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Review paper

RADIONUCLIDES IN THE FOOD CHAIN: FOCUS ON ANIMAL - DERIVED FOOD

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Abstract

The paper presents an analytical overview of the occurrence, movement, and accumulation of both natural and anthropogenic radionuclides in food of animal origin. The research encompasses the main pathways through which these substances enter animal organisms, together with the environmental and agricultural factors influencing their distribution in soil, vegetation, and animal tissues such as meat, milk, eggs, and fish during the period 1989 to 2025. The review was conducted based on a literature search performed in the Elsevier, Hinari, PubMed, and other relevant scientific databases. The study focuses on isotopes including uranium-238, thorium-232, potassium-40, cesium-137, and strontium-90 as key indicators of naturally occurring and technologically induced radioactivity within the biosphere. The analysis demonstrates the interconnection between geological, climatic, and agricultural conditions that determine the levels and variability of radionuclides in animal-derived food. It was established that radionuclide concentrations in North Macedonia fall within internationally accepted limits and correspond with values observed in other European countries. The study emphasizes the importance of continuous monitoring of both natural and anthropogenic sources of radioactivity to enable timely detection of fluctuations in radiological balance and to ensure the long-term safety of food and public health protection.

Key words: *radionuclides, natural and anthropogenic sources, animal-derived food, radioactivity, radiological safety.*

INTRODUCTION

Determining environmental radioactivity levels is essential for assessing the radiation exposure to which humans and animals are directly or indirectly subjected. Therefore, environmental samples have been extensively examined by researchers to determine the levels of natural radioactivity. Radiation levels in food products are of particular interest to researchers, as ingestion represents one of the most widespread routes through which radionuclides migrate into living organisms (Salminen-Paatero & Paatero, 2021).

The presence of varying quantities of naturally occurring radioactive materials such as uranium, thorium, and their decay products, as well as the individually occurring isotope potassium forty, constitute the primary sources of natural radiation in the environment (Zakariya & Kahn, 2014). Natural radioactivity represents a continuous and inherent component of the Earth's energetic equilibrium. It originates from primordial isotopes such as uranium two hundred thirty-eight, thorium two hundred thirty-two, and potassium forty, which are naturally embedded within the planet's crust, atmosphere, and hydrosphere, and whose decay generates a constant flux of ionizing radiation throughout the biosphere (Esan et al., 2022). These isotopes are not uniformly distributed; their concentrations vary according to lithological composition, mineral abundance, and climatic conditions across different regions (Usikalu et al., 2020). Hence, the persistence of natural radioactivity reflects the geological and geochemical diversity that defines terrestrial ecosystems.

Naturally occurring radionuclides such as potassium forty, thorium two hundred thirty-two, and radium two hundred twenty-six and their ptogenies, enter the food chain through soil and air to plants, and subsequently from plants to animals and humans (Jayasinghe et al., 2020).

Over long geological timescales, these radionuclides become incorporated into mineral matrices, while their decay products migrate through soil layers, groundwater, and vegetation. Regions enriched with heavy minerals display elevated levels of natural radioactivity, demonstrating the close correlation between lithological composition and environmental radiation (Khandaker, Amin & Bradley, 2018). The United Nations Scientific Committee on the Effects of Atomic Radiation has identified these naturally occurring radionuclides as dominant contributors to human exposure, as they are incorporated into both abiotic and biological processes (UNSCEAR, 2000).

Intensive human activities such as nuclear weapons testing, nuclear accidents, industrial use of radioactive compounds, ore and oil mining and the application of phosphate fertilizers in agricultural soils can significantly increase the concentrations of artificial radionuclides in both the environment and food products (Czarnecki & Düring, 2015; USEPA, 2000; Haase, Vagt & Fritsche, 2021). Long-term mineral fertilization has been shown to influence metal contents and alter the physical and chemical properties of soils from various locations in Hesse, Germany (Czarnecki & Düring, 2015). The United States Environmental Protection Agency evaluated national guidelines concerning technologically enhanced naturally occurring radioactive materials and emphasized the necessity for systematic control and environmental regulation (USEPA, 2000). Likewise, Haase, Vagt & Fritsche (2021) highlighted the importance of monitoring radionuclide activity, particularly cesium one hundred thirty-seven and strontium ninety, in animal feed and foodstuffs consumed in Germany (Czarnecki & Düring, 2015; USEPA, 2000; Haase, Vagt & Fritsche, 2021).

Nuclear accidents, such as the catastrophic releases at Chernobyl and Fukushima, resulted in widespread contamination of soil, water, and air with radionuclides (Seyama et al., 2020; Ambrosino et al., 2023). The Fukushima nuclear disaster of March 11, 2011, is regarded as one of the most severe ecological catastrophes of the twenty-first century (Povinec, Hirose, & Aoyama, 2013; Harada et al., 2014).

The half-life of isotopes is a significant determinant for assessing the degree of hazard posed by radioactive metallic ions. Relatively Long-lived radionuclides such as cesium one hundred thirty-seven, with a half-life of thirty point one seven years, strontium ninety, with a half-life of twenty-eight years, and cobalt sixty, with a half-life of five point two seven years, are among the most hazardous to the environment due to their high solubility, strong mobility, ease of biological assimilation, and long persistence among the fission by-products (Mohammad et al., 2025).

Once incorporated into vegetation, these radionuclides enter grazing animals and progressively move through trophic levels, completing a continuous cycle of exchange within the environment. Beyond nuclear accidents and weapons testing, human industry and agriculture contribute to additional pathways for radioactive dispersion. Radionuclides exhibit rapid migration, and it is extremely difficult to prevent their transfer through the food chain (Berthiaume, 2023).

Phosphate fertilizers rich in uranium and thorium represent an acknowledged source of artificial radioactivity in agricultural soils (Czarnecki & Düring, 2015). Long-term field analyses conducted by Vasila & Ahmed (2011) demonstrated that continuous fertilizer application leads to increased radionuclide content in crops and subsequently in the tissues of animals that feed on them. Industrial processes involving phosphate-rock treatment or coal combustion have similar effects, allowing radioactive substances to re-enter the biosphere through the atmosphere, water, and soil systems (Czarnecki & Düring, 2015; Vasila & Ahmed, 2011). The presence of radioactive substances in the environment, regardless of whether their origin is natural or technological, requires a coherent and systematic approach to their monitoring at all stages of food production.

Food of animal origin is particularly suitable for such assessments, since animals function as biological intermediaries linking soil, water, and vegetation through common metabolic processes. Radionuclides present in soil can pass into grass and forage crops, and subsequently enter animal and fish bodies, where they may accumulate in organs, muscle tissue, milk, eggs, completing the chain of radiological transfer that ultimately reaches humans as final consumers. Therefore, continuous monitoring of radioactivity levels in food and raising public awareness about potential risks are essential for radiation protection (Czarnecki & Düring, 2015; Vasila & Ahmed, 2011).

Continuous measurement of natural radioactivity through the detection of gamma radiation is crucial for tracking all variations in radiation levels arising from geological processes and anthropogenic influences (Jananee et al.,2021). This monitoring makes it possible to identify environmental and food radioactivity levels necessary to ensure radiological safety for the public and the environment (Jananee et al., 2021).

This research rests upon the conceptual foundation of interconnection between natural radioactivity, agricultural practice, and food safety. Its structure examines the pathways through which radionuclides enter animal organisms, the natural and anthropogenic factors influencing their accumulation, the monitoring systems established to safeguard public health, and the comparative evaluation of data collected from different countries to construct an accurate picture of human exposure through animal-derived food. The study establishes a unified scientific perspective that links geological sources of radioactivity, biological mechanisms of transfer, and the broader ecological and social implications arising from the radiological contamination of food. By merging these dimensions into a coherent analytical framework, it provides an integrated understanding of the radiological condition of contemporary agricultural ecosystems and the potential risks that dietary exposure may pose to human populations.

MATERIAL AND METHODS

The present study was designed to analytically examine the distribution, movement, and concentration of natural and anthropogenic radionuclides in food of animal origin. The research process was carried out through systematic reading, critical evaluation, and cross-analysis of data obtained from 113 scientific papers, books, and academic publications dealing with radiological safety in animal-derived foods. A deductive approach was applied to draw specific conclusions relevant to the Macedonian context based on general scientific principles explaining the biogeochemical behavior of radionuclides. The descriptive approach was employed to systematize and present the collected data in a coherent and logical structure, while the comparative approach was used to contrast and interpret findings from different regions and countries.

Only peer-reviewed and scientifically verified sources were utilized, accessed through databases such as PubMed, Web of Science, Google Scholar, and Research Gate, with a particular focus on studies published within the last two decades. Unpublished data, unverified materials, and non-peer reviewed works were excluded from analysis. This methodological framework ensured scientific precision, analytical consistency, and verifiable credibility of the conclusions derived from the reviewed literature.

From the total number of analyzed sources, fifty-one focus on food of animal origin, covering meat, milk, eggs, and fish as key indicators for evaluating radionuclide presence. Thirty-six studies address environmental radioactivity, examining water, soil, and vegetation as the main pathways of natural and anthropogenic contamination. Six sources are of regulatory character, encompassing national and international standards, reports, and safety guidelines. The remaining twenty publications focus on modeling, analytical techniques, and dose assessment methodologies, providing a technical foundation for the interpretation and comparison of the obtained results.

CONTAMINATION ROUTES IN ANIMALS

Human interaction with the environment continuously reshapes the radiological balance of the biosphere. Agricultural activity, industrial expansion, and atmospheric processes facilitate the redistribution of radionuclides within soil, water, vegetation, and animal organisms. Routine human practices such as phosphate fertilization, metal ore processing, and atmospheric deposition have increased the concentration of radioactive isotopes in environmental matrices and consequently in animal feed and food products (Czarnecki & Düring, 2015). These interactions, though gradual and often imperceptible, determine the long-term exposure of biological systems to ionizing radiation.

Radionuclides travel through multiple environmental pathways, including the atmosphere, hydrosphere, and lithosphere. Once released, they circulate among these media, becoming part of the natural and agricultural cycles. Investigations conducted near uranium tailings in China confirm that both soil and water can retain measurable concentrations of uranium and its decay products, which later migrate through groundwater and irrigation systems into crops and pastureland (Liu et al., 2021). This multi-path transport mechanism increases the likelihood of radioactive transfer from soil to plants, animals, and finally to humans. The continuous redistribution of radionuclides underscores the need for effective strategies to protect food systems from radiological contamination and to mitigate long-term health consequences arising from ingestion of contaminated products.

Both naturally occurring and anthropogenic radionuclides contribute to this complex exposure chain. Their migration into the food cycle depends on their chemical form, solubility, half-life, and environmental conditions. The extent to which radionuclides are incorporated into crops and animal products varies widely across ecosystems and agricultural contexts. These variations are largely governed by the physicochemical properties of each isotope, combined with local soil characteristics, climate, and agricultural practices (Hofmann et al., 2024). Studies encompassing 476 countries compiled by the International Atomic Energy Agency emphasize that approximately ninety percent of the annual effective dose derived from dietary intake is attributable to natural radionuclides from the uranium and thorium decay series (IAEA, 2023). In contrast, man-made radionuclides such as cesium-134, cesium-137, strontium-90, and carbon-14 contribute only around eight percent of total annual dietary exposure.

The environmental persistence of radionuclides such as cesium-137 within aquatic systems highlights another critical dimension of the problem. Due to its solubility and relatively long half-life, this isotope remains active within riverine and marine ecosystems, where it accumulates in sediments and aquatic organisms. Research in Arctic rivers of northwestern Russia has demonstrated measurable concentrations of natural and artificial radionuclides in fish, reflecting both atmospheric deposition and runoff from industrial activities (Puchkov et al., 2023). These findings confirm that radiological contamination is not limited to terrestrial ecosystems but extends through aquatic food webs, demanding effective purification and monitoring strategies.

In livestock production, the persistence of radioactive substances poses a continuous risk since radionuclides remain active for long periods and can move through feed systems, markets, and supply chains before ultimately entering human diets (Mihaljev et al., 2019). Because of this extended persistence, agricultural raw materials used for animal feed require systematic monitoring to prevent radiation exposure and to identify possible contamination arising from both natural and anthropogenic sources (Mihaljev et al., 2019). Special attention is warranted for isotopes formed during nuclear weapons testing, particularly strontium-90, cesium-137, plutonium, and americium, which remain in surface soil layers and can be transferred into crops and animal feed, thereby re-entering the human food chain (Lee & Herrman, 2024; Sorokin et al., 2025).

Livestock can become contaminated through multiple exposure routes, with ingestion representing the predominant pathway. Feed, water, and inhaled air collectively contribute to the accumulation of radioactive isotopes within animal tissues (Carvalho et al., 2006; Casacuberta et al., 2009; Shanthi et al., 2010). Dynamic modeling frameworks, such as ECOSYS-87, have demonstrated that post-accident contamination follows predictable biological kinetics in which radionuclides rapidly integrate into metabolic processes (Obrador et al., 2022). Carvalho et al. showed that radiocesium interferes with potassium uptake in tropical vegetation, indirectly affecting the nutritional composition of feed and increasing isotopic accumulation in animals (Carvalho et al., 2006). Casacuberta et al. (2009) identified significant radioactive content in mineral feed supplements such as dicalcium phosphate, underlining the necessity of regulating phosphate-based additives to reduce internal radiation exposure. Similar analyses by Desideri et al. (2014) confirmed that alpha and gamma spectroscopy are effective for characterizing the radiological profile of animal feed. Recent research in North Macedonia has revealed detectable concentrations of uranium-238, thorium-232, and potassium-40 in commercial poultry feeds, illustrating the ubiquity of natural radioactivity in animal nutrition systems (Angeleska et al., 2022a).

The accumulation of radionuclides within animal organisms is facilitated by biochemical affinity between radioactive and essential elements. Cesium behaves analogously to potassium and therefore integrates into muscle tissue, while strontium substitutes for calcium and becomes embedded in bones and teeth. Through such chemical mimicry, isotopes persist within biological structures long after environmental exposure subsides (Carvalho et al., 2006; Mihaljev et al., 2019). Studies conducted in Texas demonstrated that animal feeds may contain measurable levels of both natural and anthropogenic radionuclides, reinforcing the need for comprehensive monitoring programs and radiological risk assessment in livestock production systems (Lee & Herrman, 2024).

Long-term investigations indicate that radionuclides enter animal metabolism through mineral additives containing phosphate derivatives also (Howard, 2021; Voigt, Howard & Beresford, 2007). Phosphate-based mineral supplements are recognized as significant contributors to the total activity of uranium and thorium series isotopes within animal tissues. Once incorporated, these isotopes migrate through metabolic pathways and accumulate in edible tissues, creating potential sources of exposure for consumers.

Beyond background radiation, animal exposure may occur as a result of nuclear accidents, medical waste mismanagement, or other human technological activities. The expansion of nuclear industries and increased use of radioactive materials over recent decades have intensified environmental concentrations of uranium, cesium, cadmium, and cobalt, affecting both wildlife and livestock (Olobatoke & Mathuthu, 2015; Gagnaire et al., 2011). Because these radionuclides circulate through air, soil, and water, they inevitably reach vegetation and forage, eventually entering the food consumed by humans (Olobatoke & Mathuthu, 2015).

Environmental contamination does not occur instantaneously but follows an ecological rhythm shaped by atmospheric dynamics, agricultural cycles, and biological interactions. Radionuclides inhaled, ingested, or absorbed through skin contact accumulate gradually within organisms, building a complex interplay of internal and external exposure routes (Paiva et al., 2015). Ingestion remains the dominant exposure pathway since food and water are unavoidable necessities linking human physiology to environmental radioactivity. Once incorporated into soft tissues, isotopes alter biochemical equilibrium, and their persistence contributes to cumulative health risks.

Ultimately, radionuclide migration through soil, air, and water reveals a continuous and reciprocal movement between the physical and biological spheres. Animals serve as intermediaries that convert environmental radiation into measurable biological doses, acting as both indicators and transmitters of contamination. This intricate linkage establishes the conceptual foundation for further analysis of natural and anthropogenic contamination in animals and the mechanisms that determine radionuclide accumulation across trophic levels.

From the discussion above, it becomes evident that the routes through which radionuclides enter the organisms of animals are not isolated phenomena but interconnected segments of a unified biogeochemical system linking all environmental media. Inhalation, direct absorption through plant surfaces, deposition of radioactive particles on vegetation and animal tissues, and the ingestion of contaminated plants and water represent the main mechanisms establishing the radiological connection between air, soil, vegetation, and animal organisms.

The inhalation of gaseous radionuclides and fine particulate matter constitutes the fastest route of entry into the organism following radioactive releases. After nuclear incidents, particles enriched with isotopes such as cesium and iodine are deposited in the pulmonary alveoli, from where they are transferred via the bloodstream to other tissues, producing immediate but short-lived radiological stress on biological systems (Obrador et al., 2022).

Radionuclides may also penetrate through the surfaces of plants, particularly when they exist in volatile or gaseous form. Research has shown that radiocesium can be absorbed directly through plant stomata and incorporated into the biochemical matrix of leaves and stems, leading to elevated concentrations of radioactivity in crops later used for livestock feeding (Carvalho et al., 2006). This process highlights the essential mediating role of vegetation between atmospheric deposition and biological assimilation.

Another mechanism involves the deposition of radioactive particles on the outer surfaces of plants and animal bodies. Phosphate-based compounds that often contain traces of uranium and thorium can remain attached to the epidermal layers of plants such as cereal grains and leaves, maintaining measurable activity over extended periods (Casacuberta et al., 2009). When such vegetation is consumed by livestock, the accumulated particles serve as a direct route of radionuclide transfer into the animal system.

During grazing, animals ingest small amounts of contaminated soil adhering to plants, a process that further increases internal exposure. Studies have established that uranium and thorium progenies tend to accumulate within bone and muscular tissues, revealing the biological persistence of these isotopes once they enter the organism (Mihaljev et al., 2019). This transfer connects the geological substrate to the biological metabolism of animals, illustrating how environmental contamination becomes integrated into the food web.

Contaminated water sources represent another major pathway of exposure. Rivers and lakes located near industrial or mining zones frequently contain radioactive isotopes that settle into sediments and enter aquatic organisms. When animals drink from such sources or consume vegetation growing in contaminated wetlands, radionuclides are absorbed and stored within organs characterized by high metabolic activity, such as the liver and mammary glands (Puchkov et al., 2023). Consequently, water functions as a long-term carrier of radioactive elements across ecological systems.

All these exposure routes interact continuously. Radionuclides inhaled, ingested through feed, or absorbed from water tend to accumulate in metabolically active organs, including bones, the liver, and glandular tissues, where their radioactive decay persists for extended periods. This persistence transforms radiological contamination into a gradual and long-lasting process, exerting chronic pressure on biological functions (Desideri et al., 2014).

Understanding and mapping these pathways are crucial for tracing the movement of radionuclides through ecosystems and evaluating the associated radiological risks in livestock production. Their identification provides the analytical foundation for developing preventive strategies that limit radioactive transfer into food of animal origin and safeguard public health.

After identifying the pathways through which radionuclides enter animal organisms, a crucial question arises: how do these substances persist and accumulate within their tissues? This process is not instantaneous but represents a continuous intersection between nature and chemistry. It is within this intersection that the examination of natural and artificial contamination in animals begins, together with the factors influencing their accumulation.

NATURAL AND ARTIFICIAL CONTAMINATION IN ANIMALS AND THE FACTORS INFLUENCING THEIR ACCUMULATION

The intensity of natural radioactivity varies with the geological framework, climatic conditions, and water circulation that shape each ecosystem. Soils rich in phosphate minerals contain higher concentrations of uranium and thorium, resulting in greater levels of radionuclides within plants. When those plants become part of animal nutrition, radioactive isotopes are transferred into their organisms, accumulating in bones, muscles, and mammary glands. In this way, a natural radiological chain emerges, linking soil, vegetation, animals, and humans into a continuous biological network. Radiation within this context is not an external threat but a natural energy sustaining the harmony of living systems.

Alongside these primordial sources, modern civilization has generated artificial pathways of radiation arising from human activity.

Nuclear power production, weapons testing, industrial processes, medical applications, and the widespread use of phosphate fertilizers in agriculture are among the most influential causes of elevated contamination in the environment (Czarnecki & Düring, 2015; USEPA, 2000; Haase, Vagt & Fritsche, 2021). These actions release radionuclides that once had no place in the natural order, disturbing the long-standing balance of radioactivity within the biosphere. Radiation has therefore become both a technological byproduct and a biological challenge that tests the resilience of life itself.

The catastrophe at Chernobyl in 1986 marked a profound turning point in the history of radioactive contamination. Roughly two hundred radionuclides were discharged into the atmosphere, among which iodine-131, cesium-137, and strontium-90 exerted the strongest impact on human and animal health. According to the Federal Committee for Labor, Health and Social Security (1987), about 2.4 percent of all released radionuclides settled within the territory of the former Yugoslavia, illustrating the vast geographical reach of the fallout (Federal Committee for Labor, Health and Social Security,1987).

Artificial radioactivity, however, is not confined to disasters. In agriculture, phosphate fertilizers containing natural traces of uranium and thorium have become a continuous source of radioactive input, gradually transferring activity into soil, plants, and animals (Vassila & Ahmed, 2011). Studies in Germany revealed that long-term fertilizer application significantly elevates radionuclide concentrations compared with untreated soils (Czarnecki & Düring, 2015). Industrial operations that process phosphate rock or burn coal produce residues rich in radioactive minerals that enter farmlands through air and water, becoming embedded in the agricultural cycle and absorbed by livestock feed (USEPA, 2000; Haase, Vagt & Fritsche, 2021). These findings demonstrate that artificial contamination has become intertwined with the very mechanisms of production, not only with catastrophic events.

Radioactive substances, regardless of origin, follow universal physical and biological principles. The route from soil to animals is governed by numerous factors that determine how radionuclides accumulate within living organisms. One such factor is the interception and retention of particles upon plant surfaces. When radionuclides are released into the atmosphere through dust, precipitation, or industrial emissions, they settle upon leaves, stems, and fruits, initiating the first link between contamination and living tissue. Some are washed away by rainfall, yet many remain bound to the surface, where they are absorbed and gradually migrate into internal plant structures. The longer they remain in contact with vegetation, the greater their probability of entering the biological chain and eventually reaching animals. Climatic variables exert a major influence in this process: humidity enhances absorption, whereas arid air and strong winds promote resuspension and redistribution of radioactive particles (Vassila & Ahmed, 2011).

The chemical form of each isotope dictates its mobility and biological accessibility. Soluble compounds pass easily into soil solutions and are taken up by plants, whereas insoluble forms remain fixed within mineral structures or trapped within the digestive systems of animals. When isotopes occur as free ions, they can replace essential elements such as calcium, potassium, and magnesium in metabolic reactions, creating the conditions for persistent retention within tissues and organs. This substitution mechanism explains why cesium-137 and strontium-90 become deeply embedded in muscle and bone, where they can remain for years (Haase, Vagt & Fritsche, 2021).

Processes of fixation within the soil control both the stability and movement of radionuclides across the environment. Soils with high content of clay and organic matter can trap isotopes within their structure, limiting their transfer to plants. In contrast, sandy soils with low organic content permit greater mobility, allowing isotopes to percolate into groundwater, from where they re-enter the biological cycle through irrigation or plant uptake. This phenomenon is especially significant in agricultural landscapes where intensive irrigation accelerates radionuclide migration, particularly in areas heavily treated with mineral fertilizers (Czarnecki & Düring, 2015).

The biological absorption of radionuclides varies among plant species. Leafy plants tend to absorb more through their foliage, cereal crops through their roots, while root vegetables often concentrate higher quantities because their root systems extend deeper into the mineral layers where radionuclides accumulate. This explains why grasses, potatoes, and carrots frequently exhibit greater levels of activity than plants with shorter growth cycles.

Animal nutrition forms another decisive component of the contamination chain. Animals that graze on fresh vegetation or consume forage directly exposed to the open atmosphere ingest more isotopes than those fed with stored or processed feed. Within the digestive system, soluble isotopes pass easily through the intestinal wall into the bloodstream, where they are distributed to organs and incorporated into tissues, whereas insoluble particles are expelled through excretion. Research by (Mihaljev et al., 2019) indicates that roughly seventy percent of ingested cesium-137 is retained within muscle tissue, while strontium-90 accumulates primarily in bones and teeth.

The transfer of radionuclides within animal tissues evolves with time and physiology. Concentrations shift according to species, age, and reproductive condition. In dairy cattle, for instance, isotopes frequently concentrate in the mammary glands, appearing in milk shortly after exposure to contaminated feed (Howard et al., 2021). In meat, the highest levels are found within muscle, while in eggs isotopes distribute differently between yolk and albumen, depending on their solubility and chemical nature.

Contamination within tissues is not a fixed condition but a dynamic balance governed by exposure duration and the organism's capacity for biological elimination. Certain isotopes, such as iodine-131, have short half-lives and decay quickly, whereas others, such as cesium-137 and strontium-90, persist for decades, altering biochemical processes long after their introduction.

Human dietary habits complete this intricate cycle. Through the consumption of animal products, radionuclides return to the human organism, making the consumer the final link in the radiological chain. The origin of food, the degree of its processing, and the patterns of nutrition determine the actual level of exposure. In this way, the entire sequence, beginning with the fine dust rising above the soil and ending with the food placed upon the human table, reflects a continuous flow of energy and matter. The connection between natural and artificial radiation within living systems thus forms the basis for the subsequent examination of the monitoring of food derived from animals and its importance for the protection of public health.

THE IMPORTANCE OF MONITORING ANIMAL-DERIVED FOOD

Monitoring food of animal origin stands at the intersection of science, public welfare, and ecological responsibility. Within the modern framework of food safety, radiological control of such products is not a marginal concern but a defining aspect of how societies protect human health and maintain confidence in the food chain. Animals function as biological intermediaries between the environment and the human population, translating every environmental change into measurable biological signals. Variations in the concentration of radionuclides in soil, water, and vegetation inevitably manifest within their tissues, milk, eggs, meat, and fish. These products therefore serve as living records of the ecosystem's radiological balance and as essential indicators for environmental assessment and public health protection.

Scientific attention in recent decades has converged on the quantification of natural and anthropogenic radionuclides in food, recognizing ingestion as the most direct route through which ionizing radiation reaches the human body (Alsaffar et al., 2015). Reliable assessment of exposure requires detailed measurement of radionuclide activity in market-available animal products and comparison with national consumption data. Such evaluations reveal the true radiological context of a region and provide the basis for establishing reference limits that safeguard consumers. The International Atomic Energy Agency (IAEA, 2023) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000) have issued harmonized methodologies that enable countries to monitor food safety using comparable and transparent standards.

Continuous observation of radiological activity in animal-based food ensures early detection of irregularities within the agricultural cycle. Livestock and aquatic organisms absorb radionuclides through forage, water, or sediments, transferring them into milk, eggs, meat, and fish, which are fundamental components of human nutrition (Angeleska et al., 2022a; El-Araby & Shabaan, 2024). Relatively long-lived isotopes such as cesium-137 and strontium-90 persist within ecosystems for decades, creating cumulative effects that demand sustained vigilance. Monitoring therefore operates not merely as a scientific exercise but as a preventive mechanism that reveals temporal patterns of accumulation and enables proactive management of potential contamination. Modern analytical techniques allow the measurement of these processes without destroying samples or sacrificing animals, transforming radiological surveillance into a humane and precise practice (Haase, Vagt & Fritsche, 2021).

The radionuclides most frequently examined in such programs include the natural isotopes potassium-40, lead-210, radium-226, uranium-238, and thorium-232, together with the artificial isotopes strontium-90, iodine-131, and cesium-137 (Cinelli et al., 2019). Each of these substances follows characteristic biological pathways. Potassium and cesium accumulate readily in muscular tissue, strontium binds to bones and teeth, while iodine concentrates in glandular and reproductive organs. Fish, owing to their aquatic habitat, often display elevated levels of polonium-210 and cesium-137, reflecting the mobility of these isotopes in sedimentary environments. Understanding these pathways clarifies why radiological control cannot be restricted to a single product but must encompass the entire spectrum of animal production.

Across the globe, regulatory authorities have developed norms to ensure minimal human exposure to radioactivity through diet. The United States Food and Drug Administration (FDA, 2020) defines guidance levels for radionuclide concentrations in domestic and imported food to maintain coherence among national and local agencies. Within the European Union, Regulations 852/2004 and 853/2004 outline hygiene rules for products of animal origin, reinforcing the obligation to monitor radioactive content in every stage of production. The Commission Implementing Regulation (EU) 2020/1158 establishes import conditions for food and feed from third countries affected by nuclear incidents, prescribing maximum permissible activities of 370 Bq/kg for milk and dairy products and 600 Bq/kg for other categories. These limits represent internationally accepted thresholds intended to protect consumers from chronic internal exposure.

The system of radiological monitoring extends beyond laboratory measurement; it embodies an institutional framework combining legislation, scientific coordination, and public communication. Through the International Food Safety Authorities Network (INFOSAN, 2011), the World Health Organization facilitates cooperation among national agencies during radiological emergencies. This coordination ensures that analytical data, certification, and trade verification follow unified protocols, preventing misinformation and reinforcing public confidence. The International Atomic Energy Agency (IAEA, 2013a) emphasizes that such transparency is indispensable for maintaining trust during crises and for confirming that marketed products comply with globally recognized safety criteria.

From a public-health perspective, the significance of monitoring animal-derived food lies in its capacity to trace the subtle passage of radiation into biological systems. Radionuclides entering the human diet through milk, eggs, meat, or fish may lead to internal exposure with long-term physiological effects (Howard et al., 2009; UNSCEAR, 2000). Cesium-137 tends to accumulate in soft tissues, strontium-90 integrates into the skeleton, and iodine-131 concentrates in the thyroid gland, forming internal sources of radiation that can disrupt cellular integrity and promote disease. Accurate determination of radionuclide concentrations in animal products therefore serves as an indirect yet powerful indicator of population-level risk, linking agricultural safety with human wellbeing.

The magnitude of these effects depends on the isotope involved, its activity, and the duration of exposure (Olobatoke & Mathuthu, 2015). Persistent accumulation in the organism may generate chronic imbalance, interfere with metabolic stability, and increase the probability of degenerative conditions. Such evidence underscores the necessity of constant surveillance throughout the food chain. Preventive observation functions as the most reliable defense, providing timely insight before contamination reaches levels of medical concern.

Efforts to reduce contamination encompass environmental, agricultural, and dietary strategies. Agricultural soils used for forage cultivation require periodic testing, and if elevated activity is detected, techniques such as deep plowing or the cultivation of species with limited uptake capacity can be applied (Beresford & Howard, 2011). Control over water sources and exclusion of animals from potentially affected zones are equally important.

Feed intended for livestock must undergo thorough laboratory examination to identify and remove any potential sources of radionuclide contamination. The process of selective grazing, combined with a carefully timed slaughter period, allows natural biological mechanisms to reduce the internal burden of radioactive elements in animals. Methods of food preparation such as boiling, fermenting, and controlled processing further decrease radioactive residues by altering the chemical state of isotopes and reducing their persistence in edible tissues. These practices transform theoretical radiological knowledge into tangible measures that protect communities whose nutrition depends on animal-derived products.

In the Republic of North Macedonia, the regulation of such measures is grounded in the Law on Protection from Ionizing Radiation and Radiological Safety, published in the Official Gazette No. 48/2002. This law establishes the institutional framework for oversight, licensing, and coordinated action during radiological events under the supervision of the national Directorate for Radiological Safety. It ensures that research findings, administrative procedures, and practical interventions operate within a coherent and responsive structure dedicated to safeguarding both the population and the environment (Official Gazette, No. 48/2002).

Within this multidimensional system, food monitoring assumes the character of a living process rather than a procedural obligation. Scientific laboratories, public food authorities, and veterinary institutions cooperate in a shared network that preserves the radiological integrity of the products entering the consumer market. The ongoing observation of food from animal sources thus represents a lasting scientific and moral undertaking to uphold the purity of nourishment, linking ecological responsibility, legal order, and human well-being in a continuous cycle of protection and awareness.

Within this intricate network of scientific responsibility and ethical awareness, the research perspective turns toward the origin of food and its connection with the natural environment. The study of radiological safety does not conclude with laboratory measurements but extends to uncovering the ways in which natural isotopes become embedded in biological processes and enter the food chain. From this understanding arises the need to examine how various types of food transfer natural radioactivity from soil, water, and plant life to animals and, indirectly, to humans.

VARIOUS TYPES OF FOOD THAT NATURALLY CONTAIN RADIONUCLIDES THAT ARE TRANSFERRED FROM THE SOIL TO CROPS AND FROM WATER TO FISH

The levels of naturally occurring radionuclides in food and drinking water are generally low and are regarded as safe for human consumption. Their concentration, though, differs among various food categories, depending on the physicochemical properties of soil and water, agricultural conditions, and other environmental influences that determine the transfer of radionuclides from the natural surroundings into agricultural crops and animal-derived products (Touranlou et al., 2024). These fluctuations reveal the importance of maintaining continuous surveillance of radioactivity in food and of cultivating public understanding of the potential health outcomes associated with its presence.

Scientific findings indicate that the ingestion of radiation through food and water does not remain constant but changes in accordance with the geological and biological characteristics of each region. For this reason, the estimation of the annual effective dose received by the population must be approached with precision and care, particularly when assessing products from ruminants that occupy a prominent position in the human diet (Gradaščević et al., 2015).

A variety of analytical methods are employed in the detection and quantification of radionuclides in food and water. Among the most widely used are portable radon detectors, high-purity germanium gamma spectrometry, inductively coupled plasma mass spectrometry (ICP-MS), proportional gas-flow counters, and liquid scintillation counting (LSC). The combined use of gross alpha and beta counting, gamma spectrometry, and scintillation measurements allows for more reliable identification and quantification of radionuclides within analyzed samples (Touranlou et al., 2024).

Gamma spectrometry remains the most frequently applied technique, providing high precision in the determination of radioactivity levels in diverse environmental and food matrices. The subsequent section examines results referring to meat, milk, eggs, and fish, as animal-derived food products through which human radiological exposure can be effectively evaluated.

Meat

Meat and poultry constitute fundamental nutritional resources that support human development and survival (Asghar et al., 2023). Rich in essential nutrients such as proteins, vitamins, and minerals, meat contributes significantly to maintaining physiological balance and overall health (Klurfeld, 2018). Global demand for meat has been increasing steadily, with projections indicating that total consumption will reach approximately 154 million metric tons by 2031, reflecting changes in population dynamics, economic growth, and dietary preferences (Da Silva et al., 2024).

Within the context of radiological studies, the transfer of radionuclides to meat has drawn considerable scientific attention. Empirical data indicate that radionuclide accumulation in muscle tissue often exceeds that observed in milk and other animal products, revealing distinct metabolic pathways and retention rates that depend on animal species, feeding systems, and environmental exposure (Nakov et al., 2016; Howard, 2021) Such findings underscore the need for continuous surveillance of meat products, not only from the standpoint of nutritional quality but also regarding potential radiological safety for human consumption.

Milk

Milk and dairy-based foods represent a fundamental component of human nutrition due to their nutritional richness and their adaptability within daily diets (Sharma et al., 2024; Wei et al., 2025). Beyond being a major source of proteins, fats, and minerals, milk plays a vital role as the primary nourishment for infants and children and as a consistent dietary element for adults (Ali et al., 2020). However, because of its biological composition, milk is particularly susceptible to contamination by both natural and artificial radionuclides such as Cesium-137 and Potassium-40, which are transferred through the grass–cow–milk pathway (Ababneh et al.,2010).

Monitoring the activity levels of radionuclides in both fresh and powdered milk is therefore a key element in assessing the annual effective radiation dose received by populations. Research has demonstrated that the transfer routes from soil to grass and from grass to milk largely determine the degree of radionuclide accumulation in dairy products (Bilgici Cengiz, 2019). Because potassium is highly mobile in the environment, most studies have reported that Potassium-40 is the predominant radionuclide in milk samples. This is due to its natural abundance and essential metabolic role in plants and animals (Zeng & Brown, 2000, Bilgici Cengiz, 2019).

Milk contamination can also occur when cows are kept indoors through the inhalation of airborne radionuclides, the ingestion of contaminated water, or the consumption of tainted feed (Pervin et al., 2024b). Veterinary and sanitary monitoring of milk production and distribution remains a crucial component of ensuring biological quality and protecting consumer health. Studies indicate that Radium-226 tends to accumulate in the lungs and kidneys, Thorium-232 in the liver and skeletal tissues, while Potassium-40 primarily concentrates in muscle tissue. Exposure to these radioactive contaminants may lead to a range of health disorders, including radiation sickness, weakened immunity, and in severe cases, organ failure (Singhal, 2020).

Among all radionuclides, Cesium-134, Cesium-137, Iodine-131, Strontium-89, and Strontium-90 are of greatest concern regarding milk, although they differ in their decay rates (IAEA, 1989). Continuous monitoring of their activity levels provides crucial information for establishing scientifically based assessments of public exposure and radiological safety (Angeleska et al., 2022b).

Eggs

After examining meat and milk as primary vectors through which natural radionuclides may enter the human diet, attention must next be directed toward eggs, which constitute another biologically significant medium in the radiological food chain. Several studies have demonstrated that the transfer of radionuclides into eggs is higher compared to meat, primarily due to the metabolic pathways through which hens accumulate radioactive elements in reproductive tissues (Howard, 2021). The presence of radionuclides in eggs results from the ingestion of contaminated feed, water, or air, with radioactive particles becoming incorporated into the albumen and yolk depending on their chemical composition and solubility.

Ramazanian and Alrefae (2022) report that the activity concentration of 40K in eggs overlaps with its corresponding values in cereals, milk, and palm dates, while being an order of magnitude higher than in seafood. In contrast, the activity concentration of 228Ra in eggs both overlaps with and exceeds its corresponding value in cereal.

These findings emphasize the necessity of continuous monitoring of radionuclide concentrations in eggs, since they, like milk, serve as a direct biological link between soil, vegetation, and humans. Understanding the mechanisms of radionuclide transfer in poultry is crucial not only for assessing potential health risks but also for developing reliable regulatory standards to maintain radiological safety within the food supply system.

Fish

Fish, whether from rivers, lakes, or marine environments, represent a crucial ecological and nutritional component of both natural ecosystems and the human diet. Their biological structure allows them to reflect environmental changes rapidly, making them valuable indicators of contamination. Marine food, including fish, provides essential nutrients such as omega-3 fatty acids, vitamins, and minerals, while also remaining a preferred dietary choice for many populations (FAO, 2020). Monitoring contaminants in fish and seafood is therefore an integral part of global food safety systems (Uzorka et al., 2025). Evaluating radioactivity levels in edible species is particularly important for tracing the transfer of radionuclides from aquatic environments to humans, especially following nuclear accidents such as Chernobyl and Fukushima (Rask et al., 2012; Olurinl., 2024).

Natural and artificial radionuclides in aquatic systems have long been recognized as serious environmental concerns. Their entry routes include groundwater discharge, river inflow, and airborne particle deposition. Radionuclide concentrations in fish depend on absorption through gill and intestinal tissues and on adsorption to the body surface (Carvalho, 2018). Once internalized, radionuclides accumulate in organs and are transferred through the food web. Among them, Radium-226, Thorium-232, and Potassium-40 occur naturally and are commonly introduced into the human body through ingestion (UNSCEAR, 2000).

Polonium-210 and Cesium-137 are particularly significant for assessing radiation exposure through seafood. Polonium-210 contributes the highest internal dose from marine food consumption, while Cesium-137, originating from atmospheric nuclear testing, accumulates in fish muscle because of its similarity to potassium (Saito et al., 2020). Although the contamination of river fish tends to decline faster due to continuous water flow, cesium levels in lake and marine species remain elevated for years, as confirmed after the Chernobyl and Fukushima events (Rask et al., 2012).

Cesium remains the most hazardous radionuclide for human health, capable of long-term persistence in aquatic systems and even distribution in soft tissues once ingested (Smith et al., 2002). Strontium-90 behaves similarly to calcium, accumulating in bones and fins, thus posing additional risks. Despite localized contamination, the overall levels of radioactivity in fish remain generally low, largely due to dilution processes in open waters. Nonetheless, ongoing international monitoring and strict regulatory standards remain essential for ensuring public safety (European Commission, 2023).

COMPARATIVE ANALYSIS

The comparative framework emerging from this study reveals a clear radiological symmetry between North Macedonia and the broader Southeastern European region, contrasted with the markedly lower radionuclide concentrations observed in Western and Northern Europe. The measured activity levels of radium-226 and thorium-232 in Macedonian animal products align closely with those recorded in Turkey and Serbia (Bilgici Cengiz, 2019), reflecting a shared geological foundation characterized by uranium-bearing sediments and limestone formations. In contrast, the lower values reported in Germany, France, and the Netherlands (BfS, 2003; Tanzi & Knetsch, 2021) correspond to more stable soil geochemistry and stricter regulation of livestock feeding systems, which minimize radionuclide uptake.

Potassium-40, the most ubiquitous natural isotope, demonstrates remarkable consistency across all examined countries, yet its biological distribution varies significantly depending on animal diet and farming systems. In Macedonia, the values measured in meat and milk are comparable to those reported in southern Italy and Spain (Desideri et al., 2014), regions sharing similar agroecological conditions where livestock graze on potassium-rich pastures. In Northern Europe, where controlled feeding practices prevail and grazing exposure is limited, the concentrations of potassium-40 tend to be lower, suggesting that the mobility of this radionuclide is directly governed by pastoral intensity and soil mineral content.

When the anthropogenic isotopes cesium-137 and strontium-90 are considered, a pronounced regional differentiation emerges. In Macedonia, the activity levels of these isotopes remain lower than those documented in Poland, Germany, and Ukraine (Pietrzak-Flis et al., 2001; BfS, 2003), countries that experienced heavier fallout deposition following the Chernobyl accident. This finding confirms that geographic distance and prevailing air circulation patterns acted as natural barriers reducing cesium contamination in the Balkans. However, the gradual decline of cesium concentrations observed in Macedonian milk and aquatic samples mirrors long-term bioreduction trends documented in Finland and Norway (Rask et al., 2012; Heldal et al., 2019), indicating a shared pattern of ecological stabilization through natural dilution and biological turnover.

A particularly strong correlation is observed between Macedonian and Italian milk products, both exhibiting comparable ratios of radium-226 to potassium-40 (Desideri et al., 2014; Angeleska et al., 2022b). This parallel likely arises from similar mineralogical soil profiles and Mediterranean-type climatic influences, which facilitate the cycling of radionuclides through the plant–animal–human chain. Conversely, fish species analyzed in Macedonian aquatic environments showed lower overall radioactivity than those reported in Portugal and Japan (Carvalho, 2018; Saito et al., 2020), suggesting reduced radionuclide transfer from sediments and limited accumulation in trophic networks due to the lower salinity and closed-basin hydrology of regional lakes.

Viewed comparatively, the radiological values in Macedonian animal products fall within the same safety range as those in most European Union member states, confirming that the country's agroecosystems remain radiologically balanced. Southern European nations tend to exhibit slightly elevated levels due to their geological and climatic context, whereas Northern Europe benefits from lower soil permeability and higher technological control of feed sources. This cross-country synthesis demonstrates that regional variations in natural radioactivity are not anomalies but reflections of each ecosystem's inherent mineral and biological equilibrium.

The comparative evidence therefore underscores that the radiological safety of animal-based foods in North Macedonia is consistent with European standards and that the spatial variations in radionuclide levels primarily reflect natural geochemical diversity rather than anthropogenic influence. The findings highlight the necessity of maintaining a harmonized regional monitoring system that integrates environmental, agricultural, and health data to ensure long-term comparability and to safeguard public well-being within the continuum of ecological and radiological processes. The following table presents a tabular overview.

Table 1. Comparative analysis of radionuclide distribution in animal-based foods across Europe and neighboring regions (The table provides a comparative summary of the study's overall findings).

Region / Country	Type of Radionuclides	Radiological Status	Key Characteristics	Comparative Trend	References
North Macedonia	Natural and traces of artificial	Balanced levels of Ra-226, Th-232, and 40K; low traces of Cs-137 and Sr-90	Geochemically and biologically stable envi-ronment with moderate transfer through livestock chain	Within EU radiological safety standards; close values to Turkey and Serbia	Angeleska et al. (2022a);
Turkey	Natural	Moderate presence of natural isotopes; low anthropogenic contamination	Balkan geology with uranium and limestone formations	Similar radiological profile to North Macedonia	Bilgici Cengiz (2019);
Serbia	Natural	Moderate presence of natural isotopes; low anthropogenic contamination	Balkan geology with uranium and limestone formations	Similar radiological profile to North Macedonia	Vitorovic et al. (2009)
Italy	Natural	Higher 40K levels due to pasture systems and potassium-rich soils	Mediterranean agroecological conditions and open grazing fields	Similar natural radioactivity to North Macedonia	Desideri et al. (2014);
Spain	Natural	Higher 40K levels due to pasture systems and potassium-rich soils	Mediterranean agroecological conditions and open grazing fields	Similar natural radioactivity to North Macedonia	Hernández et al. (2004)
Germany	Natural and minimal artificial	Low levels of all radionuclides; limited Cs-137 transfer	Strict livestock feeding regulations and stable soil geochemistry	Lowest radiological levels in Europe	BfS (2003);
France	Natural and minimal artificial	Low levels of all radionuclides; limited Cs-137 transfer	Strict livestock feeding regulations and stable soil geochemistry	Lowest radiological levels in Europe	Renaud et al. (2015);
Netherlands	Natural and minimal artificial	Low levels of all radionuclides; limited Cs-137 transfer	Strict livestock feeding regulations and stable soil geochemistry	Lowest radiological levels in Europe	Tanzi & Knetsch (2021)
Poland &	Artificial	Higher Cs-137 and Sr-90 concentrations due to Chernobyl legacy	Fallout contamination affecting soil and animal feed	Higher than North Macedonia but gradually declining	Pietrzak-Flis et al. (2001)

Portugal	Artificial	Higher 210Po:210Pb ratio in the diet in comparison with other countries	Food Contamination, Radioactive; Human; Lead Radioisotopes; Plants, Plutonium; Seafood;		Carvalho (1995)
Finland &	Natural with long-term Cs-137 traces	Radiologically stable ecosystems; minimal residual Cs-137 due to cold climate and slow biodegradation	Biologically self-regulating systems with natural radionuclide reduction	Full ecological stability and safety	Rask et al. (2012)
Norway	Natural with long-term Cs-137 traces	Radiologically stable ecosystems; minimal residual Cs-137 due to cold climate and slow biodegradation	Biologically self-regulating systems with natural radionuclide reduction	Full ecological stability and safety	Heldal et al. (2019)

CONCLUDING REMARKS

This study demonstrates that the concentrations of radionuclides found in animal-based foods in North Macedonia are low and fall well within internationally approved safety thresholds. The overall radiological profile of these products aligns with observations across Southeastern Europe, confirming a stable and balanced agroecosystem. Naturally occurring isotopes such as radium-226, thorium-232 and potassium-40 were predominant, while artificial radionuclides like strontium-90 and cesium-137 were detected only in minimal amounts. These results suggest that present agricultural and environmental management effectively restrict radioactive transfer through the food chain. Ongoing, standardized monitoring is therefore vital for timely identification of potential changes. Continued scientific supervision will help protect consumer health, ensure environmental sustainability, and preserve confidence in the safety of food supplies.

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ПРИСУСТВО НА РАДИОНУКЛИДИ ВО СИНЏИРОТ НА ХРАНА: ФОКУС НА ХРАНА ОД ЖИВОТИНСКО ПОТЕКЛО

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Резиме

Трудот претставува аналитички преглед на појавата, движењето и акумулацијата на природните и антропогените радионуклиди во храната од животинско потекло. Истражувањето ги опфаќа главните патишта преку кои овие супстанции навлегуваат во животинските организми, како и еколошките и земјоделските фактори што влијаат врз нивната распределба во почвата, растителната биомаса и животинските ткива како месо, млеко, јајца и риби. Во трудот се разгледуваат изотопите ураниум-238, ториум-232, калиум-40, цезиум-137 и стронциум-90, кои се издвојуваат како главни показатели за природното и технолошки предизвиканото радиоактивно присуство во биосферата. Анализата ја открива меѓусебната поврзаност меѓу геолошките, климатските и земјоделските услови што го определуваат нивото и варијабилноста на радионуклидите во храната од животинско потекло. Констатирано е дека концентрациите на радионуклиди во Северна Македонија се движат во рамките на меѓународно прифатените граници и се совпаѓаат со вредностите утврдени во други европски земји. Трудот ја нагласува неопходноста од континуирано следење на природните и антропогените извори на радиоактивност со цел навремено откривање на промени во радиолошката рамнотежа и обезбедување долгорочна безбедност на храната и заштита на јавното здравје.

Клучни зборови: *радионуклиди, природни и антропогени извори, храна од животинско потекло, радиоактивност, радиолошка безбедност.*