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Review

Unraveling the nuclear isotope tapestry: Applications, challenges, and future horizons in a dynamic landscape

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A B S T R A C T

Nuclear isotopes, distinct atoms characterized by varying neutron counts, have profoundly influenced a myriad of sectors, spanning from medical diagnostics and therapeutic interventions to energy production and defense strategies. Their multifaceted applications have been celebrated for catalyzing revolutionary breakthroughs, yet these advancements simultaneously introduce intricate challenges that warrant thorough investigation. These challenges encompass safety protocols, potential environmental detriments, and the complex geopolitical landscape surrounding nuclear proliferation and disarmament. This comprehensive review embarks on a deep exploration of nuclear isotopes, elucidating their nuanced classifications, wide-ranging applications, intricate governing policies, and the multifaceted impacts of their unintended emissions or leaks. Furthermore, the study meticulously examines the cutting-edge remediation techniques currently employed to counteract nuclear contamination while projecting future innovations in this domain. By weaving together historical context, current applications, and forward-looking perspectives, this review offers a panoramic view of the nuclear isotope landscape. In conclusion, the significance of nuclear isotopes cannot be understated. As we stand at the crossroads of technological advancement and ethical responsibility, this review underscores the paramount importance of harnessing nuclear isotopes' potential in a manner that prioritizes safety, sustainability, and the greater good of humanity.

1. Introduction

Nuclear isotopes, distinguished by their unique neutron numbers, play a pivotal role in various sectors [1], including medicine [2,3], energy [4,5], and environmental studies [6]. Their distinct characteristics, such as radioactivity and half-life, render them invaluable in a range of applications from diagnostic procedures [7] and therapeutic interventions [8], to serving as a clean energy source [9]. Recent advancements have expanded their applications, showcasing their versatility in addressing contemporary challenges. However, alongside these benefits, the usage of nuclear isotopes presents significant environmental and safety concerns, particularly regarding their handling, storage, and potential environmental impact [10–12].

Current research in the field is increasingly focusing on mitigating these risks. Strategies for safe handling, advanced containment methods, and efficient disposal techniques are continually evolving [13]. Despite progress, gaps remain in understanding the long-term ecological effects of nuclear isotopes, their interaction with various environmental matrices, and the development of universally applicable remediation strategies. The complexity of nuclear isotope management calls for an interdisciplinary approach, integrating insights from physics, chemistry, biology, and environmental science.

This review meticulously synthesizes the recent developments and enduring challenges in the field of nuclear isotopes, particularly emphasizing their environmental implications and management strategies. Through a critical examination of the current state of knowledge, gaps in research and practice have been identified, paving the way for future inquiry. The review endeavors to provide an all-encompassing overview of the applications of nuclear isotopes, shedding light on the intricate relationship between their use and ecological impact, and highlighting the critical need for advancing research in this area to ensure sustainable and safe applications. The analysis involved a comprehensive collection and

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examination of literature primarily published from 1970 to November 2023. This process was conducted using the Web of Science, ScienceDirect, and Google Scholar databases, employing a combination of keywords, including “nuclear isotope”, along with a series of related terms such as “incident”, “accident”, “medical”, “war”, “energy”, “weapon”, “leak”, “distribution”, “application”, “policy”, “management”, “governance”, “public awareness”, “emissions”, “aquatic environments”, “soil”, “sediments”, “impact”, “human health”, “waste disposal”, and “monitoring”. This strategic approach in keyword selection facilitated a nuanced and comprehensive summarization of the latest advancements in the field. By integrating these insights, the review contributes significantly to the ongoing discourse on responsible nuclear isotope management, effectively intertwining scientific innovation with environmental stewardship.

2. The comprehensive scope of nuclear isotopes: from applications to policy

This section delves into the extensive scope of nuclear isotopes, encompassing their varied applications, environmental interactions, and the overarching policy framework that governs their use. A bibliometric analysis initiates the discussion, offering a quantitative insight into research trends and thematic evolutions within the field. Subsequent attention is given to the environmental distribution and concentration of nuclear isotopes, underscoring the complexities of their interaction with different ecosystems. The multifaceted applications of these isotopes, ranging from energy production to medical uses, are then thoroughly explored, highlighting ongoing innovations and technological advancements. In addressing the intricate governance landscape, the focus shifts to the regulatory and policy challenges, reflecting the need for balancing technological benefits with safety and ethical considerations. Building public awareness and trust emerges as a pivotal theme, emphasizing the role of informed discourse and community engagement in shaping nuclear policies. The section concludes with a forward-looking analysis of “Navigating the Road Ahead”, contemplating future challenges and opportunities that lie in the continued utilization and management of nuclear isotopes.

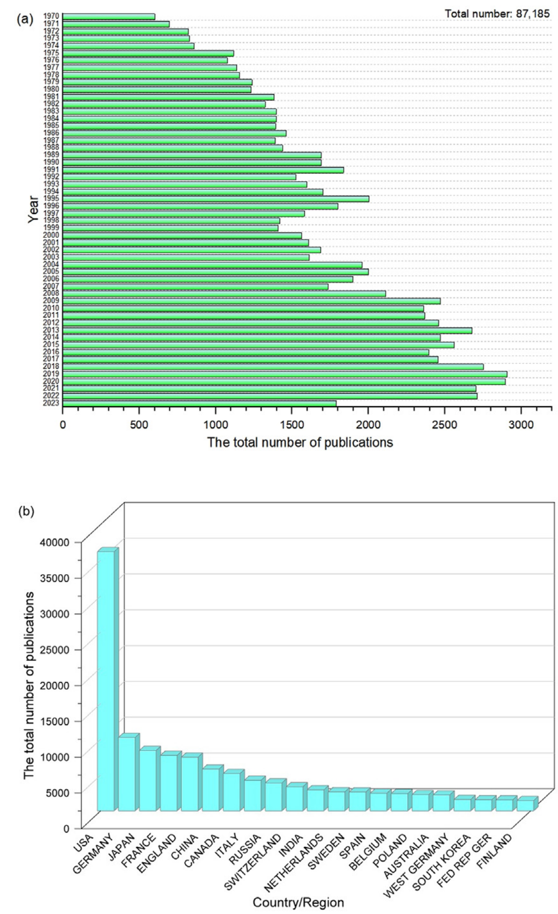

Fig. 1. Statistic chart based on Web of Science Core Collection database searched by the keywords “nuclear isotope”: (**a**) numbers of published articles from 1970 to November 2023; (**b**) numbers of published articles from different country/region (1970–November 2023).

2.1. Bibliometric analysis

Utilizing data from the Web of Science Core Collection database, this study presents an extensive bibliometric analysis of nuclear isotope research from 1970 to November 2023. The findings reveal a dynamic, predominantly ascending trajectory in scholarly output. This analysis, as depicted in Fig. 1a, offers a nuanced delineation of the evolving research landscape within nuclear isotope science. The initial phase, during the early 1970s, was characterized by a modest yet consistent compilation of foundational studies, epitomized by 600 publications in 1970. This embryonic period, marked by seminal explorations and theoretical developments, established the essential groundwork for subsequent advancements in the field. Progressing through the decades, a significant escalation in publication volume was observed, culminating in 1,564 publications by the year 2000. This surge reflected a global inclination towards fortifying energy security, propelling advancements in medical diagnostics via isotopic technologies, and stimulating innovation across a myriad of nuclear isotope applications.

The early 2000s era witnessed a pronounced increase in scholarly output, reaching a peak of 2,003 publications in 1995. This period was primarily fueled by the incorporation of nuclear isotopes into advanced diagnostic tools and an intensified pursuit of alternative, cleaner energy sources. This epoch represented a fundamental shift towards more sustainable energy solutions and a profound comprehension of the environmental ramifications, underlining the research community's dedication to confronting contemporary challenges. In contrast, the period post-2015 observed a noticeable decline in publication numbers, suggesting a phase of thematic maturation, a strategic redirection towards renewable energy resources, and a potential plateau within the research domain. The decrease to 1,787 publications in 2023 could be interpreted as indicative of either a persistent trend or a temporary deviation shaped by the prevailing global dynamics. Despite this fluctuation, the enduring significance and adaptability of the field in addressing a broad spectrum of scientific challenges remain unequivocally underscored, attesting to the persistent relevance of nuclear isotope research in the constantly evolving scientific arena.

Upon reevaluation of bibliometric data against the backdrop of the Chernobyl and Fukushima disasters, classified as level 7 events on the International Nuclear Event Scale (INES), a nuanced trend in nuclear isotope research publications emerges. Contrary to the anticipated immediate surge in scholarly output following these significant nuclear accidents, the data reveal a more gradual and complex pattern in the scientific community's response. Post-Chernobyl in 1986, a heightened focus on nuclear safety, environmental impact, and emergency response strategies was observed. However, this increased attention translated into a moderate rise in publication numbers, evolving from 1,462 publications in 1986 to 1,579 by 1997. This gradual uptick suggests a more subdued immediate impact than expected, possibly due to the extensive time required for conducting in-depth research and navigating the rigorous peer-review process inherent in scholarly publication.

Similarly, the Fukushima disaster in 2011, another level 7 INES event, prompted a resurgence in research efforts around nuclear safety and disaster mitigation. Yet, this revival did not manifest in a marked increase in publication numbers in the immediate years following the accident. While a rise in relevant research activities was noted, the influence on annual publication counts was not as dramatic as might be anticipated in the wake of such a major event. This pattern indicates that the scientific community's engagement with these nuclear accidents was characterized by a methodical, sustained approach rather than an abrupt increase in research output. The response to large-scale nuclear disasters entails complexities and extensive scale, necessitating thorough, comprehensive research efforts, often spanning several years before culminating in published works. Consequently, the bibliometric data highlight a consistent, ongoing commitment within the scientific community to address the challenges posed by these nuclear accidents, reflecting a strategic, long-term approach in research rather than an immediate, short-term surge in publication trends.

In the bibliometric assessment delineated in Fig. 1b, the attribution of publication counts to each country was meticulously executed, reflecting the collaborative essence of nuclear isotope research. This analysis ensured that each nation associated with a multi-authored publication received a singular count, thereby accurately depicting the global contributions to the field without redundancies for individual nations. This approach underscores the interconnected nature of scientific endeavors, highlighting the diverse geographic origins of research inputs. The United States, leading in publication count, exemplifies a profound commitment and an established framework in nuclear research, bolstered by significant investment and institutional support. Germany's noteworthy publication output, indicative of its scientific precision and robust research tradition, likely benefits from synergistic academia-industry collaborations. In the wake of the Fukushima accident, Japan has significantly intensified its focus on nuclear safety and alternative energy research, as reflected in its increased scholarly output. Concurrently, France and the United Kingdom sustain strong publication records underpinned by national policies and a historical foundation in nuclear science.

China's increasing publications signal its ascent as a research powerhouse, in line with its strategic developmental initiatives and ambition to lead in scientific innovation. Canada and Italy's notable contributions, driven by their long history in nuclear applications, especially in healthcare and power generation, affirm the interdisciplinary nature of nuclear research. Similarly, Russia's output denotes its sustained focus on nuclear science, complemented by Switzerland's precision in high-quality research.

The engagement from India and the collaborative efforts within European countries, including the Netherlands, Sweden, Spain, Belgium, and Poland, as well as the Asia–Pacific region represented by Australia, highlight the collective and interconnected approach to nuclear isotope research. This collaborative network likely benefits from regional support and is indicative of the international community's concerted efforts in the field. The separate mention of West Germany alludes to historical data categorizations that provide a snapshot of its contributions within a certain time frame. South Korea and Finland, while contributing fewer publications, affirm the widespread and inclusive nature of nuclear isotope research, emphasizing its significance and applicability across global scientific initiatives.

Employing VOSviewer software and leveraging data from the Web of Science Core Collection database, Fig. 2 presents a network relationship graph that was meticulously generated. This graph encapsulates the data retrieved through a comprehensive search using the keywords “nuclear isotope” spanning from 1970 to November 2023. It profoundly elucidates key trends in nuclear isotope research, depicted through the graphical representation of the largest spheres, namely “Nuclei”, “Structure”, and “Measurement”, juxtaposed against the most brightly illuminated spheres identified as “Separation”, “Process”, and “Evolution”.

The terms “Nuclei”, “Structure”, and “Measurement” represent entrenched research areas within the ambit of nuclear isotope studies. “Nuclei” signifies a fundamental emphasis on the atom's core component, a cornerstone for comprehending atomic behavior and interactions. “Structure” probes into the complex configurations and dynamics of particles within the nucleus, shedding light on the forces and reactions at play in nuclear physics. “Measurement” accentuates the empirical aspect of this research, highlighting the imperative for precise and robust methodologies in investigating and deciphering nuclear phenomena. The substantial size of these spheres in the graph reflects their long-standing centrality and the extensive research investments in these areas.

Conversely, the terms “Separation”, “Process”, and “Evolution”, illuminated as the brightest spheres, signify nascent yet burgeoning research interests in nuclear isotope studies. “Separation” is likely indicative of advancements in the isolation of specific isotopes, a critical process for diverse applications spanning medical, industrial, and energy sectors. “Process” suggests innovations in techniques and methods employed in the management and application of nuclear isotopes. “Evolution”

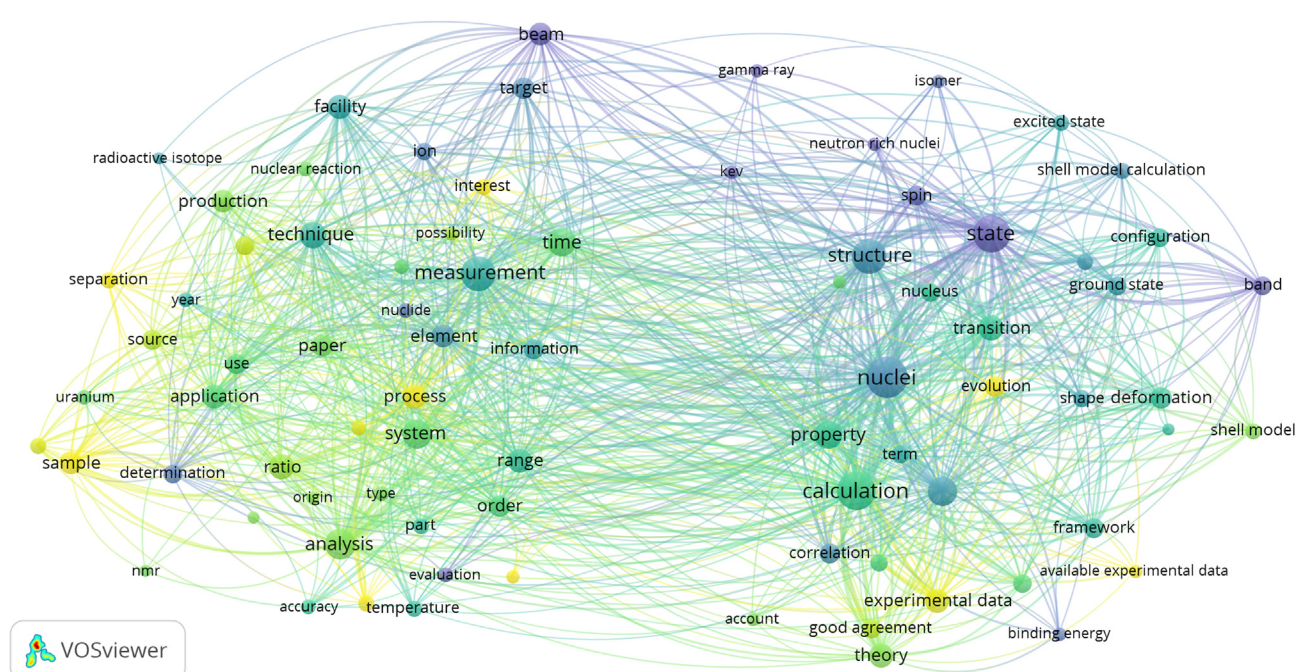

Fig. 2. Network diagram based on Web of Science Core Collection database searched by the keywords “nuclear isotope” (1970–November 2023).

connotes a progressive shift in the theoretical comprehension and practical application of nuclear isotopes, signaling a movement towards novel paradigms and the exploration of previously uncharted scientific territories. The pronounced luminosity of these terms in the graph denotes an escalating research interest and significance in these evolving areas, marking their increased prominence in the contemporary scientific discourse.

2.2. Environmental distribution and concentration

The environmental dynamics of nuclear isotope distribution are shaped by a multitude of variables, each contributing to a complex interaction between these isotopes and their surroundings. This section provides a comprehensive exploration of the pathways and behaviors of nuclear isotopes, highlighting the intricate nuances in their environmental spread and accumulation. Table S1 summarizes the environmental distribution and concentration of key nuclear isotopes.

In aquatic environments, isotopes such as tritium and strontium-90 exhibit unique dispersion patterns, driven by their chemical properties and interaction with water bodies. Tritium, characterized by its high solubility, is known to permeate through large aquatic systems, creating uniform concentration levels [14]. This contrasts with its behavior in smaller, closed systems where it tends to accumulate, surpassing environmental safety thresholds [15]. On the other hand, cesium-137, with its affinity for particulate matter, predominantly settles in sediments, creating potential hotspots of contamination [16,17]. These nuances in isotopic behavior necessitate a tailored approach to monitoring and remediation, particularly in diverse aquatic systems ranging from vast oceans to enclosed lakes and reservoirs.

The terrestrial distribution of isotopes, such as uranium and plutonium, is equally complex, heavily influenced by soil composition and vegetation cover. These isotopes tend to bind with organic materials and clay particles in the soil, leading to concentrated zones of contamination, especially in regions with higher organic content [18,19]. The implications of such distribution are significant, affecting everything from plant uptake and the terrestrial food chain to soil fertility and overall ecosystem health [20]. The interaction between these isotopes and various soil types underscores the importance of soil-specific risk assessment and targeted remediation strategies to mitigate their environmental impact.

The atmospheric dispersion of nuclear isotopes, particularly those emitted during nuclear incidents or testing, presents another layer of complexity. Factors such as meteorological conditions and geographic features play a crucial role in their distribution [21]. Noble gases like xenon and krypton, for instance, exhibit widespread dispersion in the atmosphere, influenced by air currents and altitude [22]. The understanding of these atmospheric behaviors is critical for developing predictive models and strategies to monitor and mitigate the impact of airborne isotopes, both on a local and global scale.

An overarching theme in the environmental behavior of nuclear isotopes is the interconnectedness between various environmental matrices and the isotopes themselves. This intricate relationship demands a multidisciplinary approach to effectively understand and manage the distribution and concentration of nuclear isotopes. The insights gained from such comprehensive studies are invaluable, informing risk assessment models, shaping environmental policies, and guiding remediation efforts. They highlight the importance of integrating scientific research with environmental management practices to address the challenges posed by nuclear isotopes in our ecosystems.

2.3. Multifaceted applications and ongoing innovation

Nuclear isotopes have enabled transformative scientific and technological advances across diverse sectors, including medicine [23,24], industry [25,26], energy production [27,28], and defense [29,30]. Their unique signatures and radioactivity confer capabilities that have catalyzed innovations across decades.

In the medical realm, radioisotopes permitted the emergence of new diagnostic modalities such as positron emission tomography and single photon emission computed tomography imaging, providing unprecedented visibility into physiological processes and metabolic aberrations [31,32]. The development of novel radioisotopic tracers continues to enhance imaging capabilities in terms of resolution, specificity, and sensitivities. Isotopes have also broadened the repertoire of targeted radiation treatment options for oncological and certain autoimmune conditions, facilitating the delivery of curative radiation doses while minimizing collateral damage to adjacent tissues [33,34]. Ongoing research strives to further refine the therapeutic application of nuclear isotopes. Moreover, industrial sterilization processes have productively leveraged gamma radiation's penetrative capacity for efficient disinfection of healthcare products [35].

In the industrial sphere, nuclear isotopes have driven advancements across domains including materials analysis [25], manufacturing [36], environmental studies [37,38], and process optimization [39]. Radioisotopic tracers have illuminated the intricate dynamics of flows [40], mixing, and residence times in complex chemical [41], petrochemical [42], and wastewater treatment systems [43], enabling significant performance improvements. Ionizing radiation has facilitated beneficial physical and chemical modifications in polymers [44], foodstuffs [45], and other materials [46]. Techniques such as nuclear magnetic resonance spectroscopy have permitted deeper insights into molecular structures [47]. Emerging horizons for near-future applications include expanding therapeutic radioisotope capabilities and harnessing nuclear fusion as an energy source.

In the realm of environmental and ecological studies, nuclear isotopes serve as indispensable tools for tracing and understanding complex environmental processes. For instance, isotopes like Carbon-14 and Tritium are utilized in hydrology to trace water sources and flow paths, offering invaluable insights into groundwater dynamics and pollution dispersion [48,49]. In climatology, isotopes such as oxygen-18 provide critical data for reconstructing past climatic conditions, aiding in the understanding of climate change patterns [50]. In the field of medicine, advancements in radioisotopic applications go beyond diagnostic imaging. Isotopes like Iodine-131 and Lutetium-177 have revolutionized targeted radionuclide therapy, allowing for precise tumor targeting while minimizing damage to surrounding healthy tissues [51]. This therapeutic use of isotopes represents a significant leap forward in oncological treatments, providing patients with more effective and less invasive treatment options. In energy production, the role of isotopes extends beyond traditional nuclear power generation [52]. Research into the use of isotopes in nuclear fusion technology is progressing, with the potential to provide a cleaner and more sustainable energy source.

However, the multifaceted applications of nuclear isotopes also pose formidable challenges with regard to radiation exposure hazards, radioactive waste generation, financial costs, ethical dilemmas, and risks of militarization. The implementation of prudent safety practices and oversight mechanisms are indispensable across all domains in order to ensure these technologies are employed responsibly and sustainably as innovation progresses.

2.4. The intricate governance landscape

The discovery of nuclear fission reactions prompted the inception of governance structures and mechanisms to responsibly guide this groundbreaking technology, acknowledging its immense promise alongside unprecedented risks. The technology's uniquely impactful nature necessitated the development of binding international accords coupled with national regulatory bodies wielding technical expertise and enforcement capabilities.

Key agreements such as the Treaty on the Non-Proliferation of Nuclear Weapons have sought to restrict the spread of nuclear weapons while facilitating the peaceful usage of nuclear technology for energy production and other beneficial purposes [53]. Entities, including the International Atomic Energy Agency (IAEA) and national regulatory agencies, have instituted stringent safety protocols, transport regulations, radioactive waste disposal policies, and emergency preparedness plans [54]. Policymaking processes have increasingly incorporated public sentiment and actively engaged diverse stakeholders [55]. Recent high-priority governance facets include the development of intrinsically safe advanced reactor designs, radioactive waste volume minimization, and the strengthening of nuclear security provisions against theft and sabotage risks.

However, effective nuclear sector governance remains an evolving, multifaceted challenge with complex trade-offs. Differing national priorities and constraints must be reconciled with broader collective objectives within the international policy sphere. The rapid pace of technological progress within the domain demands nimble yet rigorous regulatory oversight. Continued public engagement paired with ethics-driven policy formulation is integral given the sector's deep societal and environmental ramifications. Overall, the global nuclear governance landscape aims to foster beneficial applications where suitable, while simultaneously instituting stringent controls to minimize concomitant risks.

Looking to the future, nuclear governance must also adapt to emerging technologies such as small modular reactors (SMRs) and the advent of nuclear fusion. SMRs, with their potential for reduced waste and increased safety, challenge traditional regulatory frameworks designed for larger, conventional nuclear reactors. Similarly, the prospective commercialization of nuclear fusion technology, offering a virtually limitless and cleaner energy source, will necessitate novel regulatory approaches and international collaboration to address unique safety, environmental, and non-proliferation concerns [56]. This evolving landscape underscores the need for a dynamic and anticipatory governance approach, one that is flexible enough to accommodate technological innovations while maintaining a steadfast commitment to safety, environmental protection, and non-proliferation. The effective governance of these burgeoning technologies will be instrumental in their acceptance and success, shaping the future trajectory of nuclear energy's role in a sustainable energy mix.

2.5. Building public awareness and trust

Public sentiment regarding nuclear technology varies significantly across different nations based on historical experiences, energy policy landscapes, and the influence of key events such as major nuclear accidents. Overall, the establishment of substantial nuclear energy infrastructure and global leadership in nuclear R&D correlates strongly with relatively more supportive public attitudes. Meanwhile, apprehension or opposition often arises from ingrained worries related to safety, security, or nuclear waste storage. Post-Fukushima Japan exemplifies a mixed public sentiment with both residual anxieties and pragmatic acceptance [57]. Germany's planned nuclear phase-out reflects growing public skepticism of the technology [58].

Education initiatives and awareness campaigns are thus crucial to fostering informed public opinions grounded in facts and rigorous science communication [59]. Integrating nuclear physics basics into educational curricula, publicizing applications via multimedia campaigns and exhibitions, and maintaining open discourse through consultations all help dispel myths and prepare citizens for constructive debates. Tailored outreach to stakeholders such as journalists, educators, and policymakers also enables accurate and balanced public messaging.

Ultimately, public acceptance hinges upon transparent operations, stringent safeguards, demonstrable reliability, and earnest engagement with concerns such as nuclear waste storage. Policies should emphasize constructive discourse and partnerships that respect public interests and reservations [60]. Nurturing this confidence is essential for enabling the sustainable adoption of any nuclear technology.

In the digital age, online platforms and social media have assumed an increasingly pivotal role in shaping public perceptions of nuclear technology [61]. The rapid dissemination of information through these channels can significantly influence public opinion, both positively and negatively. While these platforms offer an unparalleled opportunity to engage with a wider audience, they also pose challenges in combating misinformation and ensuring the accuracy of communicated content. Efforts to leverage digital media for nuclear education and awareness must be strategic and fact-based, utilizing multimedia tools, interactive webinars, and expert-led online discussions to provide clear, accurate, and accessible information [62]. Recognizing the power of social media influencers and online communities, collaborations with credible digital personalities can be instrumental in reaching diverse demographics, particularly the younger generation. This approach demands a proactive stance in monitoring online discussions, responding to queries and concerns in real time, and countering misinformation with scientifically backed data [63]. In essence, harnessing the potential of digital platforms necessitates a concerted effort to engage in meaningful online dialogs, fostering an informed and balanced public discourse on nuclear technology.

2.6. Navigating the road ahead

The nuclear sector's trajectory is currently shaped by a juxtaposition of burgeoning technological advancements and evolving global challenges. This section delves into the multiple dimensions that will influence the future course of nuclear technology, offering insightful perspectives on how these elements intertwine to shape the road ahead.

Rapid advancements in nuclear technology, including the development of next-generation fission reactors and enhanced fuel cycles [64, 65], are poised to redefine the industry's landscape. These innovations promise greater efficiency, safety, and reduced waste production. The emergence of sophisticated monitoring technologies and artificial intelligence applications in nuclear operations will likely necessitate a recalibration of regulatory frameworks [66], ensuring that they align with the evolving technological paradigms.

Amidst the escalating climate crisis, nuclear power's role as a reliable, low-carbon energy source is increasingly emphasized. The integration of nuclear energy into broader renewable energy strategies is becoming increasingly crucial [67]. This necessitates policies that facilitate a pragmatic balance between energy security, economic feasibility, and environmental sustainability, keeping in view the overarching goal of mitigating climate change.

Economic factors, alongside the imperatives of nuclear non-proliferation, will significantly dictate the nuclear sector's future [68]. Cost-effective deployment of nuclear technology, especially in developing countries, requires innovative financing models and international support. Concurrently, upholding non-proliferation standards remains a global imperative, demanding robust international cooperation and vigilance.

The long-standing challenge of radioactive waste management is expected to gain heightened global focus. Developing sustainable, safe, and community-accepted waste disposal solutions will be a critical aspect of nuclear technology's future viability [69]. This area calls for concerted efforts in research, policy formulation, and public engagement to find solutions that are both technically sound and socially responsible.

Building and maintaining public trust through sustained engagement and transparent communication is paramount [70]. Addressing societal concerns, especially those related to safety and environmental impact, is essential for the sector's social license to operate. Furthermore, a commitment to environmental stewardship, including the conservation of biodiversity and the protection of ecosystems, must be at the core of nuclear policy and practice.

3. Impacts of nuclear isotope emissions or leaks

The release of nuclear isotopes, whether through accidents or leaks, poses significant challenges to both the environment and human health. This section provides a comprehensive overview of the multifaceted impacts of such releases. It begins with a historical perspective, exploring notable nuclear accidents and incidents, thereby setting a contextual foundation for understanding the subsequent impacts. The pathways through which nuclear isotopes enter and interact with the environment are then examined, revealing the complex dynamics of their dispersion and accumulation. The focus shifts to the specific impacts on natural environments, including aquatic ecosystems and soil and sediments, highlighting how these isotopes affect various ecological components. Detailed analysis of the long-term environmental consequences sheds light on the persistent nature of these isotopes and their lasting effects on ecosystems. The discussion then transits to the implications for human health, underscoring the range of health risks posed by exposure to nuclear isotopes. Finally, the socio-economic impacts are explored, demonstrating the far-reaching effects of nuclear isotope emissions or leaks on communities and economies.

3.1. Overview of nuclear accidents and incidents

The history of nuclear energy, while marked by significant achievements and advancements, has also witnessed a series of accidents and incidents. These events, ranging from minor operational anomalies to major catastrophic failures, have left indelible imprints on the sector, shaping policies, influencing public perception, and driving technological innovations.

Nuclear accidents typically arise from a combination of technical failures, human errors, and, in some cases, natural disasters. While the nuclear industry boasts of rigorous safety protocols and redundant systems, the complex interplay of these factors has, on occasion, led to unforeseen consequences. Prominent among these accidents are the Chernobyl disaster in 1986 and the Fukushima Daiichi nuclear disaster in 2011. The Chernobyl accident, triggered by a sudden power surge during a safety test, resulted in a massive release of radioactive materials, affecting large swathes of Europe and leading to long-term health and environmental impacts [71]. The Fukushima disaster, precipitated by a massive earthquake and subsequent tsunami, underscored the vulnerabilities of nuclear facilities to external natural threats [72]. The articles comparing the Chernobyl and Fukushima nuclear accidents provide a detailed examination of their environmental impacts [73,74]. They highlight the magnitude of radionuclide release, which was significantly higher in Chernobyl than in Fukushima. The environmental consequences of Chernobyl were more severe, affecting a broader geographical area and resulting in more pronounced health impacts. The two accidents both caused widespread radionuclide contamination but differed in release characteristics, evacuation effectiveness, and long-term environmental and health consequences. These comparisons offer valuable insights for future nuclear accident management and environmental remediation efforts.

However, it is essential to contextualize these major accidents within the broader nuclear narrative. Numerous other minor incidents, often not widely publicized, have provided invaluable lessons for the sector. From coolant leaks to equipment malfunctions, these incidents, while not catastrophic, have highlighted potential vulnerabilities and areas of improvement.

The aftermath of these accidents and incidents has invariably been characterized by introspection, analysis, and action [75]. Regulatory bodies, nuclear operators, and international agencies have collaboratively embarked on comprehensive reviews, identifying lapses, and implementing corrective measures. Technological solutions have been sought to address design vulnerabilities, operational procedures have been revamped, and emergency response protocols have been strengthened.

Moreover, these events have sparked public debates on the merits and risks of nuclear energy. Communities, activists, and policymakers have engaged in discussions, weighing the benefits of nuclear power against its potential hazards. These deliberations have influenced energy policies, with certain nations opting to scale down or phase out their nuclear programs, while others have reaffirmed their commitment to nuclear energy, albeit with enhanced safety measures.

In conclusion, the legacy of nuclear accidents not only casts a long shadow but also serves as a constant reminder of the responsibilities that accompany the immense power of nuclear energy. The lessons learned from these accidents, the innovations they have spurred, and the policies they have shaped collectively contribute to a safer, more resilient, and more accountable nuclear sector. As the industry looks to the future, these historical events serve as both cautionary tales and guiding lights, emphasizing the need for vigilance, innovation, and collaboration.

3.2. Pathways of nuclear isotopes into the environment

The dissemination of nuclear isotopes into the environment is a multifactorial process intricately influenced by a range of anthropogenic and natural activities. Primarily, nuclear power plant operations, including routine and maintenance activities, are identified as significant contributors of isotopes release. These releases, typically controlled and within regulatory limits, occur primarily through gaseous and liquid effluents. Gaseous emissions, often comprising noble gases and iodine isotopes, are released into the atmosphere following stringent filtration and dilution procedures [76]. Conversely, liquid discharges, containing tritium and other soluble radionuclides, are directed into aquatic systems, subject to rigorous treatment and monitoring protocols to ensure compliance with environmental standards [77].

Though less frequent, accidental releases pose a more severe risk of environmental contamination. Historical instances such as the Chernobyl and Fukushima Daiichi nuclear disasters exemplify the catastrophic potential of uncontrolled isotope release. In such events, a combination of mechanical failures, human errors, and natural disasters culminates in the extensive dissemination of radionuclides across diverse environmental matrices [78]. The airborne isotopes from such accidents are subject to atmospheric transport mechanisms, leading to widespread distribution, often crossing international borders. Precipitation processes further facilitate the deposition of these isotopes into terrestrial and aquatic ecosystems. The terrestrial deposition predominantly impacts soil and vegetation, leading to secondary dispersion through soil-to-plant transfer and further incorporation into the terrestrial food web. Aquatic contamination, arising from both direct liquid discharges and atmospheric deposition, results in the distribution of isotopes in water bodies, sediment layers, and aquatic biota, instigating a cascade of bioaccumulation and biomagnification effects.

In radioactive waste management, it is crucial to recognize that well-implemented disposal practices are structured to preclude the entry of nuclear isotopes into the environment. These practices, encompassing storage, transportation, and disposal, are meticulously regulated and monitored to minimize any potential environmental release. Nevertheless, it is acknowledged that, while the risk is substantially mitigated, the possibility of long-term environmental impact cannot be entirely eliminated, especially in scenarios involving the leaching of radionuclides from waste containment systems under extreme conditions. These containment structures, meticulously engineered to isolate radioactive waste, are designed to withstand the rigors of time and environmental factors. However, in rare instances, their integrity might be challenged, potentially leading to the release of radionuclides [79]. The leachate, a byproduct of the interaction between waste materials and infiltrating water, is typically contained within the engineered barriers, designed to prevent its migration through geological strata and ultimately safeguard the biosphere.

In addition to anthropogenic sources, natural processes also contribute to the environmental presence of nuclear isotopes. Terrestrial radionuclide mobilization occurs through weathering and erosion of uranium-rich minerals, leading to the release of decay products such as radium and radon. These naturally occurring radioactive materials (NORM) are ubiquitous in the environment, albeit at low concentrations [80]. Radon, a gaseous decay product of uranium, is particularly noted for its ability to migrate through soil and enter the atmosphere or accumulate in enclosed spaces, such as buildings. Hydrological processes, including the dissolution, transport, and deposition of radionuclides, play a crucial role in the distribution of NORM within aquatic systems. The interaction between water and mineral substrates facilitates the transfer of radionuclides, subsequently influencing their bioavailability and ecological impact.

Collectively, these pathways of nuclear isotopes into the environment, from both anthropogenic and natural sources, underscore the complexity of managing and mitigating their ecological and human health impacts. Continuous monitoring, stringent regulatory frameworks, and the development of advanced containment and remediation technologies are essential in addressing the challenges posed by the pervasive presence of nuclear isotopes in the environment.

3.3. *Ecological impacts of nuclear isotopes*

The ecological impacts of nuclear isotopes encompass a broad spectrum of effects across various environmental matrices. This section delves into the specific ways in which these isotopes influence distinct ecosystems. To illustrate these impacts visually, Fig. 3 provides a comprehensive overview of the ecological impacts of nuclear isotopes. The analysis begins with a focus on aquatic environments, examining how nuclear isotopes interact with water bodies, aquatic flora, and fauna, thereby affecting the delicate balance of these ecosystems. The discussion then shifts to the impact on soil and sediments, where the long-term retention and mobility of isotopes can significantly alter soil chemistry and structure, influencing terrestrial life forms. The final part of this section addresses the long-term environmental consequences, including an examination of the persistent effects of nuclear isotopes on biodiversity, ecosystem health, and the complex interplay between environmental contamination and ecological resilience.

3.3.1. *Impact on aquatic environments*

The delicate balance of aquatic ecosystems, encompassing rivers, lakes, oceans, and even groundwater reservoirs, can be significantly disrupted by the inadvertent release of nuclear isotopes. Such releases, whether from nuclear accidents, waste disposal, or other sources, can have profound and lasting impacts on these water bodies and the myriad life forms they support [81].

When nuclear isotopes find their way into aquatic systems, they disperse based on water currents, temperature gradients, and their physicochemical properties. Some of these radioactive materials might adhere to aquatic sediments, settling to the depths, while others remain suspended in the water column or are absorbed by aquatic plants and microorganisms. This absorption sets the stage for bioaccumulation, where isotopes concentrate within organisms, and biomagnification, where these concentrations increase as one moves up the food chain [82].

Fish and other aquatic animals, especially those higher up in the food chain, can accumulate significant amounts of these isotopes in their tissues [83]. This not only poses a threat to their health, leading to reduced fertility, increased mortality, or genetic mutations, but also has implications for human populations that rely on these species as a food source. Consuming contaminated seafood can lead to the ingestion of radioactive materials, with potential health risks ranging from acute radiation sickness to long-term diseases like cancer.

Beyond the direct biological impacts, the presence of nuclear isotopes can alter the very dynamics of aquatic ecosystems. Radiation can influence the growth and reproductive patterns of aquatic plants, potentially leading to shifts in species dominance [84]. It can also affect microbial communities, which play crucial roles in nutrient cycling and water quality maintenance.

Human communities, especially those that rely on affected water bodies for drinking or agricultural purposes, face additional challenges. Radioactive contamination can render water sources unsafe, necessitating expensive treatment processes, or the search for alternative sources. The socio-economic implications, from affecting fisheries to impacting tourism, can be far-reaching [85].

The long-lived nature of certain isotopes further adds complexity to these challenges. Some of these radioactive materials can persist in aquatic environments for decades or even centuries, posing a long-term threat and making remediation efforts challenging [86]. Addressing the contamination might require strategies like dredging to remove contaminated sediments or introducing specific species that can help sequester or break down the isotopes.

Recent advancements in environmental monitoring technologies, such as satellite imaging and remote sensing, are enhancing our capability to detect and analyze the distribution of nuclear isotopes in aquatic ecosystems with unprecedented precision and scale [87,88]. These

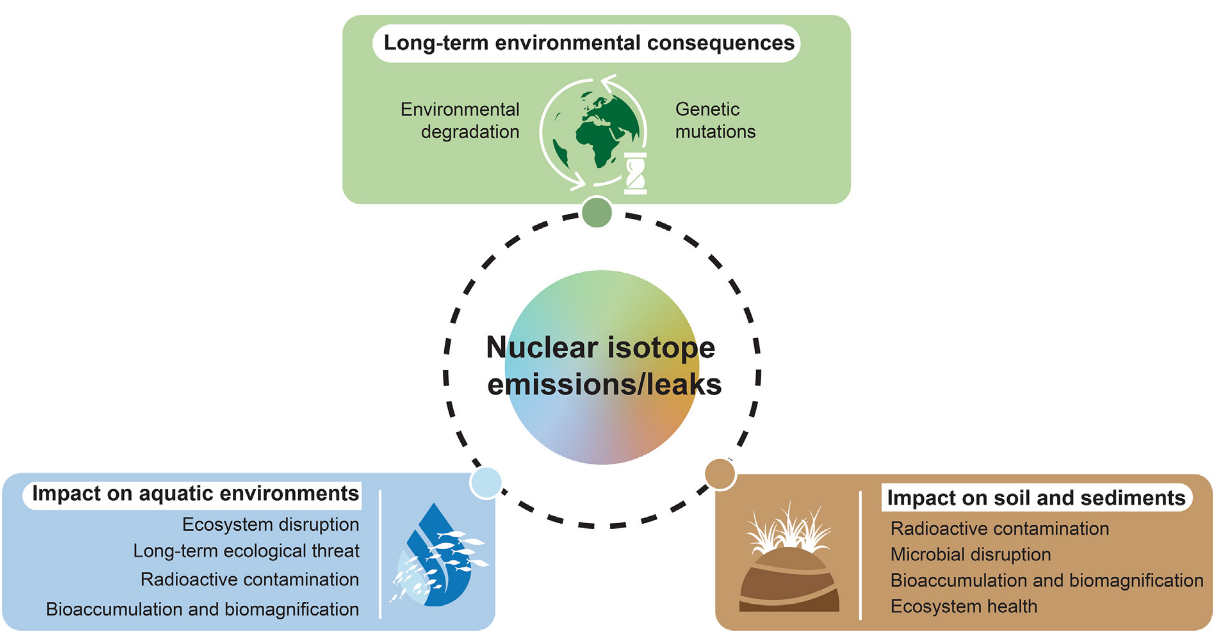

Fig. 3. Ecological impacts of nuclear isotopes.

technological developments are not only pivotal in real-time monitoring but also in predictive modeling, offering valuable insights into potential future dispersion patterns and ecological impacts. Additionally, ongoing research in the field of nanotechnology presents promising approaches for the removal of radioactive materials from water bodies. Innovations like nano-enabled adsorbents or filter systems demonstrate high efficiency in isolating and extracting nuclear isotopes from aquatic environments [89]. Looking ahead, interdisciplinary research that combines environmental science, nuclear physics, and technology development will be crucial in addressing the challenges posed by nuclear isotopes in aquatic systems. This future-oriented approach will require not only scientific innovation but also policy adaptations and international collaborations to mitigate risks and safeguard aquatic biodiversity and human health in the nuclear era.

3.3.2. Impact on soil and sediments

Soil and sediments, often overlooked in the broader environmental context, play a pivotal role in supporting terrestrial and aquatic life, respectively. The introduction of nuclear isotopes into these substrates can lead to cascading effects, influencing not just the immediate environment but also the larger ecosystems they underpin.

Upon the release of nuclear isotopes, whether through accidents, fallout, or deliberate disposal, these materials interact with the soil and sediment matrix. Factors such as soil type, pH, organic matter content, and moisture levels influence the mobility and binding affinity of these isotopes [90]. In many instances, isotopes can bind strongly to soil particles, reducing their immediate mobility but posing long-term contamination risks [91]. In contrast, in aquatic sediments, the interplay of water currents, sediment composition, and biological activity can influence the distribution and concentration of these radioactive materials.

The presence of radioactive isotopes in soil can disrupt the natural microbial communities, which are essential for nutrient cycling, organic matter decomposition, and soil structure maintenance [92]. Changes in microbial dynamics can, in turn, influence plant growth and health. Plants absorbing these isotopes through their root systems can integrate them into the terrestrial food web [93]. This can lead to bioaccumulation in herbivores and subsequent biomagnification in higher trophic levels, posing risks to wildlife and humans alike.

For sediments, the accumulation of nuclear isotopes can impact benthic organisms, i.e., those creatures that dwell on the bottom of water bodies [94]. These organisms, ranging from microscopic invertebrates to larger species like crabs and mollusks, can accumulate radioactive materials, which can then move up the aquatic food chain. Moreover, disturbances like dredging or natural events like storms can resuspend these sediments, releasing trapped isotopes back into the water column.

Humans, particularly those dependent on agriculture, confront direct challenges arising from soil contamination. Radioactive isotopes have the potential to infiltrate the human food chain through various pathways, including crops, livestock, and the direct consumption of contaminated agricultural products [95]. This scenario poses substantial health risks and carries socio-economic implications, potentially rendering agricultural lands unproductive and necessitating costly remediation efforts. The integration of these isotopes into agricultural products not only raises concerns about immediate health effects but also affects market dynamics and consumer confidence, leading to broader economic repercussions.

After Fukushima nuclear event, extensive soil decontamination initiatives were implemented to tackle the challenges in post-accident ecological restoration [96]. The remediation plan, covering a vast area of approximately 8,953 km^2, was strategically designed to reduce radiation exposure to levels below 1 mSv/yr. However, the reoccupation of the area by only about 29.9% of the original inhabitants revealed persistent challenges, including issues of diminished soil fertility and altered dynamics of radiocesium (^{137}Cs) in agricultural outputs. This situation necessitated the application of potassium fertilization as a countermeasure. A critical aspect of this environmental recovery was the unaddressed complexity in forested regions, which comprise a significant portion, roughly 71%, of the landscape. The absence of remediation in these areas led to the continued presence of ^{137}Cs in the forest ecosystems, subsequently affecting river systems and impacting the aquatic life downstream. These developments highlight the imperative for ongoing ecological monitoring and the sharing of data to enhance the understanding of ^{137}Cs mobility and its extensive ecological impacts.

Addressing the contamination of soil and sediments is a multifaceted challenge. Remediation strategies might involve the removal and containment of contaminated substrates, the introduction of plants that can phytoremediate radioactive materials, or the use of specific microbial strains that can immobilize or transform these isotopes [97,98].

Emerging research is increasingly leveraging advanced geospatial technologies and molecular biology techniques to better understand and mitigate the impacts of nuclear isotopes on soils and sediments. Innovations such as high-resolution satellite imagery and geographic information system (GIS) mapping are providing more precise data on contamination spread and hotspots [99]. Additionally, developments in molecular biology, such as metagenomics and bioinformatics, are offering deeper insights into how nuclear isotopes affect soil microbial communities and their ecological functions. Looking forward, the focus is shifting towards developing more sustainable and effective remediation approaches. Bioengineering solutions, like the use of genetically modified microorganisms or plants with enhanced uptake capacities for specific radionuclides, are being explored [100]. Furthermore, there is a growing emphasis on the long-term management of contaminated sites, considering the potential impacts of climate change on contaminant mobility and bioavailability. This holistic approach, integrating advanced science and forward-thinking management strategies, is crucial for ensuring the long-term health and resilience of soil and sediment ecosystems in the face of nuclear isotope contamination.

3.3.3. Long-term environmental consequences

Table S2 provides a comprehensive overview of the long-term environmental consequences of various nuclear isotopes, setting the context for the in-depth discussion in this section. The environmental implications of nuclear isotope emissions extend far beyond the immediate aftermath of an accident. The lingering presence of certain radionuclides in the environment means that ecosystems and the species within them grapple with challenges that can last for generations [101]. These enduring effects, while sometimes subtle, can significantly alter ecological balances, disrupt natural cycles, and complicate conservation and restoration initiatives. One of the most significant long-term effects is the disruption of ecological food chains. As radionuclides find their way into the base of the food web, processes like bioaccumulation and biomagnification come into play [102]. Over extended periods, apex predators, such as specific fish and mammal species, can amass concerning levels of radioactivity. This accumulation can jeopardize their health and reproductive capabilities, even leading to population declines or local extinctions.

Terrestrial ecosystems, particularly the soil, face a unique set of challenges. Persistent radionuclides can stifle microbial activity, which is crucial for nutrient cycling and the decomposition of organic matter. This disruption can diminish soil fertility, adversely affecting plant growth and agricultural yields [103]. Over time, these alterations can prompt shifts in plant communities, favoring species that can withstand radiation or the changed soil conditions. In contrast, aquatic ecosystems, especially freshwater habitats, are at risk of prolonged eutrophication from radionuclide interactions with water nutrients [104]. Such interactions can trigger algal blooms, deplete oxygen levels, and result in the death of aquatic life. Furthermore, sedimentation can trap radionuclides in the beds of lakes and rivers, presenting long-term contamination challenges.

The genetic repercussions of extended radiation exposure cannot be overlooked. Mutagenic effects can emerge in both plants and animals, leading to genetic anomalies, hindered reproductive success, and potential congenital disabilities in subsequent generations [105,106]. Over time, these effects can erode genetic diversity, leaving populations more vulnerable to diseases and environmental shifts [107]. From a conservation standpoint, the enduring presence of radionuclides complicates habitat restoration and species reintroduction endeavors. Habitats tainted by radiation might remain inhospitable for certain species for long durations, necessitating ongoing monitoring and potential interventions to restore ecological balance.

Zooming out to a broader perspective, these enduring environmental impacts hold profound socio-economic and cultural implications. Communities dependent on natural resources, whether for livelihood, cultural rituals, or sustenance, find their traditions and way of life imperiled. The familiar landscapes and waterscapes undergo transformations, some barely noticeable and others stark, all bearing the indelible mark of nuclear isotope emissions. In conclusion, while immediate interventions post-nuclear accidents are vital, it is equally crucial to acknowledge and brace for the long-haul environmental challenges on the horizon. These challenges, deeply linked with ecosystem health and community well-being, highlight the importance of continuous research, vigilant monitoring, and adaptable management strategies.

3.4. Impact on human health

Fig. 4 visually illustrates the impact of nuclear isotopes on human health, providing a clear depiction of this critical issue. The intersection of nuclear isotopes and human health is a topic of paramount concern due to the profound implications of radiation exposure on population well-being. While the undeniable benefits of nuclear technology in fields like medicine are significant, inadvertent exposure to nuclear isotopes—whether through accidents, environmental contamination, or occupational hazards—presents a spectrum of health risks. These risks range from acute radiation syndrome to long-term effects such as cancer and genetic mutations. Complementing the discussion, Table S3 comprehensively lists the impacts of various nuclear isotopes on human health, detailing the specific risks associated with each type of isotope exposure.

Acute exposure to high levels of radiation can result in immediate health effects, often termed as radiation sickness or acute radiation syndrome (ARS) [108]. Manifesting as nausea, fatigue, hair loss, and skin burns, ARS is a direct consequence of the rapid damage inflicted on bodily tissues. In severe cases, this can lead to organ failure, especially in highly sensitive systems like the bone marrow, and can be fatal. Chronic exposure to lower levels of radiation, while less immediately dramatic, can pose insidious long-term effects. One of the most significant concerns is the increased risk of cancer [109]. Radiation can induce mutations in DNA, and while the body's repair mechanisms often address such damage, errors can accumulate over time, potentially leading to the onset of various cancers, notably leukemia and thyroid cancer.

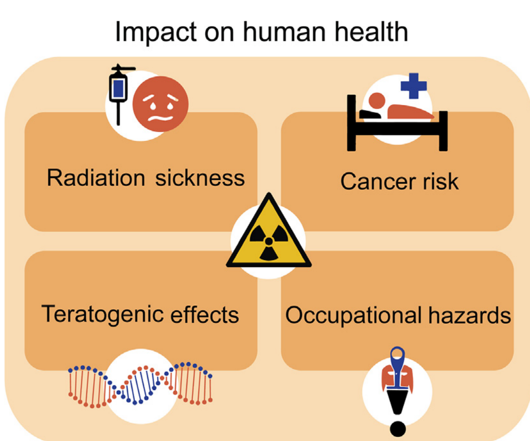

Fig. 4. Impact of nuclear isotopes on human health.

Furthermore, radiation exposure in pregnant individuals can have teratogenic effects, leading to birth defects or developmental abnormalities in the fetus [110]. There is also evidence suggesting potential genetic effects, where radiation-induced mutations are passed on to subsequent generations. Beyond direct radiation exposure, the ingestion or inhalation of radioactive isotopes poses additional risks. Isotopes like iodine-131 can accumulate in specific organs, in this case, the thyroid, leading to concentrated radiation exposure and heightened health risks [111].

Occupational exposure, especially for workers in nuclear facilities, research labs, or medical establishments, necessitates rigorous safety protocols [112]. Regular health check-ups, monitoring of radiation doses, and the use of protective equipment are essential to minimize risks. Public health challenges also arise in the aftermath of nuclear accidents. The evacuations, long-term displacement, and psychological trauma experienced by affected populations, as witnessed post-Chernobyl or Fukushima, are significant. Moreover, the fear and stigma associated with radiation exposure can have lasting socio-cultural impacts on communities.

In addition to physical health ramifications, the psychological impact of radiation exposure and nuclear accidents must not be underestimated [113]. Studies have shown that survivors of nuclear accidents and populations living in contaminated areas often experience long-term psychological stress, anxiety, and trauma [114]. This psychological burden stems not only from health concerns but also from socio-economic disruptions, such as displacement and loss of livelihoods. The stigma associated with radiation exposure further exacerbates mental health challenges, leading to social isolation and community fragmentation. These mental health considerations necessitate the inclusion of psychological support and counseling in public health responses to nuclear accidents. Moreover, the long-term surveillance of mental health in affected populations is crucial for understanding the full spectrum of health impacts and for developing targeted interventions. This holistic approach to health management, encompassing both physical and mental well-being, is essential for the comprehensive care of populations impacted by nuclear isotopes.

3.5. Socio-economic impacts

The release of nuclear isotopes into the environment, whether through accidental emissions or leaks, has far-reaching consequences that extend beyond immediate environmental and health concerns. The socio-economic ramifications of such accidents can reshape entire regions, impacting livelihoods, economies, and the very essence of communities [115]. In the immediate aftermath of nuclear contamination, the agricultural sector often faces the most direct repercussions [116]. Soil and water contamination can make crops and aquatic ecosystems unsafe, leading to significant losses in harvests and fisheries. The stigma associated with products from affected areas can result in market rejections, even if the products meet safety standards. This loss of trust can linger for years, undermining the economic foundation of many rural areas.

Beyond the immediate impacts on agriculture, other sectors also face challenges. The tourism industry, a vital revenue source for many regions, can experience a sharp decline as the fear of radiation, whether real or perceived, deters visitors [117]. This downturn affects not just direct tourism services but also cascades to related sectors like hospitality and transportation. Additionally, property values in affected regions can plummet, causing financial hardships for homeowners and reducing local government revenues. The health implications of nuclear accidents, from immediate radiation sickness to long-term conditions, further strain resources. The increased demand for healthcare systems can lead to significant economic burdens, stretching already limited healthcare capacities.

For those living closest to the contamination source, the prospect of relocation becomes a daunting reality [118]. The costs and challenges associated with such relocations are immense. Displaced populations face the loss of homes, livelihoods, and in many cases, their cultural and spiritual connections. Particularly for indigenous and local communities with deep ties to their lands, such displacement can result in a profound loss of identity and heritage. Alongside these immediate challenges, the legal landscape post-accident becomes complex. Affected parties often seek legal redress, leading to lengthy and costly legal battles, which come with their own economic implications in terms of litigation expenses and potential compensation settlements.

In response to nuclear accidents, governments undertake extensive decontamination efforts, which, while essential, are financially demanding. Moreover, the long shadow of a nuclear accident can influence a nation's energy policies, prompting shifts in policy direction and investments. These shifts have broader economic and strategic implications. In conclusion, the socio-economic landscape of regions affected by nuclear accidents is a complex tapestry of challenges and changes. Addressing these multifaceted impacts requires a comprehensive approach, combining immediate interventions with long-term strategies, to guide affected communities towards a path of recovery and resilience.

4. Remediation techniques for nuclear isotope emissions or leaks

The remediation of nuclear isotope emissions or leaks encompasses a spectrum of techniques and strategies, each tailored to address the diverse and complex nature of nuclear contamination. Addressing such contamination demands a multifaceted approach, integrating principles of nuclear science, environmental engineering, and public health. The subsequent sections delve into the core principles guiding nuclear remediation, followed by an exploration of comprehensive strategies that encompass physical, chemical, and biological methodologies. The discussion then extends to the critical aspects of waste disposal and management, highlighting their role in the overall remediation process. Furthermore, the importance of monitoring and surveillance post-remediation is underscored, emphasizing the need for ongoing vigilance in safeguarding environmental and human health. The involvement of public engagement in remediation efforts is also examined, reflecting the necessity of community involvement and transparency. Finally, the chapter culminates with a discussion on the challenges and future trajectories in nuclear remediation, offering insights into the evolving landscape of nuclear decontamination and restoration.

4.1. Principles of nuclear remediation

Nuclear remediation, following isotope emissions or leaks, is a multifaceted endeavor. Its primary goal is to safeguard the environment and human well-being, requiring a deep understanding of the ecological, socio-economic, and cultural intricacies of the impacted region [119]. Remediation transcends mere technical solutions; it aims to restore stability and assurance to communities and ecosystems that have been unsettled. Central to this is the holistic approach principle. Remediation is not solely about contaminant removal but demands a comprehensive grasp of the broader ecological and societal consequences of the contamination. This holistic perspective ensures that interventions are scientifically robust while being attuned to social and cultural sensitivities. For example, remediation tactics in a populated urban setting would likely diverge from those in an isolated, ecologically delicate area.

Safety remains at the forefront of remediation efforts. Every phase of the process must emphasize the well-being of the environment and its inhabitants. This commitment to safety extends beyond merely lowering radiation levels. It encompasses the safety of cleanup personnel, the methodologies adopted, and the tools utilized [120]. The overarching goal is to guarantee that the solutions implemented today do not morph into challenges tomorrow. Integral to this endeavor is stakeholder engagement. The insights and expertise of affected communities, local authorities, scientific professionals, and Non-Governmental Organizations (NGOs) can offer invaluable direction. Collaborative initiatives not only amplify the success of remediation but also cultivate trust and openness.

The ever-changing nature of ecosystems, combined with the intricacies of nuclear contamination, calls for adaptive management in remediation. Strategies must be malleable and poised to adapt based on ongoing monitoring and emerging data. This flexibility ensures that remediation remains pertinent and effective throughout its course. Sustainability and cost-effectiveness are also paramount. Remediation strategies should be envisioned with a long-term perspective, ensuring not just immediate safety but also long-term environmental stability. Concurrently, while safety and effectiveness are of utmost importance, the economic facets of remediation cannot be sidelined. Strategies should be economically feasible, ensuring a judicious allocation of resources.

The ethical considerations in remediation are profound. Every choice and intervention should be steered by robust ethical principles. This encompasses transparent decision-making, prioritizing the needs of the most vulnerable populations, and upholding the rights and wishes of local communities. In summary, the principles guiding nuclear remediation underscore the delicate interplay between science, society, and ethics. They spotlight the challenges and duties associated with nuclear energy utilization and reaffirm the unwavering dedication to protecting our world and its denizens.

4.2. Comprehensive strategies in nuclear contamination remediation

The remediation of nuclear contamination employs a diverse array of strategies, each tailored to meet specific challenges posed by different types of contamination and environmental contexts. These techniques, ranging from immediate containment and isolation to intricate long-term biological and chemical treatments, are operated under unique principles and timelines. The selection of an appropriate remediation approach is critical and depends on factors such as the nature and extent of the radioactive contaminants, as well as their potential impact on ecosystems and human populations. To further elucidate the variety and complexity of these techniques, Table 1 offers a detailed overview of several key methods. It outlines specific mechanisms, application contexts, and typical durations for each approach, providing valuable insights into their operational intricacies and effectiveness.

4.2.1. Physical containment and isolation

Physical containment and isolation are foundational in nuclear remediation, particularly when immediate decontamination is impractical, or the risk of spreading contaminants is elevated. These techniques focus on the sequestration of radioactive substances, ensuring they don't disperse to clean areas or present immediate dangers to the environment or human health. A prime example of physical containment is the erection of sarcophagi or protective structures [74]. These colossal edifices, constructed from concrete and steel, such as the one surrounding the chernobyl reactor, are crafted to enclose the contamination source, halting the dispersal of radioactive particles into the atmosphere. These structures represent remarkable engineering achievements intended to last for decades while more enduring solutions are conceptualized.

In regions where groundwater contamination poses risks, subterranean walls or barriers are established to halt the sideways migration of radioactive elements [121]. These barriers, typically crafted from impermeable substances or reactive compounds that neutralize contaminants, are strategically positioned to capture and contain the flow of tainted groundwater [122,123]. Capping is another prevalent technique, which is especially pertinent for contaminated soils or waste disposal locales. An impermeable layer, such as clay or synthetic liners, is overlaid atop the contaminated zone, effectively sealing it. This not only deters direct human or wildlife interaction with the contaminants but also minimizes rainwater infiltration, which could leach radioactive elements deeper underground or into adjacent water sources.

For specific radioactive waste types or tainted equipment, overpacking offers a containment solution. Waste is housed in sturdy containers, subsequently encased in supplementary shielding and containment layers. These doubly protected containers are stored in specialized facilities,

Table 1
Specific remediation methods, duration, and mechanisms.

Method	Duration	Mechanism	Application
Soil washing	Short-term (days to weeks)	Uses liquid solutions to extract contaminants from soil.	Effective for a variety of contaminants, especially inorganic.
Phytoremediation	Long-term (months to years)	Employs plants to absorb, store, and degrade contaminants from soil/water.	Suitable for a range of contaminants, particularly heavy metals, and some radionuclides.
Bioremediation	Variable (weeks to years)	Utilizes microorganisms to degrade, transform, or immobilize contaminants.	Effective for organic contaminants and some metals.
Capping	Long-term (years)	Involves covering contaminated sites with a barrier to prevent pollutant spread.	Used for large contaminated areas to prevent surface exposure.
Encapsulation	Long-term (years)	Encases contaminated material in a stable medium, preventing leaching.	Applied to highly contaminated materials or where removal is impractical.
Vitrification	Long-term (years)	Transforms waste into a stable glass form, immobilizing the radioactive elements.	Ideal for high-level waste and long-lived radionuclides.
Excavation and disposal	Short to medium-term (weeks to months)	Involves physically removing contaminated soil or material and transporting it to a disposal site.	Used when contamination is concentrated and localized.

ensuring environmental isolation of the contaminants [124]. In certain circumstances, particularly when managing vast quantities of low-level radioactive waste, engineered landfills are devised. These are not mere landfills [125], they are intricately designed with multiple liner layers, systems to collect leachate, and monitoring apparatus. Waste is methodically organized, compacted, and ultimately sealed beneath a protective covering, guaranteeing long-term confinement.

One of the emerging techniques in the management of radioactive isotopes is the use of adsorption methods. Adsorption, a surface phenomenon, employs materials known as adsorbents to capture and hold radioactive isotopes from a solution or gas phase onto their surface. This method is particularly effective for the treatment and recovery of certain radioactive isotopes [126]. Various materials, including activated carbon [127,128], zeolites [129,130], and certain types of clay [131–133], have shown potential as effective adsorbents for radioactive elements. The advantage of adsorption lies in its ability to concentrate radioactive contaminants from large volumes, making subsequent disposal or recovery processes more efficient. Recent advancements have also explored the potential of nanostructured materials and bio-based adsorbents, which offer enhanced selectivity and capacity for specific isotopes [134]. A detailed exploration of various materials and their effectiveness in adsorption is presented in Table 2, which lists pertinent case studies. The integration of adsorption techniques in nuclear remediation strategies can provide a sustainable and efficient approach to managing radioactive contaminants, especially in liquid waste streams.

In summary, the strategies of physical containment and isolation emphasize the concept of “buying time”. By effectively sequestering radioactive materials, these techniques offer a temporal respite, allowing for natural decay to diminish radioactivity, and the development and execution of more permanent remediation strategies. They stand as a testament to human innovation, our capacity to tackle challenges, and our steadfast dedication to protecting our world and its denizens.

4.2.2. Chemical and biological treatment methods

The domain of nuclear remediation has experienced remarkable progress, with chemical and biological interventions emerging as formidable solutions to the challenges of radioactive contamination. These techniques utilize the intricacies of chemistry and biology to neutralize, modify, or stabilize radioactive substances, presenting inventive solutions that prioritize both efficacy and environmental sustainability.

Chemical treatments predominantly employ specific compounds or reactions to modify the physical or chemical characteristics of radioactive pollutants [145]. Techniques such as precipitation involve introducing chemical agents to a tainted solution, prompting radioactive elements to solidify. These solids can then be isolated from the liquid, diminishing the solution's overall radioactivity [146]. Another notable chemical strategy is ion exchange, where tainted solutions traverse a resin that selectively adheres to radioactive ions, effectively purging them [147].

Biological treatments has recently gained prominence, with certain microorganisms showcasing their ability to absorb, modify, or immobilize radioactive elements due to their distinct metabolic pathways [148]. For example, specific bacteria can transform soluble radioactive ions into their non-soluble counterparts, curbing their environmental mobility. This bioremediation technique presents an eco-conscious and sustainable method for addressing radioactive pollution [149,150].

Phytoremediation, a bioremediation branch, leverages plants to combat contamination. Select plant species inherently draw and concentrate radioactive substances from their surroundings [151]. By cultivating these species in polluted zones, radioactive elements are gradually extracted. Upon reaching their absorption threshold, these plants are harvested and safely discarded, resulting in a purer environment. Biofilms, dense microbial aggregates, present another promising solution. These can be tailored to ensnare and stabilize radioactive particles, serving as living shields against contamination spread [152]. Their adaptability and robustness make them ideal for scenarios where traditional remediation might be impractical. Table 3 presents various case studies that highlight the practical applications of these innovative techniques.

In essence, the evolution of chemical and biological treatment techniques signifies a transformative advancement in nuclear remediation. Transitioning from solely physical containment tactics, these methods harness the complexities of chemistry and biology to tackle contamination at its source. With ongoing research in this sector, the anticipation is that even more groundbreaking and efficient strategies will surface, enhancing our capabilities in countering nuclear contamination.

4.3. Waste disposal and management

Managing and disposing of nuclear waste present a multifaceted challenge that demands meticulous planning, advanced technology, and commitment to long-term stewardship. As the nuclear industry has grown, so has the volume of waste it produces. This growth necessitates strategies that ensure the safety of both the environment and future generations. At the forefront of nuclear waste management is the classification system, which categorizes waste based on its radioactivity levels and longevity [161,162]. This system informs the disposal methods employed. For instance, low-level waste, which includes items like protective clothing or tools that have encountered radioactive materials, may be disposed of in near-surface facilities. These are often lined trenches or engineered structures where waste is isolated, monitored, and eventually sealed.

High-level waste, on the other hand, poses a more significant challenge. This category includes spent nuclear fuel and waste from

Table 2
Case studies for adsorption of radioactive isotope.

Adsorbent	Adsorbent properties	Adsorption conditions	Adsorption capacity	Reference
Bismuth-impregnated biochar (carbon source: coffee grounds)	Specific surface area: 124.5 m^2/g; total pore volume: 0.063 cm^3/g; average pore size: 5.7 nm; pH_{PZC}: 5.58	Adsorbent dosage: 2 g/L; targeted pollutant: radioactive iodine (IO_3^-); initial concentration of pollutant: 1–5 mg/L; adsorption time: 48 h; pH: 7.0; temperature: 25 °C	672 μg/g	[135]
Lignin-derived biochar	Specific surface area: 1385 m^2/g; mesoporous structures; abundant surface functional groups; pH_{PZC}: 4.15	Adsorbent dosage: 0.05 g/L; targeted pollutant: radioactive uranium(VI); adsorption time: 2 h; temperature: 25 °C	2826 mg/g	[136]
Tin (IV) vanadate	High chemical stability; semi-crystalline structure; main components: SnO_2 (65.32%) and V_2O_5 (26.15%)	Adsorbent dosage: 10 g/L; targeted pollutants: radioactive cesium(I) and strontium(II); initial concentration of pollutants: 50–500 mg/L [cesium(I)] and 50–500 mg/L [strontium(II)]; adsorption time: 2 h; pH: 6.0; temperature: 25 °C	26.68 mg/g for cesium(I); 45.81 mg/g for strontium(II)	[137]
Fe@Pt nanoparticles	Specific surface area: 9 m^2/g; nanoscale materials; high chemical stability; magnetically separable and recoverable	Adsorbent dosage: 0.5 g/L; adsorption time: 20 min; targeted pollutant: radioactive iodine (I^-, I_2, IO_3^- and CH_3I)	25 mg/g	[138]
Layered metal sulfide nanosheet (K/Zn/Sn/S)	Nanoscale materials; high thermal stability; layered structure	Adsorbent dosage: 0.5 g/L; targeted pollutant: radioactive cobalt(II); initial concentration of pollutant: 20–100 mg/L; adsorption time: 12 h; pH: 5.3; temperature: 45 °C	82.22 mg/g	[139]
Hexacyanoferrate-modified alginate beads	Specific surface area: 43.76 m^2/g; total pore volume: 0.4015 cm^3/g; abundant surface functional groups	Adsorbent dosage: 1 g/L; targeted pollutant: radioactive cesium(I); initial concentration of pollutant: 2–500 mg/L; adsorption time: 24 h; temperature: 25 °C	33.5 mg/g	[140]
Magnetic biochar (Carbon source: spent coffee grounds)	Specific surface area: 431.7 m^2/g; total pore volume: 0.186 cm^3/g; average pore size: 1.7 nm; pH_{PZC}: 8.8; abundant surface functional groups	Adsorbent dosage: 0.05 g/L; targeted pollutant: radioactive strontium(II); initial concentration of pollutant: 1–10 mg/L; adsorption time: 24 h; pH: 5; temperature: 25 °C	40.2 mg/g	[141]
Gum kondagogu (*Cochlospermum gossypium*)	Specific surface area: 20 m^2/g; total pore volume: 0.077 cm^3/g; average pore size: 3.721 nm; abundant surface functional groups	Adsorbent dosage: 10 g/L; targeted pollutant: radioactive uranium(VI); initial concentration of pollutant: 5–200 mg/L; adsorption time: 1 h; pH: 4; temperature: 25 °C	487 mg/g	[142]
Quaternary metal sulfide nanosheets Na/Zn/Sn/S (NaZTS)	High chemical stability; nanoscale materials; Specific surface area: 21 m^2/g; negative surface charge in pH 2–12	Adsorbent dosage: 1 g/L; targeted pollutant: radioactive strontium(II); initial concentration of pollutant: 5–100 mg/L/; adsorption time: 12 h; pH: 5; temperature: 25 °C	32.3 mg/g	[143]
Titanate nanorings	Specific surface area: 202.5 m^2/g; total pore volume: 0.94 cm^3/g; average pore size: 14.2 nm; pH_{PZC}: 2.7	Adsorbent dosage: 0.5 g/L; targeted pollutants: radioactive europium(III)/ uranium(VI); initial concentration of pollutants: 0–80 mg/L [europium(III)] and 0–170 mg/L [uranium(VI)]; adsorption time: 1 h; pH: 6; temperature: 25 °C	115.3 mg/g for europium(III); 282.5 mg/g for uranium(VI)	[144]

reprocessing activities. Due to its high radioactivity and long-lived nature, this waste requires deep geological repositories. These are underground facilities, often situated in stable rock formations, where waste can be securely stored and isolated from the biosphere for millennia [163]. The design of these repositories is a marvel of engineering, incorporating multiple barriers to prevent any potential leakage of radioactivity. An integral part of waste management is the conditioning and packaging of waste. This process transforms waste into a form suitable for transportation, storage, and eventual disposal [164]. Techniques such as vitrification, where high-level waste is incorporated into glass, or cementation, used for certain types of low and intermediate-level waste, are employed to stabilize and solidify waste materials.

Transportation is another critical aspect of waste management. Given the potential hazards associated with moving radioactive materials, stringent regulations govern the design of transport casks, route planning, and emergency response preparedness [165]. These regulations ensure that waste can be safely transported from nuclear facilities to storage or disposal sites without posing risks to the public or the environment. Public engagement plays a pivotal role in waste disposal and management decisions. The establishment of any waste facility, especially deep geological repositories, requires transparent dialog with local communities, stakeholders, and the broader public [166]. This engagement fosters trust, addresses concerns, and ensures that decisions are made with the collective well-being in mind [167].

Table 3
Case studies for bioremediation of radioactive isotope.

Remediation method	Remediation condition	Remediation efficiency	Reference
Phytoremediation (*Vetiveria zizanoides*)	Target pollutants: ^{137}Cs and ^{90}Sr in solution; initial concentration activity of pollutants: 5 × 10^3 Bq/mL (^{137}Cs) and 5 × 10^3 Bq/mL (^{90}Sr); remediation time: 168 h	94% of ^{90}Sr and 61% of ^{137}Cs were removed in single pollutant solution, respectively; 91% of ^{90}Sr and 59% of ^{137}Cs were removed in binary pollutants solution, respectively	[153]
Phytoremediation (*Ludwigia stolonifera*)	Target pollutant: ^{137}Cs and ^{60}Co in solution; initial concentration activity of pollutants: 305 Bq/mL (^{137}Cs) and 145 Bq/mL (^{60}Co); amounts of the biomass: 2 g; remediation time: 20 days	95% of ^{137}Cs and 95% of ^{60}Co were removed in a single pollutant solution, respectively; 65% of ^{137}Cs and 95% of ^{60}Co were removed in binary pollutants solution, respectively	[154]
Phytoremediation (*Vetiveria zizanioides* L. Nash)	Target pollutant: ^{239}Pu in hydroponic solution; initial concentration of pollutant: 100 Bq/mL; remediation time: 30 day	66.2% of ^{239}Pu was removed from the hydroponic solution	[155]
Microbially-induced carbonate precipitation (*Enterobacter* sp.)	Target pollutant: ^{90}Sr in solution; dosage of $CaCl_2$: 0.01 mol/L; initial concentration of pollutant: 0.0001–0.01 mol/L; remediation time: 20 day	10%–34% of immobilization rate for ^{90}Sr	[156]
Fungal isolates (*Aspergillus hollandicus* and *Penicillium citrinum*)	Target pollutants: ^{238}U, ^{226}Ra, ^{232}Th, and ^{40}K in rock; average concentration activity of pollutants in fungal: 5134.03 Bq/kg (^{238}U), 5708.64 Bq/kg (^{226}Ra), 189.51 Bq/kg (^{232} Th) and 1456.8 Bq/kg (^{40}K)	The harmful effect was potentially reduced to 50% compared to the original	[157]
Biominerals using slow-release substrates (Hydrogen Release Compound®, Metals Remediation Compound®, EHC®)	Target pollutant: ^{99}Tc in solution dosage of slow-release substrates: 5 g/L; initial concentration activity of pollutant: 100 Bq/mL remediation time: 90 day	Almost all ^{99}Tc was removed for low-level experiments	[158]
Biostimulation (glycerol phosphate)	Target pollutants: ^{90}Sr and ^{99}Tc in groundwater/sediment; initial concentration activity of pollutant: 1000 mg/kg (^{90}Sr) in sediment and 100 Bq/mL (^{99}Tc) in solution remediation time: 200 day	95% of ^{90}Sr was removed from solution (in the obtained solid phase, pH 5 Na-acetate fraction accounted for 18%, and the ion exchangeable fraction accounted for 75%); 97% of ^{99}Tc was removed to the solid phase after 200 days	[159]
Fungal isolates (*Neurospora crassa, Trichoderma viridae, Mucor recemosus, Rhizopus chinensis, Penicillium citrinum, Aspergillus niger* and, *Aspergillus flavus*)	Target pollutant: ^{60}Co in solution initial concentration of pollutant: 0.03–0.16 μM remediation time: 44 h	^{60}Co pickup capacity in the range of 8–500 ng/g of dry biomass	[160]

4.4. Monitoring and surveillance post-remediation

Post-remediation monitoring and surveillance are indispensable facets of the nuclear remediation process. Their primary role is to ensure that the remediation measures taken are effective and that no unforeseen complications arise over time [168,169]. Following remediation activities, the immediate focus shifts to assessing the effectiveness of the implemented measures. This involves collecting samples from the remediated site, be it soil, water, or air, and analyzing them for residual radioactivity. Advanced analytical techniques, coupled with rigorous protocols, ensure that even trace amounts of radioactivity are detected, offering a comprehensive understanding of the site's current state.

Continuous monitoring is paramount due to the dynamic nature of environmental systems. Factors such as rainfall, groundwater movement, or natural disasters can influence the distribution and concentration of radioactive materials. Establishing a network of monitoring stations equipped with sensors and detectors provides real-time data on radioactivity levels [66,170]. When analyzed alongside meteorological and geological information, this data offer insights into the behavior of radioactive materials and their potential pathways. Another vital aspect of post-remediation surveillance is the assessment of ecological health. The return of flora and fauna to remediated sites serves as an indicator of ecological recovery. Regular surveys of plant and animal populations, combined with studies on their health and reproductive success, paint a comprehensive picture of the site's ecological well-being.

In the realm of post-remediation surveillance, particularly in scenarios of persistent contamination, the case of Fukushima's Difficult-to-Return Zone (DTRZ) serves as a pertinent example [171]. The extensive soil and landscape decontamination efforts undertaken in this area highlight the challenges associated with long-term radioactive contamination. A primary concern has been the enduring presence of ^{137}Cs in forested regions, which contributes to its transfer to river systems and poses risks of secondary contamination. These complexities necessitate a sustained focus on innovative remediation strategies and continuous research to adapt to the dynamic nature of such environments. The situation in Fukushima's DTRZ exemplifies the critical need for evolving monitoring strategies and heightened preparedness for extreme environmental phenomena, reinforcing the importance of comprehensive and ongoing surveillance in areas affected by nuclear contamination.

Human health surveillance is of paramount importance. For communities residing near remediated sites, concerns about potential health impacts may persist. Conducting regular health check-ups, screening for radiation-induced illnesses, and maintaining a health registry can address these concerns and promptly tackle any emerging health issues [172]. Engaging with local communities is an integral part of post-remediation surveillance. Regular updates on monitoring results, open forums for addressing concerns, and educational programs not only empower communities with knowledge but also foster a sense of collective ownership over the remediated site.

Furthermore, the integration of cutting-edge technologies is revolutionizing post-remediation monitoring and surveillance. Developments in remote sensing technologies, including satellite and drone imagery, enable the tracking of environmental changes over large and inaccessible areas with unprecedented precision. The use of GIS and machine learning algorithms enhances the analysis of complex environmental data, providing predictive insights into the migration patterns of radioactive materials and potential future risks. Wearable sensor technology for individuals in rehabilitated areas offers real-time personal radiation exposure data, contributing to more personalized health monitoring strategies. These technological advancements not only bolster the efficacy of post-remediation efforts but also offer new avenues for proactive environmental management and community safety.

4.5. Public engagement in remediation efforts

Public engagement has become a pivotal component in nuclear remediation efforts. The realization that the consequences of nuclear activities span beyond just environmental and technical aspects to societal and ethical dimensions has made the inclusion of public perspectives essential [173]. Historically, nuclear-related decisions were often made with limited public input. However, events like nuclear accidents and the subsequent public reactions highlighted the need for a more inclusive approach. Today, public engagement is viewed as a tool to build trust, ensure transparency, and foster mutual understanding. Public hearings and consultations serve as primary platforms for public engagement. These forums allow local residents, especially those near affected sites, to express their concerns, pose questions, and provide insights [174,175]. Such interactions often reveal local knowledge, cultural values, and historical contexts that might be missed in strictly technical evaluations. Educational campaigns and workshops are also instrumental in breaking down the complexities of nuclear science and remediation techniques. Through accessible and accurate information dissemination, the public becomes better equipped to form informed opinions and decisions.

Collaborative projects, where community members actively partake in remediation activities, are gaining popularity. These initiatives might involve community members in tasks like monitoring radiation levels, restoring affected ecosystems, or documenting oral histories. Such collaborative endeavors not only enhance the remediation's effectiveness but also foster a sense of community ownership and pride [176]. Feedback mechanisms, whether through surveys or community meetings, are crucial. Capturing and integrating public sentiment into remediation strategies ensures that the efforts remain adaptive and responsive to evolving needs and perspectives [177].

While public engagement offers numerous benefits, challenges such as diverse opinions, conflicting interests, and skepticism toward authorities can make the process complex. However, with genuine, empathetic, and transparent engagement, these challenges can be successfully navigated. In conclusion, public engagement in remediation efforts promotes a collaborative approach, bringing together various stakeholders for a shared objective. This collective effort, rooted in mutual respect and shared responsibility, sets the stage for more comprehensive, sustainable, and socially equitable remediation outcomes.

4.6. Challenges and future trajectories in nuclear remediation

Nuclear remediation, a field critical for ensuring environmental safety and sustainability, encounters numerous challenges and opportunities for advancement. This section outlines these aspects in a structured manner.

4.6.1. Challenges

1) Technical constraints
   - Difficulty in developing universally effective solutions due to the diverse nature of radioactive contaminants.
   - Requirement for site-specific remediation strategies tailored to the unique conditions of each contaminated area.
2) Environmental factors
   - Potential ecological disruption caused by certain remediation techniques.
   - Long-term environmental implications of persistent radioactive contaminants.
3) Financial costs
   - High expenses associated with large-scale remediation projects.
   - Economic burden on governments and stakeholders for sustained remediation efforts.
4) Socioeconomic considerations
   - Impact of remediation activities on local communities and livelihoods.
   - Need for community engagement and support in remediation planning and execution.
5) Geopolitical dynamics
   - Challenges posed by transboundary contamination issues.
   - Complexities arising from international agreements and national interests in remediation policies.

4.6.2. Future trajectories and innovations

1) Nanotechnology
   - Development of nanomaterials for efficient contaminant removal and containment.
2) Bioremediation techniques
   - Utilization of radiation-resilient bacteria to naturally degrade or immobilize contaminants.
3) Drone and AI integration
   - Application of drone-enabled remote sensing and artificial intelligence for real-time contamination mapping.
4) Green remediation philosophy
   - Emphasis on sustainable practices that prioritize ecosystem restoration and minimal environmental impact.
5) Interdisciplinary collaboration
   - Leveraging diverse expertise from various fields to enhance remediation strategies.
6) Stakeholder engagement
   - Active involvement of communities and stakeholders in decision-making processes.

5. Conclusion and future outlook

This comprehensive exploration of nuclear isotopes has illuminated pivotal insights regarding their multifaceted applications alongside concomitant risks. Their wide-ranging use of nuclear isotopes in medicine, industry, and energy production significantly enhances quality of life. However, potential perils from radiation exposure or environmental contamination have also emerged. Accidents have starkly demonstrated the need for stringent oversight and prudent practices. In response, governance frameworks continue adapting to balance leveraging benefits while minimizing risks. Meanwhile, innovations in areas like nanotechnology and bioremediation point to more sustainable solutions.

These findings underscore key policy and practical implications. Robust, adaptable regulations must keep pace with technological advances. Uncompromising safety protocols and environmental stewardship are imperative. International cooperation is vital to tackle transboundary issues. Public engagement builds awareness and trust. Bolstering interdisciplinary research can catalyze progress in waste management, advanced reactors, and socioeconomic dimensions.

Future nuclear trajectories will likely integrate artificial intelligence for enhanced efficiency and safety. Quantum computing may accelerate nuclear simulations. Nanotechnology could enable better waste containment. Symbiotic integration with renewables promises consistent, low-carbon energy. However, developments must be anchored in ethical considerations and public interests. Open communication remains essential given nuclear's societal impacts.

Overall, this domain demands balanced advancement, weaving scientific rigor with social responsibility. The judicious harnessing of nuclear isotopes' potential, while safeguarding health and environment, will define the path forward. A collaborative ethos engaging diverse expertise and stakeholders is key to ensuring that nuclear applications benefit humanity equitably and sustainably.

Statement

During the preparation of this work the authors used GPT-4 in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

H.Y., Q.F.: writing–original draft; W.X.X.: investigation; Y.D.T.: validation; G.L.B.: formal analysis; Y.L.L.: software; Z.S.L.: supervision, writing–review & editing; S.B.X., Z.B.W.: funding acquisition; Y.Z.: supervision.

Declaration of competing interests

The authors have declared no conflicts of interest.

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Appendix A. Supplementary data

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