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Challenges and recovery opportunities in waste management during the mining and enrichment processes of ores containing uranium and thorium – a review

Introduction

Mining activities pass through various stages where environmental pollution may occur, from the exploration period to the production and shipment of the final material. One of these is pollution caused by waste (Namin et al. 2011; Mohamed and Paleologos 2018). Depending on the type of mining activities, different forms of waste e.g. cover layer, tailings, process waste, heap leach waste, and wastewater are formed (Çetiner et al. 2006; Kuczyńska et al. 2008; Erdemoğlu 2014). Different types of mineral waste can create

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different types of environmental risks (Agrawal et al. 2004; Wills and Finch 2016). Among these, uranium piles, evaporation ponds, and tailings ponds are common types of waste generated during uranium mining and processing. Waste generated during U mining and ore preparation may pose environmental risks due to the presence of radioactive elements and heavy metals (Przewłocki and Ślizowski 2004; Boitsov et al. 2005; Nilsson and Randhem 2008; Pala et al. 2013; Farjana et al. 2021). Various methods are being investigated to reduce the environmental impact of these types of waste, including biorecovery and biomineral processing.

An example of a method to reduce environmental impact of such waste is the fact that lead isotopes obtained from U-ores can be used as an indicator of environmental pollution caused by mineral processing wastes. The isotopic composition of lead in ambient samples can be measured to assess the amount of lead released into the environment from U mining and grinding operations (Curtis and Gancarz 1978). In a study, bio-recovery methods were investigated for U recovery from mineral waters using plant wastes as nutritional supplements (Paterson-Beedle et al. 2009). Biosorption, the ability of biomaterials to bind and concentrate heavy metals, is recognized as an innovative technology for the removal of pollutants from industrial wastewater generated during U mining and mineral processing (Hussien et al. 2015; Datta et al. 2022). Microorganisms have been used in biomineral processing to recover metals from ores, concentrates and industrial waste. Biological process techniques such as biological leaching have been developed to recover metals from sulfide ores (Sukla et al. 2014). The recovery of radioactive waste through the use of microbes via microbial bioremediation is cost-effective, feasible and environmentally friendly (Patel et al. 2022). Microbes can also be used to recover metals in wastewater from mining and metallurgical operations (Abhilash et al. 2010).

Nuclear raw materials are often associated with rare earth deposits. For this reason, nuclear raw materials can be found in the same waste together with REEs. The separation of U and Th from REEs, and the proper management of radioactive nuclides is often a major concern in the REE industry (Zhu et al. 2015; Barakos et al. 2016). In addition, nuclear raw materials are found in coal deposits (Demir et al. 2010; Soylu et al. 2022). These can create environmental risks if not managed properly. Overall, the recovery of REEs and other nuclear raw materials from waste is an important area of research due to the increasing demand for these elements and the potential environmental risks associated with their disposal (Kursun et al. 2018; Xiong et al. 2019; Reynier et al. 2021; Altınır et al. 2021; Zhou et al. 2021; Guo et al. 2022; Aziman et al. 2023). These research investigations can also be evaluated in terms of sustainable development and feasibility. The adoption of sustainable development values (Ahmad et al. 2021; Yıldırım and Kantarcı 2022; Yıldırım et al. 2023; Allesch and Huber-Humer 2023; Satrovic et al. 2023) means an increase in the environmental and social costs of the mining industry (Humphreys 2001; Badakhshan et al. 2023; Hassan et al. 2023). To return these costs, the implementation of mine waste legislation that gives importance to mine waste recovery (Gümüşsoy et al. 2023) is also an expectation of the mining industry (Yıldız et al. 2017, 2024; Yıldız 2020b).

Due to the depletion of high-grade U-ores worldwide, new challenges arise in the extraction of low-grade ores and in the development of mining and milling operations. Mining waste creates environmental anomalies and long-term management needs pose particular challenges (Falck 2015). Indeed, the expectation of imbalances in global U supply and demand after 2035 increases the importance of secondary sources to contribute to the global U supply (Hall and Coleman 2013). These resources provide an annual supply of ~12,000 tons U equivalent. In the ten years between 2020 and 2030, it is predicted that uranium demand will increase by 23.6 percent (Uzun 2016). The secondary resources include, for example, uraniferous phosphates processed by the fertilizer industry, monazite processed for REEs, uraniferous carbonaceous materials, and ultimately seawater. An important advantage of secondary resources is that the major cost of mining and processing is covered by the (primary) valuable minerals, and only the incremental cost of U recovery needs to be considered. The second biggest advantage arises from radiation safety requirements. Primary sources are associated with higher levels of radioactive U by-products due to their higher U content. This leads to the application of strict radiological safety norms for mining and processing plant personnel, industry, and the environment. In contrast to secondary sources, additional engineering features need to be incorporated for security (Gupta and Singh 2005). Therefore, while primary U sources are the main contributor to industrial U production, secondary sources are gaining importance in terms of their environmental friendliness and resource conservation (Gupta and Singh 2003).

Essentially, there are three types of mining techniques that are applied for U production: underground mining, surface mining and ISL methods. Of the world's annual production of ~70,000 tonnes of U, 57% is obtained from ISL, 36% from underground and open pits and ~7% as a by-product (Yıldız 2017). In U mining, the production method is decided after the concentration of the ore has been determined by measuring the traces of the products formed during the uranium decomposition process with radiometric devices. The ore extracted in open pit and underground mining is purified by pre-enrichment processes after crushing-grinding processes. It is converted into a solid form which is called "yellow cake" (UO_2) because of its color and shape (Mining Türkiye Magazine 2018a, 2021; Okoshi and Nakayama 2015). Some uranium mineralizations may not be suitable for either open pit or underground mining techniques. Different applications from conventional mining techniques are used to obtain ore from such deposits. In the ISL method, the H_2SO_4 solution is firstly sent to underground U mineralization through the injection wells. The uranium dissolved with the help of acid passes through the pores in the formation and is pumped to the surface through re-injection wells. It can be directly involved in ion exchange, filtration and precipitation reactions without the need for any grinding processes. The ISL method is thought to have less impact on the environment than other mining techniques (Dobrzinski 1997). Since the grinding operations are bypassed, operating costs are reduced. To apply this operating method, the bottom and top rocks of U mineralization should have the ability to form traps, the ore-containing formation should be sufficiently porous and permeable, easily soluble by acid solution and most importantly, the use of underground drinking water

should not be affected. It is not allowed to use this production method in deposits close to settlements where underground drinking water is used. When all these conditions are met in the bed, the ISL production method can be used (Ünal 2014). Heap leaching is generally used in very low-grade (below 0.1% U) ore deposits. In this method, after the crushing process, the ore piled at a height of ~5–30 meters on an impermeable area is irrigated with acid or alkaline solution for a period of weeks. U is then obtained using ion exchange and the process is repeated. In this method, ore recovery is usually between 50–80%. Since the consumed material has the potential to cause pollution, special leaching area designs are used that will not affect surface and underground water resources (Mining Türkiye Magazine 2018a, 2021; Ghorbani et al. 2016).

Depending on the mining technique, the types and amounts of waste vary. Waste management techniques also depend on waste types and waste quantities. U mineral waste constitutes the most important waste management problem due to its large volume and radioactivity. Most of the components in this radioactive waste are naturally found in soil and bedrock. During U mining and grinding operations, natural radioactive material changes its chemical and physical form, increasing its mobility potential. As a result of this mobility, U mining waste may adversely affect the public and the environment in various ways (IAEA 1976; Osmanlioglu 2022a). Radioactive components in this waste and their possible release to the environment remain a major concern today (Nabhani ve Khan 2020; Randive et al. 2023). An example of this is the fact that for over a quarter of a century, the gold mines in the Witwatersrand in South Africa produced over 6000 million tons of uranium tailings (Wymer 1999). Although the tailings have great potential (Gerstmann et al. 2020; Nwaila et al. 2021), environmental precautions need to be taken. According to data from (Waggitt 1994), this is ~20 times more than the combined total of the two largest uranium producers, the USA and Canada. Compared to an annual global U tailings production of ~20 million tonnes in 1992, the amount of gold tailings accumulated in the Witwatersrand basin is equivalent to 300 years of global production. Since large-scale U production began only ~60–70 years ago (and at significantly lower rates thereafter), it can be safely assumed that five times more U-tailings have been deposited in South African gold deposits than U-tailings worldwide (Winde 2013). In general, the chemical mobility of U is relatively high in streams polluted by mining. It is estimated that ~1.6 million people live near tailings dams in the metropolitan areas of Gauteng alone. These tailings posed a significant threat to the environment due to their proximity to densely populated settlements in South Africa and because they covered an unusually large surface area of ~400 km² compared to other U mining regions in the world (Winde and de Villiers 2002; Coetzee et al. 2002a; Winde and Sandham 2004; Winde 2006a, 2006b, 2010; Zupunski et al. 2023). Studies have been conducted to identify and reduce the extent of these environmental problems (Coetzee et al. 2002b; Wade and Coetzee 2008; Sutton and Weiersbye 2008; Sutton et al. 2011; Raji et al. 2021).

Due to increasing awareness of environmental problems and the effects of radioactivity on public health, many countries have adopted or are in the process of adopting legislation aimed at improving and strengthening environmental protection against radioactive con-

tamination (McGrath 2000; Carney 2007; Kayadelen 2009; Osmanlioglu 2022b). In many developing or underdeveloped countries, legislation on nuclear raw material mining and its environmental impacts is still unclear and incomplete (Hamby 2016; Hadiwinata and Ramadhan 2020). Previous research (Vestergaard 2015a) analyzed fifteen uranium-producing and consuming countries, which together represent 85% of global production and 70% of consumption. This report provides a map of the evolving system of agreements, guidelines and regional and national obligations at a time when the uranium market is changing both structurally and geopolitically. Developments offer opportunities to many countries (Kryzia and Gawlik 2016), developed a model to estimate the operating costs of uranium deposits over time, depending on the level of supply sufficient to meet the demand from nuclear power plants. According to this study, it is estimated that uranium prices will remain stable at around 90 US\$/kg until 2030, but prices will increase and reach a minimum of 130 US\$/kg in 2050. Many factors affect the extraction and sale of U-ore (Robison 2014). The decline in U prices has led to the closure of some U mines in the past, e.g. in Australia (Vestergaard 2015b). Nevertheless, In the last sixty years, U has become one of the most important energy raw materials in the world. Although almost all of the U is used for electricity generation, a small part of it is used in important fields such as medical isotope production and some of it is used in maritime activities for military purposes (Mining Türkiye Magazine 2018a; URL-3). It is stated that as a result of exploration activities, the total uranium resources have increased by ~25% in the last ten years. According to 2023 data, the total known uranium reserve in the world is ~5.72 million tons (MTA 2023). The Nuclear Energy Agency stated that the U reserves determined in the world will be sufficient for ~200 years under today's consumption conditions (URL-1). As a result of the research to be performed, it is estimated that this period will increase to 230–250 years with the activation of new supply sources. Due to carbon gas emissions in the world, studies are being conducted with the aim of reducing the use of fossil fuels. It is planned to meet the energy deficit with natural gas and renewable resources. Although the use of nuclear energy has come to the fore in this process, it is estimated that the share of this use in electricity generation will remain below the level of 15%. As long as nuclear technology is managed well and correctly, U reserves are in a position to meet the world's energy needs for many years. It is estimated that a total of 518 nuclear power plants in the world will be operating in 2024, 125 in the USA, 130 in Europe, 83 in China, 37 in India, 51 in Russia, 74 in (other countries) in Asia, and Eastern European countries, and 18 in other countries (Yıldız 2017). In parallel with this, there will be an increase in the amount of nuclear raw materials and waste produced.

As stated above, nuclear raw materials can be found secondary to other minerals. This situation requires the monitoring of hazardous waste procedures in the storage of waste containing nuclear raw materials after the recovery of these main minerals. Recovery of these nuclear raw materials from stored mining tailings may be possible in the future. There is no review article in the world literature that explains and discusses waste management in the mining and ore preparation processes of nuclear raw materials together with the opportuni-

ties and obstacles related to their recovery. Considering this deficiency in the literature, in this study, the nature and characteristics of waste and residues arising from the mining and mineral processing activities of nuclear raw materials are explained, new methods, difficulties, and opportunities are mentioned, and solutions for tailing recovery and waste management are presented. In this context, it is stated that there remains a waste problem in U and Th production. It is explained which REE/mineral deposits would pose a danger in terms of U and Th waste. In the presence of waste management costs, U and Th waste management perspectives are drawn. The scope of the study is as follows:

- ◆ In Section 1, U-waste and its chemicals/compounds, environmental effects, and the recovery of this waste are explained.
- ◆ In Section 2, Th-waste and their chemicals/compounds, environmental effects, and the recovery of this waste are explained.
- ◆ In Section 3, the waste management of nuclear raw materials is explained. The difficulties and opportunities encountered in waste management during the mining and enrichment processes of U and Th containing ores and the legislative issues in waste management are explained.

1. U-waste and environmental impacts and recovery

1.1. Types of U-Waste

Types of waste from U mining include (Al-Hashimi et al. 2007; Helling et al. 1997; Robinson 2004; Carvalho et al. 2005):

1. Ore tailings: these are the waste materials left after the extraction of U from the ore. Uranium mills produce waste called tailings, which are a mixture of U oxide, a refined product – U_3O_8 , often called “yellow cake” – and finely crushed, chemically treated ore and mill reagents. These forms of waste may contain various minerals and elements, including U, as well as other potentially hazardous elements.
2. Acidic waste: U-ores often contain pyrite (FeS_2), which can undergo acid-producing reactions when exposed to air and water. This can lead to acidification of the pore water in the abandoned U tailings, potentially causing groundwater pollution.
3. Radium-rich waste: some U mining operations may encounter Ra-rich mineralization, which can result in the presence of Ra in the tailings. Ra is a radioactive element and can pose environmental risks if not properly managed.

The properties of U-waste may vary depending on specific applications. Radon diffusion in soil is an important consideration in the assessment of radon-induced radiation exposure from U-waste disposed of in shallow land. Understanding the nature of radon diffusion and determining the radon diffusion coefficients in soil are key features in assessing the potential impact of U-waste (Sasaki et al. 2008). In terms of waste management, even

for the recycling of metal scraps and construction demolition waste, radiological evaluation is required first (Osmanlioglu 2012; Šljivić-Ivanović and Smičiklas 2020). Considering that these applications are being made, the management of U-waste should be considered more sensitively. Many studies have been performed on the removal of radioactivity from U liquid waste (Osmanlioglu 2006b, 2007, 2015, 2016b, 2018b; Kam et al. 2014). One such example in the context of sulfuric acid U refining is galvanochemical purification, which is a process studied for liquid radioactive waste products. This process is aimed at treating wastewater and determining the basic laws and characteristics of the treatment process (Ostrovskiy et al. 2008). Gamma spectrometry systems are used for the analysis of U tailings and potentially contaminated low-level waste. These systems use high-resolution and low-resolution spectrometry techniques to measure gamma-emitting radioisotopes in tumbled waste. They also fulfil specific measurement requirements and enable the accurate assessment of U-wastes and potentially contaminated waste (Clark et al. 2003). Characteristics of U-wastes include (Jiang et al. 2020, 2021, 2022; Wei et al. 2021; Liu et al. 2021; Mao et al. 2022):

1. Physicochemical properties: Soil physicochemical properties such as pH, electrical conductivity (EC), total nitrogen (TN), total organic carbon (TOC), and total phosphorus (TP) are measured and analyzed in U-waste ponds.
2. Heavy metals/metalloids: U-wastes may contain heavy metals and metalloids such as cadmium (Cd), lead (Pb), zinc (Zn), chromium (Cr), and arsenic (As).
3. Regional distribution: The regional distribution of soil properties and heavy metals/metalloids in U-waste ponds may vary with depth. Some properties and metal concentrations increase with depth in the vertical profile.
4. Correlations: There are significant correlations between heavy metals, radionuclides, and physicochemical properties in U-waste ponds.
5. Solidification process: The solidification process of U-wastes can affect properties such as pore structure, volume resistance, compressive strength, and radon exhalation rate.
6. Vitrification: Vitrification is a process that can be used to produce dense glass matrices of U-waste, which can affect the microstructure and mechanical properties (Sanito et al. 2022).
7. Stability assessment: The stability of more than one dam in an U-waste reservoir can be evaluated using composite risk analysis models, considering factors such as dam crest height, slope, mechanical properties, seepage capacity and resistance to natural events.
8. Permeability properties: The overload in U tailings ponds can be studied to understand factors such as the permeability properties of its soil, its pore properties, and radon exhalation.

1.2. Specific chemicals/compounds found in U-wastes

The specific chemicals or compounds found in U tailings can vary depending on the mining and processing methods used as well as the characteristics of the ore extraction (Tombal-Kara 2020). However, some common chemicals and compounds that can be found in uranium waste are as follows (Al-Hashimi et al. 2007; Carvalho et al. 2005; Huang et al. 2022):

- ◆ Uranium: This is the primary element of interest in U mining and occurs naturally in ores. It is a radioactive element and can pose environmental and health risks if not properly managed. U is a chemical element with the atomic number 92. It is a silvery-grey metal located in the actinide series of the periodic table. U has various compounds such as U dioxide (UO_2), U hexafluoride (UF_6), U trioxide (UO_3) and U tetrafluoride (UF_4) (Stevenson 1950; Mydosh 2017; von Oertzen 2017; Barbin et al. 2023).
- ◆ Thorium: This is another radioactive element that can be found in U-waste. It is often associated with U deposits. It can increase the overall radioactivity of waste. Th is a chemical element with atomic number 90. It is a silvery-white, radioactive metal found in small amounts in rocks and soil. Th has a number of compounds, including Th disilicide (ThSi_2) and Th nitrate ($\text{Th}(\text{NO}_3)_4$). Th also forms intermetallic compounds with transition metals such as iron, cobalt, nickel, manganese, copper and silver (Florio et al. 1952; 1956; Guan et al. 2022).
- ◆ Radium: This is a radioactive element that can be found in U tailings, especially where the ore contains Ra-rich mineralization. Ra can pose environmental and health risks if not managed properly. Ra is a highly radioactive element belonging to the alkaline earth metals group. It is a rare element found in U and Th ores. The chemical properties of Ra compounds depend on the oxidation state of Ra. Ra can form compounds with +2 and +3 oxidation states. Ra compounds are highly toxic and radioactive and can pose a significant health risk to humans and the environment (Zhang et al. 2023).
- ◆ Sulfuric Acid: This is widely used in the extraction and processing of U ore. It can be found in effluents as a result of acid leaching and contributes to the acidification of the pore water in the effluent.
- ◆ Pyrite: U-ores often contain pyrite, which can undergo acid-producing reactions when exposed to air and water. This can lead to acidification of the pore water in abandoned U-waste. Pyrite is a mineral known for its metallic luster and yellowish hue, similar to gold. It consists of iron sulphide (FeS_2) (Lu 2022).

1.3. Environmental impacts from U-wastes

U-waste can seep into water bodies and affect the aquatic ecosystem. Since these types of waste contain heavy metals, they cause pollution of water resources such as rivers and lakes and pose a danger to aquatic life (Winde 2013; Djenbaev et al. 2020; Savcı and Kirat

2022). The release of U-waste into the environment can affect the habitats of plant and animal species and cause a loss of biodiversity. Radioactive pollution can disrupt the balance in ecosystems and lead to the extinction of some species. Radiation exposure can cause cancer, birth defects and other health problems. The environmental effects of U-waste can be long term. Since radioactive wastes have a long half-life, they can have a lasting impact on the environment and affect future generations (IAEA 1976; Ehsani et al. 2019; Nabhani and Khan 2020). Mining and grinding activities increase the volume of radioactive waste. Bulk residues from the mining and grinding of U ore are usually very low in specific radioactivity but extremely large in volume (Osmanlioglu 2016a).

U-waste contains radionuclides such as U-238, Th-232, Ra-226, and K-40 that can pollute the environment. These radionuclides can spread and pollute the environment, including soil, surface water and groundwater (Yong-ming 2011; Harpy et al. 2020; Nygymanova et al. 2021). The presence of radionuclides in U-waste poses potential health risks to people living near these sites. Consumption of contaminated water or horticultural products grown with contaminated water causes in radiation exposure exceeding the safety limit (Bochud et al. 2011; Carvalho 2018; Xie et al. 2019). In addition, the presence of radionuclides in U-waste can cause soil pollution. The specific activity of radionuclides in the soil, including U-238, Th-232, Ra-226 and K-40, can be measured and studied to assess the environmental impact of U-waste. The transport of radionuclides with wastewater may pollute surface waters and groundwater, posing a risk to aquatic ecosystems. In addition, radionuclides could potentially adversely affect people using these water sources (Yong-ming 2011; Kadadou et al. 2023). The transport of radionuclides to the environment through waste can lead to pollution and the development of dangerous diseases (Harpy et al. 2020).

U is a chemo-radiotoxic element that can cause multifactorial health hazards (IAEA 1976; Rathod et al. 2023). Workers involved in the extraction, processing and transport of U-waste may face OHS risks (Koeyers 1996; Paschoa and Steinhäusler 2010; Ehsani et al. 2019; Nabhani and Khan 2020). Studies investigating the health effects of U mining have revealed that uranium miners have an increased risk of certain cancers, such as liver, stomach and kidney cancers (Winde 2013; Semenova et al. 2020). Health risks associated with exposure to U-waste include potential radiological hazards and exposure to radioactive particles (Rathod et al. 2023). Potential health effects of exposure to uranium mill waste (Landa 2004) include external exposure to gamma radiation, inhalation of radon gases and the consumption of food products grown in radium-contaminated soil (Denham et al. 1986; Bochud et al. 2011). Yi et al. (2018) focused on identifying potential biomarkers associated with chronic exposure to low-dose gamma radiation from U-waste. The researchers found that certain proteins were differentially expressed in the liver of mice exposed to gamma radiation, suggesting that these proteins may serve as biomarkers for radiation exposure. Remediation measures have been implemented at some uranium mining sites to reduce pollution and increase radiation safety. These measures include covering waste, treating mineral water drainage and removing contaminated materials (Carvalho 2018). Some other studies on this subject are described below.

In a study conducted around an abandoned U waste pond, Wang et al. (2018) found that the soil was contaminated with heavy metals and metalloids such as U, manganese, arsenic, lead and chromium. Winde (2002) found that the transport of adjacent waste deposits and dissolved uranium through streams caused stream pollution in a study conducted in mining areas in Germany, South Africa and Australia. Shaduka (2016) found that groundwater was contaminated with radionuclides resulting from unlined U-waste in a study in Namibia. Wang et al. (2021), in a study in China's Jiangxi Province, found that U and Th were released from deactivated U-waste and polluted the soil. Lv et al. (2021) found that uranium pollution in wastes and degradation products is a global environmental problem in a study on the microbial stabilization of U-wastes.

1.4. Recovery of U-waste

There are three known isotopes of U in nature: U-238 (99.275%), U-235 (0.72%) and U-234 (0.005%) (Ünal 2014). Of these, U-235 in particular can be used directly for energy production. U-235 is made usable in uranium reactors by enriching it to a certain amount (up to ~2–3% grade). When the degree of enrichment exceeds 20%, nuclear weapon quality is achieved, and when it exceeds 90%, nuclear bomb quality is achieved. In addition to the fact that U-235 is so poor in nature, the grade of the ore in the rock it is found in is also quite poor (~0.1–2%). This situation results in an average of 525 times as much waste as the U recovered from the ore (Yavuz 2012). The amounts (Clark numbers) of U in various rock types are as follows: 0.03 ppm in ultramafic rocks, 0.53 ppm in mafic rocks, 3.9 ppm in granitic rocks, 2.2 ppm in limestones, 1.7 ppm in sandstones, 3.7 ppm in shales and 2 ppb in surface waters.

As can be seen, U is found in almost all types of rocks and in water, albeit in trace amounts. Compared to the elements antimony, tin, cadmium, mercury, and most importantly silver, U is found in higher amounts in the earth's crust and according to this evaluation, U ranks fifty-first. U, which is never found free in nature, combines with various elements to form uranium minerals. There are ~200 different U-minerals in nature. The most commonly known minerals are uraninite, otinite, carnotite, torbernite, brannerite, and coffinite (Hammond 2000). It is not possible to produce high-grade concentrate by enriching U minerals by gravity or flotation using conventional methods. However, by flotation, the impurities contained in the ore are removed from the environment as much as possible, and pre-concentrate is produced to enable an easy method of enrichment in the next stage. The method applied to produce pre-concentrate also varies according to the structure of the ore and the uranium grade it contains. Produced concentrate and ore of suitable grade ground to the required size is enriched by extraction. Figure 1 shows the basic flow in the enrichment of U-minerals. Changes can be made in the flow charts of uranium enrichment depending on the ore structure and the economy of the business. The enrichment of U is conducted in the following stages (Yıldız 2014, 2017):

- ◆ In the first stage, the impurities contained in the ore are cleaned as much as possible by methods such as gravity and flotation. Thus, it is ensured to work with less ore in the next stages. Depending on the U content of the ore, after the ore is crushed and ground, it is usually sent to extraction circuits without enrichment.
- ◆ The U contained in the ore is taken into solution by an acid or alkali extraction method.
- ◆ After extraction, “yellow cake” is produced.
- ◆ The U-235 ratio of yellow cake to be used as fuel is increased from 0.7% to ~5%.
- ◆ The yellow cake to be used for military purposes is further enriched and the ~5% U-235 content is increased to over 95%.

Various methods have been proposed for uranium recovery from tailings. These methods include processes such as leaching, oxidation, ion exchange absorption and precipitation. The leaching method involves treating the waste with a solvent such as acid to dissolve the U-minerals and separate them from the other components. Microwave irradiation-induced composite oxidation of the Fe-Mn binary system was found to increase the leaching of U from tailings. This method involves using microwave radiation to intensify the oxidation process, which facilitates the separation of U ions from waste. Wastewater from U mining and grinding operations, including wastewater, can be recycled and reused for a variety of purposes. These processes include the use of wastewater as a leaching agent, eluent, extraction solution, washing solution and waste sludge (Guang-zhi 2010; Wang et al. 2022).

Microwave irradiation of U-waste has been studied for a variety of purposes, including increasing U recycling and immobilizing radionuclides. Wang et al. (2022) investigated the

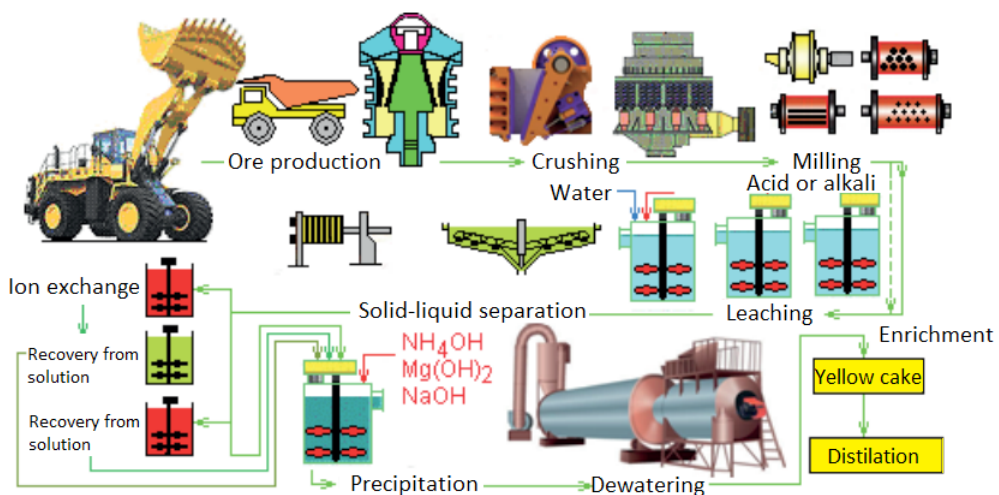


Fig. 1. The mainstream in the enrichment of U-minerals (Yıldız 2014, 2017)

Rys. 1. Główny nurt wzbogacania minerałów uranu

use of microwave irradiation to increase the leaching of U from waste. The results showed that the leaching efficiency of U significantly increased when the wastes were subjected to microwave irradiation along with the composite oxidation of Fe₃(III) and Mn(VII). (Wei et al. 2021) investigated the production of a dense glass matrix of U-waste by microwave sintering. The addition of Na₂CO₃ as a sintering aid lowered the ignition temperature and promoted condensation, resulting in vitrified forms of waste. Hunan et al. (2016) described a device and control method for the cracking and grinding of U-ores using pulsed microwave irradiation. High-power pulsed microwave irradiation reduced the mechanical strength of the ores and increased their degree of weathering, facilitating the cracking, grinding and leaching of uranium minerals.

Most of the research activities in the nuclear mining industries are devoted to the separation of heavy and radioactive minerals from rocks and sediments. This process is completed without the use of mining waste materials (Seleman et al. 2022). By contrast, the comprehensive recovery of uranium waste includes a variety of methods and techniques for managing and using waste materials from U mining and metallurgy. In a study conducted in Beishan, China (Xun et al. 2018), the effect of U-waste on soil composition and soil microbial activity was evaluated. In the study, radionuclide, heavy metal and organochlorine pesticide concentrations were analyzed in soil samples collected at different distances from U-waste. Another study, (Hui et al. 2013) conducted research on the recovery of uranium and copper from uranium ore leach solutions. The study found that U recovery can be achieved by adsorption using resin followed by desorption and precipitation. Copper recovery was obtained by replacing it with iron powder. This method provides the extensive recovery of both U and copper. Efforts are being made in China to recycle waste/tailing from U mining and metallurgy and to recover useful resources. These efforts also include U recovery from mineral water, wastewater reuse, the decontamination and recycling of radioactively contaminated metal, the backfilling of gangues and tailings, and the extensive recovery and use of associated U deposits (Guang-zhi 2010; Zhong-qiu 2012).

There are also U recovery and waste reduction possibilities from the brine in reactors (Altay et al. 2022). In addition, there are possibilities to recover U and Th metals from the ashes formed as a result of burning coal in thermal power plants. Such studies are important both economically and in terms of controlling environmental pollution (Olkuski and Stala-Szlugaj 2009; Demir and Kursun 2012; Kursun and Terzi 2015, 2016; Kursun et al. 2016; Rózański 2019). Recycling U from waste has environmental benefits. The impact on ecosystems and surrounding communities can be reduced by minimizing the amount of waste produced and minimizing the potential for radioactivity contamination in the environment (Dudgeon 1999; Wang et al. 2022). The recycling of U-waste is part of a broader effort to recover useful resources and minimize waste in the U mining and metallurgical industries. By extracting and reusing these resources, the need for new mining activities and the related environmental impacts are reduced and natural resources are protected (Araujo et al. 2022). The recycling, storing and managing U waste do not only reduce the amount of waste but also help alleviate the burden on waste ponds and storage facilities. In this

way, any leakage or spillage that may harm the environment reduces the risk of accidents. The recycling process of U-waste can be more energy-efficient than conventional mining and processing methods. By reducing the energy consumption and carbon emissions associated with mining, it can contribute to a more sustainable and environmentally friendly approach to recycling (Jung et al. 2016). Recycling of U-waste may involve techniques that restore and rehabilitate land affected by mining activities. This can help reclaim land for other purposes, such as agriculture or conservation, and reduce the long-term environmental impact of mining operations (Araujo et al. 2022). In another method, it has been determined that fly ash can be used in industry as an additive in the solidification process of radioactive waste sludge from the reactor. In this way, environmental impacts can be reduced and waste management costs can be met to some extent (Osmanlioglu 2014). Because mining waste management requires a significant share of operating costs (Yıldız 2020b; Das et al. 2023), the use of tailing as an alternative mineral resource can improve the sustainability of the mining process (Vilaça et al. 2022) and help meet these costs (Kinnunen et al. 2018; Yıldız 2020b; Machairas and Varouchakis 2023).

Many countries have made significant progress in U recovery methods. One example of this is the fact that the atomic energy industry is one of the most important branches of the Ukrainian economy. The East Concentrating Mill and Zheltiye Vody Hydrometallurgical Plant, which was the U production center of Ukraine between 1961 and 1968, conducted the first Ukrainian ISL U project in Devladovo of the Sofiivka region (Dnipropetrovsk province) and the second in Bratske (Mikolaivska province) in 1964–1969. Experiments were conducted with an acid-leaching system (IAEA 2001; Sukhovarov-Jornoviy et al. 2005). During this time, the ISL U-production method gained importance due to its competitive cost, despite its limited applicability to certain U deposits called Sandstone U-deposits (Abzalov 2012). This method has been proven to be a very cost-effective and environmentally friendly technology compared to other methods (Bakarzhiev et al. 2005; Perkov 2005; Sukhovarov-Jornoviy et al. 2005). It was also recognized that two different approaches to ISL U-production were implemented in the USA, Eastern Europe (particularly in Ukraine), and later in Kazakhstan and Uzbekistan. Commercial ISL U-mining in the United States began in the mid-nineteen-seventies. In 1968, for the first time in the former USSR, the East Concentrating Mill and the Zheltiye Vody Hydrometallurgical Plant applied ISL U-mining technology at the Devladovske U-deposit. Heap and in-situ leaching develop energy resource-saving technology for the mining and processing of low-grade U-ore with minimal impact on the environment. It is planned that four ISL modules in Ukraine, with an investment of 250 million US\$, will operate with an annual efficiency of 1000 metric tons for 10–15 years. According to Sukhovarov-Jornoviy et al. (2005), stack and block ISL technology provides:

- ◆ 30–40% reduction in U-ore mining and processing costs;
- ◆ 15–20% reduction in waste (reducing ore imbalance as well as rock and soil piles);
- ◆ reducing the amount of solid waste after the hydrometallurgy plant by 2–3 times;
- ◆ a two- to three-fold reduction of technical water for yellow cake production;

- ◆ reduction of sulfuric acid and sulfuric anhydride and aerosol emissions by 2–2.5 times;
- ◆ reducing nitric oxide emissions from the hydrometallurgical plant by 2–3 times;
- ◆ a two- to three-fold ore dust emission decrease due to the decrease in U-ore transportation;
- ◆ the utilization of waste by replacing sand in the mine.

In addition to the recovery of nuclear raw materials, negative environmental impacts can also be reduced to ensure the use of the material in different sectors. A previous study focused on processing coal ash to extract U, making it suitable for iron oxide use in metallurgy and minimizing the impact on the environment. Bunus and Dumitrescu (1986, 1992) and Cioroianu et al. (2001, 2005) developed projects in Romania that enable the recovery of U from phosphate fertilizers, which cannot be used in the agricultural sector due to their U content, and the removal of radium by processing. The recovery of U from phosphate fertilizers has led to the establishment of three new U facilities in Romania.

2. Th-waste and environmental impacts and recovery

2.1. Types of Th-waste

Thorium wastes can be found in various sources and have different compositions. Some types of Th-waste are:

1. Mining tailings: Th is often found in REE-bearing minerals found in various mineral deposits, often with other minerals that are extracted for their commercial value. To obtain a purified Th product from Th minerals, gradual physical and chemical processes are required. However, the documented experience with these processes is extensive and the inclusion of Th recovery should not be overly challenging. The use of existing mining infrastructure prevents the opening and operation of new mines. Additionally, Th recovery removes radionuclides from mine tailings. Therefore, the expected environmental impacts of Th recovery as a by-product are less than U recovery (Ault et al. 2016).
2. Waste and waste liquids: Waste and liquids defined by the production of Th dioxide from monazite sand are wastewater, waste, dust, smoke, gas and radionuclides (Enderlin 1978).
3. Leach process wastes: Ra is the main radionuclide found in tailings after leaching for uranium extraction. Ra is highly active with solid degradation products. The main danger remains not only during radioactive releases during leaching processes but also for many years after the cessation of activities (El-Halim and El-Abrdi 2021).
4. Product waste: Relates to the final purification of uranium, the product after the re-processing of Th-producing fuel (Rastogi et al. 1997).

The properties of Th-wastes may vary depending on the particular extraction and processing methods used. Some of the properties of Th-wastes that have been studied are:

1. **Composition:** The composition of Th tailings can vary depending on the particular ore being processed (Maksimova et al. 2022).
2. **Radioactivity:** Th-wastes can be radioactive due to the presence of Th and other radioactive elements. Th-waste can emit alpha, beta and gamma radiation (Kumar et al. 2013; Maksimova et al. 2022).
3. **Particle size:** The distribution of valuable components and Th in the wastes may depend on the particle size class.
4. **Durability:** The durability of Th-wastes may depend on the type of glass used for storage. Some studies have shown that thorium-containing glasses may be less durable than U-containing glasses (Peeler 2003).
5. **Chemical properties:** Th-waste may contain other radioactive elements such as U and plutonium. This can make disposal difficult. It can be difficult to separate these elements from Th-wastes (Kumar et al. 2013).
6. **Environmental impact:** Th-wastes can contaminate soil and water if not properly stored and disposed of. However, some studies have suggested that the use of humic substances can reduce the toxicity of Th-wastes and other radioactive pollutants (Tchaikovskaya and Bocharnikova 2020).

2.2. Specific chemicals/compounds found in Th-Wastes

The chemical composition of Th-wastes may vary depending on the source and processing methods used. The waste contains various compounds, including isotopes of thallium, lead, bismuth, polonium, radon, radium and actinium. Th-wastes may also contain various compounds, including U, Th and other minerals such as monazite, zircon, xenotime and ilmenite. The U and Th concentrations in the wastes may vary depending on the source, and these elements can be found at high levels in some wastes. Chemicals used in the processing of Th-ores can also be found in Th-wastes. These may include acids, bases and other chemicals used to extract and purify Th (Alnour et al. 2017; Li et al. 2019; Maksimova et al. 2022).

2.3. Environmental impacts from Th-wastes

Th-wastes may have potential environmental effects due to their radioactive nature. In general, the potential environmental effects of Th-wastes can include radioactivity and waste pollution. However, the expected environmental impacts of Th recovery as a by-product are less than the environmental impacts of U recovery, as the use of existing mining infrastructure prevents the opening and operation of new mines and Th recovery removes radionuclides from mining tailings (Oar et al. 2015; Ault et al. 2016).

Th-wastes can be radioactive due to the presence of Th and other radioactive elements. This can lead to potential exposure to radioactivity produced by airborne particulate U, Th-230, and Ra-226. Radiation exposure from building materials is mainly due to the presence of radionuclides in the U and Th series. External exposure may be due to gamma emitters found in the material, while internal exposure may be due to radon and thoron gas (Swift et al. 1976; Silva et al. 2019). The beneficiation processes of REE-containing minerals can generate large amounts of waste. The complex and heterogeneous mineral and chemical composition of waste material can make it difficult to manage and dispose of (Qiu et al. 2016; Maksimova et al. 2022). Roasting one tonne (REO50%) of rare earth concentrate will emit sulfuric acid mist, sulfur dioxide, fluoride, smoke and radioactive slag containing Th. The low recovery and large scale of concentrated sulfuric acid used in roasting processes in the rare earth industry are the main causes of high pollution and high emissions (Qiu et al. 2016). Disposal of Th-waste can be difficult due to its radioactivity and the presence of other radioactive elements such as U and plutonium. Incorrect disposal can lead to environmental pollution in the long run (Tchaikovskaya and Bocharnikova 2020).

Improper disposal of Th-waste can lead to serious environmental and health hazards. According to the United States Environmental Protection Agency (URL-4), Th-waste can cause the following problems if not disposed of properly:

- ◆ Radiation exposure: Th-waste emits alpha particles that can cause radiation exposure when inhaled or ingested. This can lead to lung cancer, bone cancer and other health problems.
- ◆ Pollution of soil and water: If Th-waste is not disposed of properly, they can pollute soil and water. This can lead to environmental damage and health hazards in the long run.
- ◆ Risk to wildlife: Th-waste may also pose a risk to wildlife if they come into contact with contaminated soil or water.

Therefore, it is important to properly handle and dispose of Th-waste to minimize the risk of these hazards. EPA has established regulations for the disposal of Th-waste to ensure it is handled safely and responsibly (URL-4).

2.4. Recovery of Th-waste

Thorium has six known isotopes: Th-227, Th-228, Th-230, Th-231, Th-232 and Th-234. Of these, only Th-232 is stable. The average concentration of Th in the earth's crust is considered to be ~7 ppm. Th is several hundred times more abundant in the Earth's crust than U. The frequency of Th in nature is ~2 times higher than molybdenum, arsenic and tin. However, their concentration in rocks is quite low (Tombal 2015; Ünal 2016; Yıldız 2017). Since Th is relatively rare in rock compared to U, more mining, grinding and refining are required to recover it at similar scales (Degueldre and Joyce 2020). Th, like U, is not found in free form in nature but is found in ~60 minerals. These minerals are generally found together with

REE mineralizations (Lewicka 2013). The most important minerals that can be produced are monazite, bastnaesite and xenotime. Allantite is an important mineral with its 0.1–2% Th concentration. Th is mainly recovered from monazite sands (Tombal 2015; Ünal 2016; Yıldız 2017) in the world, usually as a by-product of the monazite enrichment process. The Th oxide content of monazite varies between 4–12%. It is not possible to produce monazite directly for Th without producing REEs. Th is produced from monazite minerals or from the wastes left after the enrichment of REE minerals. Concentrates with 98% monazite content can be produced from coast sands around the world. Depending on the mineral content, enriched monazite concentrates may contain ~15% ThO₂. The REO in these concentrates is ~60%. The P₂O₅ ratio contained in monazite concentrate is ~30%. After Th is recovered by physical methods, it is extracted with H₂SO₄, HNO₃, HCl, or NaOH to produce ThO₂. (The most preferred Th production technique among these is the use of nitric acid). Monazite concentrate is extracted with 50–70% NaOH at ~140°C and taken into solution. Pure Th nitrate is produced by going through a series of hydrometallurgical processes such as solution, stripping and ion exchange. Th nitrate is also calcined and converted to ThO₂ after precipitation as Th oxalate. In the applied alkali leaching, the REE contained in monazite is separated into chloride compounds and Th hydroxide is obtained. Th hydroxide contains 35% ThO₂, 7% REO, 0.6% U₃O₈, and ~28% solids that do not go into solution (Yıldız 2014, 2017; Tombal 2015).

The use of Th alone as a primary energy source has been investigated for years. However, these studies have been overshadowed by the U reserves and R&D costs that can feed nuclear power plants for ~200–250 years. Th has many other current uses. Th burns with a bright white light in a normal environment. The ThO₂ melting temperature of Th oxide is 3,300°C. With this feature, ThO₂ is used in the production of bulbs, lantern jackets, arc light lamps, welding electrodes and heat-resistant ceramics. Due to its high refractive index and wavelength distribution features, high-quality lenses used in cameras and scientific instruments are produced from Th oxide-containing glass. Light Th-Mg alloys with 2–3% Th content are used in the production of aircraft with their strength at high temperatures and resistance to cracking. As Th nitrate, it is used in tungsten arc sources under gas due to its melting temperature and ability to create a stable arc at these temperatures, and in air-traffic control, observation and weather forecast radar systems because it emits electrons at microwave frequency. It is also used in the production of magnetron cathode tubes and moving wave tubes, which are used in weapon systems and microwave ovens. In addition, Th-230 is used in the U-Th age determination method (Alves et al. 2001; Ünal 2016; Yıldız 2017). Th is, above all, a radioactive element that can be used as a nuclear fuel. Th remains a key future raw material in the nuclear fuel cycle, as recycling of Th-waste can reduce the amount of waste produced and make more optimal use of available resources.

According to 2023 data, the total known Th reserve in the world is ~6.4 million tons (Cordier 2023). This reserve is estimated to contain an average of ~6–7% thorium oxide. In terms of mining methods, Th and U mining are the same (Ünal 2016; Yıldız 2017). The low average grade (0.2%) and the complexity of the reserve make it difficult to economically

extract Th alone. The consumption of Th as an energy raw material is almost non-existent today (MTA 2023). Other sectors also use Th at a low level. The storage conditions of Th are costly, for example, a budget of 5.5 billion US\$ required for the rehabilitation of the Bayan-Obo REE field in China, which also contains Th, was requested from companies from the USA and EU producing technology. Waste costs and environmental problems related to REE use seriously restrict the sustainable development of the REE industry in China. Considering that these companies use the raw materials in these mine sites and participate in these waste costs, China demanded that the companies cover the said costs (Zhou et al. 2017; Çimen 2021). New technologies are being researched to separate U and Th from REEs during REE production in China (Zhu et al. 2015). In this way, progress has been made in radioactive waste management in China (Fan et al. 2013).

There are various methods for the recovery of Th from waste. The first of these is the ultra-selective ion sieve method. Gao et al. (2021) developed an oxygen-rich microporous carbon for the ultra-selective extraction of Th ions (Th(IV)) from REEs over a wide pH range. Another method is the solvent extraction method. Flanary and Goode (1959) developed a solvent extraction process using tributyl phosphate as the extractant to separate neptunium from process tailings and this process has been proven on a semi-business scale. This method expands the use of tributyl phosphate as a solvent for heavy element recovery by adding neptunium to Th, U and plutonium. Another method is the leaching method. Moura et al. (2022) studied the leaching of aluminothermic slag for the recovery of U and Th. Process parameters analyzed are solution pH, time, granulometry and percent solids. The metallurgical recovery of U_3O_8 reached a maximum value of 71.3% with pH = 1.8, 8 hour time, 65% solids content and 200 μm granulometry. The metallurgical recovery of ThO_2 reached a maximum value of 69.7% with the same parameters. Another method mentioned in the literature is supercritical fluid extraction. Lin et al. (1995) studied the feasibility of removing Th ions from nitric acid solutions using supercritical CO_2 -containing organophosphorus reagents. The results showed that the effective extraction of Th ions can be achieved even in dilute nitric acid solutions, which can help reduce acidic waste volumes in nuclear waste treatment. Another approach involves the use of bacteria and biogenic phosphates for the bio-recovery of REEs, including Th. One method involves the enzymatic precipitation of calcium phosphate as hydroxyapatite (Bio-HA) followed by the capture of REEs, including Th. Captured REEs can be magnetically separated. This approach shows potential for the selective recovery of REEs, including Th, from mining tailings and from ore leach tailings contaminated with radionuclides (Macaskie et al. 2017). Th can be removed from wastewater by chemical precipitation, which involves adding a chemical reagent to the wastewater to form a solid precipitate that can be separated from the liquid phase (Kaynar et al. 2023). This method is widely used for Th removal. However, it has some limitations such as high pH requirements and large volumes of sludge production. Ion exchange is another method used for Th removal from wastewater. This process involves replacing Th ions in wastewater with other ions in a resin. The resin can then be regenerated and reused. This method is effective for Th removal. However, it can be costly. Adsorption is a process through which Th ions

are removed from wastewater by binding to a solid surface. This method is widely used for Th removal and can be effective for low Th concentrations. However, this method can also be costly and requires a large amount of adsorbent material. Electrosorption is a promising method for the treatment of Th-containing wastewater. This process uses an electric current to remove Th ions from wastewater; it can overcome the limitations of adsorption techniques and provide a more efficient and faster process (Aziman et al. 2021).

3. Nuclear raw material waste management

Radioactive waste management studies begin with preliminary disposal. These studies are large-scale industrial projects that involve the separation of reusable materials from final waste, appropriate conditioning and the classification of these waste types until the storage stage, depending on national waste management strategies and waste acceptance criteria. Radioactive waste must be disposed of in surface facilities awaiting sufficient degradation and requiring institutional control for several hundred years (although not provided in all countries), or in near-surface facilities if the radioactivity and half-life are too high to leave the area, or in deep geological repositories (Grambow 2022). Successful waste management and disposal programs must be both socially and technically acceptable (Ewing 2015). Ignoring this basic principle has led to the failure of many repository projects. Programs for the construction of repositories for high-level radioactive waste have recently been strongly encouraged. Many developed countries (Finland, Sweden, France, etc.) have issued or are close to granting licenses for deep geological disposal of highly radioactive waste. Switzerland has also identified and proposed a repository for high-level radioactive waste, which would also store low- and medium-level waste. Waste management organizations in these countries have demonstrated through tens of thousands of pages of scientific evidence compiled over a period of thirty or more years that the current state of basic understanding of the science and technology of long-term repository development is sufficiently advanced to accomplish geological disposal projects. The design of the architecture of the network of underground transport galleries and the residential areas of a warehouse requires a large number of closely interconnected research and development activities. This requires the development of an appropriate excavation technology, quality assurance, and an adapted waste placement technology (Grambow 2022).

U and Th have properties that can be evaluated together in terms of waste management (Lee and Ojovan 2013). Among these, more dominant U mining is not different from other types of mining in many applications. The main issue that makes the difference is the fact that U shows radioactive properties during the decay process. If the ore grade in the production area is very high, dedusting techniques may need to be used more sensitively to limit the amount of radiation to which the workers are exposed and to ensure the safety of the surrounding public. In areas with unusually high grades, the use of distance working techniques can be considered. Although U-minerals have low radioactive properties, they are closely

related to radioactive elements such as radium and radon, which are released as a result of radioactive decay over millions of years. For this reason, the ore extracted from the mine should be handled sensitively in terms of OHS, especially if it is of a high grade. As a result of the grinding process, many different types of solid waste products are obtained, from sludge to coarse-grained sand. The resulting tailings contain most of the main components of the ore. For this reason, they are radioactive especially because of the radium they contain. One of the products released when radium undergoes natural decay is radon gas. Since radon and its decay products are radioactive and the ground rock containing the wastes is carried to the surface as a result of production, measures should be taken to minimize radon gas emission. During the operational life of a mine, the material in the tailings dam should be kept covered with water to reduce surface radioactivity and radon release. Because this water contains relatively soluble radium, it must be recycled or evaporated. In many mines around the world, a ‘zero discharge’ policy is adopted in such cases. With the completion of the mining activities, the cover with sufficient rock content for the tailings dam to resist erosion is a soil covering and ~2 meters of clay. This measure aims to control both gamma radiation levels and radon emission rates. It also helps the ore deposit return to levels near the levels normally experienced in the region and necessary for the continuity of vegetation (Mining Türkiye Magazine 2018a; Ehsani et al. 2019).

The radioactivity of U is much less than the radon gas released as a result of its decay. Radon gas is released into the atmosphere in very small quantities as ore is extracted and milled. Occurring naturally in most rocks, radon leaves traces in the air we breathe for several minutes and is a significant contributor to the natural radiation dose humans receive. Special precautions should be taken to limit the contact of miners with radon gas, especially in poorly ventilated mines due to it being gaseous. Open pits are naturally well-ventilated. In this way, it becomes easier to keep radon levels at safe levels. In underground mines, a good ventilation system should be installed in the mine to ensure that the exposure rate to radon gas and radioactive by-products remains below the specified safety levels. Additionally, airborne dust and surface pollution should be regularly checked to prevent the spread of radioactive components and radon gas. The amount of radiation exposure of workers in mines, mills and waste areas should be kept as low as possible. In any possible scenario, it should be ensured that the dose limits determined by the authorities are not exceeded. In mines where high-grade U-ore is extracted, such as in Canada, production can only be performed by remote control techniques. The use of radiation detection equipment should be mandatory in all U mines and plants. Workers in the mine likely to be exposed to radiation or radioactive materials should be monitored for alpha radiation contamination, and dosimeters should be used to measure personal gamma radiation exposure. Care should be taken to enforce personal hygiene standards for workers using U oxide concentrate. Hygiene measures should be taken for personnel working in the drying and packaging areas of the grinder as U oxide causes chemical poisoning similar to lead oxide if swallowed (Skeppström and Olofsson 2007; Mudd 2008; Appleton 2012; Skubacz et al. 2019).

In situ leaching operations, the quality of the groundwater remaining after mining is completed must be restored to an initial standard set before the start of the operation and the natural order of the area must be preserved. At the end of the mining activity, the dirty water taken from the aquifer is cleaned by evaporation or purification before it is returned to the system. After the water is injected, the production wells are closed, the processing facilities are removed and the evaporation pool is rehabilitated. In this way, the mining site can easily return to the state it was before the mining activities. Mining is generally considered a temporary land use. Once this use is complete, any waste rock, overburden and confined treatment will need to be reclaimed or restored to other uses (Yıldız et al. 2016; *Mining Türkiye Magazine* 2018a, 2021; Yıldız 2020a; Şimşek 2022).

U, which has weak radioactivity in the ore state, becomes a strong radioactive element after enrichment processes (Ünal 2014). Th is a nuclear raw material with similar properties (Tombal 2015; Yıldız 2017). The basic concept in the disposal of high-level radioactive waste or spent fuel is to dispose of such waste in an underground waste disposal facility. (Osmanlioglu 2018a) identified and evaluated several technical parameters as important design parameters for a sustainable nuclear waste disposal facility. This study is based on the determination of the main effective design parameters for a sustainable nuclear waste disposal facility. Issues such as the chemical properties of the groundwater that will come into contact with the waste should be considered. The design parameters can be determined for each site in the field characterization process as a result of the analysis to ensure the long-term safety and stability of the disposal facility.

Two alternative strategies are proposed for the management and disposal of radioactive nuclear waste: regulation and conversion. The first option requires the selection of suitable geological deposits. The second option, conversion, aims to reduce the radiological effect of actinides and fission products in high-level waste through the laborious nuclear conversion of long-lived nuclides in strong neutron radiation fields (Tsvetkov 2021). The safety of radioactive waste management is paramount for any country that has not defined the practical application of general safety concepts (Sanders and Sanders 2021). Establishing a regulatory framework is the main issue in radioactive waste management (Miller and Wong 2013). Several factors should be considered in the development of a regulatory framework for the safety of waste management. These are radiological protection criteria, international agreements and guidelines, technical compliance, institutional control, and practical application (Metcalf and Batandjieva 2013). Studies conducted within the framework of the legislation contribute to the development of general safety criteria in waste management and to the improvement and revision of regulations. Regulatory procedures depend on scientific knowledge and technological developments. Security standards should be reviewed appropriately according to the technical and institutional capability of the relevant country. Although the various implementation factors depend on the specifics of each country, the main factors affecting the regulatory framework for the safety of radioactive waste management (Osmanlioglu 2006a) are as follows:

- ◆ First, each government should decide which of the waste management methods to apply in each phase of its waste management activities. This main decision can be made by decision-makers by providing data from experts. At this stage, there are several factors (such as international agreements and guidelines) that influence the decision. It should be ensured that the activity and volume of any radioactive waste originating from the sources for which they are responsible are kept to the lowest possible level. It is also expected to ensure the management of waste, i.e. its collection, treatment, conditioning, transport, storage and disposal.
- ◆ Where appropriate to the requirements of applicable standards and warranted by differences in factors such as radionuclide content, half-life, concentration, volume and physical and chemical properties, it is useful to separate the different types of radioactive waste and, if appropriate, treat them separately with consideration to the options available for waste disposal (IAEA 1994).
- ◆ Security requirements should be reviewed against organizational capabilities and technical compliance requirements. This stage is the most important in terms of obtaining information about the current situation for the safety of radioactive waste management. If these defined security requirements can be met with institutional and technical means, practical application opportunities will become utilizable. During practical implementation, safety standards will be maintained using a quality assurance program for waste management.
- ◆ Regulations should include procedural requirements, performance targets and specific technical requirements for near-surface disposal that apply to any method of the disposal of low-level waste on land (Randive et al. 2023). Low-level waste should be classified according to the half-life and concentration of radionuclides contained in the waste. According to this classification, increased requirements are placed on the waste form, the depth of disposal and the design of the disposal unit to ensure increased isolation and prevent accidental mixing into the disposed waste. Waste containing radionuclide concentrations above the classification limits are not suitable for near-surface disposal. Regulations require such waste to be disposed of in a geologic repository.
- ◆ Regulations should provide for performance targets for a disposal facility that do not result in releases into the environment exceeding an annual dose of 0.3 mSv for the whole mass. In addition, regulations require reasonable efforts to be made to keep radioactive emissions as low as possible. Radiological protection criteria should determine that no individual in the critical group should be exposed to a higher risk than (10^{-6} years⁻¹) by optimizing protection systems. Protection systems should be changed according to this value. These criteria should be consistent with the ICRP recommendation (ICRP 1985). For the post-closure period, the requirements should be met by conducting a long-term performance assessment of disposal sites.

Conclusions and suggestions

With consideration to the literature, in this study, the potential of nuclear raw material waste to pollute the environment has been emphasized. It should be noted that the specific composition of these types of waste may vary depending on the mining and mineral processing methods used, as well as the characteristics of the ore extracted. The proper management and disposal of waste is essential to minimize environmental impacts and potential pollution. Additionally, there is a need for waste legislation and practices that will allow these wastes to be recovered in the future. New studies on waste legislation revisions will enable the recycling of environmentally sensitive nuclear raw material waste.

As will be examined in this study, there are different studies and new techniques for the recovery of U and Th waste, and the reduction of environmental impact by reducing the amount of waste generated. As a result of these studies, the advantages of nuclear raw material waste management in terms of both compliance with the legislation and cost will increase gradually. This situation will further ensure environmental sensitivity in the use of nuclear raw materials and may also make nuclear raw material mining and waste recovery projects feasible. In this way, it will be possible to contribute not only to mining enterprises but also to the return on nuclear power plant costs and to feasible plant operation. Thus, in the future, environmentally friendly nuclear raw material extraction, use and recovery projects increase their advantages. The co-existence of nuclear raw materials with REEs provides opportunities for both the recovery of these minerals and waste management. Thus, new studies will contribute to the development of both sectors.

In line with the targets of reducing carbon emissions in the world, an increase is observed in nuclear reactor projects in the planning and proposal phase in addition to the nuclear reactors that are in operation. This situation will put countries with nuclear raw material reserves in an increasingly advantageous position. In parallel with the commissioning of new-generation U and Th reactors, there will be an increase in the amount of nuclear raw materials produced and the amount of waste generated. As a result, the need for more sensitive studies on environmental risks will increase in both mining and ore preparation, reactor use processes of nuclear raw materials and the storage of waste. In line with this expectation, in this study, technical studies and suggestions that can reduce the possible environmental impacts of nuclear raw materials at these stages and ensure their recovery are discussed.

The low average grade and the complex structure of the reserve make it difficult to economically extract nuclear raw materials alone in most countries in the world. This situation requires considering that the production of nuclear raw materials as secondary minerals will become more widespread in the world. Additionally, the expectation that there may be imbalances in global U supply and demand increases the importance of secondary resources contributing to the global U supply. The increasing importance of secondary sources of nuclear raw materials reveals the need to give more importance to the recovery of these resources together with primary minerals than was the case in the past.

Significant technological and scientific progress has been made in the management of radioactive waste over the last thirty years. In this study, the challenges and recovery opportunities encountered in the waste management of nuclear raw materials, especially in ore preparation processes, are explained. Since it is outside the scope of the subject, it has been chosen to mention the management, environmental effects and recycling of nuclear power plant wastes to only a very limited extent in this study. In the future, studies on the recovery of nuclear raw materials from both mining processes and nuclear power plant wastes, their feasibility, environmental costs and the application of new environmentally friendly technologies in waste management may fill the gaps in this article.

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CHALLENGES AND RECOVERY OPPORTUNITIES IN WASTE MANAGEMENT DURING THE MINING AND ENRICHMENT PROCESSES OF ORES CONTAINING URANIUM AND THORIUM – A REVIEW

Keywords

radioactive waste, radioactive waste management, uranium mining waste, uranium recovery, uranium tailings

Abstract

During the extraction of nuclear raw materials, rare earths and other elements from ores containing uranium and thorium, various types of radioactive waste and some recovery tailings are generated. Mining and ore processing residues, i.e. waste and tailings, present a variety of problems related to waste management. Their bulky structure prevents their disposal underground, and their long radioactive half-life causes various problems with regard to their long-term storage. As a matter of fact, the secondary presence of nuclear raw materials together with other minerals requires compliance with hazardous waste procedures in the storage of waste containing nuclear raw materials after the recovery of these main minerals. It may be possible in the future to recover these nuclear raw materials from stockpiles of stored mine waste. The prospect of imbalances in the global uranium supply and demand increases the importance of secondary sources contributing to the global uranium supply. The increasing importance of secondary sources of nuclear raw materials suggests that more attention should be paid to the recovery of these resources together with primary minerals than in the past. In world literature, there is no review article that describes and discusses the waste management of nuclear raw materials in mining and mineral processing together with the opportunities and obstacles for their recovery. Considering this deficiency in the literature, in this study, the properties of waste and tailings resulting from mining and ore preparation activities of nuclear raw materials are explained, the difficulties encountered are mentioned, and solution suggestions are presented by making use of the literature on the recovery of tailings and waste management.

WYZWANIA I MOŻLIWOŚCI ODZYSKU W GOSPODARCE ODPADAMI PODCZAS PROCESÓW WYDOBYCIA I WZBOGACANIA RUD ZAWIERAJĄCYCH URAN I TOR – PRZEGLĄD

Słowa kluczowe

odpady promieniotwórcze, gospodarka odpadami radioaktywnymi,
odpady wydobywcze uranu, odzysk uranu, odpady uranu

Streszczenie

Podczas wydobywania surowców promieniotwórczych, pierwiastków ziem rzadkich i innych pierwiastków z rud zawierających uran i tor powstają różnego rodzaju odpady radioaktywne oraz niektóre odpady poprodukcyjne. Pozostałości po wydobyciu i przeróbce rud, czyli odpady i odpady poflotacyjne, stwarzają szereg problemów związanych z gospodarką odpadami. Ich nieporęczna struktura uniemożliwia składowanie pod ziemią, a długi okres półrozpadu radioaktywności powoduje różne problemy związane z ich długotrwałym składowaniem. W rzeczywistości wtórna obecność surowców promieniotwórczych wraz z innymi minerałami wymaga przestrzegania procedur dotyczących odpadów niebezpiecznych przy składowaniu odpadów zawierających surowce radioaktywne po odzyskaniu tych głównych minerałów. Być może w przyszłości możliwe będzie odzyskiwanie tych surowców radioaktywnych ze składowanych odpadów kopalnianych. Perspektywa braku równowagi w globalnej podaży i popycie na uran zwiększa znaczenie źródeł wtórnych przyczyniających się do globalnej podaży uranu. Rosnące znaczenie wtórnych źródeł surowców radioaktywnych sugeruje, że należy zwrócić większą uwagę na odzysk tych zasobów wraz z pierwotnymi minerałami niż w przeszłości. W literaturze światowej nie ma artykułu przeglądowego opisującego i omawiającego gospodarkę odpadami surowców promieniotwórczych w górnictwie i przetwórstwie minerałów wraz z możliwościami i przeszkodami w ich odzyskiwaniu. Biorąc pod uwagę ten brak w literaturze, w niniejszym opracowaniu wyjaśniono właściwości odpadów i odpadów poflotacyjnych powstałych w wyniku wydobywania i przeróbki rud surowców radioaktywnych, wspomniano o napotkanych trudnościach oraz przedstawiono propozycje rozwiązań, wykorzystując literaturę dotyczącą odzysku odpadów poflotacyjnych i gospodarki odpadami.