in nuclear science.

2.0 Classification and Sources of Radioactive Waste

Radioactive waste is classified based on parameters such as radioactivity concentration, half-life of contained radionuclides, heat generation potential, and the type of radiation emitted. Proper classification is crucial for selecting appropriate treatment, storage, and disposal strategies that minimize environmental and health risks. The International Atomic Energy Agency (IAEA, 2018) provides internationally recognized classification criteria, which many national authorities adopt and adapt to local regulatory frameworks. The key determinants—activity level and longevity—are linked to the waste's radiological hazard over time and its chemical and physical stability under environmental conditions.

In general, waste can be categorized into low-level waste (LLW)**,** intermediate-level waste (ILW)**, and** high-level waste (HLW)**.** LLW typically contains radionuclides with relatively short half-lives and low activity concentrations; examples include contaminated clothing, laboratory glassware, and filters from nuclear facilities. ILW contains higher concentrations of radioactivity and may require shielding during handling and transport; common examples include reactor components, sludges, and ion-exchange resins. HLW is the most hazardous category, containing radionuclides with very long half-lives, high activity concentrations, and significant heat generation from radioactive decay; spent nuclear fuel and vitrified reprocessing waste are typical examples (Ojovan & Lee, 2014; IAEA, 2018).

Table 1 below presents a concise classification of radioactive waste according to activity level and longevity, with typical examples and recommended management approaches.

Table 1: Classification of radioactive waste by activity level and longevity

Category	**Activity Level**	**Half-life Range**	**Typical Examples**	**Management Approach**
Low-Level Waste (LLW)	Low	Hours to decades	Contaminated clothing, filters, tools	Near-surface disposal
Intermediate-Level Waste (ILW)	Medium	Years to centuries	Reactor components, ion-exchange resins	Engineered vaults or shallow burial with shielding
High-Level Waste (HLW)	High	Centuries to millennia	Spent nuclear fuel, vitrified waste	Deep geological repository with multi-barrier systems

The classification provided in Table 1 indicates the link between a waste's activity level, the persistence of its radionuclides in the environment, and the corresponding complexity of its management. LLW, despite being the least hazardous, is produced in the largest volume worldwide, representing over 90% of the total volume of radioactive waste but contributing less than 1% of the total radioactivity (IAEA, 2018). Its relatively short-lived radionuclides allow for near-surface disposal, where engineered barriers and institutional controls are typically sufficient to protect the environment until the radioactivity decays to safe levels.

ILW poses greater management challenges due to the presence of long-lived radionuclides and potentially significant radiation fields, necessitating shielding during handling. The half-life range of years to centuries means that ILW requires disposal facilities with more robust engineered barriers than LLW to prevent radionuclide migration into the environment (OECD-NEA, 2014).

HLW represents the smallest volume but contains over 95% of the total radioactivity of all waste categories (Ojovan & Lee, 2014). The combination of long-lived radionuclides and intense heat generation from decay requires highly engineered, deep geological repositories, often located hundreds of meters underground in stable geological formations. Such facilities employ multi-barrier systems—combining waste form stability, engineered container integrity, and geological isolation—

to ensure containment over timeframes that may exceed hundreds of thousands of years.

From an environmental chemistry perspective, the table underscores that as the activity level and half-life increase, the complexity of containment and the need for long-term environmental monitoring also rise. For instance, HLW management requires predictive geochemical modeling to anticipate radionuclide behavior in repository environments under varying redox, pH, and groundwater flow conditions. This directly links the classification scheme to the scientific principles guiding safe nuclear waste disposal.

2.2 Common Sources

Radioactive waste originates from a variety of civilian, research, medical, and industrial activities, each contributing unique waste streams with distinct radiological and chemical characteristics. Nuclear power plants are the largest contributors of high-level waste, primarily in the form of spent nuclear fuel and vitrified residues from reprocessing. Spent fuel assemblies contain a complex mixture of fission products such as cesium-137 and strontium-90, activation products such as cobalt-60, and transuranic elements including plutonium isotopes. In addition, power plant maintenance activities generate low- and intermediate-level waste, including contaminated equipment, tools, filters, and protective clothing (IAEA, 2018; Ojovan & Lee, 2014).

Research reactors and laboratories also produce a wide range of radioactive wastes, though typically in smaller volumes. These wastes may include irradiated experimental materials, neutron activation foils, calibration sources, and residual chemicals from radiochemical experiments. While the overall radioactivity of these waste streams may be lower than those from commercial reactors, they often contain radionuclides of high radiotoxicity, such as californium-252 or americium-241, in small but concentrated quantities (Ahn et al., 2013).

Medical applications of radioisotopes, such as in nuclear medicine for diagnosis and therapy, generate waste streams that are typically low-level but may contain short-lived radionuclides like iodine-131, technetium-99m, and fluorine-18. These wastes often decay rapidly to safe levels, but handling and interim storage must ensure that radiation exposure is kept within regulatory limits before disposal (IAEA, 2008).

Industrial uses of radioactive materials include radiography for non-destructive testing, tracer applications in oil and gas exploration, and process gauges in manufacturing. Sources such as iridium-192 and cobalt-60, once expended, become part of the radioactive waste inventory and require secure management to prevent environmental release or unauthorized access (OECD-NEA, 2014). The diversity of these sources highlights the complexity of radioactive waste management, as each waste stream differs in activity concentration, chemical composition, physical form, and required treatment or disposal pathway.

2.3 Chemical Nature and Speciation of Radionuclides

The chemical nature of radionuclides—their oxidation state, ionic radius, solubility, and propensity to form complexes—largely determines their environmental mobility, bioavailability, and persistence. Speciation studies, which identify the chemical forms of a radionuclide in a given environment, are essential for predicting its fate and transport in soils, sediments, and aquatic systems (Kaplan et al., 2013).

Table 2 summarizes key radionuclides of concern in radioactive waste management, their half-lives, dominant chemical forms, and characteristic environmental behaviors. These radionuclides were selected for their prevalence in nuclear waste streams and their environmental relevance due to mobility, bioaccumulation, or long-term radiological hazard.

Cesium-137 is one of the most environmentally mobile fission products due to its high solubility in water and low tendency to sorb to mineral surfaces, particularly in coarse-textured soils. This mobility makes it a significant contaminant in groundwater systems following accidental releases, as observed after the Fukushima Daiichi nuclear accident (Kanda, 2013).

Strontium-90 behaves chemically like calcium and is readily incorporated into the bones and teeth of living organisms, leading to prolonged internal radiation exposure. Its high mobility in aqueous systems, combined with its biological uptake, makes it a critical focus in environmental remediation efforts (IAEA, 2018). Plutonium-239, a transuranic element produced in reactors, has a very long half-life and is characterized by low solubility and strong sorption to soil particles and sediments. While this reduces its mobility, it also means that once deposited, it can remain in surface soils for extended periods, presenting long-term contamination concerns (Buesseler et al., 2012).

Table 2 Representative radionuclides in radioactive waste: half-life, dominant chemical forms, and environmental behaviour

Radionuclide	Half-life	Dominant Chemical Forms	Environmental Behavior
Cs-137	30.17 years	Cs^{+}	Highly soluble; mobile in groundwater; weak sorption to minerals, especially in sandy soils
Sr-90	28.79 years	Sr^{2+}	Mimics calcium; accumulates in bones and teeth; mobile in water
Pu-239	24,100 years	Pu^{4+}, PuO_2	Low solubility; strong binding to soils and sediments; low mobility under oxidizing conditions
I-129	1.57×10^{7} years	I^{-}, IO_3^{-}	Mobile in aqueous environments; volatile in certain forms; can migrate long distances

Iodine-129 is notable for its extremely long half-life and ability to exist in multiple oxidation states, most commonly as iodide (I^{-}) and iodate (IO_3^{-}). Its high mobility in water and volatility in some chemical forms allow it to disperse widely in the environment, making it an important consideration in long-term performance assessments of nuclear waste repositories (Kaplan *et al*., 2013).

From an environmental chemistry perspective, the management strategies for these radionuclides must account not only for their radiological hazards but also for their chemical forms and potential transformations in the environment. For example, immobilization techniques such as vitrification are designed to limit solubility and mobility, while engineered barriers aim to prevent contact with groundwater that could mobilize soluble radionuclides.

3.0 Environmental Chemistry of Waste Treatment and Disposal

The environmental chemistry of radioactive waste treatment focuses on transforming hazardous radionuclides into stable, less mobile forms, thereby minimizing environmental and human health risks. Treatment methods can be broadly classified into physical and chemical techniques, followed by immobilization and containment strategies that ensure long-term stability. The selection of a treatment method depends on the waste's activity level, chemical form, physical characteristics, and intended disposal route (IAEA, 2018).

3.1 Physical and Chemical Treatment Methods

Physical Methods

Physical treatments aim to reduce the waste volume, separate contaminants, or prepare waste for immobilization without altering the chemical identity of radionuclides. Examples include:

Compaction: Solid wastes such as contaminated clothing and tools are compacted to reduce volume prior to disposal.

$$Waste_{Bulk} \xRightarrow{pressure} Waste_{Compresed}$$

Incineration: Organic-based radioactive waste is combusted to reduce volume and destroy hazardous organic components, producing ash containing radionuclides. For example, for cellulose-based waste:

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + H_2O + heat$$

The ash is then conditioned for disposal.

Filtration: Liquids containing particulate-bound radionuclides are passed through membranes or filters to separate the solids. This is common for reactor coolant cleanup systems.

Chemical Methods

Chemical treatments alter the chemical form of radionuclides to facilitate separation or immobilization.

Precipitation: Dissolved radionuclides are converted into insoluble compounds that can be filtered out. For example, removal of strontium-90 using carbonate precipitation:

$$Sr^{2+}_{(aq)} + CO_3^{2-} \rightarrow SrCO_3$$

Ion Exchange: Radionuclides in solution are exchanged with non-radioactive ions bound to a resin or zeolite. For example, caesium removal using a sodium-form resin:

$$Cs^+ - Resin + Cs_{\ aq} \rightarrow Cs^+ - Resin + 6Na^+_{(aq)}$$

Solvent Extraction: Organic solvents selectively extract specific radionuclides from an aqueous phase. The PUREX (Plutonium Uranium Redox Extraction) process uses tributyl phosphate (TBP) in kerosene to separate uranium and plutonium from spent fuel solutions.

3.2 Immobilization and Containment

Following treatment, radioactive waste must be immobilized to prevent leaching and migration into the environment.

Vitrification: Waste is incorporated into a borosilicate glass matrix at high temperature (1100–1200 °C). This process chemically binds radionuclides in a durable glass network:

$$\text{Waste oxides} + SiO_2 + B_2O_3 \rightarrow Melt\ borosilicate\ glass\ containig\ radionuclides$$

Vitrification is especially suited for **high-level waste**.

Cementation: Waste is mixed with cement and allowed to cure, producing a stable monolith. Calcium silicate hydrates in cement physically trap radionuclides, and some isotopes chemically bind to hydration products. For example:

$$CaO + SiO_2 + H_2O \rightarrow CaO.SiO_2.H_2O(CSH\ gel)$$

Bituminization: Waste is incorporated into molten bitumen, which solidifies upon cooling, producing a water-resistant waste form. This is effective for low- and intermediate-level wastes containing soluble salts.

The combination of treatment and immobilization methods ensures that radioactive waste is reduced in volume, chemically stabilized, and securely contained, thereby mitigating the risk of radionuclide migration to soil and water. Physical processes generally precede chemical or immobilization techniques, creating an integrated waste management system that aligns with IAEA safety standards (IAEA, 2022).

3.3 Environmental Pathways

The migration and distribution of contaminants, including radioactive materials, in the environment occur through distinct pathways that influence their persistence, transformation, and eventual impact on human health and ecosystems. The key transport routes—soil, water, and air—play critical roles in determining the fate of these substances.

Soil Pathway

In the terrestrial environment, contaminants interact with soil particles through processes such as *sorption* and *desorption*. Sorption refers to the binding of substances onto soil surfaces, often involving clay minerals, organic matter, and iron/manganese oxides. This process can temporarily immobilize contaminants, reducing their mobility. Conversely, desorption releases bound substances back into the soil solution, potentially increasing their bioavailability and risk of leaching into groundwater. Additionally, contaminants can become incorporated into mineral lattices through *mineral binding*, which can either stabilize them for long periods or lead to gradual release under changing geochemical conditions.

Water Pathway

Aquatic systems serve as major transport media for dissolved and particulate contaminants. *Dissolution* of soluble substances into surface or groundwater enhances their dispersion over large distances. In parallel, colloid-facilitated transport can significantly increase mobility; colloidal particles act as carriers that protect contaminants from precipitation or sorption, enabling them to bypass natural filtration barriers. The movement of contaminated water through rivers, lakes, or aquifers can contribute to widespread environmental distribution and potential contamination of drinking water supplies.

Air Pathway

In the atmospheric environment, contaminants can move through *volatilization* and *aerosol dispersion*. Volatilization involves the transformation of contaminants into gaseous form, allowing them to enter the atmosphere where they may be transported over long distances before deposition. Aerosol dispersion occurs when fine particles, often containing adsorbed contaminants, become airborne and travel with wind currents. These airborne particles can deposit onto soil, water bodies, or vegetation, facilitating secondary contamination.

The interplay of these environmental pathways is complex, with processes in one medium often influencing transport and transformation in another. Understanding these pathways is essential for predicting contaminant behavior, assessing risks, and designing effective remediation and waste management strategies.

Fig. 1 presents the generalized environmental pathways and management process for radioactive waste, illustrating the complex interactions and movement of radionuclides across soil, water, and air systems. The figure is designed to capture the major transport routes and sequential stages in the handling of radioactive waste from the point of generation to final disposal. In the environmental context, the movement of radionuclides is governed by three primary pathways. In the soil compartment, radionuclides undergo sorption and desorption processes, as well as potential mineral binding, which influence their mobility and long-term retention. In the water medium, dissolution and colloid-facilitated transport dominate the migration of radioactive particles, posing a risk of groundwater and surface water contamination. In the air pathway, volatilization and aerosol dispersion contribute to the atmospheric spread of radionuclides, which can be deposited over large areas through dry and wet deposition mechanisms.

The waste management flowchart depicted in the figure outlines the critical steps designed to control and minimize environmental contamination. The process begins with waste generation from nuclear facilities, research laboratories, medical applications, and industrial processes. Following this, waste is subjected to collection and segregation to ensure that different categories of waste—such as high-level, intermediate-level, and low-level waste—are appropriately identified. Characterization and classification are essential for determining the radiological, physical, and chemical properties of the waste, thereby informing suitable treatment strategies. Treatment methods, which may be physical or chemical, aim to reduce waste volume, remove radionuclides, or alter waste characteristics to enhance stability. Immobilization techniques, such as vitrification and cementation, are then employed to encapsulate the waste, limiting radionuclide mobility. Storage options, whether interim or final, provide secure containment prior to ultimate disposal. Disposal methods range from engineered near-surface facilities for low-level waste to deep geological repositories for high-level and long-lived intermediate-level waste.

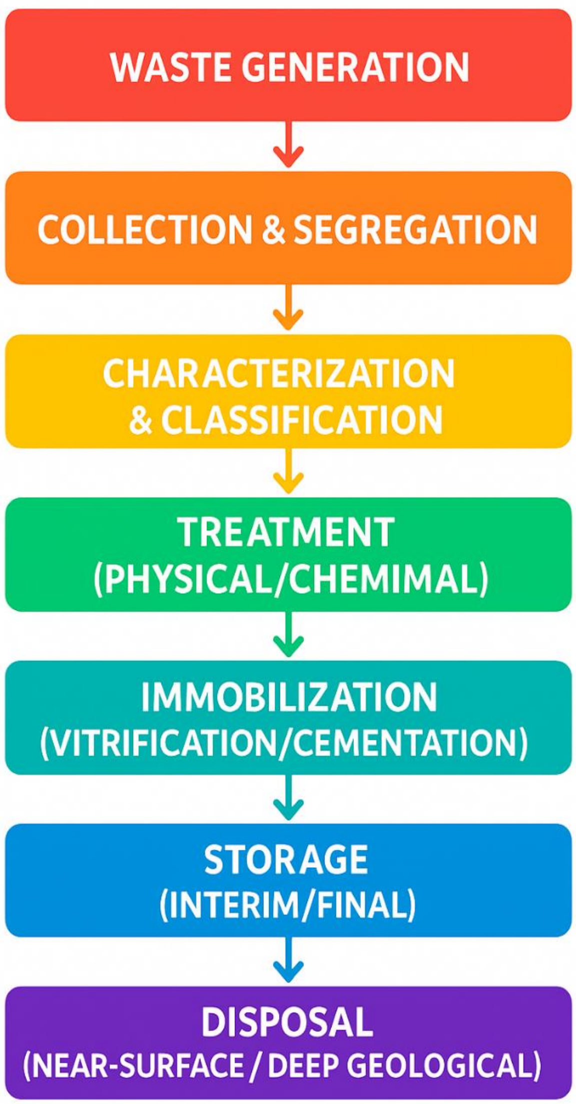

Fig. 1. Generalized Environmental Pathways and Radioactive Waste Management Process

It is evident from the study that the environmental behaviour of radioactive materials cannot be effectively addressed without an integrated waste management approach. For instance, the soil pathway is particularly relevant when considering radionuclide immobilization and long-term containment strategies, as sorption processes can be enhanced by engineered barriers. Water pathway considerations are critical in the design of treatment systems that prevent radionuclide dissolution and transport into aquatic environments. The air pathway underscores the necessity of controlling volatilisation during thermal treatments and ensuring containment during storage and disposal.

Relating this to the present research, the figure underscores the necessity of understanding the physicochemical interactions between radionuclides and environmental media, which directly inform waste immobilization techniques. By elucidating the links between environmental pathways and waste management stages, the study positions itself to contribute valuable insights into optimizing containment strategies and reducing potential exposure risks to humans and ecosystems. This integrated understanding is fundamental for advancing safe, sustainable, and regulatory-compliant radioactive waste management practices.

4.0 Case Studies and Regulatory Frameworks

Radioactive waste management practices can be better understood and improved through the examination of real-world cases where environmental chemistry, engineering design, and regulatory oversight intersect. This section presents three notable examples—Hanford Site in the USA, Fukushima Daiichi in Japan, and the Onkalo Repository in Finland—each representing different waste types, geochemical contexts, and regulatory challenges. The lessons drawn from these cases have direct implications for designing robust waste containment strategies and implementing effective environmental monitoring programs.

The Hanford Site in Washington, USA, is one of the most complex and contaminated nuclear facilities in the world. Established during the Manhattan Project for plutonium production, Hanford generated approximately 56 million gallons of high-level radioactive waste stored in 177 underground tanks (Gerber, 2017). Over the decades, more than 60 tanks have been suspected or confirmed to have leaked, releasing radionuclides such as technetium-99, cesium-137, and uranium into the vadose zone and groundwater (Peterson *et al*., 2008). The site's major challenge lies in the chemical diversity of the waste, which complicates treatment and retrieval efforts. This case highlights the necessity of early containment measures, the importance of designing corrosion-resistant storage tanks, and the critical role of continuous groundwater monitoring to detect contamination plumes before they migrate to the Columbia River.

The Fukushima Daiichi Nuclear Power Plant accident in 2011, triggered by the Great East Japan Earthquake and tsunami, released large amounts of radioactive contaminants into the environment, particularly in the form of contaminated cooling water (Steinhauser, 2014). While much of the radionuclide inventory could be removed through the Advanced Liquid Processing System (ALPS)—a multi-nuclide removal facility—tritium remains a challenge due to its chemical similarity to water and low removal efficiency (IAEA, 2022). Consequently, the treated water is stored in large tank farms pending controlled release. This case underscores the need for modular treatment systems capable of rapid deployment in emergency situations, as well as the importance of integrating emergency preparedness into nuclear facility design.

The Onkalo Repository in Finland represents one of the most advanced deep geological disposal projects in the world. Managed by Posiva Oy, it involves encapsulating spent nuclear fuel in corrosion-resistant copper canisters surrounded by bentonite clay buffers, and emplacing them in stable crystalline bedrock at a depth of approximately 420–450 meters (Posiva, 2021). The repository's location on the stable Fennoscandian Shield, combined with multi-barrier engineering, aims to ensure containment for hundreds of thousands of years. This case illustrates how geological stability, combined with engineered barriers, can provide an effective long-term isolation strategy for high-level waste.

Table 1 summarizes these case studies, highlighting their main waste types, key challenges, and the primary lessons derived from each.

Table 1. Summary of Radioactive Waste Management Case Studies

Site	**Main Waste Type**	**Key Challenge**	**Outcome/Lesson**
Hanford, USA	HLW	Tank leaks	Early containment and groundwater monitoring critical
Fukushima, Japan	Contaminated water	Tritium removal	Modular treatment units and preparedness
Onkalo, Finland	Spent fuel	Long-term isolation	Geological stability and multi-barrier containment key

The examination of these cases reveals that the environmental chemistry of radionuclides directly influences containment performance. For example, the solubility and mobility of technetium-99 in oxidizing groundwater at Hanford necessitate reducing conditions or sorptive barriers to retard migration. Similarly, the persistence of tritiated water at Fukushima demonstrates that chemical form dictates treatment feasibility. The Onkalo project, by contrast, leverages the chemical stability of copper in reducing, chloride-rich deep groundwater, ensuring minimal corrosion over geologic timescales.

4.1 Regulatory Standards

International and national regulatory frameworks play a decisive role in guiding the safe management of radioactive waste. The International Atomic Energy Agency (IAEA) provides global safety standards and technical guidance through its *Safety Standards Series*, which outlines requirements for waste classification, transport, treatment, and disposal (IAEA, 2018). The principle of ALARA—keeping radiation exposures *As Low As Reasonably Achievable*—is universally applied to minimize risk through optimized engineering and operational controls.

At the national level, the U.S. Nuclear Regulatory Commission (NRC) sets legal requirements for waste management, including licensing of disposal facilities and oversight of environmental monitoring. The United Kingdom's Nuclear Decommissioning Authority (NDA) oversees long-term waste storage and decommissioning programs, while the Nigerian Nuclear Regulatory Authority (NNRA) enforces waste handling standards in compliance with IAEA guidelines. A core element of these frameworks is the multi-barrier containment approach, which combines engineered and natural barriers to ensure radionuclide isolation over the timescales necessary to protect human health and the environment.

5.0 Challenges, Future Perspectives, and Conclusion

5.1 Emerging Technologies

One of the most promising future directions in managing radioactive contaminants lies in the development and application of emerging technologies. Partitioning and transmutation, for instance, offer a means to reduce the half-lives of certain long-lived radionuclides by converting them into shorter-lived or stable isotopes. This approach has the potential to significantly lower the radiotoxicity and storage time of nuclear waste. Additionally, advanced sorbents such as functionalized clays and metal–organic frameworks (MOFs) are being explored for their high selectivity, surface area, and binding affinity toward specific radionuclides. These materials can be engineered at the molecular level to enhance removal efficiency in contaminated water and soil systems, presenting a vital tool in remediation strategies.

5.2 Sustainability and the Circular Economy

Sustainable management of radioactive materials also aligns with the principles of the circular economy. This involves the recycling and recovery of certain isotopes from spent nuclear fuel and other waste streams, turning potential hazards into valuable resources. Such isotopes may be repurposed in medical imaging, cancer therapy, industrial radiography, or as tracers in environmental studies. Waste-to-resource approaches not only minimize the volume of waste requiring long-term storage but also create economic value from what was once considered unusable material. Integrating these sustainable practices with strict safety protocols ensures both environmental protection and resource efficiency.

6.0 Conclusion

The findings of the study indicate that environmental pathways such as soil sorption and mineral binding, dissolution and colloid transport in water, and volatilization with aerosol dispersion in air play a significant role in the transport and fate of contaminants, particularly radionuclides. It was observed that these processes influence the persistence, mobility, and bioavailability of hazardous materials, thereby determining their environmental and human health impacts. The study also revealed that emerging technologies, including partitioning and transmutation for reducing the half-lives of radionuclides and the application of advanced sorbents such as functionalized clays and metal–organic frameworks, offer promising approaches for improving contaminant removal. Furthermore, integrating sustainability and circular economy principles through isotope recycling and waste-to-resource strategies can reduce environmental burdens while creating new economic opportunities.

In conclusion, the research underscores the importance of understanding environmental transport mechanisms and adopting innovative, sustainable solutions to mitigate contamination risks. It emphasizes the potential of combining advanced technologies with resource recovery approaches to address current and future challenges in environmental remediation and radioactive waste management.

Based on these insights, it is recommended that environmental management frameworks prioritize the adoption of cutting-edge treatment methods, promote interdisciplinary research on contaminant transport, and integrate circular economy principles into waste management practices. Strengthening regulatory oversight, enhancing public awareness, and fostering collaboration between industry, academia, and policymakers are also essential for achieving long-term environmental protection and sustainable resource use.

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Authors' Contribution

Both authors participated in design, development, writing and corrections concerning the work.

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