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Uranium circularity for EU strategic autonomy and energy security

Initial analysis, future research, and policy options

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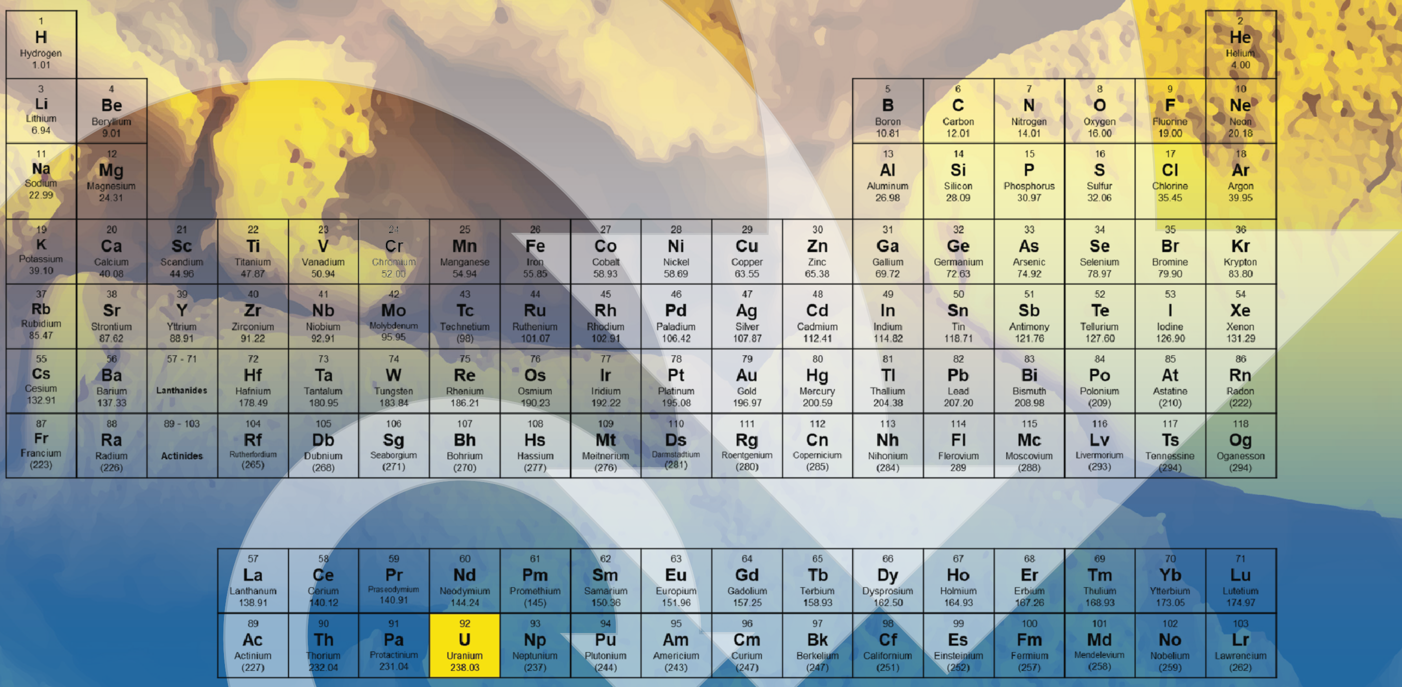

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Contents

Abstract

Nuclear energy supplies nearly 24% of EU electricity, and 95% of nuclear fuel—uranium—is imported from a handful of countries. Yet uranium is outside the EU Critical Raw Materials framework, and there is no formal circular economy strategy in place to address both resource security and waste management concerns. As the EU expands its nuclear capacity to meet decarbonisation and energy security goals, adopting a circular economy approach across the uranium supply chain becomes imperative. This report provides the first comprehensive analysis on the subject, identifying twelve circularity patterns ranging from recovering mining tailings to spent fuel reprocessing and accelerator-driven waste transmutation. A systematic review of 1,383 scientific articles reveals that circular economy research in this domain is growing rapidly but remains highly fragmented, mainly focused on end-of-life reprocessing, and stuck at medium technology readiness levels, with no study to date adopting a holistic multi-strategy perspective. Circularity is not merely an ambition: reprocessed nuclear fuel already offsets nearly 5% of annual EU natural uranium requirements, and projected secondary source use is set to triple by 2034, making recycling a concrete instrument of energy security. Moving beyond incremental measures, a holistic view of all circular strategies across the supply chain is now essential. Key EU policy actions going forward may include: funding R&I to advance circular nuclear technologies toward industrial scale and their mutual integration; addressing Euratom's ambitions for a "circular nuclear economy" by embedding circularity as an explicit pillar in nuclear coordination mechanisms; and including uranium in the Critical Raw Materials list to establish binding targets for fuel reprocessing and supply chain resource efficiency.

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Executive summary

Policy context

Why does circularity in the uranium supply chain matter for EU policy now?

Nuclear energy contributes nearly 24% of EU electricity generation, yet uranium supply remains 95% import-dependent, geographically concentrated, and outside the EU Critical Raw Materials (CRM) framework. At the same time, nuclear waste management represents one of the most complex and costly environmental and safety challenges in the energy sector. As the EU expands its nuclear capacity to meet decarbonisation and energy security goals—reinforced by the 2024 Brussels Nuclear Energy Summit and the REPowerEU Plan—addressing uranium supply vulnerabilities and waste management challenges through circular economy strategies becomes a matter of strategic urgency.

This report was developed by the JRC's Centre for Advanced Studies in collaboration with JRC Unit B.5 Circular Economy and Sustainable Industry. It directly complements the Critical Raw Materials Act, the Net Zero Industry Act, and ongoing work by EU nuclear coordination mechanisms. It adds value by providing the first holistic, supply-chain-wide analysis of circular economy strategies for uranium—a gap not addressed by previous research.

Key conclusions

Circularity is essential—not optional—across the uranium supply chain.

Circular economy strategies in the uranium supply chain are not merely an aspiration. They respond simultaneously to four distinct policy imperatives: reducing the health and safety risks associated with highly hazardous nuclear waste; mitigating the environmental footprint of uranium mining and processing; strengthening EU energy security by reducing import dependency; and improving the economic competitiveness of the nuclear fuel cycle. Addressing these challenges in isolation is insufficient—a holistic approach integrating multiple strategies across all supply chain stages is needed.

The current situation reveals both progress and significant gaps.

Reprocessed uranium and mixed oxide (MOX) fuel—which combines plutonium recovered from spent fuel with uranium—already offset nearly 5% of annual EU natural uranium requirements, and this share is projected to triple by 2034. France alone derives 17% of its electricity from recycled nuclear fuel. However, only 7 of 27 EU Member States currently reprocess or plan to reprocess spent fuel, and promising circular technologies—such as pyroprocessing and accelerator-driven waste transmutation systems—remain far from commercial deployment, operating at low to medium technology readiness levels. Scientific research on the topic is growing rapidly but is highly fragmented, concentrated almost exclusively on end-of-life reprocessing, and no study to date has adopted a truly holistic, multi-strategy perspective across the full supply chain.

Three policy directions emerge from the analysis:

— Funding R&I to advance circular solutions toward industrial scale, such as pyroprocessing, fast reactor technologies within Small Modular Reactors (SMRs), minor actinide transmutation, zirconium cladding recycling, and uranium and rare earth element recovery from mining tailings. Current EU-funded nuclear R&I programmes do not explicitly prioritise circular economy objectives, representing a gap to be addressed under future R&I programmes.

— Embedding circularity as an explicit pillar in existing EU nuclear coordination mechanisms, including the Euratom Supply Agency, Nucleareurope, and the European Industrial Alliance on SMRs. The Euratom Supply Agency has itself called for a "circular nuclear economy"—this ambition deserves concrete institutional follow-through.

— Considering the inclusion of uranium in the EU Critical Raw Materials list, which would pave the way towards proportionate circularity benchmarks, including minimum targets for fuel reprocessing, and recycled fuel utilisation—analogous to binding requirements already established for batteries under Regulation (EU) 2023/1542.

Main findings

Twelve circular economy patterns identified across the supply chain.

The uranium supply chain offers circularity opportunities at every stage. Upstream, these include optimising water use and mineral extraction in in-situ leaching, recovering residual uranium and rare earth elements from mine tailings, and re-enriching depleted uranium. Downstream, they include spent fuel reprocessing via the PUREX process, emerging pyroprocessing technologies, zirconium cladding recycling, and accelerator-driven systems to reduce the volume and radioactivity of final waste. In the use phase, fast reactors and Small Modular Reactors can dramatically improve fuel efficiency and reduce waste generation. Nine of these patterns relate directly to uranium; three concern valuable co-materials in the supply chain.

Scientific research is growing but fragmented.

A systematic analysis of 1,383 peer-reviewed articles shows that circularity research for uranium has accelerated sharply since 2020, but 65% of articles focus exclusively on end-of-life waste management, most technologies remain at validation stage (TRL 5–6), and no single study simultaneously considers multiple circular economy strategies across multiple supply chain stages.

EU supply security and waste management are two sides of the same coin.

With 84% of EU uranium sourced from just four countries and contractual coverage projected to decline after 2032, increasing the share of secondary sources through circular practices is a direct contribution to supply resilience. At the same time, reducing the volume and hazardousness of nuclear waste through advanced reprocessing lowers the burden and cost of permanent geological disposal.

Related and future Joint Research Centre work

This report complements JRC work at the intersection of circular economy, critical raw materials, and strategic technology supply chains. The JRC foresight study on supply chains and material demand for strategic technologies provides a comprehensive analysis of EU supply vulnerabilities and critical raw material needs across fifteen key technologies in five sectors. Nuclear energy and uranium are not part of this foresight framework, and uranium is currently absent from the EU Critical Raw Materials list, despite the strategic importance of nuclear for decarbonisation and energy security. This gap is beginning to be addressed through a second, complementary line of JRC nuclear work. Recent JRC studies have examined EU nuclear fuel strategic autonomy, mapping dependencies across the full nuclear fuel cycle and the geopolitical risks they entail, and conducted long-term horizon scanning for nuclear technologies, flagging the growing importance of circularity in the nuclear fuel cycle without analysing it in depth. The JRC Portfolio on Safety of Nuclear Technology further underlines the need for advanced waste-minimising technologies as part of the

EU's climate neutrality transition. The present report aims to contribute to this important trajectory with a deeper focus on circularity by providing the first systematic circularity analysis of the uranium supply chain. This report combines narrative review with an LLM-assisted systematic mapping of the literature, and the quantitative results should therefore be interpreted as indicative rather than exhaustive. Follow-up work should include qualitative stakeholder engagement across the uranium supply chain, quantitative scenario modelling of circular economy impacts on EU supply security, and deeper integration of circularity into future JRC nuclear fuel strategic autonomy assessments.

Quick guide

The uranium supply chain encompasses all steps from mining and milling through enrichment, fuel fabrication, reactor use, and finally waste storage or reprocessing. The circular economy refers to strategies that keep materials in use for as long as possible — including recycling, reuse, and resource recovery — as opposed to linear "take-make-dispose" approaches. Technology Readiness Level (TRL) is a scale from 1 (basic research) to 9 (fully deployed technology) used to assess the maturity of an innovation.

1. Introduction

Uranium is a naturally occurring heavy metal used primarily as fuel in nuclear reactors for electricity generation. It is an essential component of the nuclear energy supply chain, where it undergoes a series of processes including mining, milling, conversion, enrichment, and fuel fabrication. The uranium supply chain is geographically concentrated, with a few countries dominating global production. As of recent data, Kazakhstan is the largest producer, followed by Canada and Australia (Nuclear Energy Agency, 2023). Uranium extraction is often controlled by a limited number of companies, and geopolitical factors can impact its availability. This concentration of supply presents potential risks to energy security and price stability, making diversification of sources a topic of ongoing discussion in the energy policy arena (van Uffelen and Tanarro Colodron, 2024). The primary demand for uranium comes from the energy sector, where it is used in nuclear reactors to generate a significant share of global electricity. In 2024, net electricity generation from the 101 reactor units operating in the EU reached 617.3 TWh, accounting for 23.71% of all electricity production in the EU (Euratom Supply Agency, 2025).

Despite its economic importance and potential supply risks, Uranium is currently not included in the EU policy framework for resource security laid out by the Critical Raw Materials Act (European Parliament and Council, 2024). However, this might change going forward, considering the outcomes of the Nuclear Energy Summit held in Brussels in March 2024, where several country and industry leaders affirmed the importance of developing this power source further, to achieve energy security and climate goals (International Atomic Energy Agency, 2024). There is a growing interest in nuclear energy also in the EU, including among Member States that previously did not utilize this energy source or had taken nuclear phase-out decisions (Euratom Supply Agency, 2025).

Considering these developments, understanding the role of resource efficiency strategies (i.e., circular economy) in the supply chain of uranium for nuclear energy applications becomes important. While the nuclear market expands, alongside the required development of the fuel cycle and services, it will become increasingly crucial to reduce to the extent possible uranium imports and demand for services. Relatedly the Euratom Supply Agency has stressed the importance to promote a "circular nuclear economy" (Euratom Supply Agency, 2025). Research and Innovation in this sense is crucial. The Joint Research Centre of the EU Commission already performed studies on circularity research and innovation for other strategic technologies and sectors (e.g., Baldassarre et al., 2023a, 2023b; Buesa et al., 2023, 2024, 2025a, 2025b; Carrara et al., 2023, 2025). For nuclear energy, however, dedicated circularity research is scant. Notably, the Joint Research Centre recently conducted a long-term horizon scanning study on nuclear technologies, which mentions the relevance of increasing circularity in the EU nuclear fuel cycle, but does not analyse this aspect in detail (Tanarro Colodron et al., 2024). Oversea, another important analysis was performed by the United States Department of Energy (2022), encompassing an in-depth supply chain assessment, which discusses recycling and reprocessing of spent nuclear fuel. Few academic studies with an explicit circular economy focus are also present. For example, Pucciarelli et al. (2024) use a life cycle assessment method to quantify the benefits of using depleted uranium to produce uranyl nitrate, a chemical use for nuclear waste reprocessing, as well as the impacts of recycling zirconium metal recovered from this process. Levett et al. (2024) discuss technological solutions to recover rare earth metal by-product from uranium mine tailing. While these studies focus on important circularity aspects, they do so in segmented way, isolating specific topics from a certain disciplinary perspective. Comprehensive studies discussing circularity along the entire a supply chain of uranium, including its main nuclear energy and other application, is to date missing.

The present report aims to address this knowledge gap by gathering and analysing available interdisciplinary knowledge on circularity in the supply chain of uranium. First, a detailed description of the supply chain and its main circularity patterns is conducted by means of narrative literature review. The outcome is presented in section 3.1 and visualized in Figure 1. Subsequently, a systematic analysis of scientific literature on the subject is carried out using a large language model to categorize the dataset of existing articles according to their focus on different supply chain stages and circular economy strategies. The outcome is presented in section 3.2 and visualised in Figures 2, 3, 4 and 5. The methods employed are explained in section 2. Ultimately the report puts forward eight main insights related to circularity in the uranium supply chain and, based on that, two directions for future research and three policy options are proposed.

From a scientific perspective, this report addresses a critical knowledge gap: to date, no study has examined circularity holistically across the entire uranium supply chain, and the existing literature remains highly siloed across individual stages and disciplines—a pattern documented more broadly for critical raw materials (Schrijvers et al., 2020) and confirmed here through systematic analysis. This work aims to serve as a call to action and a structured starting point for future, more comprehensive inquiry, building on analogous holistic approaches developed for other strategic supply chains such as hydrogen technologies (Axt et al., 2025), titanium in aerospace and defence (Buesa et al., 2025a), and wind turbines (Carrara et al., 2025). From a practical perspective, the findings are directly relevant to framing EU industrial policy responses to two interlinked challenges: uranium supply security, given the high geographic concentration of supply and ongoing geopolitical pressures (van Uffelen & Tanarro Colodron, 2024; Euratom Supply Agency, 2025); and nuclear waste management, given the complexity and cost of permanent disposal (European Commission, 2024b; Théodon et al., 2024). By mapping where circular economy research and industrial practice currently stand—and where the most significant gaps lie—the report provides an evidence base contributing to inform upcoming policy decisions, research funding priorities, and coordination efforts across the EU nuclear sector.

2. Method

This section provides a concise explanation of the method employed in the research work underlying this report. First a narrative literature review method is employed to derive a detailed description of the uranium supply chain and its circularity patterns.

Narrative literature reviews are suitable to gather multidisciplinary knowledge into concise reports, which can provide a landscape to guide future research. The method has been used in former circular economy research chains (Blomsma and Brennan, 2017), as well as for the analysis of the supply chains of strategic technologies (Axt et al., 2023, 2025) and critical raw materials (Albizzati et al., 2025a, 2025b). To overcome knowledge fragmentation and capture recent information, data was gathered from both scientific and grey literature (industry and policymaking reports, news articles), progressively expanding it with a snowballing approach (Wohlin, 2014). In line approaches used in former research on circularity using the supply chain as unit of analysis, literature data is processed and aggregated into text and into a network-type visualization where circular economy patterns and mapped (Baldassarre, 2025; Miles et al., 2013).

Subsequently, a systematic analysis of scientific literature on circular economy strategies in the uranium supply chain is conducted. While the full methodology for this analysis is detailed in Annex 1, the following paragraphs provide a shorter overview.

The goal of the analysis is systematically identifying and analysing scientific articles on the circular economy in the uranium supply chain. The boundaries of the analysis are defined as follows:

- Considering all the uranium supply chain stages, defined according to the literature and reported in Table 1.
- Considering the entire spectrum of circularity strategies, defined according to the literature and reported in Table 2.
- Considering the Technology Readiness Levels (TRLs) for each strategy in the supply chain. TRLs are defined according to the literature and reported in table 3.
- The structural components and materials (e.g., concrete, steel) of nuclear power plants remain outside the scope of the analysis.

Table 1. Stages in the uranium supply chain.

1. Extraction: The process of obtaining uranium ore from the earth	**1a. Mining:** Techniques such as open-pit, underground, or in-situ recovery to extract uranium ore.
2. Processing: The transformation of raw uranium into usable forms for further refinement.	**2a. Milling:** Crushing uranium ore to extract uranium oxide, commonly called "yellowcake."
	2b. Conversion: Converting yellowcake into uranium hexafluoride (UF_6) for enrichment.
3. Manufacturing: Creating nuclear fuel and components from processed uranium.	**3a. Enrichment:** Increasing the concentration of fissile U-235 isotope in uranium.
	3b. Fuel fabrication: Producing nuclear fuel pellets from enriched uranium.
	3c. Fuel unit assembly: Arranging fuel rods into assemblies for reactor use.
4. Use: Utilizing nuclear fuel to generate energy in reactors.	**4a. Use in the energy sector:** Reactor use / nuclear fission: Producing heat and energy by splitting uranium atoms.
	4b. Use in the medical sector: Utilizes by-products of uranium fission, such as isotopes, for diagnostic imaging, cancer treatment, and sterilization of medical tools.
	4c. Use in defence and space sector: Employs enriched uranium for military applications, such as naval propulsion and nuclear weapons, as well as space missions.
5. End-of-life: Handling and storing spent nuclear fuel and waste.	**5a. Spent fuel reprocessing:** Recovering usable materials from used nuclear fuel.
	5b. Wet storage: Cooling spent fuel in pools of water immediately after removal.
	5c. Dry storage: Storing cooled spent fuel in secure, sealed casks.
	5d. Permanent storage: Disposing of nuclear waste in deep geological repositories.
	5e. Other waste management: waste management for applications that are not nuclear fuel.

Source: Texas A&M University, 2017; Unites States Department of Energy, 2022.

Table 2. Circular economy strategies.

1. Narrow resource flows: Minimizing the input of resources, thereby narrowing input flows in the production process.	**1.1. Refuse:** Avoiding the use of a material or product by either substituting it or eliminating its function, or by fulfilling the same function with a completely different product.
	1.2. Rethink: Enhancing the utilization of a material or product, often through sharing co-production or other means to increase resource-efficiency or use intensity.
	1.3. Reduce: Improve efficiency in the manufacturing processes to consume fewer natural resources and materials.
2. Slow resource flows: Extending the lifetime of products and components, thereby slowing down the flow of resources.	**2.1. Reuse:** Extend the life of a product by allowing another consumer to use a discarded product that is still in good condition and can fulfil its original function.
	2.2. Repair: Maintain or fix a defective product to enable its continued use with its original function.
	2.3. Refurbish: Update and restore an old product to bring it up to date.
	2.4. Remanufacture: Incorporate parts of a discarded product into a new product that serves the same function as the original.
	2.5. Repurpose: Use a discarded product or its parts in a new product that serves a different function from the original.
3. Close Resource flows: Preventing waste of material and energy, thereby closing resource flows.	**3.1. Recycle:** Process materials to obtain the same or a lower grade quality, such as through functional recycling or downcycling.
	3.2. Recover: Extract energy from end-of-life materials, typically through incineration with energy recovery.
4. Regenerate resource flows: Using renewable resources and restoring the natural environment	**4.1. Restore:** Restore natural ecosystems affected by industrial processes
	4.2. Renewable resources: Use renewable energy and materials within industrial processes

Source: Baldassarre & Saveyn, 2023; Bocken et al., 2016; Kirchherr et al., 2023.

Table 3. Technology readiness levels (TRL).

TRL 1	Basic principles observed.
TRL 2	Technology concept formulated.
TRL 3	Experimental proof of concept.
TRL 4	Technology validated in lab.
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
TRL 7	System prototype demonstration in operational environment.
TRL 8	System complete and qualified.
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

Source: Bruno et al., 2020

Scientific articles were searched in the Web of Science database using a comprehensive search string combining uranium-related terms (e.g., “U-235,” “yellowcake,” “spent fuel,” “nuclear reactor”) with an economy/resource-efficiency terms (e.g., “recycle,” “reuse,” “remanufacture,” “eco-design,” “material flow analysis,” etc.). The output consisted in a spreadsheet including 17,598 articles metadata and abstracts.

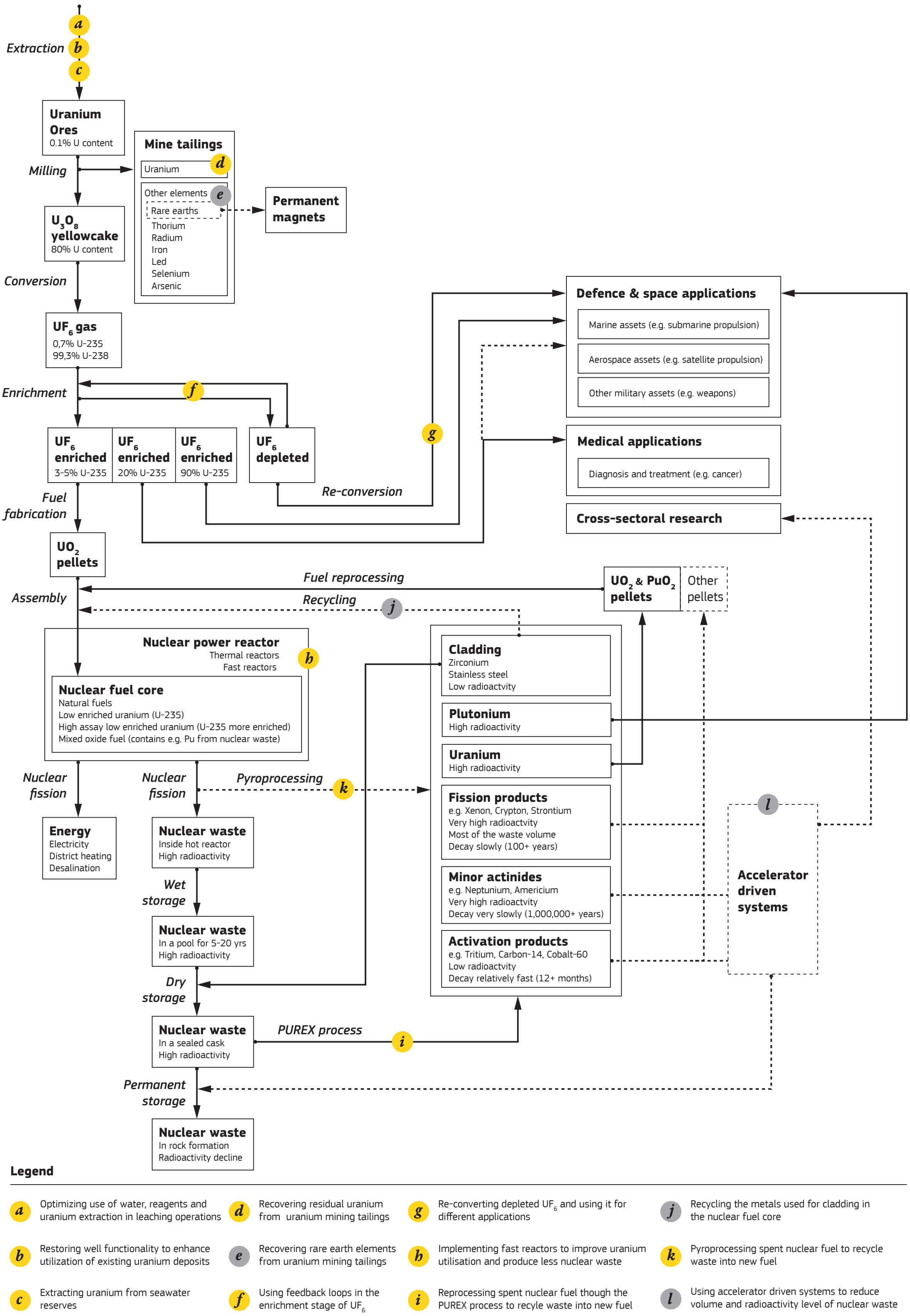
A successive filtering step was applied on the abstracts using a Large Language Model (LLM) leveraging multiple prompts to narrow down the sample based on relevance. For each abstract, the prompt required the LLM to reply to a set of key questions (e.g., To which uranium supply chain stage(s) is the abstract related, if any? To which circular economy strategy is the abstract related, if any? Could a TRL possibly be estimated?) After receiving LLM outputs, additional filters were applied to reveal the most relevant literature in this space. The relevance score of each abstract could range from 0 to 5 and retention score was set to 4 or higher. Abstracts related to TRL lower than 5 were excluded. Outdated or uncited abstracts were also excluded. This resulted in a final sample of relevant 1,383 articles categorised according to supply chain stage, circular economy strategy and TRL. Since an abstract can discuss multiple segments of the uranium supply chain and propose several circular economy strategies the final categorisation from the LLM included double counting (e.g., if an abstract discusses resource efficiency in the uranium mining stage and spent nuclear fuel recycling, it is included twice in the data frame at different locations). This resulted in 4,313 items in a final data frame, each reflecting a unique combination of supply chain stage × circular economy strategy.

3. Results

3.1. Description of the uranium supply chain and its circularity patterns

Figure 1 shows the uranium supply chain, including its different sectorial applications as well as main circularity patterns. The main supply chain processes are depicted with black arrows. The processes that are currently still in a research phase and / or not implemented at full industrial scale (e.g., pyroprocessing, cladding material recycling, etc.), are depicted with dashed arrows. The circular economy patterns are marked with coloured dots. Each dot has been assigned a specific letter, and the related circular economy pattern is briefly described in the legend at the bottom of the figure. Yellow dots relate specifically to uranium circularity while grey dots concern the circularity of other elements closely related to uranium in the supply chain.

Figure 1. Uranium supply chain and its circular economy patterns.



Source: JRC analysis.

3.1.1. Extraction and processing

The nuclear fuel supply chain is complex and globally distributed. Only a few countries—Japan, France, India, and China—have fully developed fuel cycles, while many others operate reactors and import nuclear fuel (Texas A&M University, 2017).

Uranium extraction begins with ore deposits that, while abundant in Earth's crust, are rarely concentrated enough for economically viable mining except in geological anomalies. These deposits typically occur in hard rock formations, often beneath oil and gas layers, and contain only about 0.1% uranium (Texas A&M University, 2017). Exploration relies on scintillation detectors mounted on aerial vehicles to locate viable deposits. Globally, the largest uranium resources extractable for less than $130/kg are found in Australia (28%), Kazakhstan (15%), Russia (8%), Canada (9%), Namibia (7%), Brazil (5%), South Africa (5%), China (4%), Niger (4%), Uzbekistan (2%), Mongolia (2%), Ukraine (2%), Jordan (1%), Tanzania (1%), and the United States (1%) (United States Department of Energy, 2022).

Three primary extraction methods exist (Texas A&M University, 2017):

- Open pit mining for deposits within 100 meters of the surface
- Underground mining through tunnel systems, which is more dangerous and often co-extracts gold and copper
- In-situ leaching (ISL), which pumps water mixed with sodium carbonate into the deposit and extracts the uranium-bearing solution. ISL is more cost-effective and environmentally friendly, with potential for water recycling, but can only be applied when underground minerals are water-soluble.

An important circular economy pattern in the extraction phase relates to optimizing water use and uranium recovery in in-situ leaching operations, which represents the most environmentally friendly extraction method (see “a” in figure 1). In-situ leaching requires large volumes of water mixed with leaching chemicals. The development of closed-loop water recycling systems within in-situ leaching operations can substantially reduce freshwater consumption while maintaining extraction efficiency, though successful implementation depends on local geological conditions that allow water to flow through the rock formations (Zeng et al., 2024). Water management strategies are critical for environmental reasons and go hand-in-hand with uranium resource efficiency. Adjusting the timing, flow rates and composition of solution injection and extraction can significantly improve uranium recovery by spreading the leaching agents more evenly throughout the underground ore body, thereby increasing contact between the chemical solutions and uranium minerals (Wang et al., 2024). Leaching conditions can be optimized, including controlled acid concentration, temperature, and particle size. (Raji et al., 2024, 2025). This periodic pumping approach not only enhances uranium extraction but also helps reduce the formation of mineral deposits (like gypsum) that can block the flow paths underground. Another important circular economy pattern in the extraction phase relates to specialized applications for repairing wells to enhance utilization of existing uranium deposits (see “b” in figure 1). (Kuandykov et al., 2020). Beyond terrestrial sources, uranium extraction from seawater (see “c” in figure 1) represents has a vast potential, given the reserves of approximately 4.5 billion tonnes compared to 17 million tonnes in terrestrial reserves, thus offering long-term supply security (Guidez & Gabriel, 2016). Recent laboratory advances have achieved interesting adsorption capacities from natural seawater (Zhang et al., 2024). However, economic barriers remain substantial, with extraction costs estimated at $300–600/kg, significantly exceeding current market prices of about $130/kg (Lindner & Schneider, 2015). Additional challenges include large deployment areas, limited adsorbent durability, and low energy return on investment.

Consequently, seawater extraction is currently uncompetitive but may serve as a strategic backstop option under conditions of rising uranium prices or terrestrial resource depletion.

After extraction, uranium production takes place through milling. Milling typically occurs at the mine site through a multi-stage process: crushing, sampling, grinding, leaching, washing, thickening, extraction, stripping, precipitation, filtration, drying, and packaging. This process produces U_3O_8 (uranium yellowcake) with approximately 80% uranium content alongside other minerals (Texas A&M University, 2017). In 2020, world uranium production reached a total of 47,342 tons, with Kazakhstan maintaining a dominant lead by producing 41% of the global supply. Other major contributors included Australia at 13%, Namibia at 12%, and both Canada and Uzbekistan at 8% each. Smaller shares were provided by Russia and Niger at 6% each, followed by China (3%) and Ukraine (2%) (Nuclear Energy Agency, 2023). As global demand of uranium for nuclear reactors is expected to expand by 30% over the next 5 years, the role of Kazakhstan as a global supplier is also expected to grow (Center for Strategic and International Studies, 2025). In 2023, the EU sourced the majority of its uranium from Canada, Kazakhstan, and Niger, which together represented 68% of total supply, while Russia accounted for a further 23%. In 2024, the top four supplier countries were Canada (33.90%), Kazakhstan (24.25%), Russia (15.63%), and Australia (10.54%), together accounting for 84% of total EU uranium supplies. The concentration of supply from the CIS countries decreased to less than 41.7% in 2024, down from 46.3% the year before, with Russia's share declining by 36.1% year-on-year (Euratom Supply Agency, 2025). A major EU player in the industry is the French company Orano, which provided approximately 9% of worldwide uranium output in 2021 through mining operations in Canada, Kazakhstan, and Niger (van Uffelen and Tanarro Colodron, 2024). The milling process generates tailings stored in ponds or piles that require ongoing environmental monitoring due to groundwater contamination risks. These tailings contain radioactive byproducts including thorium and radium, which need to be handled with care, as well valuable materials including rare earth elements, vanadium, iron, lead, selenium, and arsenic (Texas A&M University, 2017).

Circularity at the milling stage focuses on the residual uranium remaining in tailings (typically 0.05-0.4% uranium content). This can be recovered through advanced electro-assisted leaching methods, achieving extraction rates up to 95% compared to 55% with conventional methods, thereby reducing both waste volumes and environmental contamination while extending uranium resource availability (Dong et al., 2020) (see “d” in figure 1). It is also possible to recover valuable by-products from uranium tailings. Recent studies reveal that uranium tailings can contain approximately 3% total rare earth element (REE) content, which are particularly valuable for the production of permanent magnets used for wind energy and electric mobility applications (Baldassarre et al., 2023; Carrara et al., 2025; Tandy et al., 2024) (see “e” in figure 1). Significant portions are water-soluble—enabling potential in-situ extraction methods that could recover over 10,000 tonnes of REEs from a single tailings site, potentially exceeding the original uranium recovery (Tandy et al., 2024). Advanced separation techniques, including electrochemical methods and molecular sieve adsorption systems, have demonstrated removal efficiencies exceeding 99% for certain rare earth elements from uranium tailings, supporting both resource recovery and environmental remediation objectives (Levett al., 2024; Zhang et al., 2025). This approach offers the economic rehabilitation of abandoned mine sites while reducing environmental contamination risks, converting environmental liabilities into valuable secondary resources.

Yellowcake undergoes conversion (crystalline solid to gas) to produce UF_6 (uranium hexafluoride), which contains 0.7% U-235 isotopes and 99.3% U-238. Since only U-235 is suitable for nuclear fission, enrichment becomes necessary (Texas A&M University, 2017). Enrichment increases the relative concentration of U-235 isotopes from 0.7% to 3-5% for energy applications. This technically complex process can be accomplished through two main methods (Texas A&M University, 2017):

- Gaseous diffusion uses pressurized pipelines with sequential filter systems (barriers with tiny holes) and feedback loops. While this established technology has lower initial costs, it requires extensive space, long pipelines, higher operational costs, and more maintenance.
- Gaseous centrifuge technology is more advanced, offering faster processing and better energy efficiency through rotating cylinders in series that separate heavier U-238 isotopes (drawn from the outside) from lighter U-235 (extracted from the center). However, it requires higher initial investment and presents additional safety concerns.

Globally, Russia's Rosatom leads the enrichment market, holding a 43% share, and in 2023, Russian deliveries accounted for 38% of the EU's enrichment services. Despite this, Russian nuclear imports represented only about 1% of the EU's total imports of Russian gas in 2022. In 2024, however, EU enrichers increased their share to 63.9% of enrichment services provided to EU utilities. Russian enrichment accounted for 23.55% of the total (down from 37.9% in 2023), supplying 47.3% less enrichment services than the previous year (Euratom Supply Agency, 2025). Within the EU, Orano and Urenco provided 55% of enrichment services in 2023. Urenco, headquartered in the Netherlands and jointly owned by the UK, Germany, and the Netherlands, specializes solely in uranium enrichment, operating facilities in Europe and the United States. Both Urenco and Orano companies are expanding capacity to strengthen EU supply: Orano plans a 30% increase by 2028, while Urenco will expand its Dutch enrichment plant by 15% by 2027 (van Uffelen and Tanarro Colodron, 2024).

Circularity is achieved through feedback loops that re-enrich depleted UF_6 with low U-235 content (Unites States Department of Energy, 2022) (see "f" in figure 1). The final depleted UF_6 can be reconverted to uranium dioxide (UO_2) or uranium metal for applications outside the energy sector (see "g" in figure 1). The EU's approach to conversion services also reflects increasing diversification efforts: in 2024, Russia (Rosatom) remained the largest supplier with a 22.4% market share despite a 16% decrease from 2023, while Converdyn (United States) increased its EU market share by 18.4%, and Orano (EU) represented 21.3% of the market (Euratom Supply Agency, 2025).

3.1.2. Manufacturing and use

Enriched UF_6 undergoes fuel fabrication through reconversion to uranium dioxide powder and formation into UO_2 pellets, which requires sintering at high temperature. The pellets are then assembled into the nuclear fuel core through a precise configuration: 426 pellets are loaded into 3-meter-long zirconium alloy tubes, creating 264 rods that form one assembly unit; 193 such assemblies constitute a complete reactor core (Texas A&M University, 2017).

Nuclear fuel types include (Unites States Department of Energy, 2022):

- Natural fuels
- Low enriched uranium (LEU)
- High assay low enriched uranium (HALEU, with higher U-235 concentration)
- Mixed oxide fuel (MOX, containing plutonium from reprocessed waste)

The core inside a reactor of a power plant is mainly for electricity generation. In parallel the heat can be used in District heating and for Desalination. Reactor types fall into two broad categories (Unites States Department of Energy, 2022):

— Thermal reactors use moderators to slow down neutrons and include:

- *Light Water Reactors (LWR)* operate on LEU fuel with light water serving as both moderator and coolant. They offer high efficiency with standardized, less flexible operations but face high operating pressures and temperatures. These reactors include pressurized water reactors (dual-loop system) and boiling water reactors (single circuit). They produce significant waste with moderate proliferation risk and moderate costs.

- *Heavy Water Reactors (HWR)* use deuterium-based heavy water as moderator with either heavy or light water cooling in dual-loop systems. They can operate on natural uranium, LEU, or other fuel types with moderate efficiency. The flexibility to use various fuels and refuel during operation comes with higher costs due to heavy water requirements and elevated proliferation risks.

- *Graphite Moderated Reactors* (formerly common in the USSR) use graphite as moderator with gas or light water cooling. They can run on natural uranium, LEU, or MOX fuel, offering high efficiency and fuel flexibility. However, they face concerns regarding graphite degradation, have variable proliferation risk depending on design, and require complex waste management with variable costs.

— Fast reactors employ multi-loop systems with gas or liquid metal coolant without neutron moderators. Despite their compact size (potentially as small as a trash can), they represent very complex technology. The liquid metal coolant becomes highly radioactive and poses fire risks. These reactors use MOX fuel and achieve much higher fuel efficiency by producing their own fuel during fission, requiring less frequent refueling. However, they also produce more plutonium, creating proliferation risks, and require high enriched uranium fuel, which is more complex to produce than LEU. Currently, Russia, China, and India operate fast reactors for energy production, while Japan, France, the United States, and South Korea pursue research and development. Interest in fast reactors stems from their potential for improved fuel efficiency, waste reduction, and nuclear energy sustainability.

Fast reactors dramatically improve uranium resource utilization by converting the abundant but non-fissile uranium-238 isotope (which comprises 99.3% of natural uranium) into fissile plutonium-239 through a process called breeding. While conventional thermal reactors can utilize less than 1% of natural uranium, fast reactors can fission up to 60% of the uranium, representing a 60-fold improvement in fuel efficiency (World Nuclear Association, 2021). This is achieved through breeding ratios typically ranging from 1.1 to 1.4, meaning the reactor produces 10-40% more fissile material than it consumes (Nishihara et al., 2021). Fast reactors also achieve much higher fuel burnup rates allowing to produce less radioactive waste, while the fuel to remains productive for longer periods requiring less frequent replacement (World Nuclear Association, 2021) (see "h" in figure 1).

Future nuclear reactor designs are expected to feature Small Modular Reactors (SMRs) and microreactors. (Unites States Department of Energy, 2022). These emerging nuclear reactor technologies—Small Modular Reactors (SMRs) and microreactors—offer significant sustainability and resource efficiency advantages that complement fast reactor innovations (Black et al., 2023; European Commission, 2024; Unites States Department of Energy, 2022). These compact designs emphasize factory-based modular manufacturing rather than on-site construction, reducing construction timelines, minimizing ground disruption (less than 2 acres for some designs), and enabling economies of scale through serial production (Tanarro Colodron et al., 2024). From a resource efficiency perspective, both SMRs and microreactors can operate for extended periods without refuelling—some designs run for 8-15 years between fuel changes—substantially reducing fuel transportation requirements and associated carbon emissions (Testoni et al., 2021). Microreactors are specifically designed for remote, off-grid, or emergency deployment scenarios, providing energy resilience to isolated communities, mining operations, military installations, and disaster relief operations where conventional grid infrastructure is absent or unreliable (Black et al., 2023). In February 2024, the European Commission launched the European Industrial Alliance on Small Modular Reactors, aimed at accelerating the development and deployment of SMRs across Europe by the early 2030s (Euratom Supply Agency, 2025). Importantly, several SMR designs under development in Europe employ fast reactor technology, which combine the fuel efficiency benefits of fast neutron spectrum operation with the scalability and safety features of modular designs. The European Industrial Alliance on SMRs has selected multiple lead-cooled fast reactor projects, including the EU-SMR-LFR and newcleo's LFR-AS designs, specifically for their significantly higher fuel efficiency (European Commission, 2024a; Power Magazine, 2024). Furthermore, these advanced fast SMRs can use mixed oxide fuel containing plutonium recovered from reprocessing, thereby transforming long-lived radioactive waste into valuable fuel while maintaining the modularity, transportability, and passive safety systems that characterize small modular and microreactor technologies (Euratom Supply Agency, 2025).

Applications of uranium outside the energy sector include (Texas A&M University, 2017):

- Defence and space sector: uranium is used for nuclear propulsion in submarines at an industrial scale. It has also been tested experimentally for nuclear propulsion in spacecraft and satellites. Additionally, uranium can be processed into plutonium isotopes for weapons production using primary yellowcake, while depleted uranium is typically used in military applications such as armour piercing projectiles and protective armour.
- Medical sector: in medicine, uranium is primarily used to produce radioisotopes. These isotopes are applied for diagnostic imaging as well as therapeutic treatments. One notable use is in cancer therapy, where uranium is primarily used to produce radioisotopes for diagnostic imaging and therapeutic treatments.
- Cross-sectoral research applications: Uranium plays an important role in scientific research across multiple fields. It is used in nuclear physics experiments to study atomic behaviour. Radiochemistry and materials testing also rely on uranium for experiments and cross-sectoral applications. In the field of medical radioisotopes, the EU's dependency on foreign supply chains remains a major vulnerability, and urgent diversification and establishment of domestic production capabilities are recommended (Euratom Supply Agency, 2025).

3.1.3. End of life

Nuclear fission produces hot, high-level radioactive nuclear waste. Spent nuclear fuel is extremely radioactive, intensely hot, and poses immediate, lethal risks to human health. This waste requires careful handling through multiple storage stages with rigorous safety measures including shielding, remote handling, and secure containment.

Wet storage serves as the initial containment method. The reactor core is placed in barrels submerged in cooling pools for a minimum of 5 to 20 years (Texas A&M University, 2017). During this period, radioactivity and heat generation decrease significantly, though the spent fuel remains highly dangerous. Pool storage capacity limitations present ongoing challenges. All transportation during this phase is handled with extreme care.

Dry storage follows wet storage. The core is transferred to sealed casks subject to government regulatory approval. These casks are placed in temporary locations awaiting permanent disposal, with all transportation carefully managed (Texas A&M University, 2017).

Permanent storage involves underground placement in deep geological repositories designed for isolating the high-level radioactive waste for thousands of years. Multiple engineered barriers—metal canisters, clay buffers, and geological features—prevent radionuclide migration to the biosphere. Long-term monitoring remains essential to ensure site integrity and detect potential leaks or failures. Permanent storage is complex and expensive, and can be financed through government fees levied on utilities per kilowatt-hour generated; Until 2017, the United States had collected approximately $27 billion USD has in waste taxes for this purpose (Texas A&M University, 2017). A repository project at Yucca Mountain, Nevada had been studied since 1978, for disposal of over 70,000 metric tons of spent fuel and high-level waste. However, this has faced persistent technical, political, and legal challenges (Klaus, 2024). Despite being formally selected by Congress in 1987 and approved in 2002, funding was terminated under in 2010, due to concerns over geological suitability transportation safety, and strong political opposition from Nevada (United States Congress, 2025; Klaus, 2024). In the EU, significant policy developments have advanced nuclear waste management strategies. Already in 2011 EU Directive 2011/70/EURATOM established binding legal frameworks requiring all 27 Member States to develop national programmes for safe radioactive waste management by 2015, with mandatory three-year implementation reports (Council of the European Union, 2011). The third implementation report completed in 2024 indicates that deep geological repositories are progressing across Europe: Finland, France and Sweden progressed substantially in this direction and maintained ambitious plans (European Commission, 2024b). Finland's Onkalo repository represents the most advanced case. Located 430-520 meters underground in the granite bedrock near the Olkiluoto Nuclear Power Plant, Onkalo began full-system trials in August 2024 and is expected to begin operational disposal in 2025-2026, making it the world's first operational deep geological repository for spent nuclear fuel (Nuclear Newswire, 2024). The repository encapsulates spent fuel in copper canisters surrounded by bentonite clay within the stable granite bedrock, designed to isolate radioactive materials for up to 100,000 years (Helsinki Times, 2025; Patel, 2024). Construction began in 2004 following extensive site investigations and community engagement, with total project costs estimated at €900 million for construction plus an additional €4 billion to complete the facility, which will ultimately contain 3,250 canisters in approximately 50 km of tunnels (Vattenfall, 2023). The EURAD-2 partnership programme (2023-2025), co-funded under the EURATOM Work Programme, coordinates European research on radioactive waste management addressing the EU's 3.5 million m³ radioactive waste inventory through a holistic "cradle-to-grave" approach (Théodon et al., 2024).

A key circular economy pattern in the uranium supply chain relates to the possibility to reprocess (i.e., recycle) nuclear waste, turning it in an input for new energy generation. This can occur at the dry storage stage through the PUREX process (see “i” in figure 1). The PUREX (Plutonium Uranium Reduction Extraction) process is the standard method for recycling used nuclear fuel to recover uranium and plutonium. It uses liquid-liquid extraction, specifically employing a solvent of tributyl phosphate in a kerosene-like diluent to chemically separate these metals from fission products. By isolating these materials, the process reduces the volume of high-level waste and provides fuel for future nuclear power generation (Klaus, 2024; Texas A&M University, 2017). The PUREX process separates nuclear waste into distinct components (Pucciarelli et al., 2024; Texas A&M University, 2017; Unites States Department of Energy, 2022; Vestal et al., 2023):

— Cladding materials: zirconium and stainless steel from the fuel rods containing the pellets—exhibit low radioactivity. These materials require careful handling due to residual radioactivity and have to undergo dry storage before permanent storage, although there is research into possibilities for recycling (see “j” in figure 1).

— Uranium and plutonium: both highly radioactive, they are recovered for fuel reprocessing. They are converted again into UO_2 and PuO_2 pellets that can be combined with primary production UO_2 pellets during nuclear fuel core assembly. Reprocessed UO_2 can fuel light and heavy water reactors, while PuO_2 requires MOX-capable reactors.

— Fission products (e.g., xenon, krypton, strontium): highly radioactive, constitute most of the waste volume, and decay over hundreds of years. These result from uranium fragments created during fission.

— Minor actinides (e.g., neptunium, americium): highly radioactive, generate the most heat, and present the greatest management complexity. They form when uranium acquires a neutron during fission and decay over thousands to millions of years.

— Activation products (e.g., tritium, carbon-14, cobalt-60): exhibit low radioactivity that diminishes to very low levels over days, months, or years.

The European Industrial Alliance on SMRs is focusing on the ability of these technologies to close the nuclear fuel cycle by reusing spent fuel from previous generation plants, and waste minimization capabilities These advanced fast SMRs can use mixed oxide fuel containing plutonium recovered from reprocessing, thereby transforming long-lived radioactive waste into valuable fuel while maintaining the modularity, transportability, and passive safety systems that characterize small modular and microreactor technologies (Patel, 2024).

The PUREX process is the global standard for recycling spent nuclear fuel, recovering 96% of uranium and 1% of plutonium to reduce waste volume and radioactivity. However, PUREX creates a "proliferation" risk because it isolates pure plutonium, which is a key ingredient for nuclear weapons. To prevent this, the UREX process was developed to be "proliferation-resistant"; it extracts uranium but ensures plutonium is never separated into a pure, weapons-usable form, instead keeping it mixed with other radioactive elements. This mixture remains ideal for creating MOX fuel for energy production but is useless for nuclear weapons. Currently, global reprocessing capacity of approximately 4,000 tonnes per year is concentrated in France, Russia, India, Japan, and China, as these nations seek to maximize energy security while minimizing the long-term hazards of nuclear waste (United States Congress, 2025; World Nuclear Association, 2024). France is the global leader in nuclear reprocessing: the facility in La Hague has a reprocessing capacity of 1,700 tonnes per year, the largest in the world, accounting for nearly half of global commercial light-water reactor fuel reprocessing capacity. In this way, France derives approximately 17% of its total electricity from recycled nuclear fuel (World Nuclear Association, 2026). In 2024, MOX fuel loaded into nuclear power plants in the EU contained 6,934 kg plutonium, 45% more than in 2023. MOX fuel and reprocessed uranium can be considered as domestic secondary sources that reduce the requirements for natural uranium; in 2024, they are equivalent to 4.8% of the EU's annual natural uranium requirements (Euratom Supply Agency, 2025). Projected future use of secondary sources is expected to increase considerably, with reprocessed uranium growing from approximately 1,100 tU equivalent in 2025 to a projected peak of over 3,000 tU by 2034 before stabilizing at roughly 2,800 tU through 2044, reflecting the growing strategic importance of the circular fuel cycle for EU supply security (Euratom Supply Agency, 2025). It is up to the Member States and their corresponding national policies to decide whether to consider the spent fuel as radioactive waste or as a valuable source of new material after reprocessing. According to European Commission data, 7 of the 27 EU countries have reprocessed or plan to reprocess spent fuel, and 2 have not ruled out doing so (Euratom Supply Agency, 2025).

Pyroprocessing is also emerging as an alternative circularity pattern to PUREX (see “k” in figure 1). This uses molten salts and electricity to recycle fuel without ever isolating pure, weapons-grade plutonium, making it also highly proliferation-resistant. It also has the advantage to bundle minor actinides into the reprocessed fuel. Furthermore, since the salts are radiation-tolerant, spent fuel can be processed "hot" almost immediately, skipping the 5-10 year cooling period PUREX requires. Pyroprocessing is not yet commercially viable at scale. While the technology has been proven in laboratories (like Argonne National Laboratory) and handled several tonnes of fuel, it remains at the pilot scale (World Nuclear Association, 2024). Recent advances include the completion by Oklo Inc., in cooperation with Argonne and Idaho National Laboratories, of a demonstration of an advanced fuel recycling process in 2024, alongside the development of Moltex's waste to stable salt (WATSS) process for converting used nuclear fuel into an asset—coupling WATSS with its molten salt reactor significantly reduces nuclear waste volumes and produces new fuel for advanced reactors (Euratom Supply Agency, 2025).

Management of fission products, minor actinides, and activation products is more complex and remains primarily at the research level without full industrial-scale application yet. Accelerator-driven systems (ADS) represent a promising transmutation technology to handle them, reducing their volume and radioactivity levels (World Nuclear Association, 2021) (see “l” in figure 1). Former EU projects designed experimental and industrial-scale ADS demonstrators using lead-cooled fast reactor technology, demonstrating that ADS can theoretically reduce waste volume by 50% and decrease radioactive decay times from thousands of years to hundreds of years by transmuting long-lived minor actinides into shorter-lived or stable isotopes (World Nuclear Association, 2021). China's Accelerator-Driven Advanced Nuclear Energy System (ADNES) programme is advancing toward industrial-scale ADS construction, with research indicating that dedicated ADS facilities could eliminate over 95% of minor actinide inventory from pressurized water reactor spent fuel, substantially reducing both the mass and radiotoxicity of final high-level waste requiring geological disposal (Zhang et al., 2023)**.** However, ADS faces significant technical challenges as well as economic viability challenges when compared to geological disposal (Nishihara et al., 2021). In principle, they can be reprocessed into pellets for new reactor types or placed in ADS, which can reduce waste volume by 50% and decrease decay time from thousands to hundreds of years. ADS technology, though complex and in the research stage, allows volume reduction with outputs potentially useful for research applications.

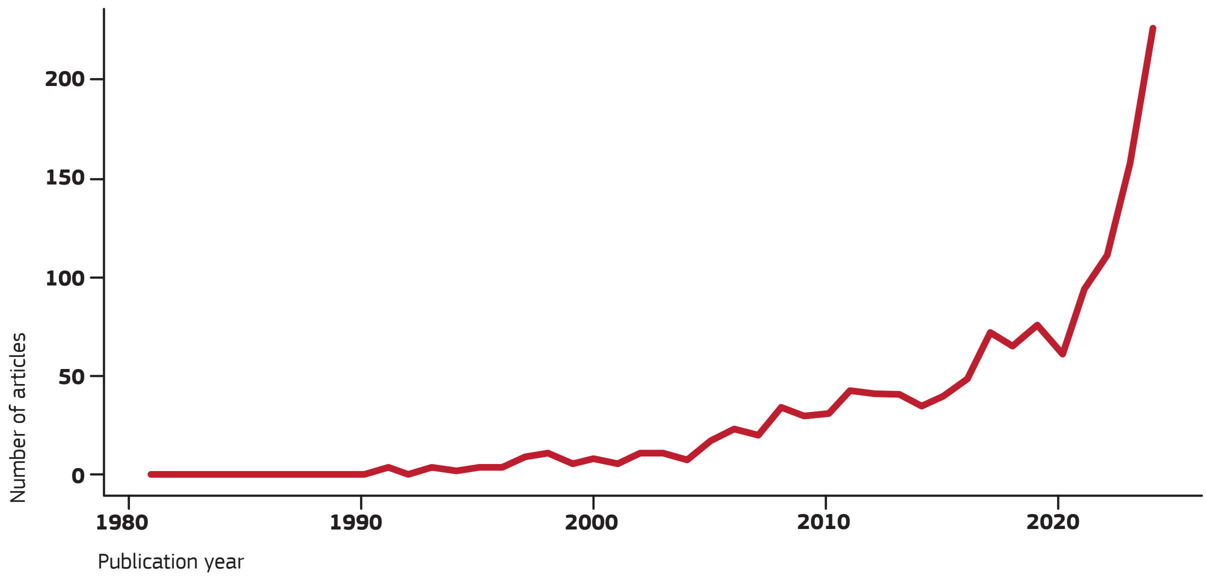
3.2. Scientific literature on circular economy strategies in the uranium supply chain

This part of the report covers a systematic review of scientific literature on circular economy in the uranium supply chain. The following sections outline the method and the results of the analysis.

3.2.1. Quantitative analysis

The analysis identified 1,383 scientific articles on the circular economy in the uranium supply chain. Figure 2 shows the number of articles published each year over time since the 1980s until 2025. The number of articles started increasing steadily in the mid 2000s, and scientific knowledge production accelerated rapidly in the past 5 years.

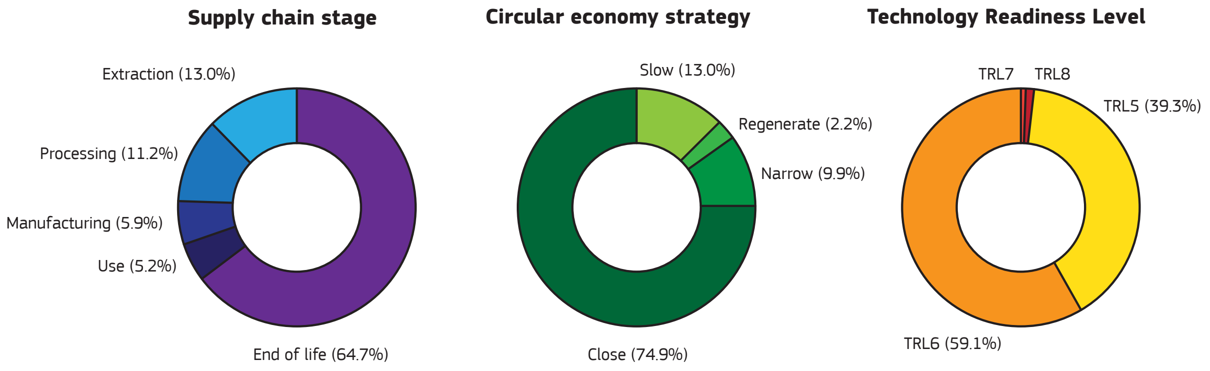
Figure 2. Number of scientific publications per year on circular economy in the uranium supply chain.



Source: JRC analysis.

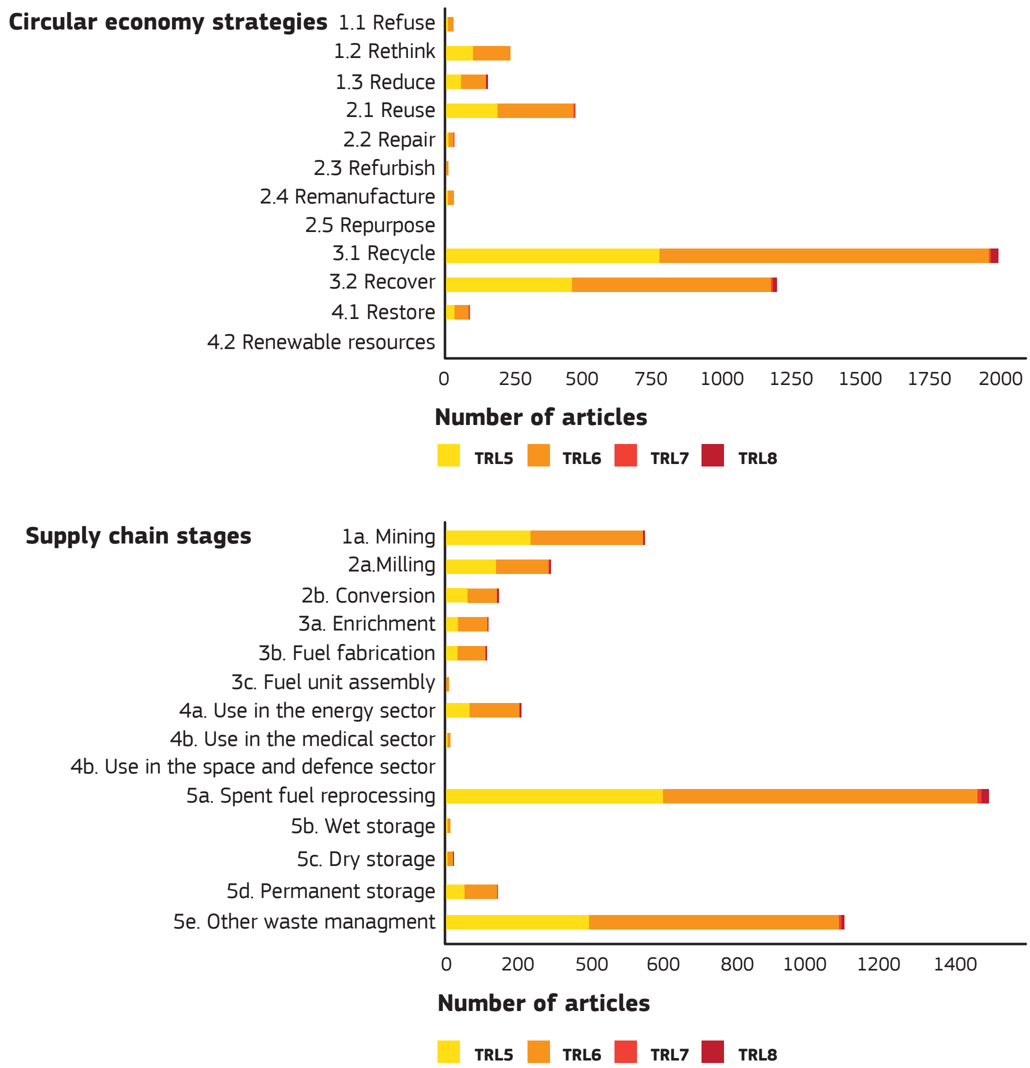
The articles were categorised according to supply chain stage circular economy strategy and TRL level, as shown in Figure 3. The figure shows that the vast majority of the articles focuses on the end-of-life stage: 64.7% of the articles are about spent fuel reprocessing, waste storage, and other waste management activities. 13% of the articles focus on extraction, which essentially consist in mining and other methods such as in-situ leaching. 11.2% of the articles focus on the processing stage, which encompasses uranium milling and conversion. 5.9% of the articles focus on the manufacturing stage encompassing uranium enrichment, fuel fabrication, and fuel unit assembly. The use stage mostly concerns the nuclear energy sector and it is covered by 5.2% of the articles. In terms of circular economy strategies, the research focuses mostly on closing resource flows, with 74.9% of the articles covering recycling and energy recovery approaches. Articles on slowing resource are 13%, They focus on reuse, repair, remanufacture, refurbish and repurpose, which may entail certain specialized applications such as well rehabilitation in mining or repeated use of sorbents in leaching. Articles on narrow resource flows are 9%, and they focus on refuse, rethink, and reduce approaches. Articles on regenerating represent the he smallest category, with only 2.2% of articles. They focus on restoring natural ecosystems affected by industrial process, or they related to renewable energy use. Concerning the TRL, articles with a TRL 1-4 were filtered out in data collection. Most articles feature a TRL of 5 and 6, respectively 39.5% and 59.1% of the total. Articles relating to TRL of 7 and 8 are extremely limited, while no articles cover TRL 9. Figure 4 provides more granular insight showing the TRL level discussed by the articles in conjunction with their focus on different circular economy strategies and supply chain stages. It is visible that the few articles about higher TRLs (i.e., 7 and 8) concern the “recycle” and “recover” strategies, while in terms of supply chain stages, they concern mostly “spent fuel reprocessing”.

Figure 3. Categorisation of scientific articles according to supply chain stage, circular economy strategies and technology readiness level.



Source: JRC analysis

Figure 4. Bar plots showing the TRL level of the articles on each supply chain stage and circular economy strategy.



Source: JRC analysis

The 1,383 articles were “exploded” into 4,313 data items corresponding to unique combinations of supply chain stage × circular economy strategy (since a single article can focus on multiple supply chain stages / and or circular economy strategies at the same time). A “heatmap” visualisation of the data items is reported in Figure 6. Each cell of the heatmap contains the number of articles which discuss a given supply chain stage in conjunction with a given circular economy strategy. This provides more granular insight into the focus of the research.

Figure 5. Heatmap showing the focus of the 1,383 articles exploded into 4,313 data items corresponding to unique supply chain stage and circular economy strategy combinations.

Supply chain stages / Circular economy strategies	1.1 Refuse	1.2 Rethink	1.3 Reduce	2.1 Reuse	2.2 Repair	2.3 Refurbish	2.4 Remanufacture	2.5 Repurpose	3.1 Recycle	3.2 Recover	4.1 Restore	4.2 Renewable resources	Total
1a. Mining	1	59	16	90	2	2	3	1	244	131	8	3	560
2a.Milling		15	8	41		1		1	139	86	6	1	298
2b. Conversion		5	6	14					77	48	3		153
3a. Enrichment	7	18	13	6	2	2	4		55	18	2	1	128
3b. Fuel fabrication	4	11	13	8	2	2	1		70	33	2		151
3c. Fuel unit assembly			1		2				2	1	1		7
4a. Use in the energy sector	7	45	22	13	6	3	4		86	29	2		217
4b. Use in the medical sector			1	2					4	2			9
4b. Use in the space and defence sector													
5a. Spent fuel reprocessing	8	61	40	138	5	3	10		744	473	24		1506
5b. Wet storage			1	2	1				1	2			7
5c. Dry storage			2	2	2				7	7			20
5d. Permanent storage	1	2	11	8	1		1		68	47	4		143
5e. Other waste managment	2	23	24	150	11	1	4	3	522	336	38		1114
Total	30	239	158	474	34	14	32	5	2019	1213	90	5	4313

Source: JRC analysis

Figure 5 shows that the vast majority of the articles focus on the circular economy strategy “recycling” (column 3.1 - 2,019 / 4,313 data items). Most of the articles on “recycling”, specifically 744, focus on the “spent fuel reprocessing” stage. This stage entails using the PUREX process, or emerging alternatives (e.g., UREX) to isolate the uranium and plutonium shares from nuclear waste. They are then turned again into powder and eventually sintered back into UO_2 and PuO_2 pellets that can be combined with UO_2 pellets from primary production when the nuclear fuel core is assembled. Depending on the final material composition of the fuel, these reprocessed materials can be used in different types of reactors. The other 522 “recycling” articles focus on “other waste management” stage. They relate to the recycling of resources in the uranium supply chain, for applications that are different than nuclear fuel, such as cross-sectoral research. 244 of the “recycling” articles focus on the “mining” stage. Here there is a prominent focus on closed-loop water systems, which reduce environmental footprint and go hand-in-hand with uranium extraction efficiency in situ-leaching. 139 of the “recycling” articles concern the “milling” stage, where it is possible to source uranium and other of secondary materials from tailings.

After the articles on recycling, the majority is on the circular economy strategy “recover” (column 3.2 – 1,2013 / 4,313 data items). Again, the majority of these articles, specifically 473, focus on “spent fuel reprocessing” stage. This is complementary recycling but here is focus is placed, rather than on the material, on the energy, since reprocessed fuel allows in fact to generate energy from waste material. Ultimately, recycling and recover in the context of reprocessed nuclear fuel are just two sides of the same coin, and the subject discussed by related articles is essentially the same. Follow 336 articles on “recover” related to “other waste management” stage. Follow 131 articles on “recovery” focus on the “mining” stage

The articles on recycle and recover together are by far the majority (3,232 / 4,313 data items). Follow distantly the articles on the circular economy strategies “reuse” (column 2.1 - 473 / 4,313 data items), “rethink” (column 1.2 - 239 / 4,313 data items) and “reduce” (column 1.3 - 158 / 4,313 data items). Regarding the articles on “reuse”, they mostly relate to “spent fuel reprocessing” and “other waste management stage, respectively 138 and 150 articles. Given the definitions provided to the LLM, and the type of core product in the analysed supply chain (i.e., a fuel) we note that the focus of these articles might actually be the same of those on “recycling” (i.e., reusing nuclear waste in new fuel). This would not apply to the 90 “reuse” articles focusing on the “mining” stage, where a focus on the reuse of sorbents in leaching is noted. Regarding the “rethink” articles, they focus on systemic resource efficiency interventions and their focus is spread relatively evenly across different supply chain stages. Articles focusing on “reduce” are also spread relatively evenly across supply chain stages.

Looking at Figure 5, from a supply chain stage perspective, it is evident that most articles focus on "spent fuel reprocessing" (row 5a – 1,506 / 4,313 data items), primarily concerning the strategies of "recycle" and "recover." This is followed by articles on "other waste management" (row 5e – 1,114 / 4,313 data items). Next are articles on "mining" (row 1a – 560 / 4,313 data items), which mainly address "recycle" and "recover" strategies, as well as "reuse." These articles may also focus on optimizing water use, resource extraction, and reusing sorbents in leaching. Following these are articles on "milling" (row 2a – 298 / 4,313 data items), potentially focusing on processing efficiency and tailings recovery. Research on "use in the energy sector" (row 4a – 217 / 4,313 data items) is also concentrated on the "recycle" strategy and may involve using reprocessed fuel in newer, more efficient reactor technologies. In contrast, research on "use in the medical sector" is extremely limited (row 4b – 9 / 4,313 data items), while research on "use in the defense and space sector" is absent (row 4c – 0 / 4,313 data items), likely due to sensitivity and confidentiality issues. Finally, research on "permanent storage," despite being a key area, is not particularly abundant (row 5d – 143 / 4,313 data items).

Importantly, we note that the final sample of 1,383 unique publications was created by assigning each article a score ranging from 0 to 5, based on its relevance to both the uranium supply chain and circular economy strategies (see Annex 1). Articles with a score below 4 were excluded. Most articles in the sample have a score of 4 for both supply chain and circular economy relevance. A score of 4 for supply chain relevance means that the article focuses prominently on one or more stages of the uranium supply chain, but may not cover multiple stages comprehensively. Only eight articles had a supply chain score of 5, meaning that the supply chain is their primary subject, providing detailed analysis across multiple stages simultaneously. On the other hand, concerning circular economy relevance, all articles have a score of 4, and zero articles have a score of 5. This means that while all articles in the sample describe at least one circular economy strategy and provide clear, actionable insights, no articles discuss a fully developed circular economy approach that considers multiple resource efficiency strategies simultaneously, connecting such a systemic view to inform industrial and policy strategies. This is a key finding of the quantitative analysis: it suggests that very few to no publications have a comprehensive focus on the entire supply chain or consider the circular economy as a holistic resource efficiency approach to be applied throughout all supply chain stages. Rather, the literature is fragmented, with a strong focus only on specific stages and strategies. This is problematic because a holistic focus spanning across supply chain stages and circular economy strategies is essential to maximize resource efficiency and derive well-informed industrial policy strategies.

3.2.2. Supplementary material for qualitative analysis

The findings from the quantitative analysis are supported by a structured dataset of 1,383 articles, provided in Excel format as supplementary material to this report. This database serves as a comprehensive repository for the evidence base, containing the following data for each article:

- Standard bibliographical data: Web of Science unique identifiers, authors, titles, publication years, and citation counts.
- Original text: The abstracts analysed during the mapping process.
- Synthesized content: An automated summary of each article's core focus designed to assist in rapid human or automated review.

While the Large Language Model (LLM) prompts were carefully engineered and multiple filters were applied to ensure high-quality outputs, the volume of data—comprising 4,313 unique combinations of supply chain stages and CE strategies—precluded a comprehensive manual review. Consequently, the individual categorizations have not been verified by human experts, and the potential for misclassification remains. These results provide a valuable high-level indication of where research activity is concentrated, but they should be interpreted with caution and treated as a representative landscape rather than an exhaustive audit.

This supplementary material is intended as a stepping stone to corroborate and build upon the quantitative results provided in the previous sections. It facilitates a transition from broad quantitative trends to qualitative depth. To maximize the utility of this resource and mitigate the limitations of automated mapping, future research should:

- Corroborate findings: use the article data original text and synthesized content to verify the LLM categorization and potentially derive a different one which may be functional for a follow up qualitative analysis.
- Perform targeted deep-dives: Derive a narrower selection of articles from the database (e.g., using publication dates and citation counts as additional filtering criteria) for detailed human qualitative analysis to gain more granular insights into the content.
- Engage interdisciplinary expertise: the qualitative analysis should engage experts in the uranium and nuclear energy sector, and circular economy. This combined expertise is essential for translating complex technical information into a clear understanding and actionable pathways for the industry and policy practice.

4. Conclusions

4.1. Main findings

This report focuses on circular economy in the uranium supply chain. This topic is relevant because as the climate crisis and energy security issues push nuclear energy into the EU energy mix, it is important to address supply constraints and waste management challenges (Baldassarre & Carrara, 2025; van Uffelen and Tanarro Colodron, 2024). In particular, uranium supply is concentrated in a few countries, and nuclear waste is highly hazardous, requiring very complex and expensive management infrastructure (Nuclear Energy Agency, 2023; Texas A&M University, 2017). During 2024, the European nuclear fuel market continued to face supply uncertainties linked to the changing geopolitical environment, while the challenge remains to reduce and sustainably eliminate remaining dependencies, including in conversion services, enrichment, and fuel for certain specific uses such as medical radioisotopes (Euratom Supply Agency, 2025). Circularity research and innovation in this domain is therefore paramount to address these challenges effectively (Baldassarre & Carrara, 2025). The aim of this report is to draw attention to this topic and conduct an initial analysis to support future research and innovation, as well as industrial policymaking.

A main outcome of the research is a comprehensive description of the uranium supply chain and its main circularity patterns was developed. This outcome points to four main findings:

Main finding #1: Twelve circular economy patterns in the uranium supply chain are present. Nine of them relate directly to uranium as a resource, while three concern related resources throughout the supply chain.

— Once uranium is loaded into the nuclear core, achieving its circularity in isolation becomes challenging, as it is ultimately mixed with other materials at the end-of-life stage. Consequently, a broader system perspective that accounts for interlinked material flows is necessary (Pucciarelli et al., 2024). This need is equally evident upstream, where uranium extraction and processing generate multiple by-products. Circular economy interventions need to consider these by-products (Dong et al., 2020; Levett et al., 2024; Tandy et al., 2024). Ignoring them would reduce resource efficiency. Therefore, a comprehensive circularity assessment should explicitly incorporate related resources across the entire life cycle.

Main finding #2: Seven circular economy patterns occur upstream in the supply chain, with a focus on maximizing outputs, improving efficiency and minimizing losses in resource extraction and processing.

— This can be achieved by fine-tuning in-situ leaching methods (Wang et al., 2024; Zeng et al., 2024), restoring well functionality (Kuandykov et al., 2020), progressing with seawater extraction methods (Zhang et al., 2024), recovering both uranium and other valuable materials such as rare earth elements from mining tailings generated at the milling stage (Dong et al., 2020; Levett et al., 2024; Tandy et al., 2024), as well as designing enrichment processes with feedback loop systems that minimize losses and divert residual materials to different sectors (United States Department of Energy, 2022).

Main finding #3: Four circular economy patterns occur downstream at the end-of-life stage, with a focus on optimizing and innovating methods to process nuclear waste.

- End of life circularity patterns have a threefold goal: first, recovering as much residual material as possible that can be turned into new fuel, such as recycling uranium and plutonium into new pellets through PUREX (Texas A&M University, 2017; World Nuclear Association, 2024); second, recycling materials that are currently difficult to process, such as using pyroprocessing to recycle minor actinides into mixed oxide fuels and developing methods to recycle zirconium from cladding (Pucciarelli et al., 2024; Vestal et al., 2023), thereby reducing the amount of material requiring permanent disposal; and third, simplifying the disposal process by reducing the time to reach permanent storage through pyroprocessing and minimizing both the volume and radioactivity decay time of materials undergoing permanent storage through technologies such as accelerator-driven systems (Nishihara et al., 2021; World Nuclear Association, 2021; Zhang et al., 2023).

Main finding #4: One circular economy pattern relates to the use phase in the energy sector, with a focus on research, innovation, implementation and scaling of new reactor technologies to use nuclear fuel more efficiently.

- This can be achieved during the fission phase through fast reactors (World Nuclear Association, 2021), which can also utilize mixed fuels, thereby acting in synergy with circularity patterns at the end-of-life stage. Small Modular Reactors and microreactors also contribute to resource efficiency through extended operational periods between refueling and reduced fuel transportation requirements (Black et al., 2023; European Commission, 2024a; Tanarro Colodron et al., 2024).

The other main outcome is a systematic analysis of all the scientific literature on circular economy in the uranium supply chain. Research articles are selected and categorized according to the stage of the supply chain and circular economy strategy they relate to. This outcome points to four additional main findings:

Main finding #5: Circular economy research for uranium has been increasing sharply, particularly after 2020.

- This trend aligns with findings from other systematic reviews on uranium and nuclear energy research, which show a sharp increase since 2004 and a strong acceleration in 2021, explaining that this is largely driven by growing global pressures for decarbonization and energy security (Addo et al., 2023). As nuclear research expands, it is therefore encouraging to see that research specifically focused on circularity aspects is also increasing in parallel. In the EU, energy security concerns following the Russian invasion of Ukraine in 2022 have further intensified efforts to diversify energy sources. The EU continues to procure approximately 20% of global uranium requirements, totalling 13,667 tU in 2024, with more than 40% of uranium imports still originating from CIS countries despite ongoing diversification efforts (Euratom Supply Agency, 2025). The increase of research into more efficient uranium use and circular approaches across the uranium supply chain might be also explained and motivated by the EU dependence from Russia on uranium supply, which accounted for 23% of EU uranium supply in 2023 (van Uffelen and Tanarro Colodron, 2024).

Main finding #6: most circularity research on uranium operates at medium TRL, indicating that most innovations remain at the validation and demonstration stages rather than full industrial deployment.

- The vast majority of the articles sampled in the study operate at TRL 5-6, with very limited studies at level TRL 7-8 and none at TRL 9. This finding is corroborated by another review with a narrower scope specifically on the innovation of processes for spent nuclear fuel recycling (Baron et al., 2019). The research found that “most processes fall in the proof of principle range with TRLs between 4 and 6, although this is an evaluation at the system level and some gaps in the individual process steps may still exist that strictly would reduce the overall TRL" (Baron et al., 2019). The study further notes that significant research and development is still needed to elevate these technologies (e.g., pyroprocessing) to higher TRL levels suitable for widespread commercial deployment. The urgency of this focus is underlined by the fact that EU dependence on external uranium supply remains high at 95.2%, with only 4.8% of requirements met through domestic secondary sources, including reprocessed uranium and MOX fuel (Euratom Supply Agency, 2025).

Main finding #7: Circular economy research in the uranium supply chain is highly concentrated on closing resource loops in the end-of-life stage by reprocessing spent nuclear fuel.

- Within the sample of articles isolated in this study, 34.9% focus on “spent fuel reprocessing”, representing the single largest research concentration. This focus reflects both the prominence of reprocessing in nuclear fuel cycle development since the 1950s and its intensification as nuclear energy has gained renewed attention as a low-carbon energy source, driving the need for innovative technologies to manage radioactive waste securely (Silverio & Lamas, 2011). Beyond spent fuel reprocessing, research attention follows a clear hierarchy across other supply chain stages. 25.8% of the articles focus on “other waste management” solutions, 13.0% focus on the uranium mining stage (e.g., water recycling and extraction efficiency in in-situ leaching), 6.9% on milling (e.g., including tailings recovery) and 5.0% on use in the energy sector (e.g., efficiency improvements through advanced reactor technologies). Notably, research on permanent geological disposal remains comparatively limited, with only 3.3% of the articles in our sample focusing on it.

Main finding #8: Research on resource management across multiple stages of the uranium supply chain is scarce, and no studies consider multiple circular economy strategies simultaneously.

- This is problematic because fully exploiting the circular economy potential of a supply chain requires a systemic approach in which multiple strategies across multiple stages are considered simultaneously (Baldassarre, 2025). A robust qualitative understanding of the supply chain, combined with systematic mapping of circularity patterns, is essential to properly inform industrial policymaking and to guide subsequent quantitative assessments that can define the parameters of effective policy interventions (Carrara et al., 2023). This type of research is particularly important for critical raw materials and strategic technologies linked to the digital transition, national security, and economy-wide decarbonization, where recent studies have adopted a systemic analytical view, such as in the cases of titanium in aerospace and defence (e.g., Baldassarre et al., 2023b; Jakimow et al., 2024), solar photovoltaic (e.g. Nyffenegger et al., 2023, 2025), hydrogen technologies (Axt et al., 2023, 2025), and wind turbines (Carrara et al., 2025). However, for many critical raw materials (Schrijvers et al., 2020), and for uranium, this holistic and multi-strategy perspective remains largely absent, revealing a critical and urgent research gap.

4.2. Future research directions

This report delivers two main outcomes. First, a comprehensive description of the uranium supply chain and its main circularity patterns (Figure 1). Second, a systematic analysis of scientific literature on circular economy in the uranium supply chain, with articles categorized according to supply chain stage and circular economy strategy (Figure 5), supported by a structured dataset of 1,383 articles provided in Excel format as supplementary material. As one of the first studies examining circular economy holistically across the entire uranium supply chain, this work provides a foundation for future research to build upon. Two key research directions are outlined below.

Future research direction #1: Conduct a systematic review of literature about circularity in the uranium supply chain, including deep qualitative analysis of key articles to generate granular insights, identify emerging themes and gaps, and define a targeted research agenda.

— The present study identified 1,383 articles categorized into 4,313 unique supply chain stage × circular economy strategy combinations, providing a first overview revealing where research concentrates (i.e., spent fuel reprocessing) and where critical gaps exist (e.g., permanent storage). However, categorization was performed using an LLM protocol without human verification, meaning potential misclassification and a margin of error remains possible. Future research may use the methodological blueprint (see annex) and the article dataset from this study (provided as supplementary material) to corroborate the outcomes through manual review and expert validation, potentially reconfiguring category clusters to better steer inquiry toward critical gaps and promising research avenues. Beyond validation and categorization refinement, future work should transition from quantitative mapping to qualitative depth through targeted deep-dives into selected clusters and selected key articles, isolated for example using publication dates and citation counts as filtering criteria.

Future research direction #2: Conduct qualitative field research across the entire supply chain by engaging with its key stakeholders to capture recent industry developments and provide a comprehensive and up-to-date account of the circularity status quo.

— This research represents one of the first attempts to examine circularity holistically across the entire uranium supply chain, as most existing research remains siloed across specific stages. This is confirmed by our systematic analysis showing few articles addressing multiple stages simultaneously and none integrating multiple circular economy strategies comprehensively. While the narrative literature review employed here provides a solid first step, it remains limited to desk research without direct engagement with supply chain stakeholders (e.g., mining companies, fuel fabricators, reactor operators, waste management firms, industry associations, regulators). This is in turn essential to gain better insight into the circularity status quo in the industry. Future research should address this through interviews, field observations, and collaborative workshops to capture detailed recent developments currently scattered across many actors. Figure 1 can serve as a foundation for iterative qualitative research to develop enhanced versions incorporating greater detail, newly emerging patterns, and stakeholder-validated insights. This approach has proven valuable to inform EU policymaking for other critical raw material supply chains (Axt et al., 2025; Baldassarre, 2025; Buesa et al., 2025) but remains absent for uranium, representing an urgent research gap.

4.3. Policy options

This report provides an initial yet comprehensive analysis of circular economy in the uranium supply chain. Based on the main findings, three high-level policy options are outlined to guide future EU action in this domain.

Policy option #1: Funding R&I to advance the TRL of circular economy solutions in the nuclear energy sector, integrating approaches across multiple stages of the uranium supply chain.

— The systematic literature analysis reveals that most circular economy innovations in the uranium supply chain operate at Technology Readiness Levels 5-6, with very limited advancement to TRL 7-9 necessary for commercial deployment. This finding is corroborated by Baron et al. (2019), whose review of spent nuclear fuel recycling processes found that "most processes fall in the proof of principle range with TRLs between 4 and 6," noting that significant research and development is still needed to elevate these technologies to higher TRL levels suitable for widespread commercial deployment. While advancing TRL levels is important for uranium research and innovation generally, it is particularly critical for circular economy technologies to ensure that resource efficiency strategies can be deployed at industrial scale alongside ongoing nuclear energy development. The Euratom Research and Training Programme allocated €121 million to 21 projects in 2024, focused on nuclear safety, waste management, and innovative technologies, including the EU-CONVERSION and PreP-HALEU projects aimed at securing fuel supplies for research reactors and medical radioisotope production, the SAVE project supporting fuel diversification for VVER reactors, and the new EURAD-II and CONNECT-NM co-funded partnerships to address radioactive waste and develop advanced nuclear materials (Euratom Supply Agency, 2025). Notably, the proposed Euratom Research & Training Programme 2028-2032 (€6.7 billion) emphasizes safety, SMRs, fusion, and skills development but does not explicitly prioritize circularity (European Commission, 2025). Similarly, current EU-funded nuclear R&I projects—including ENEN2plus, Skills4Nuclear, SNETPFORWARD, NPHyCo, and TANDEM—focus primarily on workforce development, non-electric applications, and hybrid energy systems without specific circular economy objectives (Nucleareurope, 2025). Future EU research funding under Horizon Europe and Euratom programmes should therefore prioritize advancing promising circular economy technologies from pilot to commercial scale, particularly pyroprocessing, accelerator-driven systems for minor actinide transmutation, and zirconium cladding recycling (Pucciarelli et al., 2024; Vestal et al., 2023; World Nuclear Association, 2021; Zhang et al., 2023). Equally important, circular economy R&I funding must support holistic initiatives that integrate multiple strategies across multiple supply chain stages, addressing the current fragmentation identified in this study where very few articles examine multiple stages simultaneously and none adopt comprehensive multi-strategy perspectives across the entire value chain. Such system-level research is essential to inform effective industrial policy and maximize resource efficiency across the nuclear fuel cycle (Carrara et al., 2023). This is also in line with the explicit call for a “circular nuclear economy” from the Euratom Supply Agency. The entails pursuing a diversified range of solutions to across supply chain stages from mining to end of life, enabling the production and use of alternative and recycled uranium and plutonium products, including investing in EU-based technologies such as reprocessing, uranium and plutonium recycling, re-enrichment of depleted material, and their application in advanced reactors, including fast-breeder reactors and new generation reactors (Euratom Supply Agency, 2025).

Policy option #2: Embedding an explicit circular economy focus into existing EU nuclear energy coordination mechanisms to support knowledge transfer and accelerate deployment of circular practices.

— The analysis shows that research on uranium circularity is siloed within research domains, hindering knowledge transfer. At the same time, within industry practice, knowledge is scattered across countries and supply chain actors. For example, countries like France—deriving 17% of electricity from recycled fuel—and Belgium—completing a project where residues from the production of medical radioisotopes will be purified and the recovered uranium will be reused as fuel for reactors—possess valuable circularity expertise that is vital to connect to connect through coordination mechanisms (Euratom Supply Agency, 2025). Several coordination mechanisms already exist in the EU. To different extents, they include a partial circularity focus, but they do not have a dedicated circularity pillar within their mandate. Notably, the Euratom Supply Agency serves as the primary platform for nuclear fuel supply chain coordination. Its most recent annual report explicitly calls for promoting a "circular nuclear economy", stating that EU Member States are encouraged to define clear national nuclear strategies and promote circular fuel practices (Euratom Supply Agency, 2025). This important ambition may be further crystallized and catalysed through the coordination of future cross-organisational and cross-county work, explicitly dealing with circularity alongside the dominant narrative on supply security and geopolitical diversification (Euratom Supply Agency, 2025). In this sense, Nucleareurope, the trade association representing European nuclear industry, focuses strongly on energy security, financing conditions, and skills development. However, attention to circularity, beyond supporting the European Industrial Alliance on SMRs, is more limited (Nucleareurope, 2025). The latter, fosters resource efficiency through fast reactor technologies embedded in SMRs, again reflecting a partial focus within the wider spectrum of circular economy strategies. Similarly, the Sustainable Nuclear Energy Technology Platform coordinates research and innovation but without a dedicated circularity pillar spanning the entire product life cycle. The lack of an integrated circularity focus within and across these mechanism is dissonant with the EU ambitions of scaling up the energy technologies for decarbonization in a circular way, as laid out in the RePower EU Plan and Net Zero Industry Act (European Commission, 2022; European Parliament and Council, 2024b). In fact, a more explicitly circularity focus is present for other energy technologies. For example, the European Battery Alliance exemplifies this integration: launched in 2017 with circularity embedded from inception, subsequently reinforced by the 2023 Batteries Regulation mandating recycled content targets, material recovery rates, and full life-cycle approaches (European Parliament and Council, 2023). Similarly, the discussion on the circularity of electrolyzers and hydrogen valley infrastructure, alongside the focus on scaling of the Clean Hydrogen Join Undertaking (2022). The same cannot be said for nuclear coordination mechanisms, where circularity is mentioned, yet still not explicitly positioned as a core agenda pillar, despite uranium's strategic importance for energy security and climate objectives (International Atomic Energy Agency, 2024; Nuclear Energy Agency, 2023). Future EU policy should establish a dedicated circular economy pillar within existing mechanisms, or create a separate cross-cutting circular alliance. This should serve as a central circularity coordination hub for EU industry actors across different supply-chain stages and as a single point of contact for international, non-EU partnerships.

Policy option #3: Including uranium in the EU Critical Raw Materials list to pave the way towards specific circularity targets along its supply chain, with priority on fuel reprocessing.

— This analysis identifies twelve circular economy patterns across the uranium supply chain and emphasizes the importance of holistic and integrated resource efficiency approaches for future research, innovation, and policymaking. A final, high-level point concerns the role of circularity in relation to uranium's economic importance and supply security. Despite nuclear energy's contribution to climate targets and the digital transition, and the high geographic concentration of supply, uranium remains outside the EU Critical Raw Materials list (Carrara et al., 2023; Euratom Supply Agency, 2025). It is important to note that recent scientific research has questioned current criticality assessment methods for their limited responsiveness to rapidly evolving events, their reliance on highly aggregated and low-resolution data, unjustified aggregation choices that may yield statistically unreliable results, and a systematic neglect of key aspects of quantitative risk theory — with empirical validation of indicators remaining rare and causal links largely undemonstrated (Andrieu et al., 2026). Bearing this in mind, the exclusion of uranium from the list warrants consideration, given that nuclear energy contributed 23.7% of EU electricity generation (617.3 TWh) in 2024, with 84% of the uranium sourced from only four countries, including 41.7% from Kazakhstan and Russia alone (Euratom Supply Agency, 2025). Demand is projected to increase by 30% over five years, while EU dependence on external supply remains high at 95.2%, with only 4.8% of requirements met through domestic secondary sources, including reprocessed uranium and MOX fuel (Nuclear Energy Agency, 2023; van Uffelen and Tanarro Colodron, 2024). While secondary supply allows countries such as France derive 17% of electricity from recycled nuclear fuel, these achievements remain primarily operational practices rather than policy-driven targets (World Nuclear Association, 2024; Euratom Supply Agency, 2025). In comparison, other energy technologies for decarbonisation face binding circularity requirements. Notably the Batteries Regulation mandates minimum recovery rates and recycled content for critical and strategic raw materials (European Parliament and Council, 2023) while ecodesign Requirements for PV technology are going to be set (Dodd et al., 2021). The inclusion of Uranium in the Critical Raw Materials list deserves consideration. Inclusion would align with the intention of fostering proportionate circular economy benchmarks. Starting with fuel reprocessing—both to enhance supply resilience and address radioactive waste management imperatives—targets may establish minimum shares of fuel reprocessing and recycled fuel utilization across Member States operating nuclear facilities (Pucciarelli et al., 2024; Vestal et al., 2023). Beyond end-of-life, and internationally, supply chain-wide circularity goals should encompass recovery rates for rare earth elements and residual uranium from tailings to strengthen global supply resilience and environmental sustainability, alongside water recycling objectives in in-situ leaching operations to reduce freshwater consumption and environmental footprint (Carrara et al., 2025; Dong et al., 2020; Levett et al., 2024; Tandy et al., 2024; Wang et al., 2024; Zeng et al., 2024). Crucially, the Euratom Supply Agency emphasizes that enhancing supply chain resilience through long-term contractual and political commitments, diversification, strategic stockpiling, and recycling is essential for long-term nuclear fuel security (Euratom Supply Agency, 2025)—underscoring that circular economy strategies are not merely an environmental ambition but a core instrument of EU energy security policy.

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List of abbreviations and definitions

Abbreviations	Definitions
TRL	Technology Readiness Level
UF_6	Uranium Hexafluoride
U_3O_8	Uranium Yellowcake

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Annexes

Annex 1. Full methodology for the systematic literature analysis

This annex provides a detailed account of the multi-stage systematic analysis on circular economy in the uranium supply chain, from the initial search in the Web of Science database to successive filtering steps assisted by a Large Language Model (LLM). Below it is explained how the LLM (GPT-4o) was employed, why multiple prompts were used, and the dataset was how we iteratively refined based on citation thresholds, technology readiness levels (TRLs), and abstract-level relevance checks.

Context and scope

The overarching goal is to conduct a systematic analysis of the entire supply chain of uranium, focusing on circular economy strategies such as reducing raw material input, extending the life of uranium-based products, recycling, and recovering waste streams. The analysis encompasses:

- Extraction to waste management (with primary attention on the nuclear energy sector, but also military, medical, and space applications).
- All circular economy strategies (reduce, reuse, recycle, repair, remanufacture, etc.).
- Exclusion of structural materials (e.g., concrete, steel of nuclear plants).

Database and initial keyword search

Web of Science was used in this work due to its coverage of interdisciplinary and peer-reviewed sources (geology, engineering, economics, environmental sciences, etc.).

Keyword strategy

A comprehensive search string combined uranium-related terms (e.g., "U-235," "yellowcake," "spent fuel," "nuclear reactor") with an exhaustive circular economy/resource-efficiency set (e.g., "recycle," "reuse," "remanufacture," "eco-design," "material flow analysis," etc.). For the circular economy keywords, we used the LLM to transform an initial list in a full list with as many synonyms as possible. For example, "reduc* uranium*" was transformed into "("reduc* uranium*" OR "uranium* reduc*" OR "minimiz* uranium*" OR "uranium* minimiz*" OR "lower* uranium*" OR "uranium* lower*" OR "decreas* uranium*" OR "uranium* decreas*" OR "diminish* uranium*" OR "uranium* diminish*" OR "cut* uranium*" OR "uranium* cut*" OR "curtail* uranium*" OR "uranium* curtail*" OR "lessen* uranium*" OR "uranium* lessen*" OR "limit* uranium*" OR "uranium* limit*" OR "abate* uranium*" OR "uranium* abate*" OR "mitigat* uranium*" OR "uranium* mitigat*")".

This broad search retrieved 17,598 references (articles, proceedings, etc.), spanning multiple disciplines and publication years.

LLM-assisted screening

A first LLM prompt aimed to screen abstracts for their relevance to uranium supply chain topics, circular economy strategies, and technology readiness levels (TRLs). It was designed to process a large dataset systematically and consistently, avoiding biases or fatigue inherent in manual screening.

The scope of the prompt is reported below:

- Supply chain stages: Defined stages from uranium mining, processing, manufacturing, use (e.g., energy, medical, military), and end-of-life waste management (e.g., storage, reprocessing).
- Circular economy strategies: Defined circular economy approaches, including narrowing resource flows (e.g., refuse, rethink, reduce), slowing resource flows (e.g., reuse, repair, remanufacture), closing resource loops (e.g., recycle, recover), and regenerating resources (e.g., ecosystem restoration, using renewables).
- TRLs: Ranged from basic principles (TRL 1) to proven operational systems (TRL 9).

For each abstract, the prompt required the LLM to reply to the following questions:

- Is the abstract related to any of the uranium supply chain stages?
- To what supply chain stage(s) is the abstract related, if any?
- How strongly does the abstract connect to the uranium supply chain?
- Is the abstract related to any of the circular economy strategies?
- To what circular economy strategy(ies) is the abstract related, if any?
- How strongly does the abstract connect to circular economy strategies?
- Could a TRL possibly be estimated for the processes or technologies described in the abstract?
- What is an estimated TRL of the processes or technologies described in the abstract?

A Python script iterated over all 17,598 abstracts, sending each one (with the system prompt reattached each time) to the LLM, then parsed the LLM's responses into a structured data frame.

Initial filter using heuristic criteria

After receiving LLM outputs, additional filters were applied to reveal the most relevant literature in this space. The relevance score of each abstract could range from 0 to 5 and retention score was set to 4 or higher. Abstracts related to TRL lower than 5 were excluded. Outdated or uncited abstracts were also excluded.

- Uranium supply chain relevance ≥ 4 (LLM-based).

- Score 1: The paper does not mention the uranium supply chain or nuclear applications at all. Any reference to uranium or nuclear energy is superficial or tangential (e.g., a brief historical note) without analysis relevant to the supply chain stages.
- Score 2: The paper mentions one or more uranium supply chain stages, but the reference is cursory or incidental. There is no detailed discussion, no clear linkage to how the stage is managed, optimized, or impacted.
- Score 3: The paper discusses at least one uranium supply chain stage with moderate detail—e.g., it addresses a specific process or challenge in mining or enrichment, but does not go beyond describing it. The connection is present but not explored in a comprehensive or actionable way.

- Score 4: The paper provides substantial detail on one or more key stages of the uranium supply chain. It may analyse processes, identify challenges and opportunities, or propose improvements. The supply chain is central to the paper's focus, though it may not cover multiple stages comprehensively.
- Score 5: The paper thoroughly and centrally focuses on the uranium supply chain, providing detailed analysis or insights across multiple stages. It might offer a comprehensive overview, propose integrated solutions, or assess complex interactions within the supply chain. The uranium value chain is a primary subject, not a secondary aspect.

— Circular economy relevance ≥ 4 (LLM-based).

- Score 1: The abstract is only tangentially related to circularity terms; mentions are extremely vague and offer no analysis or actionable detail. - Example: Mentions "sustainability" or "waste" without explaining how material loops or efficiency are achieved.
- Score 2: The abstract goes slightly beyond mere buzzwords but still only references circular concepts superficially. - Example: Mentions "recycling" or "resource recovery" without explaining methods, processes, or measurable impacts; no closed-loop details.
- Score 3: The abstract describes at least one circular economy strategy (e.g., a recycling process or resource recovery method) but does not provide quantification, integration into the supply chain, or frameworks. - Example: Talks about a pilot recycling technology but does not show data, scaled impact, or how results can be used.
- Score 4: The abstract describes at least one circular economy strategy and provides clear, quantifiable details and actionable steps - Example: States a percentage of recovered uranium from reprocessed fuel, how it replaces newly mined material, and references recognized circular economy methodologies.
- Score 5: The abstract shows a fully developed circular economy approach with multiple strategies interacting, supported by data, and connected to policy or industry-level frameworks. - Example: Demonstrates how reduce/reuse/recycle work together, quantifies reductions at multiple stages, and aligns with established circular economy standards or policies.

— Exclude TRL 1–4 again.

— Citation/Year Criteria:

- At least 4 citations, or
- If publication year ≥ 2023, at least 1 citation, or
- If publication year ≥ 2024 (i.e., brand-new), included automatically.

This final filtering yielded 1,383 articles that appeared strongly aligned with uranium-specific circular economy strategies.

Multi-strategy and multi-stage coding

Because an abstract can discuss multiple segments of the uranium supply chain (e.g., tailings from mining plus reprocessing in the nuclear cycle) and propose several circular economy strategies (e.g., recycle + reduce), the output format from the LLM allowed for lists of relevant supply chain stages and strategies rather than a single label. This feature intentionally accommodates double counting, so that each aspect is retained in subsequent quantitative analyses.

Quantitative analysis of the 1,383 articles

After shortlisting the 1,383 abstracts, a more granular breakdown was performed:

— Exploding data into multiple rows

- Each abstract's field (listing multiple supply chain stages or circular economy strategies) was exploded into multiple rows, one row per unique combination (supply chain stage × circular economy strategy).
- This expanded the 1,383 abstracts to 4,313 data entries, reflecting the complexity and multi-faceted nature of many studies.

Time constraints, limitations and further analysis

Given the large volume of data—comprising 1,383 abstracts and 4,313 unique combinations of supply chain stages and circular economy (CE) strategies—a comprehensive manual review was not feasible. Consequently, the 4,313 categorized rows were not individually verified by human experts.

While the LLM prompts were carefully engineered and multiple filters were applied to ensure high-quality outputs, the potential for misclassification remains. The results provide an important high-level indication of where research activity is concentrated within the uranium supply chain, but they should be interpreted with caution.

The structured dataset of 1,383 categorized articles, provided as supplementary material to this report, serves as a foundational stepping stone for further analysis. It is recommended that future studies derive a narrower selection of these articles for qualitative human analysis, which will allow for deeper and more granular insights. To ensure a meaningful and accurate evaluation, this process should involve a collaborative effort between experts in uranium industrial processes and circular economy researchers. Such interdisciplinary cooperation is essential to achieving a comprehensive understanding of the current status of research in this field.

The dataset is provided as supplementary material in excel format, providing for each article the following data:

— Web of science unique identifier

— Bibliographic data (author, title, tear of publication, and citation count)

— Abstract

— An LLM-generated summary focusing on the core findings of the article to facilitate further automated or human review

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