

# Naturally Occurring Radionuclides in Mineral Waters: Sources, Geochemical Controls, Distribution, and Radiological Dose Assessment

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## Abstract

Natural ionizing radiation is an inherent component of the Earth's environment, continuously present in geological, hydrological, and atmospheric systems. Mineral waters, sourced from deep geological formations, may accumulate naturally occurring radionuclides (NORM) including uranium-238, uranium-234, thorium-232, radium-226, radium-228, radon-222, and potassium-40 as a consequence of sustained water-rock interactions. These radionuclides contribute to internal radiation exposure of the human population primarily through ingestion pathways, with additional concerns related to inhalation of radon-enriched water vapors.

This comprehensive review synthesizes the current state of knowledge regarding the geological origin of natural radioactivity in mineral waters, the geochemical mechanisms governing radionuclide mobilization and transport in groundwater systems, methods for radiological dose assessment, and the associated public health implications. Special emphasis is placed on lithological controls, hydrogeochemical speciation, and the influence of redox conditions on radionuclide behavior. Findings from global case studies are examined to illustrate the range of radionuclide concentrations encountered across different geological settings.

The evidence indicates that radionuclide concentrations vary by several orders of magnitude depending on geological structure, water-rock contact time, pH, redox potential, and hydrochemical conditions. While most mineral waters remain within WHO and IAEA recommended guidance levels, elevated concentrations have been documented in granitic terrain aquifers in Scandinavia, Portugal, parts of Turkey, and certain geothermal regions. Continuous radiological monitoring, integrated hydrogeochemical modeling, and refined dose estimation frameworks are essential for ensuring long-term public health safety.

**Keywords:** Naturally occurring radionuclides, Mineral water, Uranium, Radium, Radon, Groundwater geochemistry, Dose assessment, Radiation protection, NORM

## Introduction

Ionizing radiation is a fundamental feature of the natural environment, arising from primordial radionuclides embedded in the Earth's crust since planetary formation, as well as from cosmogenic processes driven by interactions between cosmic rays and atmospheric gases. Humans are continuously exposed to natural background radiation through external exposure from terrestrial and cosmic sources, as well as internal exposure via inhalation and ingestion of naturally occurring radioactive materials.<sup>1</sup>

Among the various environmental pathways of internal exposure, drinking water-and particularly mineral water derived from deep geological formations-represents an important but often underestimated route for radionuclide ingestion. Unlike surface

waters, groundwater and mineral waters may undergo prolonged contact with uranium- and thorium-bearing geological formations, facilitating the dissolution and mobilization of radionuclides into solution. The resulting activity concentrations depend on a complex interplay of lithological, hydrogeochemical, and hydrodynamic factors.<sup>2</sup>

Mineral waters are legally defined in many jurisdictions as waters of underground origin, protected from contamination, and characterized by stable physicochemical composition. Their unique geochemical properties-arising from deep circulation pathways and extensive mineral dissolution-render them particularly susceptible to elevated radionuclide concentrations relative to surface-derived drinking waters.<sup>3</sup> This has attracted significant scientific and regulatory attention, particularly in the context of bottled mineral

Quick Response Code:



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**Received:** 15 May 2026

**Published:** 26 May 2026

**Citation:** Nina TUNÇEL. Naturally Occurring Radionuclides in Mineral Waters: Sources, Geochemical Controls, Distribution, and Radiological Dose Assessment: Review Article. *Glob Scient Res Env Sci.* 2026;6(1):1-10. DOI: [10.53902/GSRES.2026.06.000542](https://doi.org/10.53902/GSRES.2026.06.000542)

water consumption, which has increased substantially worldwide in recent decades.

The principal radionuclides of concern in mineral waters belong to the uranium-238 ( $^{238}\text{U}$ ) decay series, the thorium-232 ( $^{232}\text{Th}$ ) decay series, and include the naturally occurring isotope potassium-40 ( $^{40}\text{K}$ ). Within these decay chains, radium isotopes (Ra-226 and Ra-228) and radon-222 are considered the most radiologically significant due to their elevated radiotoxicity, mobility in groundwater, and distinct biological behavior upon ingestion or inhalation.<sup>4</sup>

Despite a growing body of literature on radionuclide concentrations in groundwater and bottled mineral waters, significant knowledge gaps persist with respect to the mechanistic understanding of radionuclide mobilization under varying geochemical conditions, the influence of seasonal hydrological dynamics, and the cumulative radiological risk from chronic low-level exposure. Furthermore, methodological inconsistencies across national and international monitoring programs hinder meaningful cross-regional comparisons.

This review aims to: (i) provide a comprehensive account of the geological and geochemical origins of natural radioactivity in mineral waters; (ii) describe the mechanisms governing radionuclide distribution and speciation in groundwater systems; (iii) summarize radiological dose assessment methodologies and their application to mineral water consumption scenarios; and (iv) evaluate the associated health implications in light of current regulatory frameworks. The review draws on published case studies from multiple geological environments and discusses future research priorities.

## Geological and Geochemical Origins of Natural Radioactivity

### Primordial radionuclides and decay series

The fundamental source of natural radioactivity in the terrestrial environment is the inventory of primordial radionuclides that were incorporated into the Earth's crust during accretion from the proto-solar nebula approximately 4.5 billion years ago. Among these, three decay series are of primary relevance to groundwater radioactivity: the uranium-238 series (producing Ra-226 and Rn-222 among others), the thorium-232 series (producing Ra-228 and Ra-224), and the uranium-235 series (of minor significance in groundwater contexts due to its low natural abundance of ~0.72%). Additionally, potassium-40, a monoisotopic primordial radionuclide, constitutes approximately 0.0117% of natural potassium and contributes significantly to the radiation dose from drinking water through its beta and gamma emissions.<sup>5</sup>

The uranium-238 decay series comprises 14 successive radioactive decay steps, terminating in stable lead-206 ( $^{206}\text{Pb}$ ), with a total energy release of approximately 47.4 MeV. Key

intermediate daughters include thorium-234, protactinium-234m, uranium-234, thorium-230, radium-226, radon-222, and a series of short-lived polonium and bismuth isotopes. Of these, uranium-234 and uranium-238 are the primary aqueous uranium species, while radium-226 and radon-222 are the most significant in terms of groundwater contamination and radiological dose.<sup>6</sup>

The thorium-232 series produces radium-228 and radium-224 as key groundwater-relevant daughters. Thorium itself is highly insoluble under most geochemical conditions and is rarely mobilized in groundwater; however, its soluble daughter products, particularly Ra-228 (half-life: 5.75 years), can accumulate in aquifers with sufficient residence time. The half-life ratio between Ra-228 and Ra-226 in mineral waters serves as a useful geochemical tracer of relative contributions from the two-decay series.<sup>7</sup>

Secular equilibrium—the condition under which the activity of each daughter nuclide equals that of its parent—is rarely achieved in groundwater systems due to the differential geochemical mobility of successive decay products. The preferential leaching of uranium from rock matrices, the adsorption of thorium onto mineral surfaces, and the high mobility of radium and radon all contribute to a disequilibrium state that is characteristic of natural groundwaters.<sup>8</sup> Understanding and quantifying this disequilibrium is fundamental to interpreting radionuclide activity ratios measured in mineral waters.

### Lithological controls on uranium and thorium content

The abundance of uranium and thorium in crustal rocks varies considerably across geological units and is the primary determinant of radionuclide loading in groundwater systems. Granitic and felsic igneous rocks represent the highest natural uranium concentrations, typically ranging from 3 to 10  $\mu\text{g/g}$ , with uranium-rich granites (e.g., those of the Variscan belt in Europe or the Precambrian shield in Canada) reaching values exceeding 30  $\mu\text{g/g}$ .<sup>9</sup> By contrast, mafic and ultramafic rocks (basalts, gabbros, peridotites) contain much lower uranium concentrations, typically below 1  $\mu\text{g/g}$ , resulting in groundwaters with correspondingly lower activity concentrations.

Uranium in granitic rocks is hosted primarily in accessory minerals such as zircon ( $\text{ZrSiO}_4$ ), monazite  $((\text{Ce,La,Nd,Th})\text{PO}_4)$ , uraninite ( $\text{UO}_2$ ), and apatite ( $\text{Ca}_5(\text{PO}_4)_3(\text{OH,F,Cl})$ ). The distribution of uranium between these mineral phases influences its geochemical availability: uranium occluded within resistant zircon grains is largely unavailable for dissolution, whereas uranium adsorbed onto grain boundaries, oxide coatings, or secondary mineral phases is more readily mobilized upon water–rock contact.<sup>10</sup>

Sedimentary environments can also contribute elevated radionuclide concentrations to groundwater, particularly in phosphorite-bearing sequences, organic-rich shales, and carbonate formations. Phosphate minerals exhibit a strong geochemical affinity for uranium due to ionic radius and charge similarities,

and phosphate-rich aquifer systems can yield groundwaters with uranium concentrations in excess of 100 µg/L.<sup>11</sup> Evaporite sequences and calcareous formations, while lower in uranium content, may influence radionuclide behavior through their control on pH, ionic strength, and carbonate chemistry.

Volcanic and geothermal regions constitute unique geological environments for the mobilization and enrichment of naturally occurring radionuclides. Hydrothermal systems associated with volcanic activity facilitate the transport of uranium-, radium-, and radon-bearing fluids through intense water–rock interaction and elevated geothermal gradients. These processes may lead to anomalously high radionuclide activity concentrations in geothermal and mineral waters. Elevated levels of radon and radium have been reported in geothermal spring waters from volcanically active regions including Iceland, the Azores, Spain, and Anatolia in Türkiye.<sup>12-14</sup>

Metamorphic rocks, particularly those derived from granitic or pelitic precursors, retain much of their original uranium and thorium inventory and may exhibit elevated radionuclide concentrations in associated groundwaters. Gneisses, migmatites, and amphibolites developed from uranium-rich protoliths are commonly associated with elevated groundwater uranium activities, especially where tectonic deformation has increased fracture permeability and water–rock contact surface area.

### Hydrogeochemical mechanisms of radionuclide mobilization

The release of radionuclides from geological matrices into groundwater is governed by a suite of coupled hydrogeochemical processes. Alpha recoil—the physical displacement of a daughter nuclide into the surrounding pore fluid as a result of the kinetic energy imparted by alpha decay—is a particularly important mechanism for the preferential release of short-lived daughters such as Ra-226 and U-234 into solution. The U-234/U-238 activity ratio in groundwater, which frequently exceeds unity and can reach values of 10 or more in older groundwaters, reflects this alpha-recoil enrichment of U-234 relative to its parent.<sup>8</sup>

Oxidation–reduction (redox) potential is arguably the most important geochemical variable controlling uranium mobility in groundwater. Uranium occurs in two principal oxidation states in nature: U(IV), which is highly insoluble and tends to precipitate as uraninite or adsorb strongly to mineral surfaces, and U(VI), which forms soluble complexes, particularly with carbonate, phosphate, and fluoride ligands. Under oxidizing conditions, the uranyl ion (UO<sub>2</sub><sup>2+</sup>) is the dominant aqueous species, and its interaction with dissolved carbonate (HCO<sub>3</sub><sup>-</sup>, CO<sub>3</sub><sup>2-</sup>) leads to the formation of highly stable and mobile uranyl carbonate complexes such as UO<sub>2</sub>(CO<sub>3</sub>)<sub>2</sub><sup>2-</sup> and UO<sub>2</sub>(CO<sub>3</sub>)<sub>3</sub><sup>4-</sup>.<sup>15</sup> This explains the observation that mineral waters with elevated alkalinity and dissolved CO<sub>2</sub> frequently exhibit higher uranium concentrations.

Radium geochemistry contrasts markedly with that of uranium. Radium (Ra<sup>2+</sup>) behaves as a divalent alkaline earth element, exhibiting geochemical behavior broadly similar to barium and strontium. It does not form strong aqueous complexes with carbonate or other common ligands and is relatively unaffected by redox conditions in groundwater. Radium mobility is controlled primarily by adsorption–desorption reactions on mineral surfaces (particularly manganese and iron oxyhydroxides), co-precipitation with barite (BaSO<sub>4</sub>), and ionic exchange with clay minerals. Under reducing conditions, the dissolution of iron and manganese oxyhydroxides releases adsorbed radium into solution, explaining the commonly observed inverse relationship between redox potential and radium concentrations in deep, reducing aquifers.<sup>16</sup>

Radon-222 is produced continuously by the radioactive decay of Ra-226 within rock matrices and pore fluids. Being a chemically inert noble gas, radon does not interact with mineral surfaces and is therefore highly mobile in groundwater once it escapes the crystal lattice by alpha recoil or direct emanation. Radon concentrations in groundwater are thus a function of the radium content of the aquifer matrix, the emanation coefficient of the host rock (typically 10–30% for granite), and the water–rock surface area to volume ratio.<sup>17</sup> Deep, slowly circulating groundwaters in granitic terrain can accumulate very high radon activities, sometimes exceeding 100,000 Bq/L, which can degas rapidly upon water extraction and represent an inhalation hazard.

Additional geochemical factors influencing radionuclide mobilization include pH (which affects surface charge and adsorption behavior), ionic strength (which influences competitive adsorption of major cations), temperature (which affects reaction kinetics and mineral solubility), and the presence of natural organic matter (which can form complexes with uranium and enhance its mobility). The integrated effect of these variables makes radionuclide behavior in natural groundwater systems highly site-specific and challenging to predict without detailed geochemical characterization.

### Aquifer residence time and water–rock interaction

The duration of water–rock contact is a critical determinant of radionuclide accumulation in groundwater. Confined aquifer systems with long hydraulic residence times (decades to millennia) generally exhibit higher radionuclide concentrations than shallow, unconfined aquifers with rapid recharge and short water–rock contact times. Isotopic dating of groundwater using tritium (<sup>3</sup>H), carbon-14, chlorine-36, or helium isotopes provides essential information on residence time and its relationship to radionuclide loading.<sup>18</sup>

In karstic limestone and dolomite aquifers, rapid conduit flow limits water–rock contact time despite deep circulation, often resulting in lower radionuclide concentrations than might be expected from the geological setting. Conversely, matrix

flow through fine-grained porous media in sedimentary basins promotes prolonged contact and higher dissolution of reactive mineral phases. Fractured crystalline rock aquifers represent an intermediate case, with flow occurring preferentially along fracture networks but with significant matrix diffusion into the surrounding rock mass that can extend effective contact times considerably.

## Distribution of Radionuclides in Mineral Water Systems

### Global and regional occurrence patterns

Published data on radionuclide concentrations in mineral waters span several orders of magnitude, reflecting the wide diversity of geological settings from which mineral waters are sourced. A synthesis of literature data indicates that uranium concentrations in mineral waters globally range from below 0.001 µg/L in waters from mafic geological environments to over 500 µg/L in waters from uranium-rich granitic or phosphate-bearing formations. The World Health Organization (WHO) guideline value for uranium in drinking water is 30 µg/L, a value based on chemical toxicity (nephrotoxicity) rather than radiological risk.<sup>4</sup>

Radium-226 activity concentrations in mineral waters typically range from 0.001 to 1 Bq/L in most geological settings, though values exceeding 10 Bq/L occur in deep saline aquifers, geothermal systems, and oil-field brines. Elevated Radium-228 concentrations are frequently documented in groundwaters underlain by thorium-rich granites; consequently, the Ra-228/Ra-226 activity ratio serves as a diagnostic tool to evaluate the relative contributions of the uranium and thorium decay chains. Furthermore, Radon-222 activities in groundwater and mineral waters span the widest range of any naturally occurring radionuclide, varying from near-zero in surface-influenced waters to several hundred thousand becquerels per litre (Bq/L) within confined crystalline rock aquifers.<sup>19</sup>

Regional surveys from across Europe have documented elevated radionuclide concentrations in mineral waters from the Iberian Peninsula (particularly Portugal and Galicia, Spain), Scandinavia, the Czech Republic, and parts of Germany—all regions underlain by Variscan-age granites with elevated uranium contents. In Turkey, Altikulaç et al. reported significant variability in uranium and radium activities in bottled mineral waters, with some samples exceeding WHO guidance levels.<sup>20</sup> Similar variability has been documented in Brazil,<sup>21</sup> and other regions of the world.

### Uranium speciation and mobility

In natural groundwaters at near-neutral to alkaline pH, uranium is predominantly present as uranyl carbonate or bicarbonate complexes. The speciation of dissolved uranium is sensitive to pH, dissolved inorganic carbon concentration, and ionic composition. Geochemical modeling using equilibrium speciation codes such as PHREEQC or MINTEQA2 can predict the dominant uranium species under defined hydrochemical conditions and assess the likelihood of uraninite or schoepite precipitation.<sup>22</sup>

Under reducing conditions, particularly in the presence of sulfide or organic matter, U(VI) can be reduced to U(IV) and precipitate, effectively removing uranium from solution. This reductive immobilization is the basis for roll-front uranium ore deposit formation in sedimentary basins and is also observed in anoxic groundwater systems. The oxidation state of iron (Fe<sup>2+</sup> vs. Fe<sup>3+</sup>) is closely linked to uranium mobility through both direct redox coupling and indirect effects on mineral surface charge and composition.

### Radium behavior and mobility

The geochemical behavior of radium in groundwater is strongly influenced by the presence of competing divalent cations (Ba<sup>2+</sup>, Sr<sup>2+</sup>, Ca<sup>2+</sup>) and by the abundance and reactivity of sorbing mineral phases. Manganese and iron oxyhydroxides are particularly effective radium sorbents due to their high surface area and negative surface charge at circumneutral pH. In reducing groundwater environments where these phases dissolve, radium is released concurrently with iron and manganese—a process that creates a characteristic geochemical signature useful for identifying radium-rich groundwaters.

Co-precipitation of radium with barite (BaSO<sub>4</sub>) and celestine (SrSO<sub>4</sub>) can significantly reduce dissolved radium concentrations in sulfate-rich groundwaters. Conversely, dissolution of barite scales or evaporite-derived sulfate can release previously co-precipitated radium into solution. The competition between radium sorption, co-precipitation, and aqueous complexation controls the ultimately observed activity concentration in mineral waters.<sup>23</sup>

### Radon distribution and emanation

Radon-222 is produced in the pore space and fractures of aquifer materials by the decay of Ra-226 associated with mineral surfaces. The fraction of radon that escapes from the solid matrix into pore water—the emanation coefficient—depends on grain size, porosity, and the location of Ra-226 within the crystal lattice. Fine-grained, highly porous materials with high surface area-to-volume ratios exhibit higher emanation coefficients than coarse-grained, low-porosity crystalline rocks.

Once in solution, radon accumulates to a steady-state activity determined by the balance between production from Ra-226 decay and loss through radioactive decay, diffusion, and advective transport. The very short half-life of Rn-222 (3.82 days) means that radon concentrations reflect recent equilibration conditions and are sensitive indicators of local Ra-226 abundance and water circulation dynamics. High radon activities in mineral waters are often observed in geothermal systems, where elevated temperatures enhance rock–water interaction and promote radon emanation.

### Potassium-40 in mineral waters

Potassium-40 is ubiquitous in natural waters, reflecting the abundance of potassium in crustal minerals such as feldspars and

micas. In mineral waters, K-40 activity concentrations are typically proportional to total dissolved potassium, with typical activities ranging from a few to several tens of Bq/L in potassium-rich mineral waters. While K-40 contributes to the ingestion dose from mineral water, it is generally considered less radiologically significant than radium isotopes due to its lower dose conversion factor.<sup>24</sup>

### Seasonal and temporal variability

Radionuclide concentrations in mineral water sources are not static but may exhibit seasonal and longer-term temporal variability driven by changes in recharge rate, groundwater level fluctuations, redox oscillations at the water table, and mixing between groundwater of different ages and compositions. During high-recharge periods, dilution effects can reduce radionuclide concentrations in some aquifer systems, while in others, increased hydraulic gradients may flush more reducing radionuclide-rich water from deep zones toward extraction points.

Long-term monitoring data from several European and North American sites have revealed multi-year trends in groundwater radionuclide concentrations linked to aquifer exploitation patterns, land-use changes, and climate variability. Understanding these dynamics is essential for risk characterization and for establishing appropriate monitoring frequencies in regulatory compliance programs.<sup>7</sup>

## Radiological Dose Assessment from Mineral Water

### Consumption

#### Exposure pathways and routes

The radiological significance of naturally occurring radionuclides in mineral waters arises primarily from the ingestion pathway, through which dissolved radionuclides are absorbed from the gastrointestinal tract and distributed to target tissues. A secondary, but potentially significant, exposure route is the inhalation of radon gas released from mineral water during domestic use (showering, bathing, and boiling), particularly in poorly ventilated spaces. External exposure from radionuclides in water is negligible by comparison.

The gastrointestinal absorption fraction ( $f_1$  value) for ingested radionuclides varies considerably by element and chemical form. For soluble uranium compounds,  $f_1$  is approximately 0.02 (2% of ingested uranium is absorbed). Radium behaves analogously to calcium and strontium, with  $f_1$  values of approximately 0.2 (20% absorbed). Lead and polonium isotopes, which appear as daughters in the uranium decay chain, have  $f_1$  values of 0.2 and 0.1, respectively. These absorption fractions are fundamental inputs to internal dosimetry models.<sup>24</sup>

#### Dose calculation methodology

The committed effective dose from ingestion of a single radionuclide is calculated according to the formulation

recommended by the International Commission on Radiological Protection (ICRP):

$$E = C_i \times V \times e(g)_i$$

where  $E$  is the committed effective dose (Sv/year),  $C_i$  is the activity concentration of radionuclide  $i$  in water (Bq/L),  $V$  is the annual volume of water consumed (L/year), and  $e(g)_i$  is the age-weighted dose coefficient for ingestion of radionuclide  $i$  (Sv/Bq). The total dose from multiple radionuclides is the arithmetic sum over all contributing species:

$$E_{\text{total}} = \sum_i (C_i \times V \times e(g)_i)$$

The WHO reference dose level for drinking water is 0.1 mSv/year (100  $\mu$ Sv/year), corresponding to an acceptable annual intake that accounts for all radionuclides combined.<sup>4</sup> The Atomic Energy Agency (IAEA) Safety Standards series (SSG-3)<sup>25</sup> provides detailed methodological guidance on screening and monitoring approaches for radionuclides in drinking water.

Dose coefficients ( $e(g)$ ) used in these calculations are derived from biokinetic models that account for the absorption, distribution, retention, and excretion of radionuclides in the human body following ingestion. Published ICRP dose coefficients for adults range from approximately  $2.8 \times 10^{-12}$  Sv/Bq for K-40 to  $6.9 \times 10^{-7}$  Sv/Bq for Ra-228, reflecting the vastly different radiotoxicities of these nuclides.<sup>24</sup>

#### Dose contribution by radionuclide

Among the naturally occurring radionuclides found in mineral waters, radium isotopes (Ra-226 and Ra-228) consistently emerge as the dominant contributors to ingestion dose, reflecting their high dose coefficients, significant bone-seeking behavior, and long biological retention. Radium, following absorption from the gut, is distributed to bone surfaces where it undergoes long-term retention, irradiating bone marrow and endosteal cells with alpha and beta particles from its decay progeny. The effective half-life of radium in bone is on the order of decades, making chronic ingestion exposure particularly significant from a cumulative dose perspective.

Uranium isotopes (U-238 and U-234) contribute to ingestion dose primarily at sites with elevated uranium in groundwater, but their lower dose coefficients relative to radium mean that uranium is typically a secondary contributor to total dose in most mineral waters. However, the chemical nephrotoxicity of uranium must be considered alongside its radiological effects, particularly where uranium concentrations approach or exceed the WHO guideline value of 30  $\mu$ g/L.

Radon-222, despite its very high activity in some mineral waters, contributes relatively little to ingestion dose because of its rapid exhalation from the body following ingestion. The primary radon exposure concern is via inhalation of radon released from mineral water during household activities, which is addressed

through separate inhalation dose assessments using air exchange rates and water usage patterns as input parameters.<sup>26</sup>

### Uncertainty and sensitivity analysis

Radiological dose assessments for mineral water consumption are subject to multiple sources of uncertainty, including spatial and temporal variability in radionuclide concentrations, uncertainty in dose coefficients (particularly for children and radiosensitive populations), variability in individual water consumption rates, and uncertainty in gastrointestinal absorption fractions. Monte Carlo simulation methods can be used to propagate these uncertainties through dose calculations and derive probabilistic dose distributions rather than single point estimates.<sup>27</sup>

Sensitivity analyses consistently identify the activity concentration of Ra-226 and Ra-228 as the parameters with the greatest influence on total estimated dose from mineral water, followed by the dose coefficient for Ra-228 and the assumed annual water consumption rate. This highlights the critical importance of accurate radium measurements in monitoring programs and the need for inter-laboratory calibration and standardization.

### Regulatory frameworks and guidance levels

International guidance on radionuclide concentrations in drinking water is provided primarily by the World Health Organization through its Guidelines for Drinking-water Quality and by the International Atomic Energy Agency through its Safety Standards series. The WHO reference dose level of 0.1 mSv/year serves as the basis for deriving guidance values (GVs) for individual radionuclides, taking into account their dose coefficients and an assumed annual consumption of 730 L (2 L/day) for adults.

Under this framework, derived GV values include: 3 Bq/L for Ra-226, 0.5 Bq/L for Ra-228, 100 Bq/L for U (total, based on radiological criteria), and 100 Bq/L for Ra-224. National regulations across the European Union (Council Directive 2013/51/Euratom), the United States (EPA Radionuclides Rule), and other jurisdictions have adopted or adapted these reference levels, sometimes incorporating additional safety margins or adjusting for different population water consumption patterns.<sup>28</sup>

## Health and Radiological Implications

### Epidemiological evidence

The epidemiological evidence linking chronic low-level exposure to naturally occurring radionuclides in drinking water with adverse health outcomes is limited but growing. Early ecological studies in the United States and Europe suggested associations between elevated radium in drinking water and increased rates of bone cancer and leukemia, consistent with radium's bone-seeking behavior and alpha-emitting progeny. However, the ecological study design, low statistical power, and confounding by other risk factors limited causal inference from these early investigations.<sup>29</sup>

More recent studies have examined the relationship between uranium in drinking water and kidney function impairment. Several cross-sectional and longitudinal studies from communities served by high-Uranium groundwaters in Finland, USA, and Canada have reported associations between urinary uranium and markers of tubular dysfunction, supporting uranium's known nephrotoxicity. These findings reinforce the dual nature of uranium as both a chemical toxin and a radiation source, with chemical effects potentially dominating at concentrations of public health concern.<sup>30</sup>

The relationship between radon in drinking water and lung cancer risk has been the subject of considerable scientific debate. Theoretical calculations suggest that radon released from drinking water during household use contributes approximately 1–10% of the radon dose attributable to indoor radon derived from soil and building materials. Population-level lung cancer risk attributable to water-borne radon is therefore small relative to that from geological radon, but it remains a concern in high-radon groundwater areas.<sup>31</sup>

### Radium accumulation and bone dosimetry

Radium's chemical mimicry of calcium leads to its deposition in bone minerals following absorption from the gastrointestinal tract. The distribution of radium within bone is non-uniform, with initial deposition preferentially on bone surfaces (particularly endosteal surfaces) and subsequent redistribution into bone volume over time, following the dynamics of bone remodeling. The long biological retention of radium in bone (effective half-life of several decades for Ra-226) means that committed doses from chronic ingestion extend well beyond the period of exposure, a feature that must be explicitly modeled in dose calculations for regulatory purposes.<sup>32</sup>

The bone-seeking decay chain progeny of Ra-226, including Rn-222, Pb-210, Bi-210, and Po-210, deliver additional alpha and beta radiation doses to bone marrow and endosteal cells. Polonium-210, the ultimate alpha-emitting daughter before stable Pb-206, has a particularly high radiotoxicity and contributes significantly to the committed effective dose from Ra-226 ingestion. The ingrowth of Po-210 and other progeny within bone tissue following Ra-226 deposition complicates dosimetric modeling but is accounted for in ICRP biokinetic models.<sup>32</sup>

### Vulnerable populations and age-dependent dosimetry

Radiological dose estimates for mineral water consumption are age-dependent, reflecting differences in gastrointestinal absorption fractions, biokinetics, tissue sensitivities, and annual water consumption rates across age groups. Infants and young children are of particular concern because: (i) their higher gastrointestinal absorption fractions for some radionuclides lead to greater internal contamination per unit ingested; (ii) their more rapidly dividing tissues may be more radiosensitive; and (iii) their smaller body mass results in higher organ doses per unit of radionuclide intake.

ICRP provides separate dose coefficients for infants, children, and adults to accommodate these differences.<sup>24</sup>

Pregnant women and nursing mothers represent another vulnerable group, as radionuclides ingested during pregnancy may cross the placental barrier or be transferred via breast milk to the developing fetus or infant, respectively. Modeling of fetal and neonatal dosimetry from maternal ingestion of radium-contaminated water is a specialized area that remains incompletely characterized in literature.

### **Long-term and cumulative exposure considerations**

Chronic ingestion of mineral water with low but consistent radionuclide concentrations over a lifetime may result in cumulative committed doses that are not insignificant, particularly in populations that rely heavily on mineral water as their primary source of drinking water. Lifetime committed dose calculations, integrating age-specific dose coefficients and water consumption rates over a 70-year lifespan, provide a more complete picture of radiological risk than annual dose snapshots.

In high natural background radiation (HNBR) areas-such as the monazite-rich coastal regions of Kerala (India), Ramsar (Iran), and parts of Brazil-the contribution of ingestion dose from radionuclide-rich mineral waters may be a significant fraction of the total natural background dose, warranting specific epidemiological monitoring and regulatory attention. These regions provide natural human experiments for understanding the health effects of chronically elevated natural radiation, although confounding factors and statistical limitations have hindered definitive conclusions.<sup>33</sup>

## **Monitoring, Analytical Methods, and Quality Assurance**

### **Sampling and sample preservation**

Representative sampling of mineral waters for radionuclide analysis requires careful attention to sample collection, preservation, and handling protocols. For dissolved uranium and radium analysis, samples are typically filtered through 0.45 µm membranes to remove particulate material and acidified to pH < 2 with ultrapure nitric acid to prevent adsorption of dissolved species onto container walls. Radon samples require immediate preservation in radon-tight sealed containers or on-site measurement due to the short half-life and high volatility of Rn-222.

Chain-of-custody documentation, blank samples, duplicate samples, and certified reference material analyses are essential components of quality assurance in radionuclide monitoring programs. Inter-laboratory comparison exercises, organized through IAEA and national metrology institutes, enable assessment of laboratory performance and measurement uncertainty across different analytical platforms.

### **Analytical techniques**

A range of analytical techniques is employed for radionuclide quantification in mineral waters, each with distinct advantages in terms of sensitivity, specificity, throughput, and cost. Alpha spectrometry following radiochemical separation is the reference method for uranium isotopes and radium isotopes, providing isotope-specific activity measurements with detection limits well below regulatory guidance values. However, the extensive sample preparation requirements (co-precipitation, ion exchange chromatography) make this technique time-consuming and relatively expensive for routine monitoring.

Inductively coupled plasma mass spectrometry (ICP-MS) has emerged as the method of choice for total uranium measurement in drinking water, offering sub-nanogram-per-liter detection limits, high throughput, and the ability to distinguish between U-238, U-235, and U-234 on the basis of mass. Liquid scintillation counting (LSC) methods, including alpha/beta discrimination techniques, enable measurement of gross alpha and beta activity as screening parameters, with positive screens followed by isotope-specific analyses.

Radon measurement in water is typically accomplished by emanometry (degassing of a water sample into a radon-tight chamber followed by ionization chamber or scintillation cell measurement), liquid scintillation counting of a water-scintillant mixture, or gamma spectrometry following radon degassing. Each method has specific calibration requirements and is subject to different sources of systematic error that must be carefully evaluated in method validation.

### **Regulatory monitoring programs**

Regulatory monitoring of radionuclides in mineral waters is implemented through national legislation that transposes international guidance into domestic law. In the European Union, Council Directive 2013/51/Euratom establishes requirements for monitoring of radioactivity in drinking water, including mineral water, and sets parametric values for indicator parameters (total indicative dose, tritium) and specific radionuclides. Member states are required to establish monitoring programs; report results to the European Commission and take remedial action where parametric values are exceeded.

In Turkey, where the mineral water industry is substantial and geologically diverse, the Turkish Standards Institute (TSE) and the Ministry of Agriculture and Forestry regulate mineral water quality, including radioactivity parameters. Studies by Taskin et al. and Altikulaç et al. have documented the range of natural radioactivity in Turkish bottled mineral waters and evaluated compliance with applicable standards, providing a foundation for evidence-based regulatory development.<sup>3,20</sup>

## Mitigation and Treatment Technologies

### Uranium removal

Several well-established water treatment technologies are effective for uranium removal from mineral water and groundwater. Ion exchange using strong-base anion exchange resins is particularly effective because uranium at near-neutral pH is predominantly present as anionic uranyl carbonate complexes. Coagulation–flocculation with ferric salts followed by sedimentation and filtration achieves uranium removal efficiencies of 80–95% and is suitable for community-scale treatment. Reverse osmosis and nanofiltration membranes provide high uranium rejection rates (>95%) and are increasingly used for point-of-use treatment in high-uranium areas.<sup>34</sup>

### Radium removal

Radium removal from groundwater is more challenging than uranium due to its cationic charge and resistance to common coagulation processes. Lime softening, which precipitates calcium and magnesium carbonate, co-precipitates radium effectively and can achieve removal efficiencies of 70–95%. Strong acid cation exchange resins can remove radium by ion exchange with hydrogen ions, but regeneration of resins produces a radioactive brine waste stream that requires disposal. Greensand filtration using manganese dioxide-coated media is effective for combined removal of radium, iron, and manganese and is widely used in community water systems in the United States.<sup>35</sup>

### Radon removal

Radon is effectively removed from water by aeration (packed tower or spray aeration), which promotes volatilization of the dissolved gas, or by granular activated carbon (GAC) adsorption.<sup>36</sup> Packed tower aeration routinely achieves radon removal efficiencies of 95–99% and is widely considered the preferred method for large-scale municipal treatment.<sup>37,38</sup> While GAC adsorption is highly effective, it concentrates radon on the carbon bed where the gas undergoes radioactive decay; consequently, the carbon bed becomes gamma-radioactive over time, and the spent medium must be disposed of as low-level radioactive waste.<sup>38</sup> For decentralized applications, specialized point-of-entry (POE) aeration units are commercially available for household-scale radon removal from private well water.<sup>38</sup>

### Future Research Directions

Despite substantial progress in characterizing natural radioactivity in mineral waters, several important research gaps remain. First, mechanistic understanding of coupled redox, sorption, and transport processes controlling radionuclide mobility in heterogeneous aquifer systems requires further development, particularly for radium isotopes under dynamic redox conditions. Integrated reactive transport modeling, validated against field data

from well-characterized hydrogeological settings, represents a priority research avenue.

Second, the long-term health effects of chronic low-level ingestion exposure to naturally occurring radionuclides remain incompletely characterized. Prospective epidemiological cohort studies with rigorous individual-level exposure assessment, leveraging advances in biomonitoring and geographic information systems, are needed to resolve the associations between mineral water radionuclide exposure and cancer, kidney disease, and other health outcomes.

Third, the development and validation of rapid, field-deployable analytical methods for real-time radionuclide monitoring would substantially improve the temporal resolution of surveillance data and reduce the lag between sampling and remedial action. Advances in microfluidic radiochemistry, portable gamma and alpha spectrometry, and electrochemical sensors offer promising avenues for innovation in this area.

Fourth, the impact of climate change on groundwater hydrology and geochemistry—including changes in recharge rates, water table levels, and redox conditions—may have significant but poorly understood consequences for natural radionuclide concentrations in mineral water sources. Climate-hydrogeochemistry coupling studies are needed to anticipate future changes and inform adaptive management of mineral water resources.

## Conclusion

Naturally occurring radionuclides in mineral waters are an inevitable consequence of the geological processes that shape the Earth's crust and hydrosphere. Their distribution is governed by the complex interplay of lithological inheritance, primary uranium and thorium abundances, water–rock interaction dynamics, redox geochemistry, aquifer residence time, and hydrogeological transport. Among the radionuclides of concern, uranium, radium isotopes, and radon are the most geochemically and radiologically significant, with their behavior in groundwater systems reflecting fundamentally different geochemical controls.

Radiological dose assessment from mineral water consumption indicates that most commercially available mineral waters deliver ingestion doses well below the WHO reference level of 0.1 mSv/year. However, regional geological anomalies—particularly in areas underlain by uranium-rich granitic formations, phosphate-bearing sediments, or active geothermal systems—can produce mineral waters with radionuclide concentrations sufficient to warrant regulatory attention and consumer guidance. Radium isotopes are consistently identified as the primary contributors to ingestion dose, reinforcing the need for sensitive and specific radium monitoring methods in surveillance programs.

Public health implications of long-term mineral water radionuclide exposure are real but generally modest for the majority of the global population. Vulnerable subgroups-including infants, young children, pregnant women, and individuals in high natural background radiation areas-merit targeted dose assessment and proportionate regulatory protection. The dual chemical and radiological toxicity of uranium adds an additional dimension to risk characterization that must be reflected in regulatory guidance values.

Moving forward, the convergence of advances in hydrogeochemical modeling, isotopic tracing, high-sensitivity analytical instrumentation, and epidemiological methodology offers the prospect of substantially improved understanding of radionuclide behavior in mineral water systems and their long-term health implications. Sustained investment in integrated monitoring programs, inter-laboratory quality assurance, and regulatory capacity is essential to ensure that mineral water continues to be a safe and beneficial component of human diets worldwide.

### Acknowledgements

None.

### Funding

This Review Article received no external funding.

### Conflicts of Interest

The authors declare no conflict of interest.

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