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Risk assessment and management of radionuclide leakage in nuclear power plants

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Abstract: Nuclear power plants are designed with stringent safety measures to prevent accidents and radioactive releases. However, major accidents like the Three Mile Island (1979), Chornobyl (1986), and Fukushima Daiichi (2011) have significantly impacted human health, the environment, and public perception of nuclear energy. Even during normal operation, nuclear power plants release effluents that can have some impact on the environment. These effluents are carefully monitored and regulated to minimize their environmental impact. Radioactive releases have potential long-term consequences for human health and the environment. To mitigate the risks of accidents and the environmental impact of normal operation, continued focus on nuclear safety, rigorous regulatory oversight, and improved emergency response measures are crucial. The behavior and impact of radionuclides in the environment, models and methods for simulating the transport and deposition of radionuclides in the atmosphere and ocean, toxicokinetic and toxicodynamic studies to predict the potential impacts of radionuclide releases and support risk management decisions, and environmental monitoring and control technology of nuclides, et al are discussed. The article aims to provide an overview of the importance of environmental toxicology in radioactive risk assessment and management, discuss the unique challenges associated with monitoring and remediating radioactive releases, and suggest future research directions.

Keywords: radionuclide leakage, nuclear power plants, risk assessment, environmental toxicology, remediation methods

INTRODUCTION

Utilizing nuclear power has long been a 'double-edged sword' for its benefits and potential risks. While nuclear power plants (NPPs) are designed with stringent safety measures to prevent accidents and radioactive material releases, radionuclide leakage has occurred throughout history. These incidents have had significant implications for human health, the environment, and public perception of nuclear energy. An important incident occurred in 1979 at the Three Mile Island Nuclear Power Plant (TMINPP) in the United States because a partial meltdown of the reactor core occurred due to equipment malfunctions and operator errors [1]. Although only a small release of radioactive gases and ^{131}I took place, this incident profoundly impacted

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public perception. It led to increased scrutiny and regulatory reforms in the nuclear industry. One of the most catastrophic radionuclide leaks in history was at the Chornobyl Nuclear Power Plant (CNPP) in 1986 in Ukraine. The explosion and subsequent fire in the core of Unit 4 resulted in a massive release of radioactive materials into the atmosphere, consisting of gases, aerosols, and finely fragmented nuclear fuel particles [2]. In 2011, the Fukushima Daiichi nuclear power plant (FDNPP) in Japan experienced a severe accident following a massive earthquake and tsunami. The cooling system was broken down and caused hydrogen explosions and atmospheric emission of radionuclides [3]. These accidents led to long-term health effects, environmental contamination, and a heightened awareness of the dangers associated with nuclear power. Therefore, sustained attention to nuclear safety, strict regulation and improved emergency response measures are essential to minimize similar accidents and mitigate the harm to humans and the environment.

The radionuclides released from most nuclear plants were transported and resuspended through the atmosphere, the fallout could deposit over long distances into lakes, rivers, and land, ending up with serious contamination in a large territory, a huge challenge for detection and regulation [4]. The contamination can be persistent, bioaccumulation, and potential for long-term effects on human health and the environment [5]. Regular effective monitoring and new remediation methods are developing to minimize exposure and mitigate the risks [6]. Meanwhile, radionuclides are unique due to their radioactive nature, emitting highly energetic ionizing radiation that can damage living organisms at the cellular level [7–9]. Understanding the fate and transport of radionuclides in the environment and how they are taken into the food chain helps to evaluate the potential pathways of exposure. Evaluating the effects of radiation on different organisms to understand the mechanisms of toxicity, potential health effects, and the dose-response relationships associated with radionuclide exposure helps manifest the tolerable level of radiation for risk assessment [10]. Moreover, toxicokinetics and toxicodynamics are useful tools to predict the potential impacts of radionuclide leakage and inform decision-making processes regarding risk management.

This article aims to provide an overview and highlight the importance of environmental toxicology in the risk assessment and management of radionuclides, discuss unique challenges posed by radionuclides for monitoring and remediation, and provide suggestions for future research.

RADIONUCLIDE LEAKAGE IN NUCLEAR POWER PLANTS

Types and emission quantities of radionuclides released from the power plant

These radionuclides come mainly from the "fission process" in the reactor, which begins by bombarding the nuclear fuel (uranium) with neutrons. The bombardment caused the uranium to split and release more neutrons, which continued to bombard the neighboring uranium core, leading to the beginning of the "fission chain reaction" and a wide range of daughter nuclei produced, such as ^{90}Sr, ^{131}I, ^{132}Te, ^{133}Xe, and ^{137}Cs, etc [11]. The reactor material can generate radioactive activation products as well after neutron activation, like ^{14}C, ^{55}Fe, ^{60}Co, and ^{65}Zn, etc [12]. This reaction is processed inside the reactor which is safely protected by robust in-depth safety defense and multiple redundant barriers, radionuclides can be released into the environment through accidents and effluents. The types of major radionuclides released are not always the same for different nuclear accidents. The radiogases released from the TMINPP accident were mainly ^{133}Xe and ^{131}I [13]. The two worst-case accidents releasing radionuclides directly from the reactor core erupted more

Table 1 Annual emissions of major radionuclides in Fukushima nuclear power plant wastewater [16]

Tank	K4	J1-C	J1-G
	(Bq/year)		
^{3}H	2.2×10^{13}	2.2×10^{13}	2.2×10^{13}
^{14}C	2.4×10^{9}	5.5×10^{8}	1.5×10^{9}
^{55}Fe	3.3×10^{8}	7.3×10^{7}	2.2×10^{8}
^{63}Ni	3.3×10^{8}	2.5×10^{8}	8.0×10^{8}
^{99}Tc	1.1×10^{8}	3.7×10^{7}	1.2×10^{8}
^{129}I	3.3×10^{8}	3.7×10^{7}	3.0×10^{7}

Table 2 The average monitoring radioactivity concentrations (Bq/L) of various radionuclides in seawater from 2018 to 2021 (Data obtained and organized from IAEA Marine Radioactivity Information System [17])

Year	^{3}H	^{60}Co	^{90}Sr	^{99}Tc	^{106}Ru	^{125}Sb	^{131}I	^{134}Cs	^{137}Cs	^{210}Po	^{210}Pb	^{238}Pu
	(Bq/L)											
2018	769	0.22	1.23	/	0.16	0.32	648	221	204	0.28	0.52	0.005
2019	580	/	1.04	89.3	/	/	636	223	202	/	/	0.006
2020	662	/	2.23	/	/	/	/	270	278	/	/	0.005
2021	922	/	/	/	/	/	/	272	262	/	/	/

varieties and amounts of radio contaminates. The radioactivity released into the atmosphere for CNPP was mainly ^{239}Np, ^{133}Xe, ^{131}I, ^{132}Te, ^{134}Cs, ^{137}Cs, and ^{103}Ru, while it was ^{133}Xe, ^{131}I, ^{132}Te, ^{134}Cs, ^{137}Cs [14] for FDNPP (Table 1). However, mainly the relatively short-lived fission products ^{131}I, ^{137}Cs, and ^{90}Sr contributed to the radiation dose of the local population [12]. The composition of radionuclides in gaseous and liquid effluents from nuclear power plants is also diverse. It was reported that the gaseous effluents can contain radioactive tritium, carbon-14, noble gases (Ar, Kr and Xe), particulates (Co, Cr, Nb, Br, Sr), and iodine; liquid effluents can contain radioactive tritium, carbon-14, dissolved noble gases (Xe), particulates (Sb, Cs, Co, Fe, Mn, Nb, Sr, Zr), and iodine [15]. The monitoring of radioactivity in seawater from 2018 to 2021 is listed in Table 2.

The environmental fate of radionuclides

Different physicochemical species of radionuclides interacting with prevailing abiotic properties of the environment are widely diverse, constituting environmental components [18]. Most radionuclides can leak into the environment in two ways (Figure 1): radioactive fallout over natural water and land through the atmosphere; the other way is water used to cool the nuclear reactor cores leaking out [19,20]. The migration is affected by various factors, such as wind direction, circulation, and tides, through the gas phase and the ocean (Figure 1). Many kinds of research focused on multiple models regarding the migration of nuclear materials into the environment, including these factors as parameters in the calculations and models.

Atmospheric behavior of radionuclides needs to mathematically describe the spatial and temporal distribution of them released into the atmosphere, there are two models for transport and dispersion simulation: The Eulerian model, divides the atmosphere into grid cells, and simulates transport and dispersion by solving mass and momentum equations; and the Lagrangian model, tracks particle trajectories, consider atmospheric flow and diffusion [21]. For example, Christoudias used atmospheric chemical-generalized circulation

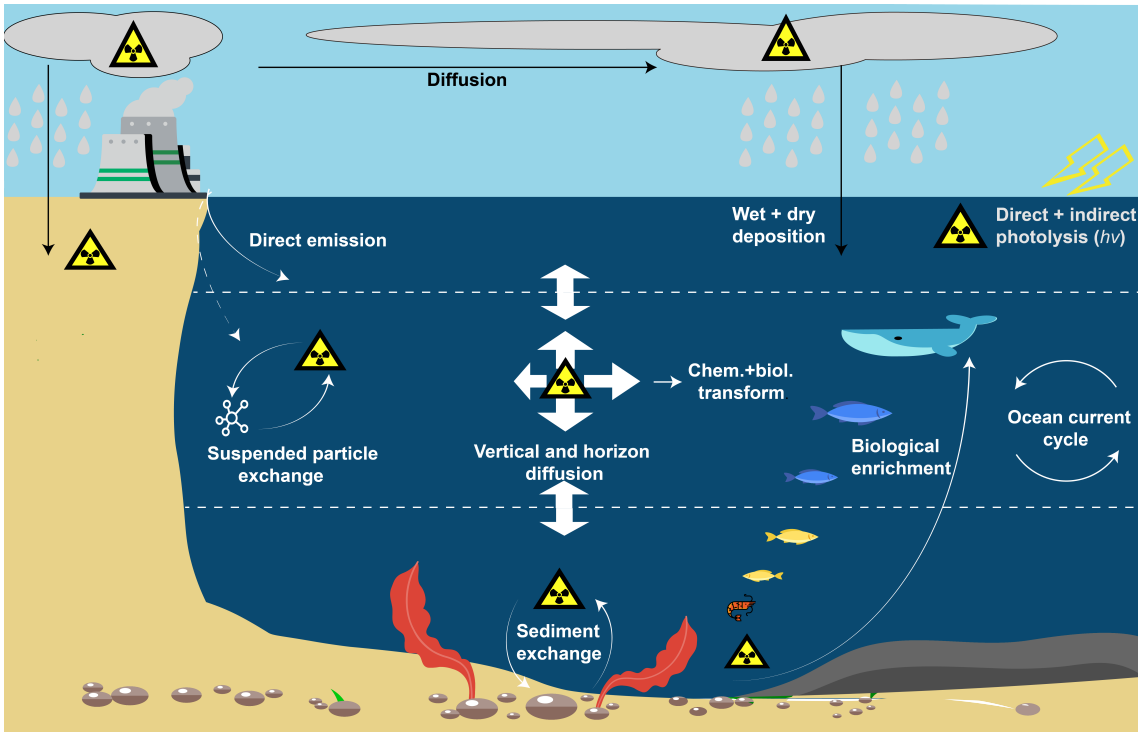

Figure 1 The environmental migration and immobilization of radionuclides from nuclear plants through the atmosphere and ocean.

models (belongs to the Eulerian model) to simulate global atmospheric transmission and deposition of radionuclides released by the FDNPP accident, showing that 80% of the radioactive material was deposited in the Pacific Ocean, and most of the inhabited land in Japan was contaminated with more than 40 kBq/m^2 [22]. However, there are differences in the optimal application scenarios for the two models. The Lagrangian model is based on the discretization of the integral approximation using particles, in which the flow is considered as a discrete phase of individual particles moving in space and carrying specific computational information [23]. It provides a more detailed, particle-based representation of transport processes and is suitable for modeling transport and fate at local or site-specific scales. In the Eulerian model, the flow field is primarily considered as a continuous phase, for which the Navier-Stokes equations governing the flow are solved using numerical methods, such as the Finite Volume Scheme (FVM) [23]. It is more suitable for modeling transport and fate at regional or global scales. It has been found that for the simulation of FDNPP leakage, the Eulerian model describes the remote transmission process better, while the Lagrangian model is more suitable for detailed estimation of the concentration near the power plant [24]. During the process of radionuclides entering land and aquatic surfaces from the atmosphere through dry and wet deposition, it is crucial to consider the influence of deposition velocity and resistance [21]. Understanding the relative contribution of dry and wet deposition is an important component of post-accident analysis, as it determines the initial interception and retention of airborne radioactive particles by plant canopy, their subsequent transfer pathways through the soil-plant system, and their dosing effects on humans. Moreover, because of the varieties of surface occlusions, it is necessary to calculate the dry and wet decomposition separately for different spatially distributed aquatic and terrestrial surfaces. For example, Gonze calculated the spatial

distribution of dry and wet deposition for ^{137}Cs released from FDNPP on different surface types (bare soil, urban environments, agricultural fields, forests, and aquatic surfaces), and found that the deposition of radionuclides can vary 3–4 times on different surface types and the contribution of dry and wet deposition changes on different landscape [25]. The contribution of wet and dry deposition is also related to the type of radionuclides. Research showed that wet deposition contributes more to ^{137}Cs, which exist in the form of particles in the atmosphere; In contrast, the contribution of wet deposition and dry deposition mechanisms is relatively equal for ^{131}I, which presents both as particulate and vapor phase material [26]. Based on the above basic models and theories, many countries and organizations have developed their models to evaluate and monitor the gaseous spatial distribution of radionuclides, such as MLDP0 (Canada), HYSPLIT (United States), NAME (United Kingdom), RATM (Japan), and FLEXPART (Austria), MEAC (Germany), and DREAM (Denmark), etc [22,27,28].

The environmental behavior of radionuclides in the ocean is related to their species, which can be categorized as conservative or non-conservative radionuclides. Radionuclides that exhibit negligible adsorption by solid phases such as suspended and bed sediment particles are referred to as conservative radionuclides, like ^{134}Cs, ^{137}Cs (relatively conservative), and ^{106}Ru; while radionuclides that are significantly adsorbed by sediment particles, both suspended in the water column or present on the seabed, are non-conservative radionuclides (^{125}Sb, ^{99}Tc, and ^{129}I, etc) [29–31]. Eulerian and Lagrangian models are used to simulate the aquatic dispersion of radionuclides in the ocean as well. Miyazawa used an Eulerian passive tracer transport model coupled with a regional circulation model to simulate the diffusion of ^{137}Cs released directly from FDNPP to the ocean and access the effects of winds, tides, and river discharge, the results showed that winds promoted the meridional expansion of the distribution of ^{137}Cs on the surface of the continental shelf, while tides had little effect [32]. For non-conservative radionuclides, the interaction with suspended particles along with the sinking, horizontal transport, and accumulation of particles in underlying sediments should be considered inside the model for their huge impact [33]. Choi used a Lagrangian particle tracking–ocean circulation coupled model to solve the migration of radionuclides leaked from FDNPP between seawater, large particulate matter, and bottom sediments, the result showed that the majority of the radionuclides adsorbing to bottom sediments likely occurred within the first month or two after the leakage and limited the migration to the open ocean [34]. For emergency response, the models could also help the government to adopt strategies in advance to prevent the spread of radionuclides. Li *et al*. established a radionuclide migration model for the Chinese Haiyang nuclear power plant (AP1000) by using Lagrange and Euler models, taking tide and decay of radiation into consideration and verifying by seawater routine monitor data [35]. The results showed that if an accident happened, the concentration of ^{137}Cs near coastal areas could be reduced by an order of magnitude within one week, and the radioactivity of ^{131}I was approximately 70% lower than that of ^{137}Cs after two weeks. However, the models above were based on coastal areas, as the distribution of radionuclides in the deep sea and on a global scale can be influenced by more complex factors. Further research is needed to evaluate the global effects of nuclear leakage better.

Potential pathways for environmental exposure

Consuming food and water contaminated with radionuclides is a frequently encountered exposure pathway. Additionally, the inhalation of radioactive particles in the air, particularly for volatile radionuclides, re-

presents another notable route of exposure. Assessing the dose of nuclear exposure to the population after a nuclear leak is also important in environmental risk and management. However, measuring the radiation dose directly resulting from the diet intake of radionuclides is not feasible, the most that can be accomplished is the measurement of the intake itself, which is particularly challenging for the general public and requires significant interference in their daily lives [36]. As a result, all doses resulting from intakes are calculated using mathematical models that simulate the metabolism of radionuclides within the human body. In general, a dynamic model is used to establish a food chain transfer model for the terrestrial food chain, considering the change of radionuclide concentration in food as a function of time after initial introduction into the environment. The agricultural animals and plants were divided into a series of compartments for modeling based on determining the food chain level and participating species. This method assumes that the concentration of radionuclides in each compartment was evenly distributed, and different distribution coefficients were used between the compartments to establish the model [36].

Combining the models of environmental distribution and food chain accumulation, the whole process of radionuclides from accident occurrence to dietary intake can be effectively predicted. A model, containing the migration of radionuclides from FDNPP to the air, deposition on the ground, transfer into the food chain, and transportation to markets, was developed to estimate the intake of radionuclides in diets in different regions after the Fukushima accident and to assess the cost and effectiveness of regulatory measures to restrict food distribution [37]. These models assist in predicting the movement of radionuclides from the nuclear plants to dietary intake, which contributes to the assessment of regulatory measures to mitigate the risks associated with nuclear accidents or help the government design the location of nuclear power plants to reduce the effect of radio effluents to publics.

RISK ASSESSMENT OF RADIONUCLIDE

The field of toxicology examines hazardous substances, their mechanisms of action, methods of diagnosis, and prevention. In the context of the dangers posed by radionuclides, a specialized branch of toxicology known as radiotoxicology focuses on the study of their effects. Radionuclides have all the chemical properties of their stable isotopes but can emit ionizing radiation, therefore the toxicity of radionuclides consists of chemical toxicity and radiotoxicity.

Mechanisms of radiotoxicity

Ionizing radiation exerts biological effects on cells through various cellular and molecular mechanisms. One of the key effects is DNA damage, which can occur through direct or indirect interactions of radiation with DNA molecules (Figure 1) [38,39]. Radiation's direct interaction with DNA molecules can induce molecular structural damage, manifesting as single-strand breaks (SSBs), double-strand breaks (DSBs), base damage, and potentially clustered DNA damage [40,41]. Radiation can disrupt the transformation of methionine (MET) to S-adenosylmethionine (SAM), inhibiting the production of sufficient methyl groups (CH_3) needed for DNA methylation replication [42]. Interaction of radiation with other molecules (mainly water) can generate hydroxyl radicals and cause oxidative stress, then indirectly cause DNA damage [10]. Ionizing

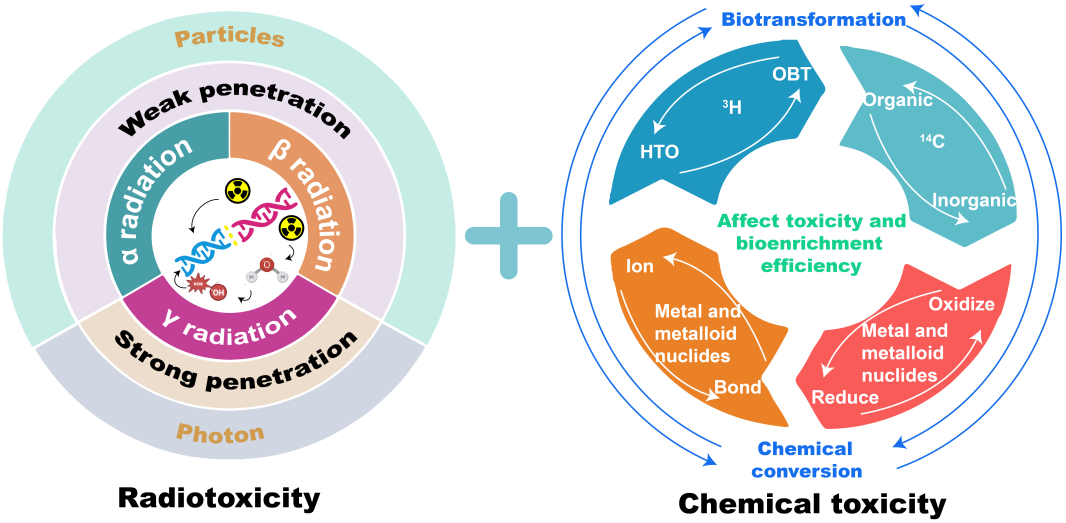

Figure 2 The types and properties of the 4 main radiation and the mechanism of generating DNA damage.

radiation can cause chemical bond breakage, base damage, and DNA strand breaks. Such DNA damage can lead to cell death, genetic mutations, and cellular dysfunction. Radiation dose is a measure of how much radiation an organism is exposed to, it can be measured as exposure dose (roentgen, R) or absorbed dose (gray, Gy) [43]. High doses of ionizing radiation directly cause DNA damage and cell death, resulting in acute radiation syndrome. Lower doses of radiation may cause DNA damage and cellular dysfunction, accumulating over time and contributing to long-term health risks such as increased cancer incidence [44]. Radiation-induced carcinogenesis involves the penetration of cells by radiation, which results in the random and non-specific deposition of its energy within the tissues and organs [44].

Different types of radiation can have varying biological effects, and the magnitude of the effect can depend on the dose rate, which refers to the rate at which radiation is received [43]. Radionuclides, unstable nuclei, undergo radioactive decay and emit several types of ionizing radiation, including particles (α and β rays) or high-energy photons (γ rays) (Figure 2). Alpha rays and beta rays are high-energy particles, however, they do not penetrate objects easily and are usually blocked by the skin. When ingested, they can produce a strong internal exposure causing more damage in short-distance penetration. Gamma rays can penetrate deep into tissues through the skin but deposit their energy over a wide range of areas causing lower biological damage [45].

The chemical speciation of radionuclides is another key factor in determining their toxicity and biological impacts (Figure 2). For example, reducing U(VI) to U(IV) is an important process to reduce uranium's solubility, mobility, and bioavailability in the environment because the U(IV) species are much less soluble and less likely to be taken up by organisms compared to the U(VI) form [46]. Similarly, tritium water (HTO) can be converted to organic tritium (OBT) by photosynthesis. It has already been proved that OBT can persist for long periods within living organisms and be transferred through the food chain to higher trophic-level organisms [47–49]. The higher concentrations of tritium detected in marine biota sampled from Cardiff Bay and the Severn Estuary are primarily due to the organisms' consumption of lower trophic level biota containing persistent OBT, rather than directly from the uptake of HTO present in the seawater [50].

Evaluation of dose-response relationships and health risk assessment

The health risks associated with radiation refer to the lifetime probability of experiencing adverse effects due to radiation exposure (Figure 3) [51]. The risk from exposure to radioactive nuclides is calculated by multiplying the radiation dose by risk factors, as follows:

$$Risk = Dose \times Risk\ Factors \tag{1}$$

where "Dose" is measured in sieverts (Sv) and "Risk Factors" is expressed in per sievert (Sv^{-1}).

For radioactive contaminants, the dose refers to the energy deposited within biological tissue due to the decay of radioactive nuclides [52]. Taking into account the exposure duration of internally deposited radionuclides, the committed effective dose integrates the effective equivalent dose over a specified future period, which is 50 years for adults and 70 years for children [52].

Human exposure to radioactive contaminants primarily occurs through three pathways: inhalation of radionuclides, ingestion of radionuclides, and exposure to external radiation from sources such as air, water, and soil [52]. The dose received from inhaling radioactive nuclides present in the atmosphere is computed by the product of the inhaled quantity and the inhalation dose conversion factors. Similarly, the dose from ingesting food contaminated with radioactive nuclides is obtained by multiplying the ingested quantity by the ingestion dose conversion factors. External doses resulting from exposure to environments contaminated with radioactive substances in soil, water, or air are calculated by multiplying the exposure quantity by the external dose conversion factors. The dose calculation formulas are specified as follows:

$$Dose = Exposure \times Conversion\ Factors \tag{2}$$

where "Exposure" refers to the quantity of radiation inhaled, ingested, or to which one is externally exposed, measured in becquerels (Bq). The "Conversion Factors" is expressed in sieverts per becquerel (Sv/Bq).

Exposure is determined by the product of the activity concentration of radioactive nuclides and the total effective exposure time. Ingesting food or water contaminated with radioactive nuclides is a common exposure pathway. Taking ingestion of radiation as an example, the formula for calculating Exposure is as follows:

$$Exposure = Concentration \times Intake \tag{3}$$

where "Concentration" refers to the number of decays per second of radioactive nuclides per kilogram of food, with different types of food having varying activity concentrations, expressed in becquerels per kilogram (Bq/kg). "Intake" denotes the mass of food consumed by an individual over a specific period, measured in kilograms (kg).

In equation (2), "Conversion Factors" can typically be referenced from values provided by the International Atomic Energy Agency (IAEA) [53–55], and the World Health Organization (WHO) [56].

Currently, "Risk Factors" in equation (1) is commonly cited from values provided by the International Commission on Radiological Protection (ICRP) [52,53,56,57], and the Environmental Protection Agency (EPA) [54].

The health effects of nuclear radiation can be distinguished into deterministic effects and stochastic effects. When exposed to high doses of radiation over a short period, individuals may experience acute radiation symptoms, including various radiation sicknesses, cataracts, skin erythema, and impaired reproductive function. These direct health impacts caused by radiation constitute deterministic effects. Conversely, prolonged exposure to low-intensity radiation does not result in immediate health consequences, but over the

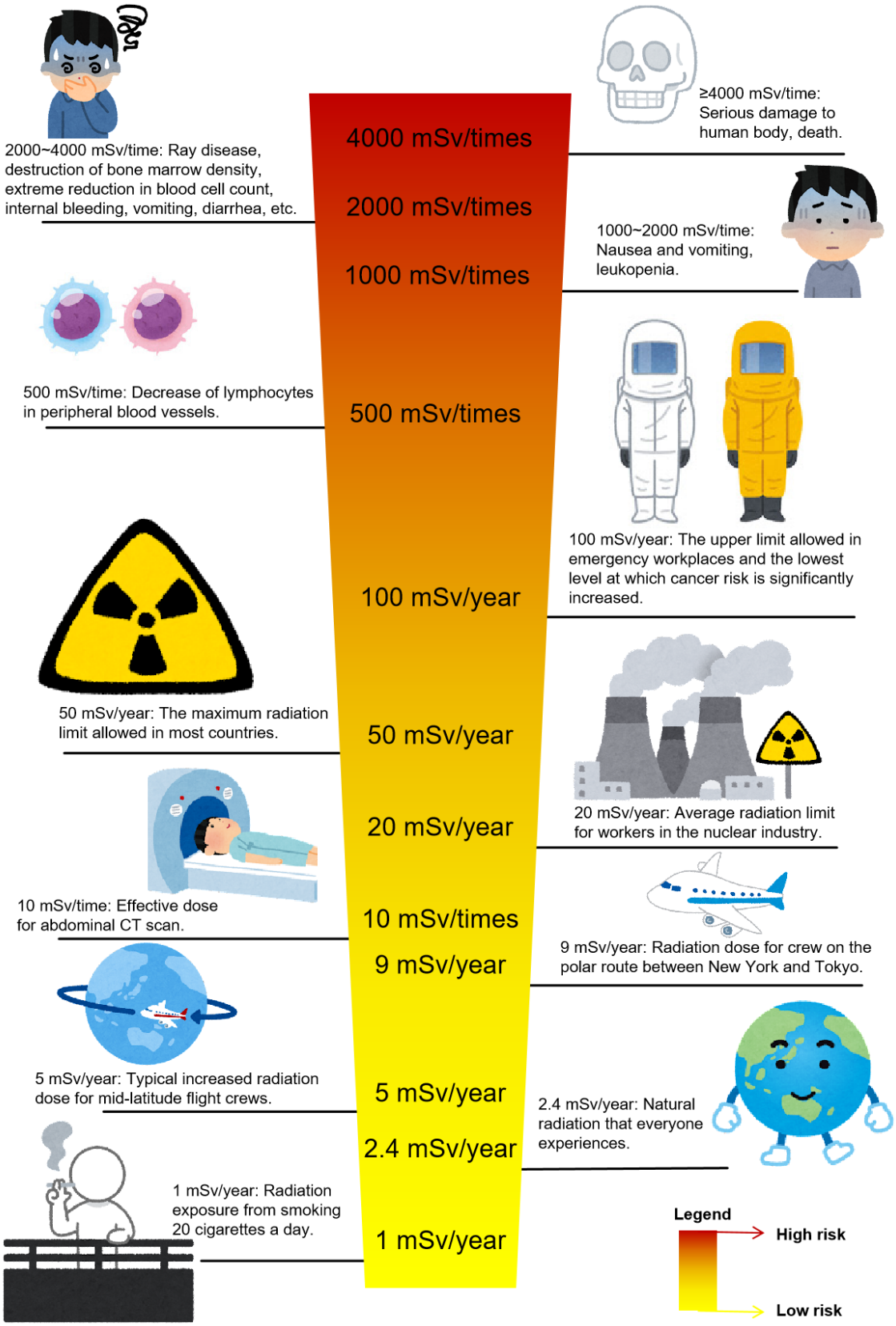

Figure 3 The specific doses of radiation and their corresponding equivalent risks.

long term, it may increase the risk of cancer and genetic diseases in populations. Due to its inherent probabilistic nature, these effects are termed stochastic effects [52].

For deterministic effects, maintaining radiation doses below a certain threshold ensures prevention. Deterministic effects can be further subdivided into fatal and non-fatal impacts, with the former causing death in a short period, while the latter mainly decreases the quality of life. When establishing relevant protective standards, priority is generally given to avoiding fatal effects [58]. Evaluation typically involves assessing exposure duration, dose, and considering differences in exposed organs and exposure scenarios. For assessing severe deterministic health risks, the concept of RBE-weighted dose is commonly utilized, with its value defined for specific radiation types depending on exposure conditions, including biological effects, tissues involved, dose, dose rate, and temporal dose distribution [59–61]. For a given type and energy of radiation, there exists an RBE value range corresponding to different radiation health effects. At low doses and low dose rates, RBE values reach maximum levels, which are used to define radiation weighting factors, addressing stochastic effects [62].

Regarding stochastic effects, even low-intensity, short-term radiation exposure may potentially increase related health risks. Assessment relies on measuring risk factors, usually based on epidemiological studies of past cases. By investigating differences in the probability of health issues occurring between populations exposed to radiation and healthy populations, a relationship between radiation dose and population health damage, namely risk factors, can be determined [52].

Ecological risk assessment

Initially, the focus of research on environmental radionuclide contamination was on human health risks, and protection standards were primarily based on recommendations from the International Commission on Radiological Protection (ICRP) [63]. However, in the 1990s, consideration began to shift towards protection standards for non-human species. The International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UN-SCEAR), and various national agencies started proposing radiation dose rate limits for biota [64]. Since the 1970s, the IAEA has initiated studies on the effects of ionizing radiation on plants, animals, and their ecosystems. International organizations such as the IAEA, UN-SCEAR, and ICRP have also discussed and reached a consensus that radiation protection should not only safeguard humans but also protect non-human species and the ecological environment [65].

There has been extensive research on the radiation effects of environmental radionuclides on biota, involving various categories of organisms including protozoa [66], brine shrimp [67], insects [68], amphibians [69], reptiles, birds, and plants. Based on existing research findings, mammals are the most sensitive to environmental radionuclide radiation, with noticeable effects observed at acute exposure doses as low as 10 mGy. For amphibians, this dose is 20 mGy, while for fish, radiation doses above 10 mGy may impact their most sensitive developmental stages [52].

These studies focus on the effects of radiation on individual organisms. To comprehensively assess the overall impact of radiation on ecosystems, ecological risk assessment (ERA) is needed. ERA is typically defined as the process of assessing the likelihood of unconventional accident risks caused by radiation accidents and their harmful effects on ecosystems. It emphasizes the impact of radiation accidents on the environment rather than routine or planned emissions. Unconventional risks and harmful effects range from

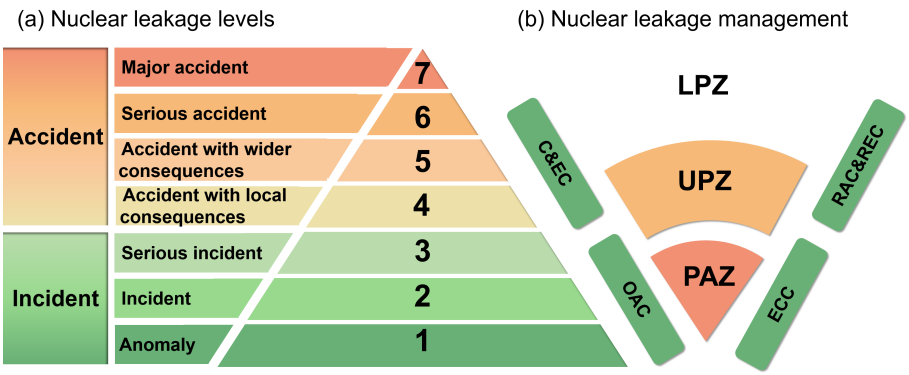

Figure 4 Process of ecological risk assessment.

individual biological deaths to widespread disturbances resulting in the loss of habitat ecosystem functions [70].

For terrestrial ecosystems, ERA is divided into five modules: selecting ecological system receptors affected by radiation effects; determining reference biota species and their survival indices; calculating critical loads (absorption rates) from the dependence between strontium-90 absorption dose rates and the radionuclide accumulation coefficients in animal and plant samples; critical doses; assessing the risk of increased animal loads on parts of the ecosystem territory; and describing the uncertainties in each stage of risk assessment [71].

Common ERA methods for marine environments include the tiered method and the ERICA integrated method, generally applicable to chronic exposure assessments. This process typically involves four steps: problem definition, risk analysis, risk characterization, and risk management [72,73], covering the identification of risk types and probabilities, the characteristics of ecological exposure, effects and responses, and risk management in each of these stages (Figure 4).

In practice, existing studies have conducted ERA analysis in nuclear power plants [70,74,75]. For example, researchers monitored emissions in one study over four days following the Fukushima accident, identifying the main released radionuclides as ^{131}I and ^{137}Cs [70]. Subsequently, using the classical ERA method, they simulated the dispersion of radioactive pollutants through a physical diffusion model, calculated external radiation dose rates, and assessed risk levels and affected areas. They also employed a tiered approach for data collection, and general screening for long-term impact assessment. Finally, the ERICA integrated method was used for ecological risk assessment. During the evaluation, researchers used parameters closer to real-world conditions based on field data, replacing default model parameters. The assessment confirmed that the radiation risk in sediments was about six times higher than in seawater in the mid to late stages of the accident. It was concluded that the Fukushima accident had a certain impact on the nearby marine ecosystem, with nearshore organisms such as fish eggs and plankton potentially suffering fatal effects.

MANAGEMENT AND CONTROL STRATEGIES

Due to its inherent physical characteristics, nuclear power generation poses potential risks. These risks can be

controlled through effective nuclear safety and security regulations, ensuring that the societal risks remain at an acceptable low level. Faced with regulatory challenges concerning nuclear energy programs, most countries have established comprehensive legal frameworks for nuclear safety regulation at the legislative level, established specialized regulatory bodies at the organizational level, and formulated scientific management rules at the operational level to ensure compliance with legal requirements for nuclear safety management. Additionally, regulatory oversight is implemented, management is scientifically effective, and nuclear facilities operate smoothly, effectively mitigating inherent nuclear risks [76].

Regulatory guidelines for environmental protection in nuclear power plants

At the international level, a series of treaties and conventions related to nuclear safety, security, liability [77–81], and non-proliferation of nuclear weapons [82] have established legal frameworks for the peaceful use of nuclear energy at the national level and formed a consensus on nuclear energy's peaceful use and risk management in the international community [76]. These conventions require countries to establish legal frameworks, and regulatory authorities with technical capabilities and adequate resources to assure nuclear safety and security to governments and societies. Only organizations with the necessary technical capabilities can construct, commission, and operate nuclear power plants. Before building a nuclear power plant, the organization must hold a nuclear site license issued by the regulatory authority and develop appropriate nuclear security arrangements. Adequate arrangements must be made domestically to manage the safe and secure handling of spent nuclear fuel and radioactive waste anticipated to be generated by the scheme. In addition to these treaties, the International Atomic Energy Agency (IAEA), as the most widely recognized international nuclear-related organization, plays a crucial supervisory and executive role in ensuring treaty implementation, constructing a cooperative framework in the global nuclear energy and nuclear safety-related fields, and providing references for countries to formulate nuclear safety management plans adapted to their national conditions through the formulation of a series of international standards related to nuclear safety [76].

Currently, China's nuclear safety laws and regulations have formed a relatively complete system consisting of one law, seven regulations, and several departmental rules. Some of the more important ones include: law on prevention and control of radioactive pollution, regulations on the supervision and management of civil nuclear facilities, regulations on emergency management of nuclear power plants, regulations on the control of nuclear materials, regulations on the supervision and management of civil nuclear safety equipment, regulations on safety and protection of radioactive isotopes and radiation devices, regulations on the safety management of radioactive material transportation, and regulations on the safety management of radioactive waste [83]. The law on prevention and control of radioactive pollution provides the legal basis for China's nuclear safety management, ensuring the implementation of laws through a series of specific regulations formulated by the State Council and ensuring that nuclear safety management is implemented at the grassroots level through a series of internal normative regulations of nuclear facility operation management units [84], truly ensuring that nuclear risks are controllable.

Establishing effective nuclear regulatory agencies is crucial to ensuring nuclear energy safety, reliable utilization, and improving public acceptance. Typically, the relative independence of regulatory agencies plays an essential role in promoting nuclear safety [85]. In the process of establishing regulatory agencies,

countries need to gradually enhance the capabilities of regulatory agencies to ensure their ability to fulfill their responsibilities in national nuclear power development plans. Additionally, regulatory agencies should have core functions such as issuing licenses, assessing, inspecting, enforcing, and communicating their activities to the public to establish and maintain confidence in the nuclear energy regulatory system. Bilateral arrangements with regulatory agencies in other countries can provide support to regulatory agencies, especially in terms of technical supply for nuclear power plants. Therefore, countries should establish and develop their nuclear regulatory agencies immediately after deciding to launch nuclear power projects and continuously enhance their capabilities and efficiency according to the progress of nuclear power projects [76].

Nuclear leakage levels and emergency response protocols for minimizing environmental impacts

Although efforts have been made by the IAEA and governments at the legal level, and some success has been achieved, the implementation of nuclear safety mechanisms also relies on scientific methods beyond the law. On one hand, it is necessary to establish an internationally accepted standard to reasonably assess and classify nuclear safety events, ensuring coordinated actions among all parties. On the other hand, post-incident handling requires a set of scientifically sound and universally applicable operational guidelines to translate nuclear safety mechanisms from legal stipulations into practical actions.

In terms of nuclear event assessment and classification, the International Atomic Energy Agency (IAEA) has developed nuclear safety and security standards and guidelines to assist countries in fulfilling their responsibilities under relevant conventions [76]. During the operation of nuclear facilities, the IAEA categorizes various nuclear incidents into different levels, aiming to set general standards and facilitate the investigation, analysis, and exchange of international nuclear incidents [86]. According to the severity of nuclear leaks, they are divided into seven levels, aiming to distinguish levels of severity ranging from level 1 to level 7, referred to as: anomaly, incident, serious incident, accident with local consequences, accident with wider consequences, serious accident, and major accident.

Level 1 indicates an anomaly with no risk but indicates a malfunction in safety measures or operation; Level 2 is an incident with no off-site impact yet, but internal contamination with nuclear material diffusion may occur, or nuclear power plant personnel may receive excessive radiation; Level 3 is a serious incident with a very small release of radioactive material, and the public radiation dose is below the prescribed limit, seriously affecting the health of nuclear power plant personnel; Level 4 indicates an accident with local consequences, with the surrounding public receiving a radiation impact equivalent to the prescribed limit. At the same time, the reactor core and radiation barrier suffer significant damage, and fatal radiation exposure to personnel may occur; Level 5 is an accident with wider consequences, with a limited release of radioactive material, and severe damage to the reactor core and radiation barrier (from the perspective of radiation protection, its quantity is equivalent to 10^14 to 10^15 becquerels of ^{131}I); Level 6 is a serious accident, indicating that fission radioactive products are released to the outside world (from the perspective of radiation protection, its quantity is equivalent to 10^15 to 10^16 becquerels of ^{131}I); Level 7 is a major accident, with a large amount of radioactive material released from the reactor core, involving a mixture of long- and short-lived radioactive fission products (from the perspective of radiation protection, its quantity exceeds 10^16 becquerels of ^{131}I). Historically, only two cases have occurred at this level. One of them is the

explosion accident at the Chornobyl Nuclear Power Plant in the former Soviet Union in 1986, and the other is the Fukushima nuclear accident in Japan in 2011.

In terms of nuclear accident handling, in the event of a nuclear leakage incident, timely emergency response measures are needed to minimize the impact of the leakage on human health and the ecological environment, which relies on Emergency Preparedness and Response (EPR) plans, typically covering from minor nuclear events to severe nuclear accidents, aimed at controlling and minimizing their impacts [87]. Generally speaking, EPR divides the nuclear incident site into three areas. According to the distance from the center of the accident, it is divided into PAZ (Precautionary Action Zone), UPZ (Urgent Protective Action Planning Zone), and LPZ (Longer-term Protective Action Planning Zone) [88,89].

In general, the response process to a nuclear accident is divided into two stages. The first stage is led by the duty supervisor to execute initial protective measures, including ensuring the safety status of the NPPs, personnel protection, and notifying relevant parties. The fire brigade and safety working group coordinate interventions within the nuclear power plant to ensure safe evacuation and implement physical protection measures. The second stage is taken over by the emergency committee, with the emergency control center management team evaluating the situation and providing information to employees and the public. Emergency management in nuclear power plant emergencies involves multiple agencies and committees. The Emergency Control Center (ECC) is responsible for internal management, while the Off-site Assessment Center (OAC) coordinates external radiation activities. The Radiological Accident Commission (RAC) and the Regional Emergency Commission (REC) coordinate actions at the national and regional levels. Control and Emergency Control (C&EC) ensure the effective implementation of regulatory agencies [88]. The emergency planning system covers aspects such as warning, notification, sheltering, and evacuation, aiming to protect personnel and facilities. In the event of a nuclear accident, the operator is responsible for limiting the development of accidents and minimizing consequences (Figure 5) [87,88].

The lack of environmental pollution standards for nuclides

To a certain extent, nuclear safety-related laws and regulations focus on preventing nuclear events before they occur. The mechanisms for classifying and assessing nuclear incidents, as well as the procedures for handling them, are designed to address accidents that are currently happening. However, post-accident management should be equally important. Post-accident efforts should primarily concentrate on assessing the subsequent environmental pollution effects, ensuring that the impact of a nuclear accident is controlled within a specific time and spatial range.

There is an evident deficiency in international and domestic standards for radioactive environmental pollution, which is not only a problem of the timeliness of standards but also includes issues of applicability and comprehensiveness. Internationally, although the International Atomic Energy Agency (IAEA) has issued a series of standards on nuclear pollution and nuclear protection, becoming references for nuclear safety management worldwide, these standards were formulated earlier, with the latest version of the International Basic Safety Standards for Radiation Protection and the Safety of Radiation Sources formulated in 2014, nearly a decade ago [90]. Due to the continuous progress of science and technology and new developments in the field of nuclear safety, these standards may no longer be sufficient to cope with the challenges of the new situation, especially in the prevention and control of radioactive environmental

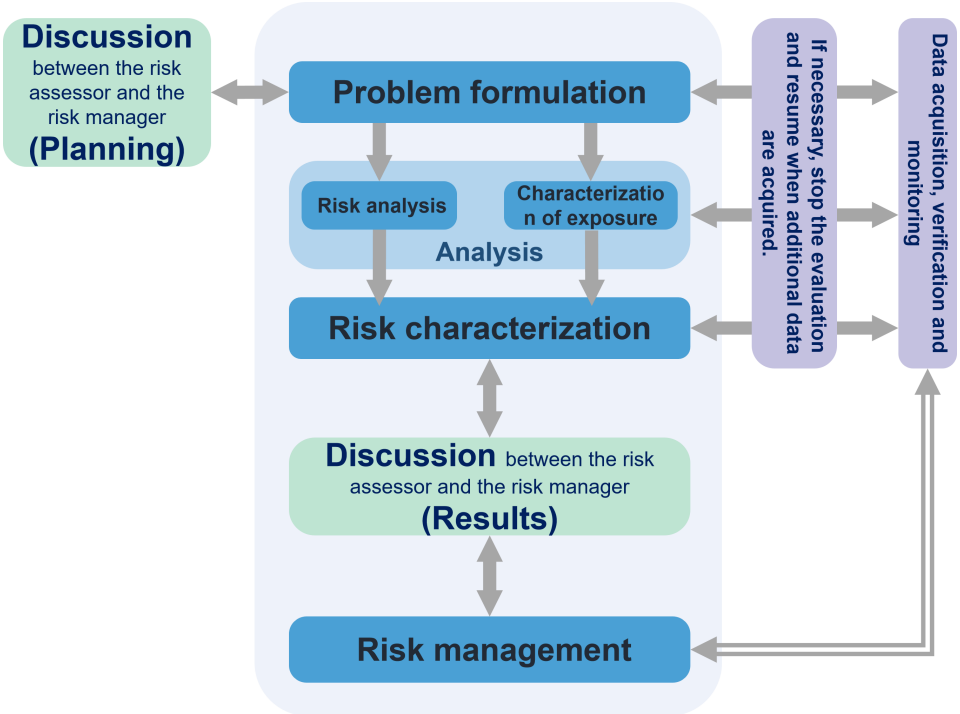

Figure 5 Classification and management of nuclear leakage. (a) Nuclear leakage levels by The International Atomic Energy Agency (IAEA); (b) Nuclear leakage management, including emergency zones and regulatory agencies. The expanded forms of the abbreviations: LPZ, Longer term Protective Action Planning Zone; UPZ, Urgent Protective Action Planning Zone; PAZ, Precautionary Action Zone; C&EC, Control and Emergency Control; OAC, Off-site Assessment Center; RAC, Radiological Accident Commission; REC, Regional Emergency Commission; ECC, Emergency Control Center.

pollution.

Domestically, although a series of general provisions for the assessment of nuclear radiation environmental quality and guidelines for the management of nuclear radiation environmental protection have been formulated, these standards also suffer from poor timeliness. For example, the general provisions for the assessment of nuclear radiation environmental quality were implemented in 1990 [91], and the latest guidelines for the management of nuclear radiation environmental protection were implemented in 2016 [92], without updates for several years.

On the other hand, both domestic and international standards often lack specific environmental criteria for nuclides, with no clear thresholds for environmental nuclide pollution. Current standards typically focus on the radiation dose absorbed by humans, neglecting to adequately regulate environmental nuclide levels. Typically, it is challenging to determine the exact radiation dose individuals receive, whereas environmental nuclide levels are easier to measure. The absence of clear standards for environmental nuclide radiation complicates governance efforts.

To address these gaps, international collaboration in nuclear safety needs to be strengthened to develop and update global standards that are relevant to today's needs. Domestically, efforts should be increased to research and establish standards for radioactive environmental pollution, ensuring these standards are regularly updated and improved. Additionally, the implementation and supervision of these standards must be emphasized, with robust mechanisms established to ensure effective enforcement and real-world impact on

environmental protection and nuclear safety.

Effective risk communication with the public is also crucial when setting environmental standards that reflect both scientific data and public sentiment. Enhanced research into public perceptions of nuclear risk, using scientific and quantitative methods to assess acceptable risk levels, is essential. This helps align regulatory measures with public expectations and effectively protects against unnecessary radiation risks by balancing perceived and actual risks.

Overall, while nuclear energy inherently carries risks, with robust regulation and international cooperation, these can be managed to maintain societal risk at acceptable levels. Continuous improvements in regulatory frameworks and emergency responses are vital for the safe and secure utilization of nuclear energy.

ENVIRONMENTAL MONITORING AND REMEDIATION

Environmental monitoring and assessment of contaminated areas

Environmental monitoring and assessment are crucial in identifying and characterizing areas contaminated with radioactive nuclides. It is necessary for source identification and tracking, emergency response and accident management, resource management and land use planning, and environmental regulation and compliance. By analyzing monitoring data, it is possible to identify specific areas or facilities responsible for radioactive nuclide releases, enabling the implementation of necessary control measures to reduce or eliminate the source and prevent further environmental contamination. In the event of a radioactive nuclide release, real-time monitoring and assessment can provide timely information on the accident's scale, spread, and affected areas. This allows for implementing appropriate emergency measures to minimize public safety risks and reduce the environmental impact of the accident. It can also help decision-makers conduct risk assessments and develop appropriate land management strategies, which ensures sustainable development and efficient resource utilization while protecting human health and environmental sustainability. Monitoring data can be used to verify whether the effluents from nuclear power banks comply with regulatory standards and ensure their adherence to radioactive nuclide management regulations.

The nuclides in the atmosphere primarily exist in the form of particles, aerosols, and gases. To analyze radioactive nuclides in the air particulate matter, pumping air through a dust sampler or air particulate sampler collects the dust on a filter. Gaseous nuclides can be collected by adsorption materials. Iodine in the air is collected on an activated charcoal filter using a dust sampler. Several filtering materials are used to collect aerosol materials (glass, PVC, or Microsorban filters). All commercial filter media, if used properly, provide sufficient efficiency. Filters are typically compressed to provide a standardized counting geometry and are subsequently dried or wetted for radiochemical analysis. Radioactive inert gases like ^{85}Kr are absorbed using an activated carbon collector cooled with liquid nitrogen. A lot of researches are now focused on how to improve these collection methods to efficiently collect samples and separate the nuclides that need to be measured. Methods of air sampling of ^{129}I are the same as for the stable iodine, but the relatively low concentration of ^{129}I compared to stable iodine requires a larger sampling time [93]. Zhang designed a cascade sampling device and optimized the sample detection program to establish an efficient method for collecting and measuring particulate matter, gaseous inorganic, and gaseous organic forms of ^{127}I and ^{129}I [94]. This method was then applied to analyze the concentrations and types of ^{127}I and ^{129}I in indoor air in

Xi'an, Shanxi, China from May to August 2020. Tritium released from NNPs exists in the air mainly as tritiated water vapor (HTO, DTO, T_2O), tritium gas (HT, DT, T_2), and hydrocarbon, among those HTO is more important given radiation attention [95]. HTO can be adsorbed on silica gel, which can further be converted to liquid water by heating it and condensing the released water vapor [95]. Tritiated water vapor can be efficiently trapped using bubblers as well. HT can be converted into HTO using platinum or CuO catalysts, then adsorbed and trapped with the above method for HTO [96]. In most cases, the collection work is carried out in the field under non-laboratory conditions, and the convenience and operability of the collection device need to be considered. While active sampling devices offer advantages, their drawbacks include high costs associated with purchase, operation, and technical personnel training. Additionally, their reliance on continuous power supply limits their applicability for long-term monitoring and field sampling. Passive sampling devices, on the other hand, effectively address these limitations. To overcome the problem of adsorbent material expansion and reduce the impact of aerosol particle deposition on the sampling inlet, Feng designed a new passive sampler for HTO. This sampler features a suspended cylindrical collection chamber with a sampling hole at the bottom, and a 4A molecular sieve (MS-4A) adsorbent, which may provide a reliable and flexible technology for field investigation of HTO in the atmosphere [97].

For marine environments, water, sediment, biota, and particulate matter samples can be collected for analysis. For water samples, it is generally recommended to process them immediately after collection to prevent irreversible physicochemical changes in the radioactive nuclide species [98]. If immediate analysis is not possible, the water sample should be stored in a sealed container to prevent the evaporation of volatile radioactive nuclides. To minimize the adsorption of radioactive nuclides onto the container walls, for nuclides except carbon and iodine, the sample can be acidified to a pH of approximately 1–3 by adding nitric acid and hydrochloric acid [99]. Hand sampling can be used for obtaining shallow sediment samples, while for samples around 60 cm depth, box corers or multiple corers are good options [100]. Biota samples (plankton invertebrates) are collected using plankton nets, typically employing four different mesh sizes (1000, 500, 250, and 100 μm) with a ring aperture of around 1 m and a length of several meters [101]. Marine particle traps consist of an upward-facing funnel that collects sinking organic and inorganic matter particulate [101]. The trap is deployed in the water column for several months, allowing for the recording of seasonal and annual variations in particle flux.

There are many methods to analyze radionuclides. Based on different detection methods can be divided into radiometric techniques, low-energy inorganic mass spectrometry, and accelerator mass spectrometry (Table 3). Radiometric techniques include alpha spectrometry recording the registered energy of the alpha particle in the form of a pulse height distribution, beta counting (liquid scintillation counter, LSC), and gamma spectrometry; low-energy inorganic mass spectrometry includes inductively coupled plasma mass spectrometry (ICP-MS), thermal ionization mass spectrometry, resonance ionization mass spectrometry, glow discharge mass spectrometry, secondary ion mass spectrometry, ^3H-^3He ingrowth mass spectrometry, and positive-ion mass spectrometry [99].

Currently, new robotic, AI-driven and supported methods are being encouraged for use in the field of environmental radioactivity monitoring. RAMONES, a new H2020-EU FET Proactive Project, has been proposed by the EU aiming to provide novel and effective solutions for in-situ, continuous, long-term monitoring of radioactivity in challenging subsea environments [102]. The project will utilize deep convolutional neural networks for hotspot detection and identification and employ state-of-the-art modeling

Table 3 The advantages and disadvantages of analytical instruments for radionuclides

Category	Analytical Instrument	Advantages	Disadvantages
Radiometric Techniques	Alpha Spectrometry	High sensitivity	Only detects alpha particles
		High resolution	High sample preparation requirements
		Simple operation	Limited alpha particle energy range
		Low cost	Sensitive to environmental conditions
	Liquid Scintillation Counter (LSC)	High sensitivity	High sample preparation requirements
		High efficiency	Sensitive to chemical quenching
		Versatility	Sensitive to chemical quenching
		Automation	High cost of scintillation solution
	Gamma Spectrometry	High sensitivity and selection	Limited to gamma emitters
		Non-destructive	Interferences
		Relatively fast	Expensive
Low-Energy Inorganic Mass Spectrometry	Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	High sensitivity	Interferences
		Multi-elemental capability	Limited information about chemical speciation
		Isotopic analysis	Expensive
	Thermal Ionization Mass Spectrometry (TIMS)	High precision and accuracy	Limited elemental coverage
		High sensitivity	Time-consuming analysis
		Isotopic analysis	Limited sample size
		Quantitative analysis	Expensive
		Long-term stability	
	Resonance Ionization Mass Spectrometry (RIMS)	High sensitivity and selection	Limited elemental coverage
		Isobaric interference-free	Time-consuming analysis
		High spatial resolution	Limited availability
		Quantitative analysis	
	Glow Discharge Mass Spectrometry (GDMS)	High sensitivity	Expensive
		High elemental coverage	Limited sample size
		Quantitative analysis	Time-consuming analysis
		Depth profiling capability	Limited spatial resolution
	Secondary Ion Mass Spectrometry (SIMS)	High spatial resolution	Expensive
		High sensitivity	Limited sample size
		Isotopic analysis	Time-consuming analysis
		Depth profiling capability	
		Multi-elemental capability	
	^{3}H-^{3}He Ingrowth Mass Spectrometry	High sensitivity	Only for tritium
		Isotopic specificity	Time-consuming analysis
		Quantitative analysis	Limited information about chemical speciation
	Positive-Ion Mass Spectrometry	High sensitivity	Limited elemental coverage
		Multi-elemental capability	Limited information about chemical speciation
		Isotopic analysis	Quantitative analysis challenges
		Fast	Interferences
Accelerator Mass Spectrometry	Accelerator Mass Spectrometry (AMS)	Ultra-high sensitivity	Complex instrumentation
		Isotopic specificity	Time-consuming analysis
		Quantitative analysis	High capital cost
		Wide range of applications	Limited availability

Figure 6 The remediation technology for radionuclides contaminated soil and water.

solutions for tasks such as radiation dose assessment, geological hazard modeling, and industrial waste modeling [103]. The monitoring system of RAMONES will exhibit rapid response capabilities during emergencies, while also being portable, durable for extended periods, and capable of autonomous operation

Remediation strategies for minimizing environmental contamination and restoring ecosystems

For the removal and remediation of nuclides in the environment, physical, chemical, and biological remediation can be the three fundamental remediation strategies. Due to the common physical and chemical properties of radionuclides and their stable isotopes, most remediation studies are based on stable isotopes. Membrane and osmosis technologies, sorption, ion exchange, precipitation, coagulation and flocculation, photo-induced advanced oxidation process, and electro-remediation were used for the removal of radioisotopes from water and wastewater (Figure 6) [104]. Huang found rapid sorption of U(VI) and Eu(III) from aqueous solutions using porous-Al_2O_3 microspheres [105]. Ryu utilized titanate nanotubes (TiNT) to remove strontium (Sr^{2+}) from seawater despiting the presence of competition among different ions, and an ion exchange reaction was observed between nitrate ions (N^{+}) and strontium ions (Sr^{2+}) [106]. Wu presented a hydraulic pellet co-precipitation microfiltration (HPC-MF) process for removing Sr^{2+} from raw water, where increasing seed crystal dosing enhances Sr^{2+} removal via particle growth, nucleation, or Ostwald ripening and

agglomeration [107]. Nariyan studied U(VI) removal from mine water using electro-coagulation, finding that U(VI) from the anode reacted with contaminants to form oxides or hydroxides that precipitated, primarily as sparingly soluble U_3O_8 and UO_2, which resisted acid breakdown [108].

The ultimate remediation of radionuclide-contaminated soils likely involves physically removing the soil from the affected site and treating it with various dispersing or chelating chemicals. However, Removing contaminated surface soil (often up to 40 cm) or immobilizing radionuclides in the soil using mineral and chemical amendments is impractical due to physical challenges and high costs [109]. Since the main risk of radionuclides in agricultural soil is intake by animals and the human body through plant absorption and accumulation, it may be more economical and efficient to treat radionuclide-contaminated soil from the perspective of reducing plant absorption. Soil amendments, fertilizers containing competing ions, and bioremediation are the primary methods currently used for remediating radionuclide-contaminated soils (Mainly metal or metalloid nuclides) (Figure 6). Various matrices, including basic rock-forming minerals and auxiliary minerals like phosphates, titanates, and titanium zirconate, can be used for the adsorption of radionuclides. For example, natural and synthetic zeolites and ammonium-ferric-hexacyano-ferrate(II) are considered promising amendments for mitigating soil contamination with radiocaesium [109]. The suppressive effects of K fertilization on plant uptake of radiocaesium were also proved by many researchers [110,111]. Microorganisms residing in soil, such as bacteria, fungi, and microscopic algae, effectively absorb or transform radionuclide compounds through biotransformation, achieving biological soil remediation [112]. Biosorption has advantages such as low cost, significantly higher efficiency, environmental sustainability, improvement of soil properties, and stimulation of the development of soil microbial biofilm, which can bind radionuclides into a form inaccessible to plants [113]. Bioremediation techniques based on bacterial biomass remain a promising approach for remediating soils contaminated with radionuclides.

Tokyo Electric Power Company (TEPCO) applied an Advanced Liquid Process System (ALPS) to treat nuclear wastewater. The process includes distillation, oil-water separation, inorganic ion exchange for the removal of radioactive cesium, reverse osmosis for removal of inorganic ions, precipitation of iron hydroxide for removal of transition metals, lanthanides, and actinides, carbonate precipitation for removal of strontium, and a 14-stage column separation system for removal of other radionuclides. ALPS is very effective for the removal of heavy metal radionuclides such as strontium, cesium, and cobalt, which can reduce their radioactive concentration to below the regulatory concentration limit; however, it can not remove tritium, and is inefficient for removal of ^{14}C (Figure 6) [114]. The latest research shows that low-dose exposure to ^{3}H and ^{14}C can have toxic effects on organisms, especially due to their high bioaccumulation potential [115,116]. Therefore, effectively removing various forms of 3H and 14C in the environment will be meaningful and challenging research in the future.

FUTURE DEVELOPMENTS AND RESEARCH NEEDS

In future research, considering the current lack of studies concerning environmental radionuclide standards, emphasis should be placed on the long-term effects of these radionuclides on human health, particularly the risks associated with low-dose radiation exposure. Existing research has addressed the measurement of environmental radionuclides [117,118], and additional studies have estimated the human intake of radio-

active nuclides to explore the health effects of certain radiation levels [119–121]. Yet, no studies have directly examined the relationship between environmental radionuclide concentrations and human health risks. Owing to the difficulty in accurately determining the amount of radioactive nuclides ingested by humans in real time, researchers need to develop methods for estimating the radiation dose humans receive at specific radionuclide concentrations in the environment. These estimates should then inform the creation of environmental radionuclide standards. Developing effective methods for removing ^{3}H and ^{14}C from the environment remains a crucial and possible research direction. These represent an important research agenda for future studies in the field.

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Author contributions

B.H. and Y.L. wrote the manuscript; X.S. drew the figures; L.H., S.D., and L.M. revised the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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