Radioecology: from early studies to modern challenges, with a focus on Serbia

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Abstract

Radioecology is an interdisciplinary scientific field that studies the migration of radionuclides in the environment, their interactions with ecosystems, and the biological effects of ionizing radiation on non-human biota. Since its origins in the late 19th century, radioecology has evolved in response to nuclear testing, industrial activities, and major nuclear accidents such as Chernobyl and Fukushima. This paper explores both natural and anthropogenic radionuclides, their environmental pathways, and bioavailability, and a methodological approach for asseing the effects of ionizing radiation on non-human biota. Particular emphasis is placed on radioecology in Serbia, covering historical research developments, contamination sources, including depleted uranium, detection techniques for radionuclides and the principles of radiological protection. Through a systematic review of available data, this study highlights the importance of an integrated approach to protecting ecosystems from radiological contamination.

Keywords: *radioecology; NORM; nuclear accidents; reference animals and plants; Serbia*

Izvod

Radioekologija je interdisciplinarna naučna oblast koja proučava migraciju radionuklida u životnoj sredini, njihovu interakcije sa ekosistemima i biološke efekte jonizujućeg zračenja na živi svet. Od svog nastanka krajem 19. veka, radioekologija se razvijala kao odgovor na nuklearna testiranja, industrijske aktivnosti i velike nuklearne nesreće poput Černobilja i Fukušime. Ovaj rad istražuje prirodne i antropogene radionuklide, njihovu migraciju kroz životnu sredinu, uključivanje u karike lanca hrane i metodološki pristup za procenu dejstva jonizujućeg zračenja na živi svet. Poseban naglasak je stavljen na radieokološka ispitivanja u Srbiji, istorijski razvoj, izvore kontaminacije, uključujući osiromašeni uranijum, tehnike detekcije radionuklida i principe radiološke zaštite. Kroz sistematski pregled dostupnih podataka, ova studija ističe važnost integrisanog pristupa zaštiti ekosistema od radioaktivne kontaminacije.

Ključne reči: *radioekologija; NORM; nuklearni akcidenti; referentne životinje i biljke; Srbija*

Introduction

Radioecology is a scientific discipline that investigates the migration of radionuclides within the biosphere, the impacts of ionizing radiation on living organisms in their natural habitats, and the broader ecosystem. By integrating knowledge from multiple scientific fields, radioecology examines how natural or anthropogenic radionuclides move through ecosystems and affect organisms. Researchers study their distribution in air, water, and soil, as well as their influence on non-human biota, tracking their pathways and bioavailability through food chains. Understanding these processes provides crucial insights into the fate and long-term biological and environmental consequences of radionuclides [1-4]. Addressing these complex challenges requires collaboration among experts in physics, chemistry, geochemistry, biology, fostering a multidisciplinary approach to radioecological research.

Radioecology, as a subfield of ecology, emerged after the discovery of ionizing radiation in the late 19th century. One of the earliest studies, conducted in 1896 by scientist Tarkhanov, examined the

effects of X-rays on aquatic plants and animals, laying the foundation for both radiobiology and radioecology [5]. The term "radioecology" was introduced in the 1950s by American researchers Eugene Odum and Stanley Auerbach, alongside Soviet scientists Aleksandr Mikhailovich Kuzin and Aleksey Alekseyevich Peredelsky [3].

The end of World War II, marked by the dropping of the atomic bombs on Hiroshima and Nagasaki, as well as a large number of nuclear tests conducted in the post-war period, led to a major development of radioecology, which was accompanied by the development of new techniques for radionuclide detection. At the end of the 20th century, a nuclear accident occurred in Chernobyl (1986), resulting in widespread radioactive contamination [6]. These events highlighted the vital role of veterinary science in the case of nuclear accidents [7, 8]. Specifically, veterinary expertise is essential for protecting animal health and ensuring the production of radiologically safe food of animal origin.

Radionuclides in environment

All living organisms on Earth are continuously exposed to ionizing radiation due to the presence of radioactive elements in the environment, including soil, water, and air. These elements can be classified as natural or anthropogenic. There are two groups of natural radionuclides, primordial and cosmogenic. Primordial radionuclides, also referred to as terrestrial radionuclides, consist of the parent isotopes of three radioactive decay series: ^{238}U, ^{232}Th, and ^{235}U (Table 1), along with their decay products, as well as ^{40}K and ^{87}Rb [9].

According to the International Atomic Energy Agency [10], Naturally Occurring Radioactive Materials (NORM) are defined as materials containing radionuclides of natural origin where human activities have increased the likelihood of exposure compared to their natural state. This includes cases where radionuclide concentrations remain unchanged or are elevated, the latter often termed Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). Activities such as mining, fossil fuel combustion, the phosphate industry, and oil and gas extraction can concentrate or redistribute these radionuclides, posing heightened risks to both the environment and human health. Taking into account the current considerations of lithium exploitation in Serbia, it is necessary to highlight the potential exposure to NORM that accompanies this process. Lithium is an industrial resource, but its extraction and processing can lead to exposure to naturally occurring radionuclides originating from the decay series of ^{238}U and ^{232}Th. People can be exposed through the inhalation of dust contaminated with alpha particles, the inhalation of radon and thoron with their decay products, the ingestion of drinking water containing alpha and beta emitters, as well as direct gamma radiation. These radioactive elements are inherent in the geological formations being mined for lithium [11].

Depleted uranium (DU) is a by-product or waste material generated during the enrichment of uranium for nuclear reactors. It is produced from natural uranium ore through industrial processes and has been utilized in various applications. Notably, DU has been used in military contexts, such as armor-piercing munitions and vehicle shielding. Its use in conflicts, including the First Gulf War (Iraq, 1991), the Bosnian War (1995), and the Kosovo conflict (Yugoslavia/Serbia, 1999), has raised significant environmental and health concerns due to its radioactive properties [12, 13].

Cosmogenic radionuclides are formed in the Earth's atmosphere through the interaction of primary cosmic radiation with air atoms (Table 1) [9, 14]. The most common cosmogenic radionuclides are present in Table 1. Only ^{3}H and ^{14}C are significant in terms of the dose to humans and non-human biota.

Table 1. Natural radionuclides in environment [9]

Radionuclide	Half-life	Radionuclide	Half-life
Primordial radionuclides			
^{238}U	4.47×10^{9} years	^{40}K	1.28×10^{9} years
^{232}Th	1.41 x 10^{10} years	^{87}Rb	4.75×10^{10} years

^{235}U	74 x 10^8 years		
Cosmogenic radionuclides			
^{3}H	12.3 years	^{35}S	87.51 days
^{7}Be	53.3 days	^{32}P	14.3 days
^{14}C	5730 years	^{33}P	25.3 days
^{22}Na	2.60 years	^{33}S	87.5 days

Nuclear fission, nuclear fusion and neutron activation are the main physical processes that lead to the creation of artificial radionuclides. Nuclear testing and accidents at nuclear power plants have led to widespread contamination of the environment with artificial radionuclides. Among more than 300 different radionuclides produced by nuclear fission, the most important for living organisms are the isotopes caesium, strontium, ruthenium, cerium, iodine, plutonium and americium (Table 2) [15-17]. Radioactive isotopes of caesium and strontium are chemically similar to potassium and calcium, respectively. This similarity arises because they belong to the same groups in the periodic table. The caesium and the potassium are alkali metals (Group 1), while the strontium and the calcium are alkaline earth metals (Group 2). Due to this chemical similarity, when these radioactive isotopes enter a living organism, they can mimic the behavior of their non-radioactive analogues.

Table 2. The most significant artificial radionuclides [15]

Radionuclide	Half-life	Radionuclide	Half-life
^{89}Sr	50.53 days	^{137}Cs	30.17 years
^{90}Sr	28.79 years	^{141}Ce	32.51 days
^{106}Ru	373.59 days	^{144}Ce	284.91 days
^{131}I	8.02 days	^{239}Pu	2.41 x 10^4 years
^{134}Cs	2.06 years	^{241}Am	432.2 years

Chernobyl and Fukushima Nuclear Disasters

The Chernobyl disaster in 1986 and the Fukushima Daiichi nuclear accident in 2011 are the only two nuclear accidents classified as Level 7 on the International Nuclear Event Scale (INES) [18], representing the most severe level. Although both events caused significant environmental pollution and public concern, they were significantly different in their causes, like the radioactive releases and in the extent of their effects.

The Chernobyl accident (April 26, 1986) was primarily attributed to human error during a poorly planned and executed safety test. The operational staff violated several safety procedures, leading to an uncontrolled power surge that resulted in the catastrophic destruction of the reactor. This led to an uncontrolled nuclear chain reaction that caused a steam explosion, instantaneously destroying the reactor and its building. The explosion was followed by a graphite fire that burned for over ten days, leading to a prolonged and substantial release of a wide range of radioactive materials into the atmosphere [19 - 20] (Table 3). According to the Kashparov report [21], one of the characteristics of the accident was the dispersal of hot particles in the radioactive fallout. The microscopic particles were made of a matrix predominantly composed of uranium oxides, but also of various other materials that were part of the reactor fuel. These distinctive fuel particles were found near the Chernobyl site and in Finland, Sweden, Germany and other European countries [21].

Table 3. Main radionuclides, released into the atmosphere (TBq) following the nuclear accidents at Chernobyl [21-22] and Fukushima [23*-24**]

Radionuclide	Chernobyl	Fukushima

^{131}I	1760	100 – 500**
^{134}Cs	47	8.3 – 50*
^{137}Cs	85	6 – 20**
^{90}Sr	4	0.003 – 0.14*

The Fukushima Daiichi accident, which occurred on March 11, 2011, was the result of a natural disaster. A strong earthquake of magnitude 9.0 struck off the east coast of northern Japan, triggering a massive tsunami that subsequently struck the east coast. At the Fukushima Daiichi Nuclear Power Plant, the tsunami flooded the facility, resulting in the total loss of both off-site grid power and on-site emergency power supply. This power failure shut down the cooling systems of three of the six reactor units. Without cooling, the residual heat caused the reactor cores in these units to gradually overheat, oxidise, and eventually melt over an extended period. These damages led to radioactive material being released into the surrounding region. Unlike Chernobyl, the release of radioactive material at Fukushima occurred over an extended timeframe [23, 24].

The total radioactive release from the Chernobyl accident (5300 PBq, excluding noble gases) was much higher than of Fukushima Daiichi (520 PBq, from 340 PBq to 800 PBq), which represented 10% to 40% of the Chernobyl emissions [19]. Approximately 80% of the radionuclides released during the Fukushima Daiichi accident were transported to marine environments through multiple pathways. These included atmospheric fallout of radioactive particles, as well as direct releases and leakage of contaminated cooling water into the Pacific Ocean [19, 25].

The high radiation levels caused morbidity and mortality among plants and animals in highly contaminated zones around Chernobyl. Within a radius of 7 km around the reactor, the pine trees have been exposed to extreme radioactive contamination from the mixed release of radioactive materials (combining both short and long-lived isotopes). Intense radiation exposure was fatal to vegetation, with gamma radiation doses exceeding 5 mGy per hour during the initial period of exposure. Pine needles absorbed cumulative gamma doses of 80 Gy to 100 Gy, leading to a rapid deforestation of forests. This heavily contaminated area has become known as the Red Forest because of the characteristic brown-red color of the dying trees - one of the most visible biological effects of acute radiation exposure [6, 26]. In addition, the numerous studies have shown elevated mutation rates, chromosomal aberrations, and genetic damage in various in various non-human species (birds, mammals, insects) within the Exclusion Zone (30 km) [27-29]. Following the Chernobyl disaster, significant environmental contamination has been observed within 30 km of the Chernobyl Nuclear Power Plant, with long-lived radioactive materials, such as ^{90}Sr, ^{241}Am, and plutonium isotopes [30].

The nuclear accident at Fukushima, Japan, resulted in the release of significant quantities of water containing radioactive materials into the Pacific Ocean. The high levels of radioactive deposition were reported in the evacuation zone of 20 km, but significant contamination was also detected in regions beyond this immediate area [24]. The surface area contaminated with more than 185 kBq/m² of ^{137}Cs in the Fukushima region has been estimated at approximately 1,700 km² [19]. According to UNSCEAR [24], in areas with enhanced radiation levels, various cytogenetic, physiological, and morphological effects (at the sublethal, individual level) in plant and animal species were observed. The Japanese red pine and Japanese fir trees exhibited developmental abnormalities after the Fukushima accident that were comparable to those observed in Chernobyl [31-33], strongly suggesting that radiation exposure during development was the primary cause of these aberrations. However, the underlying genetic and physiological mechanisms responsible for these radiation-induced developmental effects in conifers remain largely unknown. Also, contrary to expectations, a study on field mice exposed to high radioactive contamination near the Fukushima nuclear power plant showed no detrimental effects on spermatogenesis, underscoring the need for further research into taxonomic variations in radiation sensitivity [34]. Despite the appearance of radiation-induced

base-exchanges in mDNA, masu salmon collected from the radioactively contaminated Mano River showed no phenotypically significant alterations in the sampled population [35].

The Reference Animals and Plants (RAPs)

To support environmental protection, the International Commission on Radiological Protection (ICRP) established a system of Reference Animals and Plants (RAPs), analogous to the concept of the "Reference Man" used in human radiological protection [15]. This framework provides a scientific basis for understanding the relationships between radiation exposure, absorbed dose, and resulting biological effects in selected animal and plant species [36]. The selection of RAPs [36, 37] follows clear ecological and radiological criteria. Chosen species are ecologically important, widely distributed, and representative of both terrestrial and aquatic environments. The process considers various life stages, habitat types, and the organism's potential to accumulate radionuclides. RAPs are also expected to have relatively high exposure levels and sensitivity to radiation. In addition, they should be well studied biologically to allow accurate modelling of radiation dose and effects.

In the field of radioecology, the assessment of the effects of ionizing radiation on non-human biota requires a structured and integrated framework consisting of five key elements [24]. The first element, exposure characteristics, involves analyzing the spatiotemporal dynamics of radionuclide distribution in the environment, understanding of species-specific uptake pathways and bioaccumulation processes, and the internal distribution of radionuclides within organisms, to enable accurate dose estimation. The second element recognizing the diversity of non-human biota, is essential to select suitable reference organisms (Table 4) that are representative of the ecosystems under study and relevant to the geographical area of interest. The selection should be based on ecological relevance, data availability, and, where applicable, conservation status.

The third element, dosimetry modelling, plays a crucial role in the accurate estimation of absorbed dose, either to the whole organism or specific target tissues. Dosimetric calculations should include geometric corrections to account for the size, shape, and internal anatomy of the organism, as these factors influence energy deposition and dose distribution. The use of appropriate relative biological effectiveness (RBE) values is necessary to account for differences in the biological impact of various radiation qualities. The fourth element is the definition of ecologically significant endpoints in radiological assessment, which emphasize population-level deterministic effects like mortality and reproductive capacity, as well as the formulation of corresponding reference dose levels. The fifth element, a comprehensive understanding of the effects of radiation on biota, requires a clear link between individual radiation-induced responses and their potential impact on population dynamics. This involves considering the ecological relevance of observed biological effects, such as changes in survival, reproduction, or behavior, and evaluating whether these responses are likely to result in measurable impacts at the population scale. It is also necessary to take into account the role of background radiation and natural biological variability within and between populations, both of which can affect the sensitivity and resilience of species to radiological stressors [24].

Table 4. The Reference Animals and Plants (RAPs) [24]

Reference organism	Description
Earthworm	soil invertebrate
Rat	burrowing mammal
Bee	above ground invertebrate
Wild grass	grasses, herbs and crops
Pine tree	tree
Deer	herbivorous mammal

Duck	bird
Frog	amphibian
Brown seaweed	microalgae
Trout	pelagic fish
Flatfish	benthic fish
Crab	crustaceans

In radioecological assessments, threshold doses, dose rate limits, and Derived Consideration Reference Levels (DCRLs) are used to assess the radiological risk to non-human biota [24, 36]. A threshold dose refers to the minimum absorbed dose of ionizing radiation required to induce a measurable biological effect in an organism. This value is typically determined from laboratory or field studies that examine endpoints such as mortality, reduced reproduction, developmental abnormalities, or behavioral changes. Threshold doses are often used in dose–response analyses and expressed in gray (Gy) or milligray (mGy) [24].

A dose rate limit is a fixed value of radiation absorbed per unit time (typically in μGy/h) that serves as a screening criterion in radiological assessments. Below this limit, adverse effects at the population level are not expected, and no further detailed evaluation is usually required. For example, the ERICA Tool [38, 39] and FASSET framework [40] propose generic screening dose rates of 10 μGy/h (0.24 mGy/day) for terrestrial and freshwater organisms and 40 μGy/h 0.96 mGy/day] for marine organisms These limits are developed to ensure a high level of protection across taxa.

In 2008, the International Commission on Radiological Protection (ICRP) introduced the concept of Derived Consideration Reference Levels (DCRLs) [36], which define bands of dose rates within which there is a probability of detecting radiation-induced effects in Reference Animals and Plants (RAPs). For instance, ICRP [41] reports that dose rates between 0.1 mGy/day and 1 mGy/day may cause limited effects on sensitive endpoints in some organisms. From 10 mGy/day to 100 mGy/day, effects become likely for many endpoints across diverse biota; however, sensitivity varies considerably among RAPs, for example, bees, crabs, and earthworms generally show lower sensitivity [41]. DCRLs are not strict regulatory limits but help inform decision-making for environmental radiation protection. If estimated dose rates are within or exceed a DCRL band, a more detailed, site-specific ecological assessment should be carried out to evaluate whether protective measures are needed [36]. The establishment of RAPs and associated dose assessment frameworks represents a significant advancement in environmental radiological protection. By providing standardized reference points, these instruments enable consistent assessment of radiation effects on non-human biota, with the aim of protecting environmental integrity.

Radionuclide Detection Techniques in Radioecology

In radioecological investigations the determining the content of radionuclides is fundamental to assess their distribution, transfer, and potential impacts on non-human biota and the environment. One of the most common techniques used in radionuclide detection is gamma spectrometry. Its primary benefit, besides wide accessibility, is the ability to simultaneously identify and quantify multiple radionuclides in a single measurement [42, 43]. The technique is non-destructive, allowing for the analysis of samples without altering their physical or chemical properties [44]. However, it has limited sensitivity for low-energy gamma emitters [45]. Furthermore, the resulting spectra can be complex, making additional analysis and interpretation challenging and requiring specific skills and experience [46].

Alpha spectrometry, not so widely accessible as gamma spectrometry, due to limited application only on alpha emitters and requirement specialized equipment and expertise. Sample preparation requires specialized instrumentation and analytical expertise [43, 47]. Nonetheless, alpha spectrometry is

highly sensitive to alpha-emitting radionuclides, allowing for the detection of low concentrations. It can also provide information regarding specific radionuclides in a sample and precise quantification of alpha-emitting isotopes [48].
Liquid Scintillation Counting (LSC) is another useful technique, particularly for beta-emitting radionuclides, and it has proven effective for low-energy beta emitters. LSC can be used for a variety of samples, including biological tissues and liquids. However, without additional research, LSC provides limited insight into the specific radionuclides present [49].
In many academic disciplines, such as the biological sciences, agriculture, industry, and food and nutrition, Neutron Activation Analysis (NAA) is frequently used due to its high level of accuracy and sensitivity for trace elements (<0.01%). NAA can also analyze multiple elements from a single sample [50].
Mass spectrometry is another common analytical method encountered in radioecology. Its main advantages are high precision and sensitivity, leading to versatile applications. Mass spectrometry is very efficient in determining isotopic ratios, which are important for tracing the origin of radionuclides. Some disadvantages include high cost and relatively complex sample preparation. Additionally, mass spectrometry provides limited information about the chemical and molecular structure of compounds [51-53].

Radioecology investigation in Serbia

The radiation protection legislation in the Federal People's Republic of Yugoslavia was established in 1947 with the adoption of the Rulebook on Protective Measures during Work with X-ray Devices and Radioactive Substances [54, 55]. This pioneering regulation established fundamental safety standards for the use of radioactive materials in both medical and industrial settings. It marked the beginning of a structured approach to radiation protection, later expanded through the adoption of the Law on Protection from Ionizing Radiation in 1959. Further legislative development followed in 1965 with the adoption of the Basic Law on Ionizing Radiation Protection in the Socialist Federal Republic of Yugoslavia (SFRY), forming the core of the national radiation safety framework.
The Yugoslav Society for Radiation Protection was founded on October 11, 1963, during the Yugoslav Symposium on Radiological Protection held in Portorož. In 1969, the society became a full member of the International Commission on Radiological Protection (ICRP). Between 1972 and 2003, the organization underwent several changes in response to evolving political circumstances, ending in the establishment of the Society for Radiation Protection of Serbia and Montenegro in 2005.
The development of radioecological research within the territory of the former Yugoslavia, presently Serbia, can be most effectively tracked by examining the number of publications presented at the conferences of the Society for Radiation Protection. Research conducted by Todorović et al. [56] indicated a significant increase in the number of published works in the field of radioecology after 1975. Notably, the conference proceedings published in 1996, marking a decade since the Chernobyl accident, with 50% of the papers focused on radioecology, and those from 2016, commemorating its 30th anniversary, with 95% of contributions in this area, stand out. In addition to their participation in symposia, scientists have published a considerable number of papers in both domestic and international journals. Numerous studies have investigated the levels of radionuclides in various environmental compartments in Serbia. Regarding soil, studies have measured natural radionuclides such as 40K, 238U,226Ra, 232Th, across different regions [56 - 58], including the cities of Belgrade and Novi Sad [59] as well as mountain regions [60, 61]. The artificial radionuclide 137C was also detected in Serbian soils, resulting from the Chernobyl accident and historical atmospheric nuclear weapons testing [62 - 66]. Moreover, studies across Serbia have used the fallout radionuclide ^{137}Cs to quantify soil erosion rates [67, 68]. The non-human biota of Serbia also contains measurable levels of radionuclides. Studies on plants, particularly medicinal herbs, have reported the presence of 40K, 238U, 226Ra, 232Th, and 137Cs [69 - 71]. In animals, including fish, livestock, and game meat, the

40K is the primary contributor to radiation exposure, while ^{137}Cs was also frequently detected [60, 4]. Researchers have also employed tools like ERICA and RESRAD to assess radiation exposure to both human and non-human biota in the Serbian environment [72, 73].

During the 1999 Kosovo conflict, NATO aircraft deployed depleted uranium (DU) weapons against specific targets in Kosovo, Southern Serbia, and Montenegro. NATO confirmed to the United Nations that over 30,000 DU rounds were used in Kosovo, more than 2,500 rounds in Serbia, and 300 rounds in Montenegro [78]. According to the SEPA [76], an estimated 15 tons of DU were used during the NATO bombing of Kosovo. The use of DU weapons has raised significant concerns about the long-term environmental and health impacts on the affected regions. Depleted uranium, while less radioactive than natural uranium, can still pose serious health risks due to its chemical toxicity and potential to cause kidney damage and cancer. Efforts to clean up contaminated sites have been ongoing [77], but the full extent of the contamination and its effects on local populations are still being studied. To assess DU contamination in soil, water, air, and bioindicators, environmental monitoring has been carried out [78 - 81]. After the NATO attack, in certain regions, elevated uranium levels and non-natural isotopic ratios have been found. Between 2002 and 2007, the Vinča Institute of Nuclear Sciences carried out cleanup operations in southern Serbia to remediate DU-contaminated sites [77]. Due to the use of depleted uranium weapons and the targeting of industrial facilities such as large power plants, chemical plants, and oil refineries, the bombing of the former Yugoslavia caused serious environmental harm. This resulted in the release of numerous toxic chemical substances into the atmosphere, hydrosphere, and lithosphere. Consequently, these pollutants entered the biosphere via natural cycles and trophic pathways, accumulating in living organisms. A number of these substances have been shown to cause genetic mutations, cancer, and developmental abnormalities. Since pollutants are expected to have long-term effects on human health, non-human biota, and the ecosystem as a whole, a multidisciplinary scientific team must collaborate to fully evaluate the environmental effects of the bombing [82].

The environmental radioactivity monitoring program in Serbia uses systematic and ongoing measurements of the radionuclide content of different environmental samples to track the level of radioactivity in the country's environment. This monitoring covers air, precipitation, soil, surface waters, drinking water, food products of plant and animal origin, milk, and animal feed. The legal basis for this monitoring is established by the Rulebook for establishing a programme of systematic environmental radioactivity examination [83]. The Serbian Radiation and Nuclear Safety and Security Directorate (SRBATOM) is the primary authority responsible for overseeing and implementing these monitoring activities. SRBATOM also publishes annual reports detailing the levels of population exposure to ionizing radiation from the environment. These reports are available from 2010 to 2024, with specific reports for 2016 and 2017 focusing on locations affected by depleted uranium. To ensure timely response in case of radiological emergencies, Serbia has established a Programme of early warning of emergency [84]. Furthermore, Serbia actively participates in the European Radiological Data Exchange Platform (EURDEP), facilitating the real-time exchange of environmental radiation monitoring data with other European countries. Radioactivity monitoring has also been carried out in previous periods. Between 1965 and 1987, the Federal Committee for Labour, Health and Social Welfare Yugoslavia released yearly reports on environmental radioactivity under the title “Radioactivity of the Environment in Yugoslavia” [55].

The radioecological investigations in Serbia provide data on the state of radioactivity in the environment, the presence of natural and anthropogenic radioactive elements and their impact on living beings. This research will allow a broader understanding of the behavior of radioactive substances in complex ecosystems. Future studies will likely focus on refining dose assessment models, mitigating long-term contamination effects, and strengthening environmental protection strategies to protect the ecological integrity.

Conclusion

Radioecology has developed into an important interdisciplinary field that addresses the transport, bioavailability, and ecological effects of radionuclides in the environment. The historical evolution of this discipline has been shaped by nuclear energy production, accidental releases of radionuclides, and industrial activities, all of which have necessitated methodological advancements in radionuclide detection and radiological risk assessment. The environmental impacts of nuclear disasters, such as Chernobyl and Fukushima, highlight the need for continuous monitoring and improved radiological protection measures. In Serbia, radioecological research has played a crucial role in assessing contamination levels from both natural sources and anthropogenic activities, including the legacy of depleted uranium usage. Researchers provide valuable insights into the state of radioactivity in the environment and radiological safety by integrating international standards, dose assessment models, and advanced detection techniques. The findings emphasise the importance of sustained scientific collaboration, environmental policy development, and further refinement of methodologies for assessing radiation effects on non-human biota. Future research should focus on improving dosimetric models, refining ecological risk assessment frameworks, and exploring mitigation strategies to ensure effective environmental radioprotection.

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