

Review

Radium recovery from mining tailings: A comprehensive review of techniques and applications

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ABSTRACT

Radium, a naturally occurring radioactive element, has been historically recognized for its medical and industrial applications. However, with the advent of synthetic radioactive iso-topes, radium's prominence declined, and the former radium sealed sources were relegated to radioactive waste. Recent developments include the potential of radium to be used as target in a nuclear reaction to produce a radioisotope used in nuclear medicine. This has prompted the retrieval of radium sources from radioactive waste storage facilities and renewed attention on radium recovery from mining/milling residues. This review explores radium's historical significance, chemical properties, and isotopic characteristics while addressing contemporary challenges in radium extraction and applications. Particular focus is given to radium recovery techniques from residues of uranium, thorium, and rare earth element processing, emphasizing their environmental implications and regulatory considerations. The analysis highlights advancements in radium separation methods, such as ion exchange, co-precipitation, and chromatographic techniques, as well as emerging technologies aimed at optimizing recovery while mitigating environmental risks posed by mining and milling waste. By consolidating current knowledge, this study underscores the dual importance of radium recovery in resource sustainability and environmental stewardship.

1. Introduction

Radium is a chemical element found in minerals containing thorium and uranium, occurring at a ratio of approximately one part radium to three million parts uranium by mass (Jia and Jia, 2012). Discovered by Marie and Pierre Curie in 1898, it was first isolated from pitchblende, a mineral extracted from a mine in Jáchymov, present-day Czech Republic (Thomas, 1981). Radium is the heaviest naturally occurring alkaline earth metal and forms naturally as a decay product of thorium and uranium (Patel et al., 2023). To date, 30 isotopes of radium have been identified, all of which are radioactive. Among these, only four occur naturally: ^{223}Ra , a member of the ^{235}U decay series; ^{226}Ra , associated with the ^{238}U series; and the isotopes ^{224}Ra and ^{228}Ra , both part of the ^{232}Th day series (IAEA, 1987; IAEA, 1990a). Shortly after its identification, radium found applications in medical and industrial contexts in the early 20th century. However, the extremely high cost, due to its rarity in nature and the challenges associated with its obtaining, limited

its use primarily to medicine.

Sealed radium sources were employed in cancer therapy, where small quantities of radium salts were enclosed within steel or platinum needles, which were then sealed and implanted in tumors to kill cancer cells through irradiation, thereby inhibiting tumor growth (Patel et al., 2023). Industrial applications were minimal, with trace amounts used in luminescent paints for watch dials, compasses, and other military objects de-signed to be visible in the dark.

This unsealed source use revealed radium's high toxicity and health risks, with chronic exposure leading to an increased incidence of bone, liver, and breast cancers (Gunderman and Gonda, 2015). These risks became evident in the 1920s, when numerous cases of digestive tract cancers were reported among workers who painted luminous dials in the United States, in what became known as the "Radium Girls" case. The workers, who were instructed to shape their paintbrushes with their lips, inadvertently ingested radium, which accumulated in bone tissue due to its chemical similarity to calcium, leading to osteonecrosis of the jaw,

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aplastic anemia, bone sarcomas, and other malignancies. This episode marked a turning point in occupational health, contributing significantly to the establishment of industrial safety standards and the development of modern radiological protection principles (Missimer et al., 2019).

In the first half of the 20th century, ^{226}Ra was the only practical radioactive material available, valued for its high specific activity, long half-life ($t_{1/2} = 1,600\text{y}$), and natural occurrence in extractable quantities from uranium rich minerals. During this period, it is estimated that millions of tons of uranium ore were processed in many countries to extract approximately only 4.5 kg of radium (IAEA, 1991). From the 1940s and 1950s onward, the advent of the nuclear industry introduced a plethora of artificial radioactive isotopes produced in nuclear reactors. These isotopes, available at a significantly lower cost, offered tailored properties for various applications. Consequently, radium sources were gradually replaced by artificial isotopes between the 1960s and 1980s and were subsequently classified as radioactive waste (IAEA, 1991; IAEA, 2011).

Beyond its historical and technical relevance, contemporary radioactive waste management requires a fundamental conceptual shift. Modern nuclear safety philosophy establishes that long term radiological protection must rely primarily on passive safety systems, based on containment, isolation and intrinsic stability, independent of continuous institutional control (IAEA, 2011; ICRP and Recommendations of the International Commission on Radiological Protection, 2007). This principle arises from recognition that social and institutional systems are inherently unstable over timescales comparable to the half-life of long-lived radionuclides such as ^{226}Ra (ICRP and Recommendations of the International Commission on Radiological Protection, 2007).

Intergenerational ethical responsibility thus become a core axis of radioactive waste governance, with monitoring and surveillance acting as complementary, rather than central, safety mechanisms (IAEA, 2011). In parallel, emerging industrial and environmental paradigms, particularly the circular economy, promote a reinterpretation of wastes as potential strategic secondary resources (Geissdoerfer et al., 2017; Thakur et al., 2021). Within the nuclear sector, this transition enables the integration of radiological safety, environmental sustainability, and resource efficiency within a unified decision-making framework (IAEA, 2013).

Interest in radium resurged in the late 2010s following the recognition of ^{225}Ac as a highly effective alpha-emitting radionuclide for targeted cancer therapies (Kratochwil et al., 2016; IAEA, 2009). A viable production route involves cyclotron irradiation of ^{226}Ra targets, which are compatible with hospital-based infrastructure (IAEA, 2009). This demand has triggered global efforts to recover and secure ^{226}Ra sources, many of which remain in interim storage facilities. Another application for radioactive isotopes has also reemerged. During the latter half of the 20th century, nuclear batteries, referred to as radioisotope thermoelectric generators (RTGs), were employed in outer solar system space missions where solar panels were ineffective (IAEA, 1991). RTGs have powered deep space missions such as Voyager and Cassini (IAEA, 2013).

According to IAEA (Ropp, 2013) this same technology has also been deployed on earth, particularly in remote arctic weather stations and communication towers, due to its long-lasting autonomous energy output. However, the limited availability and restricted production of traditional radioisotopes such as ^{90}Sr , ^{238}Pu , currently the main isotope used in space missions, have renewed interest in alternative radionuclides capable of powering nuclear batteries (O'Brien et al., 2008; Schock et al., 1995). In this context, ^{226}Ra ($t_{1/2} = 1602\text{y}$) and ^{228}Ra ($t_{1/2} = 5.75\text{y}$) have been proposed as potential candidates (Ropp, 2013). However, their practical application is constrained by factors such as relatively low specific power and generation of gaseous decay products, particularly radon in the decay chain of ^{226}Ra (Knoll, 2000), which must be addressed through appropriate encapsulation and shielding strategies.

Since radium extraction declined in the mid-20th century, existing

quantities are primarily found in the residues of uranium and thorium processing. Moreover, the mining and milling of ores from which elements such as phosphorus, niobium, tin, and rare earth elements are extracted, many of which also contain thorium and uranium as accessory elements, has resulted in mining residues enriched with radium. These mineral wastes containing uranium and thorium are also referred to as Naturally Occurring Radioactive Materials (NORM) wastes. Monazite is one such source, being a mineral comprising rare earth phosphate compounds (Jordens et al., 2013). As monazite often contains uranium, thorium, and their radioactive progeny (Martres and Burastrero, 1971), its processing residues may also harbor appreciable amounts of radium. While radium's historical significance and diverse applications have driven its early extraction and utilization, contemporary challenges and opportunities arise from its occurrence in mining residues. These residues, often enriched with radium as a byproduct (IAEA, 2013), present both a challenge for waste management and a potential resource for radium recovery.

The resurgence of interest in radium recovery from mining residues stems not only from the need to address environmental challenges but also from the element's renewed value in advanced industrial and medical applications. The extraction of radium from residues offers a dual benefit: mitigating environmental risks while unlocking a sustainable source of isotopes critical to nuclear medicine and nuclear battery technology for terrestrial as well as space applications. This review examines the historical context, physicochemical properties, isotopic composition, applications, and environmental and regulatory dimensions of radium recovery and reuse. To achieve this, data collection and literature searches were conducted using databases such as Scielo, Scopus, ScienceDirect, Google Scholar, and IAEA Publications, among others. Keywords employed in the search included: "Radium extraction", "Radium separation", "Radioactive isotopes", "Rare earth processing", and "Separation techniques for radium". The review incorporated articles published in English, Spanish, and Portuguese up to the present year (2025). These articles addressed topics such as physical chemical separation methods, industrial processes, purification techniques, and geological studies related to radium extraction.

However, it must be emphasized that most studies found in the literature do not pursue radium recovery in the sense of product valorization or reinsertion into the nuclear industry or medical supply chain. Instead, the majority focus on radium removal or immobilization, particularly via adsorption, precipitation, or treatment of effluents, as part of environmental remediation strategies. This distinction is crucial, as it suggests that true radium recovery for reuse is either technically or economically challenging under current conditions, which partially explains the limited number of works explicitly aligned with the objective proposed in this review.

2. Materials and methods

A structured thematic narrative review was conducted to analyze the occurrence, chemical behavior, and extraction methods of radium isotopes (^{226}Ra and ^{228}Ra), with a focus on wastes originating from monazite processing and from minerals associated with thorium and uranium. The review was conducted in a structured and reproducible manner, following predefined search and selection criteria. Literature searches were performed in international scientific databases (Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar), complemented by technical reports from official organizations such as the International Atomic Energy Agency (IAEA), the United States Nuclear Regulatory Commission (USNRC), and the Brazilian Nuclear Industries (INB).

The search strategy employed combinations of descriptors in Portuguese, English, and Spanish, including: "radium extraction", "radium recovery", "radium isotopes", " ^{226}Ra ", " ^{228}Ra ", "monazite processing", "thorium tailings", "uranium residues", "radioactive waste management", "NORM", and "chemical separation of radium". Boolean

operators (AND, OR) were used to refine results. The temporal scope prioritized publications from 1980 to 2025, while seminal historical works relevant to the early industrial and medical uses of radium were included when necessary to contextualize the discussion. Only peer reviewed articles, conference proceedings, theses with methodological detail, and official technical reports were considered. Publications lacking methodological transparency or clear analytical procedures were excluded.

The comparative discussion of extraction techniques primarily considered reported recovery efficiencies, chemical reagents employed, and applicability to different types of matrices (solid residues, tailings, or aqueous systems). When available, operational parameters such as pH conditions and selectivity were qualitatively discussed. In the early 20th century, the discovery of radium spurred significant interest, driving the mining of uranium containing minerals such as carnotite, particularly in the Colorado Plateau of the United States. Companies processed these ores to meet medical and military demands, especially during World War I, cementing radium's economic and strategic importance (Borrowman and Brooks, 1974). Radium naturally occurs as a decay product of uranium and thorium in minerals such as uraninite and carnotite. Early reserves were primarily located in Europe (Joachimsthal) and the United States (Aronowitz and Lubenau, 2012).

The extraction of radium from uranium ores became a focal point of industrial efforts during the early 20th century. For example, the milling of carnotite ores in the United States required the development of complex chemical separation methods. Despite technological advances, these processes faced technical and economic challenges, as radium's low concentration in ores required labor-intensive purification steps, making production expensive (United Nations Scientific Committee on, 2015). According to Aronowitz and Lubenau (2012), “*radium was, by far, the most precious substance on earth. Between 1910 and 1922, its cost was greater than \$100,000 per gram (peaking at \$180,000 in 1913, equivalent to almost \$4 million in 2012)*”.

3. State of the art and historical background

The present work provides an integrated synthesis of the main findings in the literature on radium, contextualizing its discovery, physicochemical and radioisotopic properties, as well as its historical evolution in medical, industrial, and energy applications. Subsequently, the residues associated with its processing are discussed, with emphasis on environmental impacts, radiological risks, and the technological approaches available for their treatment and reuse. Finally, this section addresses environmental and regulatory aspects, mitigation strategies, advances in monitoring techniques, and the main historical and normative milestones, enabling a comprehensive understanding of the role of radium over time and the current challenges related to its safe and sustainable management.

3.1. Historical background and discovery of radium

Radium was discovered in the late 19th century by Marie and Pierre Curie, who isolated it as radium chloride (RaCl_2) from pitchblende, a uranium ore. The Curies named the element “radium”, derived from the Latin word *radius*, meaning “ray,” due to the intense radiation it emitted. To isolate just one hundred milligrams of radium, the Curies processed approximately one ton of ore (Thomas, 1981).

Aronowitz and Lubenau (Mehdizadeh et al., 2019) explain that this discovery occurred within a broader context of scientific advancements, including Henri Becquerel's identification of radioactivity in 1896. This groundbreaking work earned Marie Curie two Nobel Prizes (the 1903 in Physics and the 1911 in Chemistry) and laid the foundation for understanding radioactivity. Initially, radium found applications in cancer treatment and industrial processes, even though the risks associated with radiation were not yet fully understood (Thakur et al., 2021).

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interest, driving the mining of uranium containing minerals such as carnotite, particularly in the Colorado Plateau of the United States. Companies processed these ores to meet medical and military demands, especially during World War I, cementing radium's economic and strategic importance (Borrowman and Brooks, 1974).

The extraction of radium from uranium ores became a focal point of industrial efforts during the early 20th century. For example, the milling of carnotite ores in the United States required the development of complex chemical separation methods. As shown in Fig. 1, mining methods can generally be classified into surface and underground categories, each associated with specific deposit geometries and operational characteristics.

Surface techniques, such as open-pit mining and strip mining, have been predominantly applied to shallow deposits, while underground methods, including room and pillar mining and cut and fill mining, were required for deeper ore bodies all of which contributed to the accumulation of NORM-containing tailings, which remain a central concern in radioactive waste management today.

3.2. Properties and isotopes of radium

Radium occurs naturally as a byproduct of the radioactive decay of ^{238}U and ^{232}Th . Of its 34 known isotopes, only four occur naturally: ^{228}Ra , ^{226}Ra , ^{224}Ra and ^{223}Ra (Thakur et al., 2021). Radium isotopes are not found in nature as a primordial element, but are continuously formed within the decay chains of uranium and thorium.

The ^{238}U , ^{235}U and ^{232}Th day series, as illustrated in Fig. 2, show the positions of ^{226}Ra and other relevant radium isotopes within these natural radioactive chains. Among these, ^{226}Ra is the most notable due to its long half-life of approximately 1600 years, making it environmentally and industrially significant (Roulier et al., 2024). From a chemical perspective, radium belongs to Group IIA of the periodic table and shares similarities with barium (Ba), including ionic radius and behavior in solutions (Kratochwil et al., 2016). Radium predominantly exhibits a +2-oxidation state, is resistant to redox reactions, and forms low-solubility ionic compounds such as carbonates and sulfates. In aqueous solutions, radium predominantly exists as the Ra^{2+} ion, independent of pH, facilitating its removal via ion exchange or adsorption techniques an important property for its extraction from complex matrices such as monazite residues (Szabo et al., 2012).

The speciation of radium isotopes in mineral residues is influenced by chemical factors such as pH and temperature, which affect their mobility and extraction efficiency. For example, Yousfi et al. (1999) demonstrated that varying chemical conditions significantly impact radium recovery, necessitating precise parameter optimization for efficient separation. Among radium isotopes, ^{226}Ra has been extensively studied for its environmental and geochronological applications (Barker et al., 2017). Analytical methods such as thermal ionization mass spectrometry (TIMS) offer high precision in measuring ^{226}Ra , enabling its differentiation from interfering elements like calcium and barium (Ghaleb et al., 2004). Additionally, alpha spectrometry has proven effective in analyzing radium in environmental samples, provided that optimized preparation techniques such as digestion with concentrated acids or pyrosulfate fusion, are employed (Thakur et al., 2021).

The chemical resemblance of radium to barium underscores the necessity of specific separation techniques for radium purification. Chromatographic methods such as ion exchange and extraction chromatography are commonly employed for this purpose (Apostolidis et al., 2005). Ensuring a state of radioactive equilibrium with daughter radionuclides, such as ^{228}Th , is a crucial consideration for the analytical determination of radium isotopes. This equilibrium allows for the quantification of the parent radionuclide by measuring the activity of its decay products, which simplifies the analytical process (Oliveira and Carvalho, 2006). The environmental implications of radium are significant. Due to its solubility in aqueous media and chemical similarity to calcium, radium can bioaccumulate in living organisms, posing

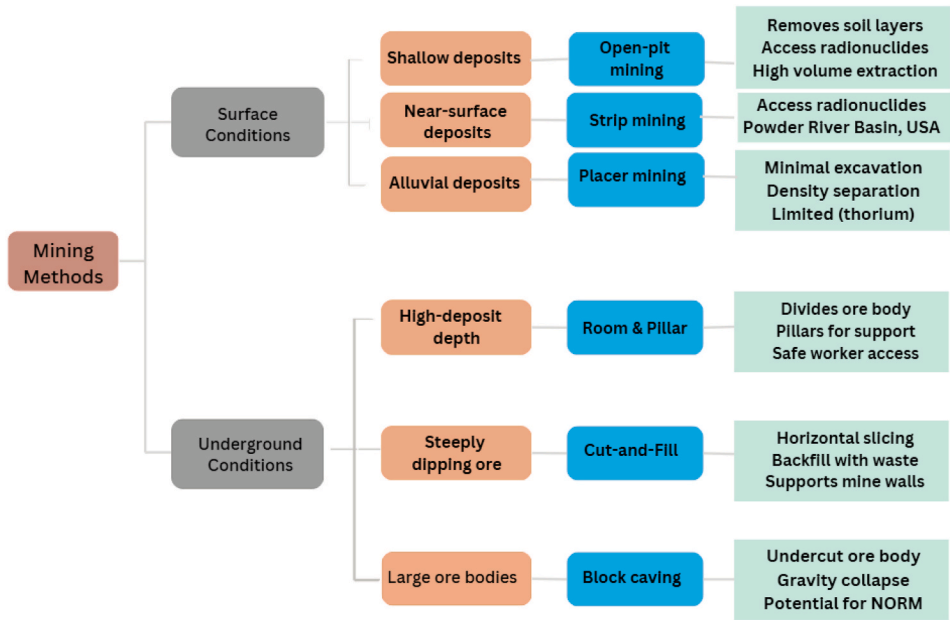


Fig. 1. Diagram of mining methods. Adapted from (Eddy et al., 2025).

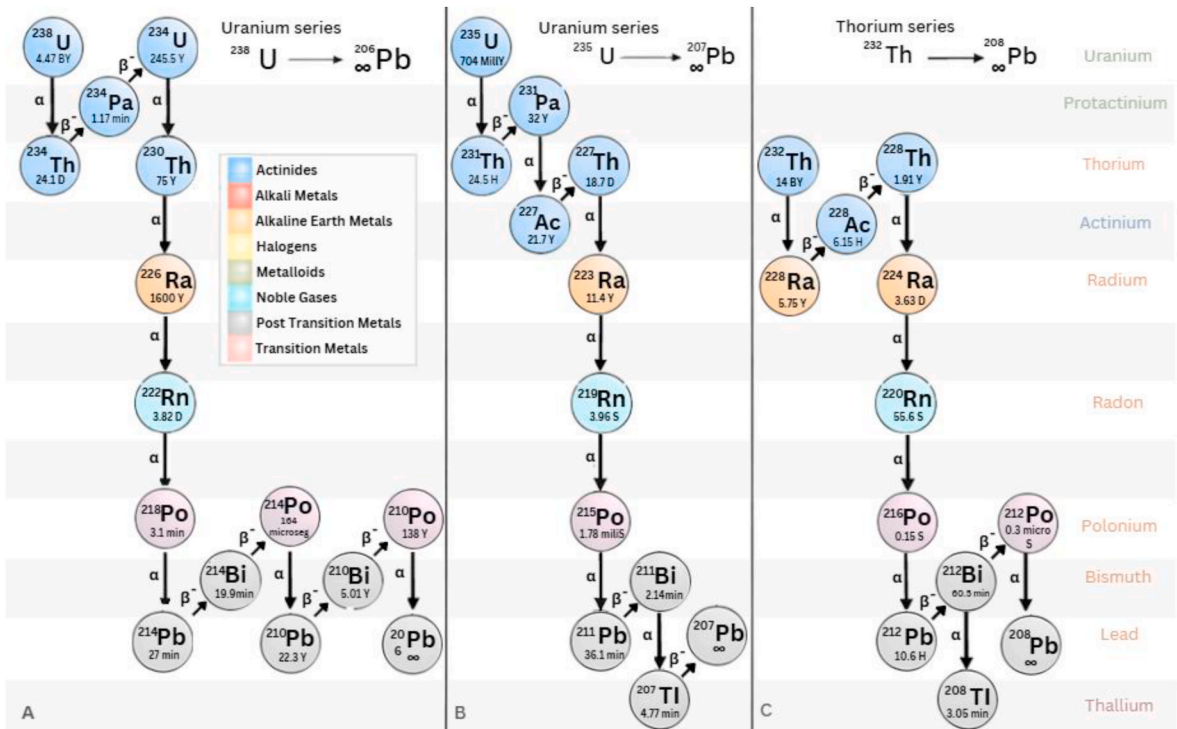


Fig. 2. Radium isotopes within the natural decay chains of ^{238}U , ^{235}U and ^{232}Th . Adapted from (Tan, 2016).

contamination risks (Roulier et al., 2024).

3.3. Applications of radium

Radium has seen diverse applications, particularly in nuclear medicine, radiotherapy, environmental studies, and geochronology. Due to its high radioactivity and associated hazards, it saw many of its initial applications discontinued as its risks became better understood and alternative methods were developed. However, radium remains crucial in certain niche applications.

In the early 20th century, radium's uses were notable, diverse, and

often hazardous, as detailed by Gunderman and Gonda (2015). The authors describe how one of the most widespread uses was in radio luminescent paint, extensively applied to watch dials, particularly for military purposes. Additionally, radium was incorporated into a wide variety of consumer products, including toothpaste, face creams, and even food, often accompanied by health benefit claims. While Gunderman and Gonda (2015) emphasize the dangers associated with these applications, they also highlight its use in medicine by practitioners like Howard Kelly for treating malignancies such as cervical and uterine cancers, as early as 1915. However, much earlier papers gave account of the power of radium as therapeutic resource (Martres and Burastero,

1971; BELL, 1909).

By the 1920s, the primary industrial application of radium was the production of luminescent paints for watch dials (Zagà et al., 2022). Companies such as the U.S. Radium Corporation and the Radium Dial Company monopolized the market in the United States, according to Zagà et al. (2022). The workers, known as the “Radium Girls”; were responsible for painting the dials and were instructed to use their lips to fine-point the brushes, a practice that resulted in the ingestion of dangerous amounts of radium (Zagà et al., 2022).

The tragic case “Radium Girls”; vividly illustrates the initial dangers and the lack of understanding about radium's toxicity, which bio-accumulated in the body due to its chemical similarity to calcium. The work environment of the dial painters in a radium factory is shown in Fig. 3, such events were crucial for public awareness and the eventual establishment of radiological protection committees and legal precedents for occupational diseases.

According to Mould and Pierre (Mould, 2007), radium's versatility extended to detecting counterfeit diamonds, performing radiographs of steel and iron castings, and locating pearls within oysters. The author also highlights the imaginative military applications envisioned, such as luminous weapon sights and methods for remotely igniting gunpowder in enemy depots. These examples illustrate the broad spectrum of real and potential applications for radium, which, at the time, justified the interest and demand for the element. As the renewed interest in radium, in the medical field, Apostolidis et al. (2005) note that one of the primary applications of purified radium is the production of ^{225}Ac , used in cancer therapies.

Its emission of alpha particles allows for highly specific and effective treatments. Similarly, Parker et al. (2013) discuss ^{223}Ra , an alpha-emitting isotope with highly desirable properties for therapeutic applications. Its ability to emit high-energy particles with a short range (less than 100 μm) is particularly noteworthy. Parker explains that this limited radiation range focuses the cytotoxic effect on tumor cells while minimizing exposure to healthy tissues. It is important to note that the physical and chemical properties of radium isotopes justify the growing interest in obtaining them from alternative sources. Understanding these aspects is crucial for developing separation and purification routes for isotopes derived from mineral residues, especially considering the presence of natural radium in materials such as monazite.

These applications underscore the need for advanced separation and purification techniques to recover radium isotopes from mineral residues, ensuring their effective utilization in scientific and industrial domains. The renewed demand for ^{226}Ra is largely driven by its usefulness as a target for the production of ^{225}Ac , a promising radioisotope in

targeted cancer therapies (IAEA, 1990b). Likewise, Apostolidis et al. (2005), mention that the conversion, purification, and recycling process of ^{226}Ra is a complex operation requiring rigorous quality control (QC) and specialized separation techniques, often involving leaching steps, chromatographic purification, and analysis by gamma spectrometry and inductively coupled plasma optical emission spectrometry (ICP-OES). A typical workflow for the production of ^{225}Ac from a sealed source of ^{226}Ra is illustrated in Fig. 4 with a clear focus on recycling the unconverted radium fraction.

According to Fig. 5a, prior to 1995, research on “radium” and “naturally occurring radioactive materials” was either non-existent, scarce, or other keywords could have been used. However, there has been an impressive increase in publications on this topic in recent years, reaching its highest peak in mid-2025. A notable example of this recent academic interest is the work by Zagà et al. (2022), which contributes to the current discourse on the subject. This surge, compared to the previous maximum of 23 annual publications, indicates that radium has attractive interest and reemerge as a highly active area of research. Two main clusters are depicted in Fig. 5b. The initial cluster is primarily linked to measurements, such as gamma spectrometry, radiation monitoring, and other elements commonly found with radium, e.g. thorium and uranium. The second cluster focuses on applications and the industrial, environmental, or medical aspects of radium.

3.4. Residues associated with radium milling

The formation and composition of radioactive residues are extensively discussed in the literature, particularly regarding the milling of monazite for rare earth extraction. This process typically involves alkaline digestion followed by acid leaching, which transfers most of the radium into the residual phase (IAEA, 2014). The resulting waste is characterized as a slurry rich in radium, often incorporated into matrices of barium sulfate (BaSO_4) and frequently associated with lead sulfide (PbS). Concentrations of ^{228}Ra in these residues range from 7 to 20 kBq.g^{-1} , with estimates suggesting that up to 80% of the original radium remains in the solid waste (IAEA, 2014).

On a global scale, the production of monazite generates significant volumes of residues. Annual production contributes approximately 6 TBq of ^{228}Ra to the waste stream, with accumulated stockpiles potentially ten times larger (IAEA, 2014). This scale underscores the need for effective strategies for radium extraction and waste management. Thomas (1981) reported that approximately 97% of the ^{226}Ra in raw materials remains in solid residues after processing, leading to the continuous emission of ^{222}Rn , a short-lived radioactive gas with substantial health implications.

3.4.1. Environmental impacts and risks

The presence of radium in industrial residues poses significant environmental risks, especially in waste generated from the mining and milling of thorium and uranium bearing minerals (Barker et al., 2017). Radon emissions, combined with the potential for leaching and mobilization of radionuclides, can contaminate water bodies and soils.

Gao et al. (2010) highlighted that improper disposal of radioactive residues from phosphate processing can release ^{226}Ra and trace metals into aquatic systems. For instance, contamination of the Winterbeek River (Belgium) demonstrated the influence of local geochemical processes on the mobilization of these contaminants. Additionally, Raicevic (1979), noted that residues from Elliot Lake (Canada), rich in pyrite, undergo bacterial oxidation, generating sulfuric acid and promoting the release of heavy metals. This increases the complexity of managing such residues.

3.4.2. Technological approaches

Various technological approaches have been investigated for the extraction and analysis of ^{226}Ra and ^{228}Ra from residues, with some of the key techniques reported in the literature summarized in Table 1 and

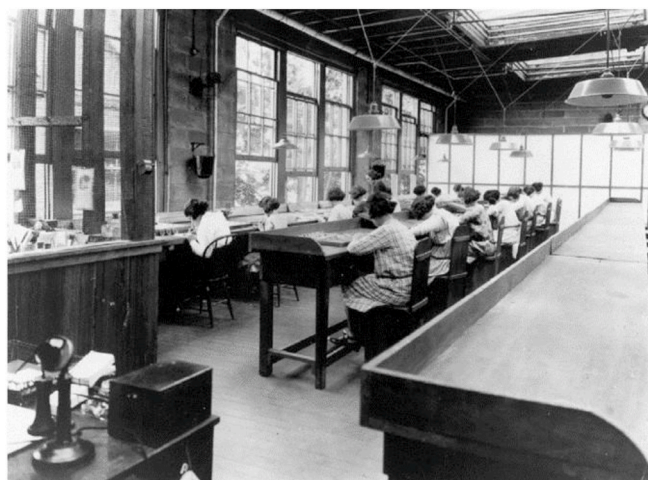


Fig. 3. Dial painters' work room at a radium factory (Gunderman and Gonda, 2015).

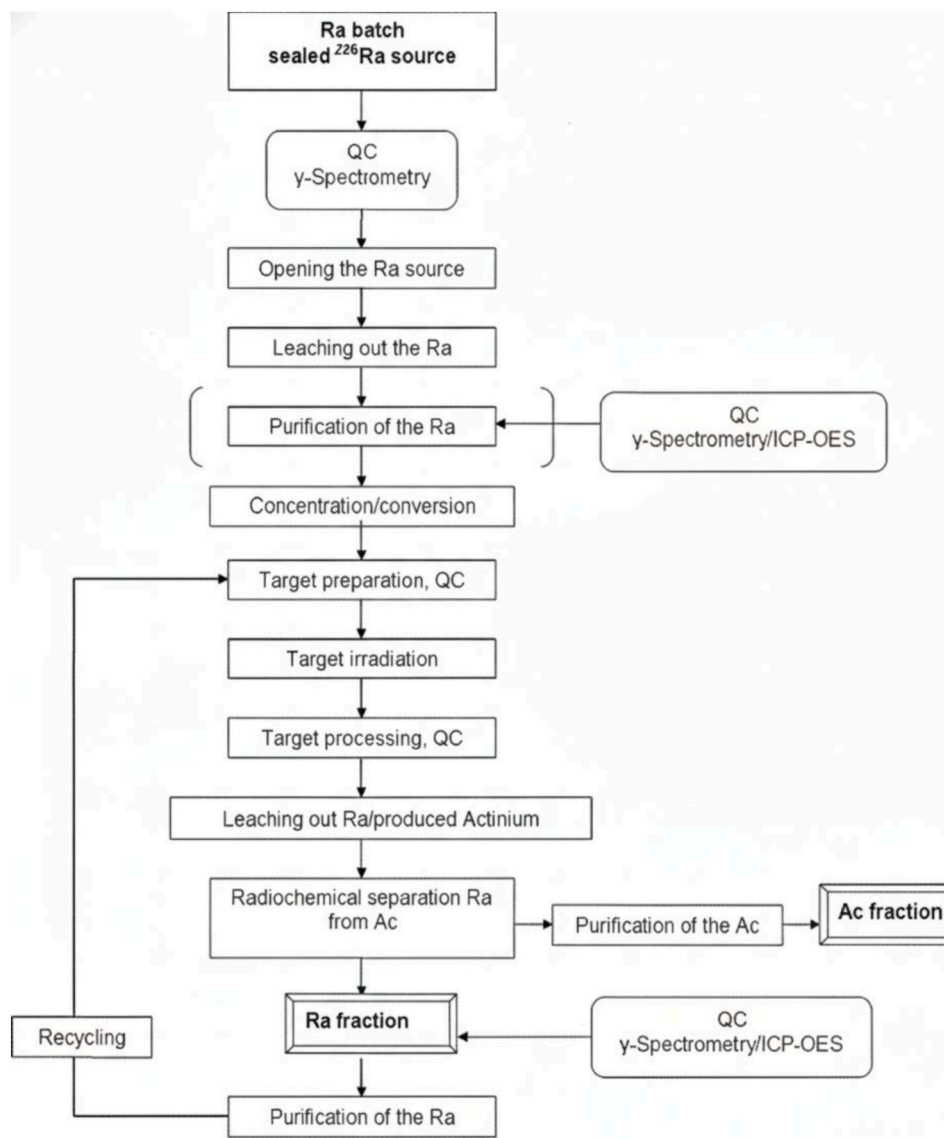


Fig. 4. Process flowsheet for radium purification and actinium production (Gao et al., 2010).

further discussed in the following sections. In general, the radium extraction process involves four main stages: ore pretreatment, radium recovery from the solution, purification, and conversion into a useable final product.

As illustrated in Fig. 6, the techniques analyzed are classified into methodological families based on their selectivity and complexity. The progression includes methods such as leaching, coprecipitation (including variations with BaSO_4 and CaPO_4 combined with alpha spectrometry), the use of synthetic zeolites, fusion, digestion, and chelation with EDTA. The specific characteristics of each family, as well as their application in different matrices, are detailed in Table 1.

The overall workflow from raw ore or tailings to purified radium are summarized in four stages as schematically illustrated in Fig. 7. In the pretreatment stage, the ore or residue is subjected to fine grinding to increase the surface area, followed by leaching. Acid leaching, for example with sulfuric acid (H_2SO_4), is capable of dissolving radium, although with lower efficiency than for other elements. Alkaline leaching, using for example $\text{Na}_2\text{CO}_3/\text{NaHCO}_3$, is applied to preferentially separate uranium, keeping radium in the residue. The use of phosphate compounds for the simultaneous extraction of ^{230}Th and ^{226}Ra from uranium ores and their residues was reported by Hawley (1980).

Radium recovery from the solution is generally carried out by coprecipitation, with coprecipitation using BaSO_4 being the most common and effective method. This technique, described in detail by Choppin et al. (2013) and also by the IAEA (IAEA, 1986) exploits the chemical similarity and ionic radius of radium to barium, adding BaCl_2 or $\text{Ba}(\text{NO}_3)_2$ to the leach solution to form the precipitate $\text{Ba}(\text{Ra})\text{SO}_4$. More modern approaches, suitable for low-concentration solutions, include the use of synthetic zeolites, ion-exchange resins, manganese dioxide (MnO_2), or activated carbon. Chalupnik et al. (Chalupnik et al., 2013) demonstrated that synthetic zeolites can remove more than 90% of radium from mining waters. The extraction efficiencies reported for each technique in Table 1 are graphically compared in Fig. 8.

Leaching with 3 M NaCl salts and chelation with EDTA achieved the highest recovery rates (80 to 94% and >90%, respectively), followed by synthetic zeolites (>90%), while precipitation with BaSO_4 showed comparatively lower efficiency (42%). These differences reflect the influence of matrix complexity, radius speciation, and the selectivity of each method, and should be considered when choosing an extraction strategy for a given residue type.

Chelation-based methods have also been proposed to selectively solubilize radium in complex matrices, such as mining residues. Nirdosh (Nirdosh et al., 1984) reported that ethylenediaminetetraacetic acid

Table 1
Radium extraction and analysis techniques.

Technique	Technique Analysis
Salt Leaching	The use of 3 M NaCl solutions demonstrated extraction efficiencies ranging from 80% to 94%, depending on the processed mineral (Ryan and Levins, 1980).
Co-precipitation and Resins	The presence of alkaline-earth metals and high salinity in residues requires robust methods, such as co-precipitation with MnO ₂ or extraction using crown-ether resins, to minimize interferences (Thakur et al., 2021).
Precipitation with Barium Sulfate	Mehdizadeh et al. (2019) (Mehdizadeh et al., 2019) developed a radiometric method based on precipitation with BaSO ₄ , achieving an extraction efficiency of 42% and a specific activity 2.12 times greater than the original sample.
Synthetic Zeolites removing	Chalupnik et al. (2013) (Chalupnik et al., 2013) demonstrated the effectiveness of synthetic zeolites in radium from mining wastewater, with efficiency exceeding 90%, presenting an alternative to traditional barium chloride
Fusion and Chemical Digestion	For quantification and laboratory analysis, methods such as microwave digestion with aqua regia, alkaline fusion with lithium metaborate, and fusion with pyrophosphate are applied, ensuring complete dissolution of the solid matrix and precise radionuclide detection (Barker et al., 2017; Kempema et al., 2005).
Co-precipitation with Calcium Phosphate and Alpha Spectrometry	These methods also show effectiveness in detecting 226Ra and 228Ra in aquatic and industrial matrices (Abd El-Ghaffar et al., 2014).
Extraction with EDTA	According to the literature, the use of EDTA as a chelating agent combined with sodium hydrosulfite was proposed, achieving more than 90% radium removal in residues (Nirdosh et al., 1984). Similarly, Nixon et al. (1983) (Nixon et al., 1983) obtained up to 85% removal of 226Ra under controlled conditions of pH, concentration, and contact time.
Additional Techniques	Alkaline fusion, acid leaching, flotation, and phosphate treatments have been widely investigated (Borrowman and Brooks, 1974; Roulier et al., 2024; Hawley, 1980).

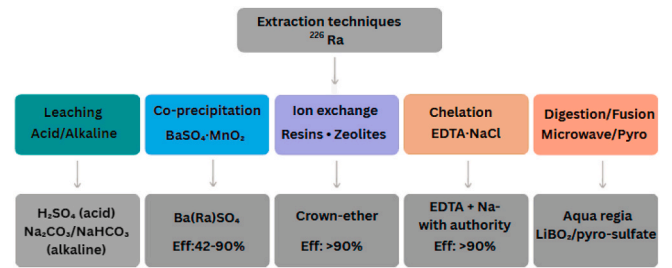


Fig. 6. Structural diagram of technique categories. Adapted from (Thakur et al., 2021; Barker et al., 2017; Nirdosh et al., 1984).

surveillance (Canada's Nuclear Regulator, 2020). Improper disposal of radium-bearing waste can result in the release of radon ²²²Rn, contamination of surface and groundwater, and mobilization of radionuclides into biological systems (Thomas, 1981; Nixon et al., 1983). Consequently, radium extraction and reuse require regulatory clearance or exemption and continuous monitoring of radionuclide activity concentrations (CNEN, 2024).

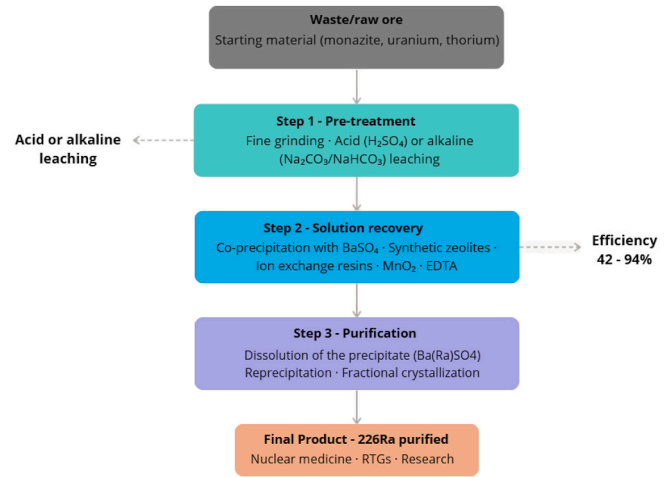


Fig. 7. Stages of the radium extraction process, adapted from pretreatment (Hawley, 1980; Ryan and Levins, 1980) recovery from solution (Thakur et al., 2021; Mehdi-zadeh et al., 2019; Chalupnik et al., 2013) Purification (Curie et al., 1898) and conversion into a useable 226Ra product (Kratochwil et al., 2016; IAEA, 2009; Schock et al., 1995).

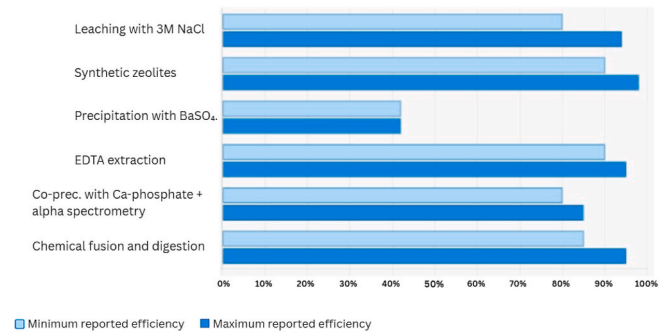


Fig. 8. Comparison of the efficiency of extraction techniques (Data from Table 1).

3.6. Mitigation strategies

Several authors have proposed methods to mitigate the environmental impacts of radium containing residues. For instance, Ryan (Ryan and Levins, 1980) developed an efficient extraction process that minimizes gamma emissions, radioactive dust, and radon release. Similarly, modern chemical techniques, such as those described by Yousfi et al. (1999), described modern chemical techniques that enable radium recovery with improved environmental safety. Innovative approaches such as zeolite adsorption have also been investigated for removing radium from contaminated water (Chalupnik et al., 2013). Nirdosh et al. (1984) further proposed radium recovery using EDTA recycling, promoting sustainability and safe residue disposal. Advanced chemical treatment methods have also been explored for the stabilization of complex radioactive residues. For example, ozone-based oxidation process can degrade organic compounds present in radioactive oil sludge, modifying its physicochemical structure and facilitating subsequent waste management or conditioning steps (de Araujo et al., 2020).

In monazite mining and milling tailings, the IAEA (IAEA, 2014) emphasized the accumulation of significant quantities of ²²⁶Ra and ²²⁸Ra in BaSO₄ slurries. These residues retain up to 80% of the radium initially present in monazite, with concentrations ranging from 7 to 20 kBq.g⁻¹. Environmental risks are exacerbated by weathering processes, which promote radium leaching and mobilization into soil and water bodies, despite coprecipitation with sulfate (IAEA, 2014).

Beddow (Beddow et al., 2006) noted that the production of

phosphate fertilizers and the disposal of “produced water” by the petroleum industry also increase the release of ^{226}Ra and ^{228}Ra into the environment. In regions near offshore oil platforms, radium concentrations can be up to a thousand times higher than natural levels. Incomplete precipitation of radio barite enables radium transport through fine crystals, necessitating complementary tracers to distinguish anthropogenic sources (Beddow et al., 2006).

3.7. Monitoring and advances in techniques

Effective monitoring is critical for managing radium-associated risks. Techniques such as emanometry for ^{222}Rn enable quantification of ^{226}Ra in low-mass solid samples (Barker et al., 2017). Rapid methods, like those described by Kempema et al. (2005) and Ghaleb et al. (2004), provide timely responses for remediation and regulatory compliance. Traditional gamma spectrometry remains a well-established method for determining ^{226}Ra activity, typically quantified through the characteristic gamma lines of its short-lived progeny (^{214}Pb and ^{214}Bi) after secular equilibrium with ^{222}Rn is achieved (IAEA, 1990a). Although robust and nondestructive, the method relies on strict control of sample sealing to prevent radon loss and generally requires extended equilibration times. Recent analytical advances, however, have significantly improved detection limits, sample throughput, and speciation capabilities.

In parallel, high-resolution inductively coupled plasma mass spectrometry (HR-ICP-MS) has emerged as a powerful tool ultra-trace radium quantification in environmental water and leachates, enabling detection at mBq.L^{-1} levels when combined with preconcentration methods (Su et al., 2025). Coupled technique integrating ICP-MS with extraction chromatography or radium selective resins (for example, crown ether based systems) allow selective separation from competing alkaline earth elements such as barium and strontium, significantly enhancing analytical reliability (Philip Horwitz et al., 1992; Maxwell, 2006).

Recent developments in radon manometry have also improved indirect ^{226}Ra determination in solid matrices, particularly through closed-loop accumulation systems with alpha spectrometry or Lucas cell scintillation detection, offering improved sensibility and reduced equilibrium times compared to conventional methods, especially for low activity samples (IAEA, 2013). Beyond monitoring, technological advances in radium recovery have moved beyond classical BaSO_4 coprecipitation. Studies by Horwitz et al. (Philip Horwitz et al., 1992) demonstrated the efficacy of coprecipitation with BaSO_4 and extraction chromatography in reducing waste volume and management costs.

Dalencourt et al. (2018) emphasized the importance of rigorous emission controls during radium milling to minimize environmental impact. While barite coprecipitation remains a robust industrial technique, emerging approaches aim to increase selectivity, reduce secondary waste, and improve process sustainability. Ion Exchange materials incorporating functionalized sulfonic or phosphoric groups have demonstrated enhanced radium selectivity under varying pH and salinity conditions (Knee et al., 2011). Additionally, manganese oxide-based sorbents and nano-structured iron oxides have promising adsorption capacities for radium removal from mine waters (Tanaka et al., 2024).

From a process-integration perspective, life-cycle-based optimization frameworks are now being applied to compare precipitation, adsorption, and membrane systems under economic and radiological criteria, aligning technological with circular economy principles and waste minimization strategies (IAEA, 2017). Collectively, these advancements indicate a shift from conventional precipitation dominated approaches toward multi barrier, selective, and sustainability-oriented radium monitoring and recovery systems.

3.8. Historical and regulatory milestones

The history of the “Radium Girls” had a profound impact on regulatory frameworks. According to (Gunderman and Gonda, 2015) this case led to the establishment of radiological protection committees, the development of medical physics, and legal precedents for occupational diseases. These milestones have influenced current safety requirements for handling radium, including automation of processes and quality control measures (Apostolidis et al., 2005). Organizations like the NRC and IAEA play essential roles in consolidating information and establishing standards for radium-containing products still in circulation (O'Brien et al., 2008). The validation of methods using IAEA reference materials, as emphasized by Oliveira and Carvalho (2006) is crucial for ensuring international standards and preventing environmental impacts in mining regions.

4. Discussion

The results of this review indicate that radium, historically treated predominantly as a radiological liability, can be reinterpreted as a strategic resource when analyzed in light of contemporary technological and medical demands. The main contribution of this work lies in the integration of historical, technological, environmental, and regulatory information, enabling a systematic view of the wastes associated with the processing of monazite and other minerals containing thorium and uranium. By gathering and comparing different extraction, monitoring, and mitigation approaches, the study highlights the potential for adapting already consulted methods to current context, reinforcing the relevance of management strategies based on value recovery and the application of circular economy principles in the nuclear sector. This perspective broadens the existing understanding by connecting technical advances with regulatory and environmental implications, which are often analyzed in isolation in the literature.

As with any bibliographic reviews, this study reflects the characteristics and scope of the works available in the literature, relying on the quality and availability of the reported data, as well as on the diversity of methodological approaches adopted, which may limit direct quantitative comparisons. Despite these limitations, the results point to important practical implications, suggesting that the recovery of radium isotopes from wastes can simultaneously contribute to reducing environmental liabilities, strengthening radiological safety, and supplying radioisotopes of strategic interest. Future studies should advance toward experimental validation of these processes at laboratory and pilot scales, as well as integrated assessments of technical, economic, and regulatory feasibility, in order to support public policies and industrial decisions aimed at the safe reuse of radioactive wastes.

4.1. Conceptual reframing: radium as a strategic resource

Historically, radium was predominantly treated as a radioactive liability, associated with environmental, occupational, and public health risks, which led to its progressive segregation as radioactive waste following the consolidation of artificial radioisotope production (IAEA, 1988; UNSCEAR and Sources and Effects of Ionizing Radiation, 2010). This perception was reinforced by the availability of cheaper and more versatile artificial radionuclides produced in nuclear reactors, which displaced radium from most industrial and medical application (IAEA, 1988).

However, recent transformation in nuclear medicine, energy systems, and advanced technologies have reconfigured this framing. The growing demand for alpha-emitting radionuclides for targeted cancer therapies, particularly ^{225}Ac , has restored the strategic value of ^{226}Ra as a precursor material (Kratochwil et al., 2016; IAEA, 2009). In parallel, renewed interest in long-lived radioisotopes for space energy systems and radioisotopic power sources has further strengthened this repositioning (O'Brien et al., 2008). This shift moves radium from a purely

passive category to the status of a strategic coproduct. Its recovery can simultaneously serve radiological safety, environmental sustainability, and technological supply objectives. Under this paradigm, radioactive waste management ceases to be guided exclusively by isolation logic and begins to incorporate criteria of material valorization, resource efficiency, and integration into high-value production chains, in alignment with circular economy principles (Geissdoerfer et al., 2017; IAEA, 2013).

4.2. Passive safety versus resource recovery

Contemporary nuclear safety doctrine establishes that long-term protection must be ensured by passive mechanisms, independent of permanent institutional control (IAEA, 2011; ICRP and Recommendations of the International Commission on Radiological Protection, 2007). This principle is particularly applied for long-lived radionuclides such as ^{226}Ra , whose environmental persistence exceeds any realistic horizon of institutional stability (ICRP and Recommendations of the International Commission on Radiological Protection, 2007). Within this framework, radium recovery from residues should not be interpreted as a substitution for passive safety, but as a complementary mechanism for radiological inventory optimization.

The selective removal of radiotoxic radionuclides can reduce radon fluxes, decrease geochemical mobilization risks, and increase the robustness of final disposal systems, provided that recovery processes are conducted under strict radiological protection standards, occupational dose control, and proper management of secondary wastes (IAEA, 2014). Thus radium recovery does not contradict the logic of passive safety but can reinforce it when integrated into waste engineering strategies that prioritize long-term physical, chemical, and radiological stability (IAEA, 2011; IAEA, 2013).

4.3. Integrated economic and regulatory decision framework

The historical non-viability of radium recovery from mining residues was associated less with technical limitation than with economic, regulatory, and scale-related factors. The processing of large volumes of tailings to obtain small quantities of radium was unjustifiable under a decision logic focused solely on improving site radiological safety (IAEA, 1990a; IAEA, 2014). However, the explicit inclusion of the market value of recoverable products in decision-making models fundamentally alters this equation.

When radium recovery is integrated into coproduct systems, multi-component recovery models, and polymetallic valorization strategies, processing costs can be distributed and economic feasibility becomes supported by complementary value chains (IAEA, 2013; Philip Horwitz et al., 1992). In this context radium should be understood as a strategic coproduct whose viability is rarely autonomous but become technically and economically sustainable when embedded within integrated values-recovery systems, rather than isolated extraction schemes.

4.4. Intergenerational ethics and long-term governance

Radium recovery also possesses a structuring ethical dimension. The transfer of unmanaged radiological liabilities to future generations constitutes a form of risk externalization incompatible with contemporary principles of technological responsibility and environmental justice (IAEA, 2011; ICRP and Recommendations of the International Commission on Radiological Protection, 2007).

Accordingly, strategies that combine radiological inventory reduction, reinforcement of passive safety, and rational resource utilization contribute to more fair and sustainable intergenerational governance models (IAEA, 2013; UNSCEAR and Sources and Effects of Ionizing Radiation, 2010). Radioactive waste management therefore ceases to be an exclusively technical problem and become a challenge or governance, public ethics, and science policy, in which present decisions

shape future risks, opportunities, and responsibilities.

5. Conclusions

While the recovery of radium from mining residues presents significant technical and economic challenges, it also offers unparalleled opportunities for innovation. By fostering collaboration between academia, industry, and regulatory bodies, stakeholders can develop holistic solutions that balance resource utilization with environmental protection. The path forward requires continuous investment in research, the adoption of best practices in radiological safety, and the integration of radium recovery into sustainable development frameworks. Such efforts will ensure that radium's full potential is realized in addressing critical needs across multiple sectors.

CRediT authorship contribution statement

Osman Cesar Granada Galvis: Writing – original draft, Methodology, Conceptualization. **Leandro Goulart de Araujo:** Writing – review & editing. **Roberto Vicente:** Supervision, Project administration. **Sabine Neusatz Guillen:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to assist with English language revision and editing. After using this tool, the author(s) carefully reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Osman Cesar Granada Galvis reports financial support was provided by Coordination for the improvement of Higher Education Personnel. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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