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Assessing the Impact of Radioactive Contamination in Groundwater and Environmental Quality: A Comparative Study of Remediation Technique

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Abstract

Radioactive contamination is a pressing environmental issue that requires effective remediation techniques. Chemical and biological remediation methods have been proposed as potential solutions, but their comparative effectiveness remains unclear. This study seeks to address this gap by comparing the efficacy of these two remediation techniques in reducing radioactive contamination. The study involved a comprehensive review of existing literature on chemical and biological remediation techniques for radioactive contamination. The advantages and limitations of each technique were analyzed, and their effectiveness in reducing radioactive contamination was compared. Additionally, the practical application of these techniques in a real-world scenario was evaluated based on online data. The findings revealed that both chemical and biological remediation techniques have shown promise in reducing radioactive contamination. Chemical techniques, such as ion exchange and precipitation were observed as effective techniques in removing radioactive contaminants from soil and water. On the other hand, biological techniques, such as phytoremediation and microbial remediation, offer a sustainable and cost-effective approach to remediate radioactive contamination. However, the effectiveness of these techniques may vary depending on the specific characteristics of the contaminated site. Therefore, the choice of remediation technique should be based on the specific characteristics of the contaminated site and the desired outcome. Based on our findings, a holistic approach that combines both chemical and biological remediation techniques to address radioactive contamination effectively is recommended. Furthermore, future research should focus on developing integrated remediation strategies that leverage the strengths of both techniques to achieve optimal results.

Keywords: Radioactive contamination, Groundwater, Environmental quality, Remediation techniques, Nuclear contamination.

1 | Introduction

Radioactive contaminants are substances that emit radiation, posing a threat to human health and the environment. The issue of radioactive contamination in groundwater and its impact on environmental quality is a pressing concern that requires immediate attention [1].

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It can have long-lasting and devastating effects, leading to contamination of water sources, soil, and air. Radioactive contamination occurs when radioactive substances are released into the environment, either through natural processes or human activities such as nuclear power plants, mining, and industrial activities. These substances can seep into groundwater sources, posing a significant threat to human health and the environment. Some of the primary concerns associated with radioactive contamination in groundwater are as follows:

I. Potential for exposure to harmful radiation, radioactive substances such as uranium, radium, and radon can seep into groundwater sources, contaminating drinking water supplies and posing a risk to human health [2], [3].

II. Exposure to high levels of radiation can lead to a range of health problems, including cancer, genetic mutations, and organ damage [4].

III. The presence of these radioactive substances in groundwater can also have negative impacts on the environment: radioactive substances can accumulate in soil and water, affecting plant and animal life and disrupting ecosystems. Contaminated groundwater can also leach into surface water sources, further spreading the contamination and impacting aquatic ecosystems [5].

In addressing the challenges posed by radioactive contamination in groundwater, various remediation techniques have been developed. These techniques aim to remove or reduce the levels of radioactive substances in groundwater, thereby minimizing the risks to human health and the environment [6]. This study centers on the impact of radioactive contamination on groundwater and environmental quality, as well as the remediation techniques. Radioactive contamination in groundwater poses a serious threat to environmental quality and human health. The impacts of this contamination can be far-reaching and long-lasting, requiring effective remediation techniques to mitigate the risks. By implementing strategies such as pump-and-treat systems, in-situ immobilization, and phytoremediation, we can work towards protecting our groundwater sources and preserving the quality of our environment.

2 | Types of Radioactive Contaminants

There are several types of radioactive contaminants, each with its own unique properties and sources. Understanding the different types of radioactive contaminants is crucial for effectively managing and mitigating their impact on our surroundings. Some of the most common types of radioactive contaminants are highlighted as follows:

I. Radon: radon is a colorless and odorless gas that is produced naturally from the decay of uranium in soil and rocks. Radon can seep into buildings through cracks in the foundation, posing a significant health risk to occupants (*Fig. 1*). According to the Environmental Protection Agency (EPA), radon is the second leading cause of lung cancer in the United States, responsible for an estimated 21,000 deaths annually [7].

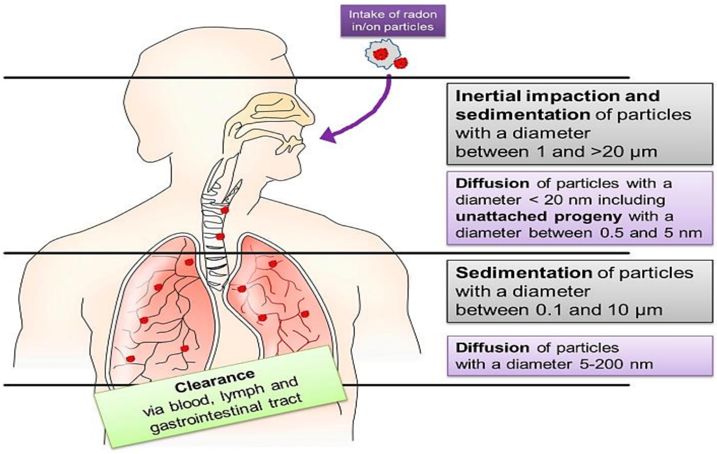

Fig. 1. Radon radioactive contaminants [8].

II. Cesium-137: cesium-137 is a by-product of nuclear fission that is commonly found in nuclear waste and fallout from nuclear accidents. Cesium-137 has a half-life of 30 years, meaning it remains radioactive for a long period. Exposure to cesium-137 can cause radiation sickness, cancer, contamination in the food chain, contamination of agricultural fields, and atmospheric contamination, as shown in *Fig. 2* [9], [10]. The Chornobyl and Fukushima nuclear disasters are notable examples of incidents where cesium-137 was released into the environment, leading to widespread contamination.

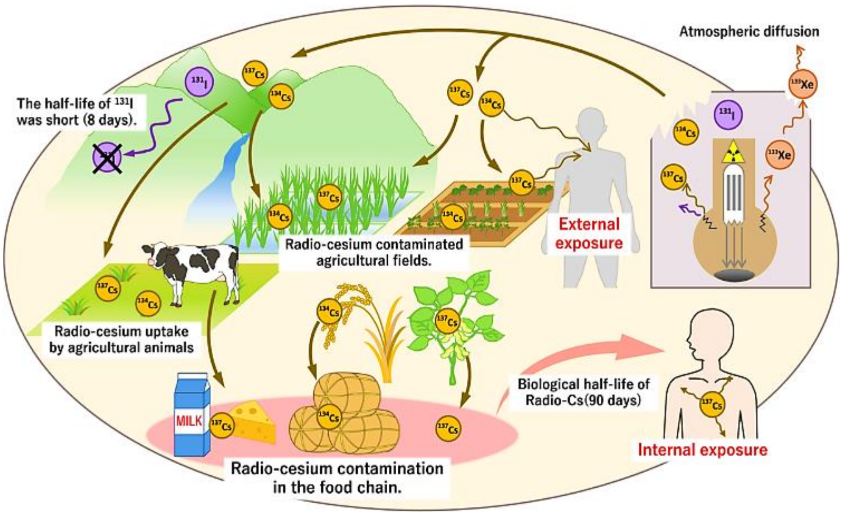

Fig. 2. Cesium-137 radioactive contaminants [11].

III. Plutonium: this is another radioactive contaminant that is highly toxic and poses a significant threat to human health. Plutonium is a by-product of nuclear reactors and weapons production, and it can remain radioactive for thousands of years [12]. For example, a typical radioactive/radiochemical plant generates numerous toxic plutonium compounds (*Fig. 3*) that are detrimental to public health and the environment. Upon inhalation or ingestion of these plutonium particles, the victims are prone to lung damage and other serious health effects [13].

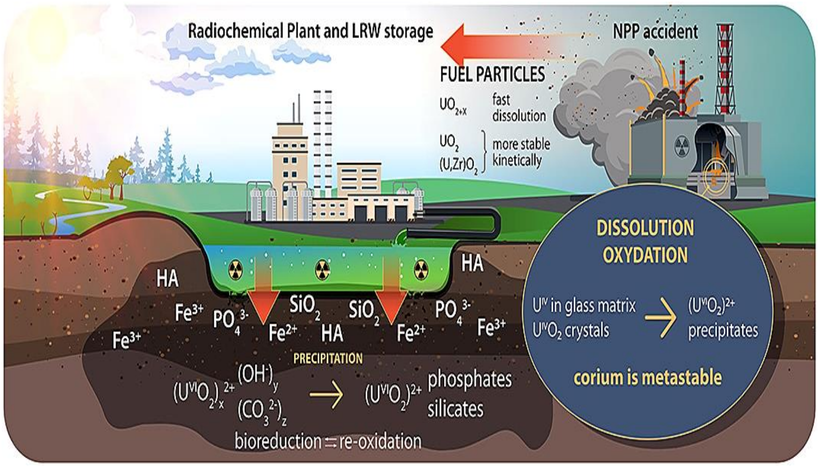

Fig. 3. Plutonium radioactive contaminants [14].

Radioactive contaminants come in various forms and pose a significant threat to human health and the environment. It is essential to understand the different types of radioactive contaminants and their sources in order to manage and mitigate their impact effectively. By implementing strict regulations and safety measures, we can minimize the risks associated with radioactive contamination and protect future generations from its harmful effects.

3 | Classification of Radioactive Contaminants in Groundwater and Environmental Quality

Radioactive contaminants in groundwater pose a significant threat to environmental quality and human health. These contaminants can originate from various sources, including nuclear power plants, mining activities, and medical facilities [15]. In order to effectively manage and mitigate the risks associated with radioactive contaminants in groundwater, it is essential to classify them based on their properties and potential impacts. Some of the classification systems for radioactive contaminants in groundwater are:

I. Based on their half-life: radioactive contaminants can be classified as either short-lived or long-lived based on the amount of time it takes for half of the radioactive atoms in a sample to decay [16]. Short-lived contaminants, such as tritium, have half-lives on the order of days to years, while long-lived contaminants, such as uranium-238, have half-lives on the order of thousands to millions of years. The classification of radioactive contaminants based on half-life is important because it can help determine the appropriate remediation strategies and monitoring protocols.

II. Based on their chemical properties, radioactive contaminants can be classified as either soluble or insoluble based on their ability to dissolve in water. Soluble contaminants, such as radium-226, can easily migrate through groundwater and pose a greater risk to human health. Insoluble contaminants, such as plutonium-239, tend to remain in place and may pose a greater risk to the environment [17]. The classification of radioactive contaminants based on their solubility is important because it can help determine the potential pathways of contamination and the likelihood of exposure.

The classification of radioactive contaminants in groundwater is essential for understanding their properties and potential impacts on environmental quality and human health. By classifying these contaminants based on their half-life and chemical properties, we can develop more effective strategies for managing and mitigating the risks associated with radioactive contamination. Policymakers, regulators, and scientists must work together to implement appropriate monitoring and remediation measures to protect groundwater resources and ensure environmental quality.

4 | Properties of Radioactive Contaminants

Radioactive contaminants are substances that emit radiation as a result of their unstable atomic nuclei. These contaminants can pose serious health risks to humans and the environment if not properly managed. Understanding the properties of radioactive contaminants is crucial in order to mitigate their impact effectively. The key properties of radioactive contaminants are stated as follows:

I. Their half-life which is the time it takes for half of the atoms in a sample to decay: different radioactive contaminants have different half-lives, ranging from fractions of a second to billions of years. This property is important in determining how long a contaminant will remain in the environment and continue to emit radiation [18].

II. Their ability to bio-accumulate in living organisms: this means that these contaminants can build up in the tissues of plants and animals, leading to higher concentrations of radiation in higher trophic levels of the food chain. This can result in serious health effects for humans and wildlife that consume contaminated organisms [19], [20].

Understanding the properties of radioactive contaminants is essential in order to effectively manage and mitigate their impact on human health and the environment. By considering factors such as half-life, bioaccumulation, and migration, strategies can be developed to handle and dispose of these hazardous substances safely. There must be continual research and monitoring of radioactive contaminants in order to protect both current and future generations from their harmful effects.

5 | Sources of Radioactive Contaminants

Radioactive contaminants are a serious concern in today's world, as they pose a significant threat to human health and the environment. There are various sources of radioactive contaminants, each with its own unique characteristics and potential risks. Sources of radioactive contaminants are as follows:

I. Nuclear power plants: these facilities produce electricity by splitting uranium atoms in a process known as nuclear fission. While nuclear power is a relatively clean source of energy compared to fossil fuels, it also generates radioactive waste that must be carefully managed to prevent contamination of the environment (*Fig. 4*). Accidents at nuclear power plants, such as the infamous Chornobyl and Fukushima disasters, can release large amounts of radioactive contaminants into the air and water, posing a serious threat to nearby populations [21], [22].

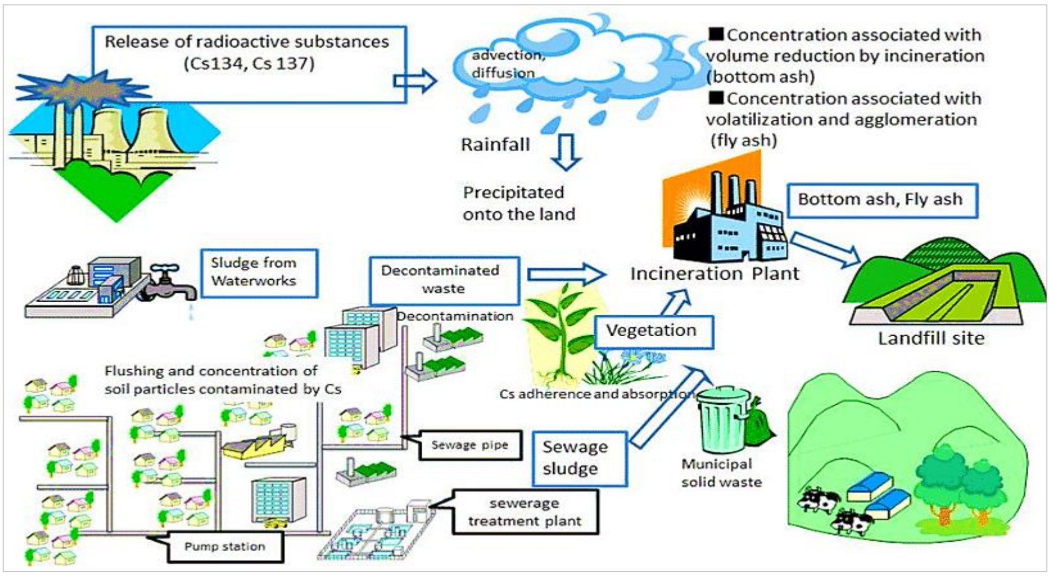

Fig. 4. Nuclear power plants [23].

II. Medical facilities that use radioactive materials for diagnostic imaging and cancer treatment: while these procedures can be life-saving, they also produce radioactive waste that must be properly disposed of to prevent contamination of the environment. Improper handling of radioactive materials in medical facilities can lead to leaks and spills that pose a risk to both patients and healthcare workers [24].

III. Industrial activities such as mining and processing of uranium and other radioactive materials can also release radioactive contaminants into the environment. These activities can contaminate soil, water, and air, posing a risk to nearby communities and ecosystems [25]. In addition, the use of radioactive materials in industrial processes such as oil and gas drilling can also lead to the release of radioactive contaminants into the environment.

Various sources of radioactive contaminants pose a significant threat to human health and the environment. Nuclear power plants, medical facilities and industrial activities all contribute to the release of radioactive materials that can contaminate the air, water and soil. Governments, industries and individuals need to take steps to minimize the release of radioactive contaminants and to properly manage radioactive waste to protect public health and the environment. Radioactive contaminants also have the ability to migrate through soil and water, spreading their radiation over large distances. This property can make it challenging to contain and clean up contaminated sites, as the contaminants may continue to leach into surrounding areas over time.

6 | Impacts of Radioactive Contaminants on Ground Water

Radioactive contaminants pose a significant threat to the quality of groundwater, which is a vital source of drinking water for millions of people around the world. The release of radioactive materials into the environment can have serious consequences for human health and the environment. Some of the primary concerns associated with radioactive contaminants in groundwater are highlighted as follows:

I. The potential for long-term health effects: exposure to radioactive materials can increase the risk of developing cancer, genetic mutations, and other serious health problems. For example, exposure to radium in drinking water has been linked to an increased risk of bone cancer and other health issues [26].

II. Radioactive contaminants can also have a detrimental impact on the environment: radioactive materials can accumulate in soil and water, leading to contamination of plants and animals. This can disrupt ecosystems and have far-reaching consequences for biodiversity and ecosystem health [27].

III. The presence of radioactive contaminants in groundwater can also pose challenges for water treatment facilities: traditional water treatment methods may not be effective at removing radioactive materials, leading to potential exposure risks for consumers. This can result in increased costs for water treatment and infrastructure upgrades to ensure the safety of drinking water supplies [28].

The effects and impacts of radioactive contaminants on groundwater are significant and far-reaching. It is essential to take proactive measures to prevent the release of radioactive materials into the environment and to monitor and mitigate the impacts of existing contamination. By addressing these issues, we can protect human health, safeguard the environment, and ensure the availability of safe drinking water for future generations.

7 | Impacts of Radioactive Contaminants on the Soil

Radioactive contaminants have a significant impact on soil and ground soil, posing serious threats to the environment and human health. The presence of radioactive substances in the soil can lead to long-term environmental degradation and health risks. The primary effects of radioactive contaminants on soil are stated as follows:

I. The disruption of soil structure and composition: radioactive substances can alter the physical and chemical properties of soil, leading to decreased fertility and productivity. This can have detrimental effects on agricultural activities and food production, as contaminated soil may not be suitable for growing crops or supporting plant life [29].

II. Radioactive contaminants can also leach into groundwater, posing a threat to drinking water sources. Contaminated groundwater can lead to widespread health risks, as exposure to radioactive substances can cause various health problems, including cancer and genetic mutations. In addition, radioactive contaminants can also bioaccumulate in plants and animals, further increasing the risk of exposure to humans through the food chain [30].

III. The presence of radioactive contaminants in soil can also have long-term environmental impacts: radioactive substances can persist in the environment for extended periods, leading to ongoing contamination and potential risks to ecosystems. This can disrupt the balance of natural habitats and biodiversity, affecting the health and survival of various plant and animal species.

The effects and impacts of radioactive contaminants on soil and ground soil are significant and far-reaching. It is crucial to address this issue through effective monitoring, remediation, and prevention measures to protect the environment and human health. By raising awareness and taking action to mitigate the risks associated with radioactive contaminants, we can work towards a healthier and more sustainable future for our planet.

8 | Description of Containment Method of Controlling Radioactive Contaminants

In order to effectively control and mitigate the spread of these contaminants, containment methods are crucial. Containment refers to the practice of isolating radioactive materials in a controlled environment to prevent their release into the surrounding environment. This method is essential in preventing the spread of radioactive contaminants and minimizing their impact on human health and the environment [31]. Some of the most common containment methods used to control radioactive contaminants are:

I. The use of engineered barriers: these barriers are designed to prevent the migration of radioactive materials from their source into the surrounding environment. Engineered barriers can include materials such as concrete, steel, and lead, which are used to encapsulate radioactive waste and prevent its release. These barriers are designed to be durable and long-lasting, ensuring that radioactive materials remain contained for extended periods of time [32].

II. The use of physical barriers such as fences and enclosures: these barriers are used to restrict access to areas contaminated with radioactive materials, preventing unauthorized individuals from coming into contact with the contaminants. By limiting access to contaminated areas, physical barriers help to reduce the risk of exposure to radioactive materials and protect human health.

III. The use of monitoring and surveillance systems: these systems are used to continuously monitor levels of radiation in the environment and detect any leaks or breaches in containment barriers. By providing real-time data on radiation levels, monitoring and surveillance systems help to identify potential risks and take prompt action to prevent the spread of radioactive contaminants [33].

Overall, containment methods play a crucial role in controlling radioactive contaminants and protecting human health and the environment. By isolating radioactive materials in controlled environments, using engineered and physical barriers and implementing monitoring and surveillance systems, we can effectively prevent the spread of radioactive contaminants and minimize their impact on society.

These containment methods must be implemented and maintained to ensure the safety and well-being of current and future generations. Containment methods are essential for controlling radioactive contaminants and preventing their spread. By using engineered and physical barriers, as well as monitoring and surveillance systems, we can effectively isolate radioactive materials and protect human health and the environment. These containment methods must be implemented and maintained to ensure the safety and well-being of all individuals.

9 | Classification of Containment Method of Controlling Radioactive Contaminants

The containment method is classified into capping, vertical in-ground barrier and Permeable Reactive Barrier (PRB).

9.1 | Capping Method

Controlling radioactive contaminants is a critical aspect of environmental protection and public health. One method that is commonly used for this purpose is capping (*Fig. 5*). Capping involves placing a barrier, such as soil or concrete, over a contaminated area to prevent the spread of radioactive materials. This method is often used in conjunction with other remediation techniques to effectively contain and manage radioactive contaminants [34], [35].

The primary goal of capping is to prevent the migration of radioactive materials into the surrounding environment. By covering the contaminated area with an impenetrable barrier, capping helps to reduce the risk of exposure to harmful radiation.

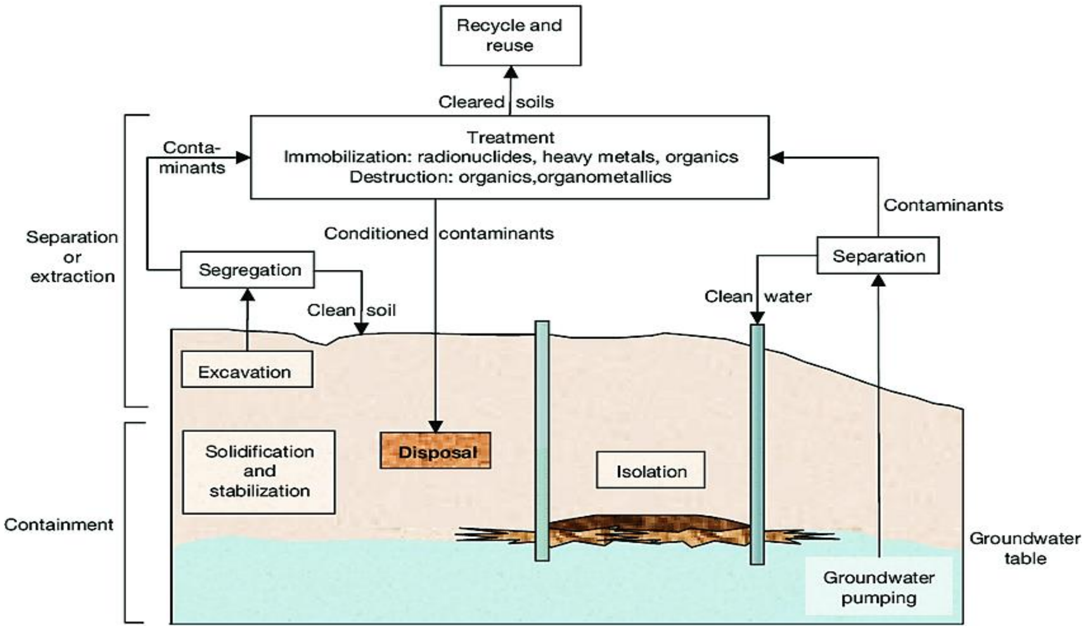

Fig. 5. Capping remediation techniques by function [36].

This is particularly important in areas where radioactive waste is stored or disposed of, such as nuclear power plants or radioactive waste sites. Several different types of capping methods can be used to control radioactive contaminants, which are:

I. The use a multi-layered cap, which consists of multiple layers of different materials, such as soil, clay, and concrete. This type of cap is designed to provide a strong and durable barrier that can withstand environmental conditions and prevent the release of radioactive materials [37].

II. The use of engineered caps, which are specifically designed to contain radioactive contaminants. These caps are often made of specialized materials, such as geo-membranes or geotextiles, that are resistant to radiation and provide a high level of protection against contamination [38]. Engineered caps are typically used in areas where the risk of radioactive exposure is high, such as nuclear waste storage facilities.

In addition to preventing the spread of radioactive contaminants, capping can also help to stabilize and secure contaminated areas. By covering the contaminated site with a protective barrier, capping can reduce the risk of erosion, leaching and other processes that can release radioactive materials into the environment. This can help to minimize the long-term impact of radioactive contamination and protect the health and safety of nearby communities.

While capping is an effective method for controlling radioactive contaminants, it is not without its limitations. One of the main challenges of capping is ensuring the long-term effectiveness of the barrier. Over time, the cap may degrade or become damaged, allowing radioactive materials to escape. Regular monitoring and maintenance of the cap are essential to ensure its continued effectiveness.

9.2 | Vertical In-Ground Barrier Method

The vertical in-ground barrier method is a highly effective technique for controlling radioactive contaminants in soil and groundwater. This method involves the installation of impermeable barriers vertically into the ground to prevent the migration of contaminants [39]. The barriers are typically made of materials such as concrete, steel, or plastic and are designed to create a physical barrier that prevents the movement of radioactive particles. The key advantages and disadvantages of the vertical in-ground barrier method are:

I. Its ability to effectively contain radioactive contaminants in a specific area: by creating a barrier that extends deep into the ground, the method can prevent the spread of contaminants to surrounding areas and protect nearby water sources from contamination. This containment approach is particularly important in areas where radioactive waste is present, as it can help to minimize the risk of exposure to harmful radiation [40].

II. The vertical in-ground barrier method also offers long-term stability and durability: once installed, the barriers can remain in place for many years without the need for maintenance or replacement [41]. This makes the method a cost-effective solution for controlling radioactive contaminants over an extended period of time.

III. The vertical in-ground barrier method is a versatile technique that can be customized to suit the specific needs of a site. Barriers can be installed at varying depths and configurations depending on the nature of the contamination and the site conditions. This flexibility allows for the method to be tailored to address a wide range of radioactive contamination scenarios [42].

IV. Despite its effectiveness, some critics argue that the vertical in-ground barrier method may not be a sustainable long-term solution for controlling radioactive contaminants. They point to potential issues such as barrier degradation over time, the possibility of groundwater seepage around the barriers, and the need for ongoing monitoring and maintenance. However, proponents of the method argue that these concerns can be addressed through proper design, construction, and monitoring protocols.

The vertical in-ground barrier method is a valuable tool for controlling radioactive contaminants in soil and groundwater. Its ability to contain contaminants, provide long-term stability, and offer customization options make it a practical and effective solution for managing radioactive waste. While there may be some challenges associated with the method, these can be mitigated through careful planning and implementation. Overall, the vertical in-ground barrier method represents a critical approach to protecting the environment and public health from the dangers of radioactive contamination.

9.3 | Permeable Reactive Barrier

PRBs are a method used to control radioactive contaminants in the environment. This technology involves the installation of a barrier made of reactive materials, such as zero-valent iron or activated carbon, in the path of the contaminant plume [43]. As the contaminated groundwater flows through the barrier, the reactive materials react with the contaminants, either immobilizing them or transforming them into less harmful forms. Some of the key advantages and disadvantages of PRBs are as follows:

I. Their ability to treat contaminants in situ, meaning that the treatment occurs at the location of the contamination without the need for excavation or removal of the contaminated soil or groundwater [44]. This can result in significant cost savings compared to traditional remediation methods.

II. PRBs have been successfully used to treat a variety of radioactive contaminants, including uranium, radium and technetium. A PRB containing zero-valent iron can effectively reduce uranium concentrations in groundwater to below regulatory limits [45].

III. Despite their effectiveness, PRBs are not without limitations. One of the main challenges is ensuring that the reactive materials remain effective over time. This can be addressed through regular monitoring and maintenance of the barrier, as well as periodic replacement of the reactive materials [40].

PRBs are a promising method for controlling radioactive contaminants in the environment. By leveraging the reactivity of certain materials, PRBs can effectively treat contaminated groundwater in situ, offering a cost-effective and sustainable solution for remediation efforts. Further research and development in this area will be crucial to improving the efficiency and longevity of PRBs for the long-term management of radioactive contaminants.

9.4 | Biological Remediation

Biological remediation, also known as bioremediation, is a process that utilizes living organisms to remove or neutralize contaminants from the environment [46]. In the case of radioactive contaminants, bioremediation offers a promising solution for cleaning up contaminated sites and reducing the risk of exposure to harmful radiation. The key advantages of biological remediation are:

I. Biological remediation ability to target specific contaminants and break them down into less harmful substances: this process is often carried out by microorganisms such as bacteria, fungi, and algae, which have the ability to metabolize radioactive materials and convert them into non-toxic forms [47]. For example, certain bacteria have been found to be capable of reducing the toxicity of uranium by converting it into a less harmful form that is less likely to leach into the environment.

II. Biological remediation can also help to immobilize radioactive contaminants, preventing them from spreading further into the environment. This can be achieved through processes such as bioaccumulation, where organisms absorb and store contaminants within their tissues, or through the formation of mineral precipitates that trap the contaminants in the soil [48].

III. Biological remediation is a cost-effective and environmentally friendly solution for cleaning up radioactive contaminants. Unlike traditional remediation methods such as excavation and incineration, which can be expensive and can cause further environmental damage, bioremediation is a natural process that works with the environment to restore balance and reduce contamination levels [49].

Biological remediation offers a promising solution for cleaning up radioactive contaminants by utilizing the natural abilities of living organisms to break down and immobilize harmful substances. By harnessing the power of microorganisms, bioremediation provides a cost-effective and environmentally friendly alternative to traditional remediation methods. As research in this field continues to advance, the potential for biological remediation to play a key role in cleaning up radioactive contamination sites is becoming increasingly clear.

9.5 | Physical Remediation Methods

Physical remediation methods involve the physical removal or containment of radioactive contaminants from the environment. Some of the commonly used physical remediation techniques are:

I. Excavation and separation: excavation and separation, which are crucial steps in the remediation of radioactive contaminants in soil and groundwater. Excavation is the process of removing contaminated soil or groundwater from a site to isolate and contain the radioactive contaminants [50]. This step is typically done using heavy machinery such as excavators and bulldozers, which can efficiently remove large quantities of soil and debris. Excavation is often necessary when the contamination is widespread or deeply embedded in the soil, making it difficult to treat in place. By excavating the contaminated material, it can be transported to a secure disposal facility where it can be safely stored or treated. Separation is the process of isolating radioactive contaminants from the excavated material to ensure that they do not pose a risk to human health or the environment [21]. This step is typically done using a combination of physical and chemical methods, such as filtration, sedimentation, and ion exchange. These methods can effectively separate radioactive contaminants from the soil or groundwater, allowing for the safe disposal or treatment of the contaminated material. The excavation and separation of radioactive contaminants are essential steps in the remediation process, as they help to prevent further spread of contamination and reduce the risk of exposure to harmful radiation. By effectively removing and isolating radioactive contaminants, we can protect human health and the environment from the negative impacts of these hazardous materials.

II. Encapsulation: encapsulation involves the containment of radioactive materials within a stable matrix to prevent their release into the surrounding environment. Encapsulation can be applied to a wide range of radioactive contaminants, including radionuclides such as uranium, thorium, and radium [51]. One of the key advantages of encapsulation remediation is its ability to effectively isolate radioactive contaminants from the environment, thereby reducing the risk of exposure to humans and wildlife. By encapsulating radioactive materials within a stable matrix, such as concrete or polymer, the contaminants are effectively immobilized and prevented from leaching into the soil or groundwater. Furthermore, encapsulation remediation is a cost-effective solution for managing radioactive contaminants, as it eliminates the need for costly and time-consuming excavation and disposal of contaminated soil or waste. Instead, encapsulation allows for the containment of radioactive materials on-site, reducing the overall remediation costs and minimizing the environmental impact of the clean-up process [52]. Despite its effectiveness, encapsulation remediation is not without its limitations. One of the main challenges associated with this technique is the long-term stability of the encapsulated materials. Over time, the encapsulation matrix may degrade or become compromised, potentially leading to the release of radioactive contaminants into the environment. To address this issue, ongoing monitoring and maintenance of encapsulation sites are essential to ensure the continued effectiveness of the remediation process.

9.6 | Chemical Remediation Methods

Chemical remediation methods involve the use of chemical agents to neutralize or immobilize radioactive contaminants. Chemical remediation methods can be effective in treating a wide range of contaminants but may require careful monitoring to ensure that they do not cause unintended environmental harm [53]. Some of the commonly used chemical remediation techniques are:

I. Soil washing/flushing in-situ: soil washing/flushing is a commonly used in-situ remediation technique for the removal of radioactive contaminants from soil. This method involves the use of water or other chemical solutions to flush out the contaminants from the soil, thereby reducing their concentration to acceptable levels [54]. The effectiveness of soil washing/flushing as a remediation technique has been widely studied and proven in various contaminated sites around the world. One of the key advantages of soil washing/flushing is its ability to target specific contaminants in the soil, such as radioactive isotopes, without disturbing the surrounding environment. This targeted approach minimizes the impact on the ecosystem and reduces the risk of spreading contaminants to other areas [55]. Additionally, soil washing/flushing is a cost-effective remediation technique compared to other methods, such as excavation and disposal, making it a preferred choice for many contaminated sites. The success of soil washing/flushing as a remediation technique depends on various factors, including the type and concentration of contaminants, soil properties, and the effectiveness of the flushing solution. In some cases, multiple rounds of flushing may be required to achieve the desired level of decontamination [56].

II. Solidification and stabilization: another chemical remediation technique is solidification and stabilization, which involves the addition of chemicals to contaminated materials to reduce the mobility of radioactive contaminants and prevent their spread. Solidification and stabilization (S/S) is a widely used remediation technique for treating radioactive contaminants in soil and groundwater [57]. This method involves the addition of binding agents to the contaminated material to immobilize the contaminants and reduce their mobility. The goal of S/S is to create a solid, stable matrix that encapsulates the contaminants and prevents them from leaching into the surrounding environment. One of the key advantages of S/S remediation is its ability to effectively treat a wide range of radioactive contaminants, including radionuclides such as cesium, strontium, and uranium. The binding agents used in S/S can vary depending on the specific contaminants present, but common materials include cement, lime, and fly ash [5]. These agents react with the contaminants to form insoluble compounds, effectively trapping them within the solid matrix. In addition to immobilizing the contaminants, S/S remediation also helps to improve the physical and chemical properties of the contaminated material. The binding agents can enhance the stability and strength of the soil or groundwater, making it less susceptible to erosion and leaching [58]. This can help to prevent the spread of contamination and reduce the risk of exposure to harmful radiation.

III. Ion exchange: ion exchange remediation is a widely used method for controlling radioactive contaminants in various environmental settings. This technique involves the use of ion exchange resins to remove radioactive ions from contaminated water or soil. The process works by exchanging ions in the resin with the radioactive ions present in the solution, effectively trapping them and preventing further migration [59]. One of the key advantages of ion exchange remediation is its high efficiency in removing radioactive contaminants. The resin used in this process has a high affinity for certain ions, making it highly effective in capturing radioactive species. Additionally, ion exchange remediation is a relatively simple and cost-effective method compared to other remediation techniques, such as excavation or chemical treatment [60]. Furthermore, ion exchange remediation is a versatile technique that can be applied to a wide range of radioactive contaminants, including cesium, strontium, and uranium. This flexibility makes it a valuable tool for addressing various types of radioactive contamination in different environmental settings. Despite its effectiveness, ion exchange remediation does have some limitations. One of the main challenges is the disposal of the spent resin, which may contain concentrated radioactive contaminants. Proper disposal of the resin is crucial to prevent further environmental contamination and ensure the safety of workers and the public.

9.7 | Temporary Containment

Temporary containment for controlling radioactive contaminants is a crucial aspect of nuclear safety and environmental protection. Temporary containment includes the following remediation techniques for controlling radioactive contaminants:

I. Engineered hydraulic barriers: engineered hydraulic barriers are a commonly used remediation technique for controlling radioactive contaminants in soil and groundwater and for containing them within a designated area. These barriers are designed to prevent the migration of contaminants by creating a physical barrier that restricts their movement [61]. Examples of engineered barriers include concrete walls, steel containers, and underground storage facilities. These barriers are designed to withstand the effects of radiation and to prevent the escape of radioactive materials. Engineered hydraulic barriers can be classified into two main types: impermeable barriers and permeable barriers. Impermeable barriers, such as slurry walls or sheet piles, are designed to completely block the movement of contaminants by creating a physical barrier that is impermeable to water and contaminants [62]. Permeable barriers, on the other hand, allow water to flow through while trapping contaminants within the barrier. Examples of permeable barriers include reactive barriers, which use chemical reactions to immobilize contaminants, and bio-barriers, which use biological processes to degrade contaminants. One of the key advantages of engineered hydraulic barriers is their ability to contain and control radioactive contaminants effectively. By creating a physical barrier that restricts the movement of contaminants, these barriers can prevent the spread of contamination to surrounding areas and protect human health and the environment [63].

II. Monitoring and surveillance systems: monitoring and surveillance systems play a crucial role in controlling radioactive contaminants and ensuring the safety of the environment and public health. These systems are designed to detect, track, and assess the presence of radioactive materials in various environments, such as air, water, soil, and food [64]. By continuously monitoring and surveilling these contaminants, remediation efforts can be implemented promptly to mitigate their impact on human health and the environment. One of the key aspects of monitoring and surveillance systems remediation is the use of advanced technologies and techniques to detect and quantify radioactive contaminants accurately. For example, gamma spectrometry, alpha spectrometry, and liquid scintillation counting are commonly used methods for analyzing samples and identifying the presence of radioactive isotopes. These techniques provide valuable information on the type and concentration of contaminants present, allowing for targeted remediation efforts to be implemented. In addition to advanced analytical techniques, remote sensing technologies are also utilized in monitoring and surveillance systems remediation. Remote sensing allows for the collection of data from a distance, enabling the monitoring of large areas and inaccessible locations [65]. Satellite imagery, aerial surveys, and Unmanned Aerial Vehicles (UAVs) are commonly used in environmental monitoring to detect and track radioactive contaminants, providing valuable information for remediation efforts. Furthermore, real-time monitoring systems are essential for quickly identifying and responding to radioactive contamination events. These systems continuously monitor environmental parameters, such as radiation levels, air quality, and water quality, and provide instant alerts when abnormal levels are detected [66].

III. Thermal treatment techniques: thermal treatment techniques have been widely used for controlling radioactive contaminants in various industries and environmental remediation projects. These techniques involve the application of heat to treat contaminated materials and waste streams, with the goal of reducing the concentration of radioactive contaminants to safe levels [67]. Some of the most commonly used thermal treatment techniques for controlling radioactive contaminants include incineration, vitrification, and thermal desorption.

- *Incineration is a thermal treatment technique that involves the combustion of contaminated materials at high temperatures. During the incineration process, organic contaminants are oxidized, while inorganic contaminants* *are converted into ash. The high temperatures used in incineration can effectively destroy radioactive contaminants, reducing their concentration to safe levels* [68]. *However, incineration can also produce emissions of toxic gases and particulate matter, which must be properly controlled to prevent environmental pollution.*

- *Vitrification is another thermal treatment technique that involves the melting of contaminated materials at high temperatures to form a glass-like substance. The radioactive contaminants are immobilized within the glass matrix, preventing their release into the environment. Vitrification is particularly effective for treating radioactive waste with high concentrations of heavy metals and other inorganic contaminants* [69]. *However, the high temperatures required for vitrification can be energy-intensive, making this technique costly to implement on a large scale.*
- *Thermal desorption is a thermal treatment technique that involves heating contaminated soils or sediments to vaporize organic contaminants. The vaporized contaminants are then collected and treated using air pollution control devices. Thermal desorption is effective for treating soils contaminated with organic compounds, such as Polychlorinated Biphenyls (PCBs) and petroleum hydrocarbons* [70]. *However, the high temperatures used in thermal desorption can also volatilize radioactive contaminants, potentially leading to their release into the atmosphere.*

9.8 | Redox Stabilization

Redox stabilization is a remediation technique used to control radioactive contaminants in the environment. This technique involves the use of chemical reactions to convert the contaminants into a less mobile or less toxic form, thereby reducing their impact on the surrounding environment. Redox stabilization can be an effective method for treating contaminated soil, groundwater, and sediment and has been used successfully at numerous sites around the world [71]. One of the key advantages of redox stabilization is its ability to immobilize radioactive contaminants in situ without the need for excavation or removal of contaminated material. This can significantly reduce the cost and time required for remediation, as well as minimize the potential risks associated with handling and transporting hazardous materials [72]. In addition, redox stabilization can be applied to a wide range of contaminants, including radionuclides such as uranium, thorium, and radium, as well as heavy metals like lead, mercury, and arsenic. Several different techniques can be used for redox stabilization, depending on the specific contaminants and site conditions, which include:

I. The addition of chemical amendments, such as iron or sulfur compounds, which can react with the contaminants to form stable, insoluble compounds. These compounds can then act as a barrier, preventing the contaminants from migrating through the soil or groundwater [73].

II. The use of PRBs. PRBs are constructed underground and filled with reactive materials that can capture and immobilize contaminants as they pass through. This can be particularly effective for treating contaminated groundwater, as the barriers can intercept and treat the contaminants before they reach sensitive receptors such as drinking water wells [74].

10 | Conclusion

The assessment of the impact of radioactive contamination of groundwater and environmental quality is a critical issue that requires immediate attention. This comparative study has highlighted the importance of implementing effective remediation techniques to mitigate the adverse effects of radioactive contamination on the environment and human health. The findings of this study have shown that different remediation techniques have varying degrees of effectiveness in removing radioactive contaminants from groundwater. It is evident from this study that the choice of remediation technique should be based on a thorough understanding of the specific characteristics of the contaminated site, including the type and concentration of radioactive contaminants present, the hydrogeological conditions, and the potential risks to human health and the environment. In addition, the cost-effectiveness and feasibility of implementing the remediation technique should also be taken into consideration.

In light of the findings of this study, it is recommended that a holistic approach be adopted in addressing radioactive contamination in groundwater, which includes a combination of remediation techniques tailored to the specific needs of the contaminated site.

Author Contributions

Imoh Ime Ekanem, Michael Okon Bassey, and Aniekan Essienubong Ikpe contributed collaboratively to this study. Imoh Ime Ekanem spearheaded the conceptualization, research framework design, and manuscript drafting. Michael Okon Bassey carried out data collection, analysis of radioactive contamination levels, and comparative assessment of remediation techniques. Aniekan Essienubong Ikpe focused on the environmental quality analysis and the synthesis of results. All authors participated in critical manuscript revisions and approved the final version for submission.

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Data Availability

All data and resources used in this study are presented within the manuscript. Additional datasets and detailed methodologies can be provided by the corresponding author upon formal request.

Conflicts of Interest

The authors declare no conflicts of interest related to this research and its publication.

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