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Exploring the Opportunities for Sustainable Management of Critical Raw Materials in the Circular Economy

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Abstract: Critical raw materials are essential for various industries due to their importance, significance, and various applications. They are classified into various types, such as rare earth elements and strategic minerals, and have key characteristics such as scarcity, high economic importance, and geopolitical implications. Factors influencing the availability of critical raw materials include geological factors, environmental challenges, regulations, trade, and geopolitical factors. Global demand and supply of critical raw materials are also analyzed, with a focus on recycling and sustainable practices. Potential risks and challenges associated with critical raw materials include environmental and social impacts, dependence on these raw materials, and dependence on foreign countries. Understanding these factors is crucial for ensuring the continued success of critical metals in various industries. The research paper discusses the importance of critical metals in the circular economy, their definition, and the research's objectives. It also discusses the circular economy concept and its relevance to resource management, identifying critical metals and their specific roles, and discussing challenges and opportunities related to their use. The article focuses on the potential for critical raw material management within the circular economy. The study's goal is to investigate and analyse the various tactics and methodologies that can be used to successfully utilise, recycle, and reintroduce key metals into the economy. The circular economy is viewed as a method of improving sustainable resource management by closing the material flow and encouraging renewability and recycling. The circular economy is currently understudied in the context of critical metals - a set of raw materials that are vital for modern technology but are limited in supply and cause significant environmental damage.

Keywords: Critical raw materials, Critical metals, Circular economy, Engineering economics, Industrial engineering

Introduction

Critical raw materials represent an important part of the modern economy and industry. Essential to various sectors, including electronics, automotive, and green energy, these raw materials play a key role in our daily lifestyles and economic activity. (Hool et al., 2023) Despite their importance, access to some of these raw materials is limited, and their stocks are subject to various risks. This topic is essential because it requires learning how to sustainably manage critical raw materials, search for alternatives, and optimise their use in an increasingly developing global economy. The circular economy and critical raw materials are linked through an approach that promotes the sustainable use, recycling, and optimisation of raw materials, including those considered critical for various industries. (Hristova, 2022) This cyclical model of economic activity aims to reduce dependence on new extraction of raw materials, extend the life of materials, and encourage innovation that reduces the use of critical raw materials in products and production, supports sustainability, and reduces negative environmental impacts. (Piotrowski, 2023)

The Impact of the Circular Economy in the Context of Critical Raw Materials

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Within conventional linear business models, the process often involves the extraction of key materials, subsequent use in the manufacturing of a product, and eventual disposal. Nevertheless, these approaches are no longer compatible with the present supply chains, increasing demand, current and future sustainability targets and regulatory requirements. The critical raw mineral supply chain is faced with several main difficulties, which encompass:

- The rapid acceleration of the energy transition poses challenges to supply chains, which are currently strained and potentially unable to promptly adjust to meet the increasing demand. According to Deloitte, it is projected that by the year 2035, a total of 74 additional lithium mines and 97 additional graphite mines will be required. However, it is important to note that the process of transitioning a mineral deposit from its initial discovery to full-scale production typically entails a time frame of approximately 10 to 12 years. (Deloitte, 2023)
- The security of supply pertaining to the mining and processing of essential minerals is subject to significant concentration and vulnerability due to geopolitical conflicts and fluctuations in prices. For instance, a mere three nations currently dominate almost 75% of the worldwide production of cobalt, lithium, and rare earth elements.
- There are several environmental, social, and governance issues associated with the mineral extraction process. These encompass elevated carbon emissions, degradation of land, loss of biodiversity, water scarcity, and more extensive concerns regarding safety and human rights.

A circular strategy decreases exposure to these difficulties by lowering the need to mine essential minerals.
The progression towards achieving net zero emissions will persistently gain momentum, hence intensifying our dependence on essential minerals. The implementation of a circular economy has the potential to decrease dependence, enhance the adaptability and durability of organisations, and present novel avenues for commercial ventures. Companies that utilise key minerals in their goods must modify their approach to product manufacturing and utilisation, and embrace novel business models and digital technologies that facilitate circularity.

Identification of Critical Raw Materials

The European Commission defines critical raw materials as raw materials of great importance to the EU economy and with a high risk associated with their supply. (European Commission, 2023). Critical raw materials form a strong industrial base and serve as the basic material basis for the development of modern society. (Ruan et al., 2023).

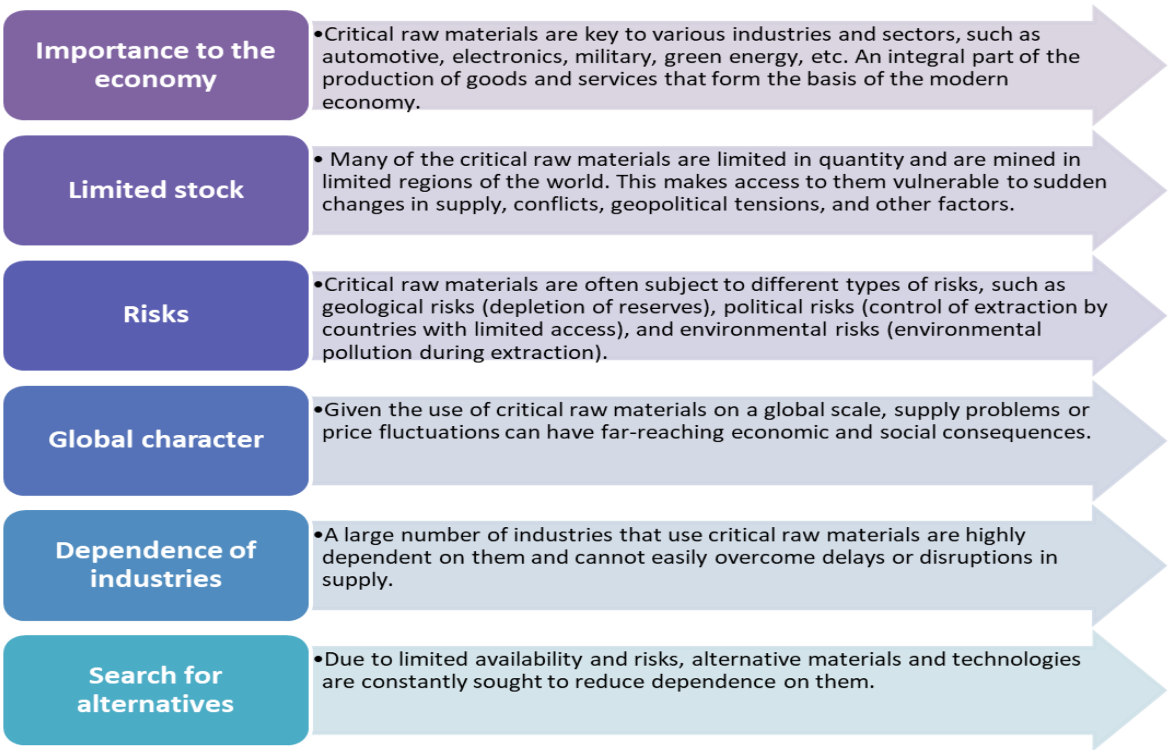

Figure 1. Basic characteristics of critical raw materials (Author's research)

They are a major building block, an element of growth and competitiveness, and crucial for Europe's economy. In this regard, reliable and unhindered access to certain raw materials is an increasing commitment, both for Europe and the whole world. Fig. 1 marks the main characteristics of critical raw materials. All these features highlight the need for sustainable management of critical raw materials. It is essential for the economic stability and sustainability of countries and the global economy as a whole. The importance of critical raw materials is determined by their strong link with industry—non-energy raw materials are linked to all industries at all stages of supply—but also by modern technology. On the threshold of the next industrial revolution, technological progress and quality of life rely on access to an increasing number of raw materials. The role of the environment is no less important; raw materials are closely related to clean, green technologies, and it is believed that the next industrial revolution will be dedicated to them. Critical metals such as copper, aluminium, nickel, and titanium are widely used and indispensable in solar panels, wind turbines, electric vehicles, energy-efficient lighting, and high-tech industries such as semiconductors, healthcare, defence, and aerospace. (Watari et al., 2020).

Critical raw minerals are important not only for industrial and technological needs but also for sustainable development and ecological balance. As the consumption of these resources increases, so do the challenges of sustainable management and supply. To address these challenges, the European Commission has created a list of critical raw materials for the EU, which is subject to review and updating every three years. Table 1 presents the critical raw materials included in the five EU lists

Table 1 Critical raw materials lists 2011 - 2023

Critical raw material	2011	2014	2017	2020	2023
Aluminium/Bauxite				x	x
Antimony	x	x	x	x	x
Arsenic					x
Baryte			x	x	x
Beryllium	x	x	x	x	x
Bismuth			x	x	x
Boron/Borate		x	x	x	x
Chromium		x			
Cobalt	x	x	x	x	x
Cocking Coal		x	x	x	x
Copper					x
Feldspar					x
Fluorspar	x	x	x	x	x
Gallium	x	x	x	x	x
Germanium	x	x	x	x	x
Hafnium			x	x	x
Heavy rare earth elements		x	x	x	x
Helium			x		x
Indium	x	x	x	x	
Light rare earth elements		x	x	x	x
Lithium				x	x
Magnesium	x	x	x	x	x
Manganese					x
Natural graphite	x	x	x	x	x
Natural rubber			x	x	
Nickel					x
Niobium	x	x	x	x	x
Phosphate Rock		x	x	x	x
Phosphorus			x	x	x
Platinum group metals	x	x	x	x	x
Rare Earths	x				
Scandium			x	x	x
Silicon metal (Silicium)		x	x	x	x
Strontium				x	x
Tantalum	x		x	x	x
Titanium metal				x	x
Tungsten (Wolframium)	x	x	x	x	x
Vanadium			x		x

Impressive are copper and nickel, which do not cross the threshold of critical raw materials but are included in the fifth list from 2023 as strategic raw materials, in accordance with the Law on Critical Raw Materials. Their role in bringing about a green transformation is key, especially copper, which is involved in every single low-carbon green technology. It is believed that the list of critical raw materials would support the development of recycling policies and the transition to a more circular and sustainable economy, as well as more efficient use of resources and strengthening the competitiveness of the continent. (Blengini et al., 2019). Europe is relatively poor in critical raw materials, also due to the fact that the natural reserves of these raw materials are concentrated mainly in China, Russia, South Africa, Brazil, and the USA. (Massari, Ruberti, 2013) However, critical raw materials are not only the focus of Europe and the European Commission. They are the subject of study by researchers and institutions around the world.

Classification of Critical Raw Materials

The classification of critical raw materials is a key element in understanding and managing this type of mineral resource. It is carried out depending on a number of criteria, such as geographical spread, degree of dependence on imports, importance for different industrial sectors, and potential risks in relation to their supply. Critical raw materials can also be classified according to their degree of availability and digestibility. This kind of classification not only helps in prioritizing economic strategies and innovations but also in formulating policies for sustainable management and recycling of critical raw materials. At the same time, it emphasizes the importance of diversity and sustainability in the energy and raw materials sectors, striving to reduce dependence on limited resources and promote alternative technologies and materials. It is important to emphasize that the classification of critical raw materials changes over time, as new technologies and innovations may change the importance of certain metals or cause new critical elements to appear. For this reason, continuous monitoring and analysis of the supply of critical raw materials is essential for the economy and the scientific community.

This publication examines some of the critical raw materials relevant to modern technology and provides an analysis of their availability and substitutability (Table 2). The classification of critical raw materials represents an important tool for understanding and managing the supply of these key resources, promoting the sustainability, innovation, and efficient use of raw materials required for the modern world.

Table 2 Classification of a part of critical raw materials (Author's research)

Critical Raw Material	Key Use	Geographical Distribution	Comments
Cobalt	In the manufacture of lithium-ion batteries, electronics, automobile batteries, and other products.	Specifically, the Democratic Republic of the Congo.	Cobalt mining in the Democratic Republic of the Congo is linked to human rights violations, child labour, and hazardous working conditions. The environmental impact of cobalt mining is a source of contention.
Lithium	In the production of lithium-ion batteries for mobile devices, electric vehicles, and batteries for the storage of energy from renewable sources.	Chile (major global producer), Australia, Argentina, and China	Lithium mining can be affected by restrictions related to environmental protection, regulations, and social issues.
Niobium	In the production of superconductors, light industry, and military equipment	Brazil (the main global producer), Canada, and Australia	Political and economic instability in the mining regions is one of many factors that can affect niobium mining and production. The niobium processing process is complex and requires specialised technologies. Processing restrictions may limit the availability of finished products. Despite these challenges, there are currently no widespread, economically viable alternatives to replace niobium. Instead, efforts are focused on

			optimising production and making efficient use of available resources.
Platinum group metals (platinum, palladium, rhodium, iridium, ruthenium, and osmium)	In the production of catalysts and in the automotive industry.	South Africa, Russia, Zimbabwe, the USA, and Canada have limited supply and high prices.	Supply is considered risky. Replacing PGMs is challenging due to their unique combination of properties that are difficult to replace with other materials. However, research and the development of new technologies are focused on the development of alternative materials and methods to use less platinum-group metals or even completely without them. Some of the options for substitution include the use of other metals, such as nickel, copper, gold, or silver; the development of new catalysts and materials with similar properties; and the transition to more efficient and sustainable production processes.
Rare Earth Elements (neodymium, praseodymium, dysprosium, etc.)	In the production of magnets for electric motors, magnetic materials, and catalysts	China, Australia, the USA, Brazil, and Russia	The elements are not literally rare in the earth's crust but are scattered in very small concentrations and are difficult to extract and process. There are geopolitical challenges and risks associated with the supply of raw materials.
Tantalum	In the production of capacitors, mobile phones, computers, aerospace, and other high-tech systems.	Australia, Brazil, and Canada	The process of processing tantalum ore into the final product is complex and requires specialised technologies. Processing limitations and low efficiency can limit the availability of finished products. Despite these challenges, research is being conducted, and alternative materials and technologies are being developed to reduce dependence on tantalum. Some of the replacement options include the use of other materials such as ceramics, polymers, or other metals with similar electrical and physical properties. In addition, the recycling of tantalum from used products is becoming increasingly important for the recovery of available resources. However, currently, tantalum remains an important and indispensable element in high-tech devices, and efforts are being made to ensure a stable supply and sustainable use of this metal.

Methods and Technologies for Recycling Critical Raw Materials and Evaluating Their Efficiency and Environmental Impact

Recycling critical raw materials, including metals and rare elements, is an important process aimed at optimizing the use of limited resources and reducing dependence on new mining. It enables the recovery of valuable materials from waste products and waste, including metals such as gold, silver, platinum, palladium, and other critical metals that can be reused in various industrial and technological applications. Recycling reduces the need for new extraction of raw materials, which has a positive effect on the environment. The extraction of raw materials is often associated with significant environmental impacts, including water pollution, ecosystem destruction, and greenhouse gas emissions. Recycling raw materials requires less energy and resources compared to the process of extracting and processing new raw materials. This helps to reduce energy consumption and optimize the use of limited resources. Recycling critical raw materials creates economic opportunities in the form of new business models and jobs. This can encourage the development of a recycling industry and innovation in recycling technology.

Despite these benefits, recycling of critical raw materials still faces some challenges, including technological and economic limitations, a lack of efficient collection and recycling infrastructure, and complex waste collection systems. The continuous improvement of recycling technologies and the development of sustainable and innovative raw material management models are essential to achieving sustainable use of critical raw materials in the future. There are various methods and technologies for recycling critical metals, and their efficiency and environmental impact can vary depending on the process and application. Some of the main methods of recycling critical metals include:

1. Physical separation and sorting - physical separation and sorting of waste, separating valuable materials from other components. It may involve the use of various methods, such as magnetic separation, size sorting, or gravity methods.
2. Pyrometallurgy – these processes use high temperatures and chemical reactions to extract the metals from the waste. It can involve melting the materials and passing them through various phases of extraction, purification, and recycling of the metals.
3. Hydrometallurgy - use solvents and chemical reactions to dissolve metals from waste and extract them. This may involve various steps such as leaching, extraction, and electrodeposition of the metals.
4. Biotechnologies - use microorganisms or biological processes to degrade or extract metals from waste. It may involve the use of bacteria, fungi, or other biological agents capable of degrading or accumulating the metals.

Assessing the effectiveness and environmental impact of these methods and technologies can be complex and depends on many factors, including waste types, process conditions, energy requirements, emissions of harmful substances, and waste management. It is important to carry out a comprehensive assessment of the entire life cycle of the recycling process, from waste extraction to the final product or material.

The continued development of new technologies, innovations in recycling processes, and strict adherence to environmental standards and norms are essential to reducing the adverse impact on the environment and achieving a sustainable recycling industry.

Technological Innovations for the Recovery of Critical Metals

Technological innovations for the recovery of critical metals are being developed to efficiently use limited resources and reduce dependence on new mining. (Patil et al., 2022) Here are some of the main innovations in this area:

1. Use of high-efficiency chemical processes. New methods and processes are being developed to efficiently extract critical metals from various sources. This may include the use of chemical solvents and extraction techniques that allow for more efficient separation and extraction of the metals from the waste.
2. Nanotechnology. Nanomaterials and nanotechnology play an important role in the recovery of critical metals. Nanoparticles can be used to efficiently extract metals from waste or to facilitate metal separation and purification processes.
3. Biotechnologies. The use of microorganisms and biological processes can be an innovative method to recover critical metals. Some microorganisms are able to accumulate metals or extract metal ions from waste, which can facilitate the recycling process.
4. Development of new materials and alternatives. Options for replacing critical metals are being explored extensively. New materials and technologies are being developed to reduce or eliminate the use of critical metals in various applications. For example, alternative materials for lithium-ion batteries are being investigated to reduce or eliminate the use of critical metals such as cobalt.

These technological innovations have the potential to change the landscape of critical metal recovery by reducing reliance on new mining and optimising the use of limited resources. (Song et al., 2022) However, many of these innovations are still in their early stages of development and require further research and development before they can be widely implemented on an industrial scale.

Results and Discussion

The present study will contribute to the understanding and development of strategies and practices that can help achieve sustainable use and management of critical raw materials within a circular economy. Critical metals are a group of raw materials that are of strategic importance to modern technology but are limited in availability and are found in geographically concentrated areas. They are used in various industries, such as electronics, power systems, automotive, military, and others. Replacement of critical raw materials can be accomplished by developing alternative materials, changing product design, increasing use efficiency, recycling, and improving extraction methods. Investments in research and development projects are essential to finding sustainable solutions for the use of critical raw materials. (Dimov, et al., 2020). To achieve more sustainable management of critical raw materials and metals, the following improvements can be made and certain guidelines followed:

1. Changing production processes: Manufacturers can use more sustainable methods and technologies to extract, process, and manufacture critical metals. This may include the use of energy-efficient processes, the reduction of waste disposal and emissions of harmful substances, as well as the use of renewable energy sources.
2. Convert to closed supply chains: For critical metals, closed supply chains are a viable way to implement the circular economy principle. This means increasing the efficiency of recycling, recovery, and secondary use of critical metals, as well as reducing dependence on new mining.
3. Develop standards and certifications: Establishing standards and certifications for the responsible management of critical metals can help track and ensure ethical, environmental, and socially responsible behaviour throughout the supply chain. Such standards and certifications can be applied both in the mining industry and in the production and consumption of critical metals.
4. Investment in research and innovation: Funding research projects and innovation in the field of critical metals can lead to the development of new technologies and processes for the efficient recovery, recycling, and replacement of these materials.
5. Cooperation and knowledge sharing: It is important to support cooperation between governments, industry, academia, and civil society to exchange knowledge and experience in the field of critical metals management. This may include organising forums, working groups, and projects to share good practices and research.

The implementation of these improvements and guidelines can contribute to achieving more sustainable management of critical metals, reducing environmental burden and independence from mining, as well as creating more sustainable and innovative business models in this area.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

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References

Blengini, G., Mathieux, F., Mancini, L., Nyberg, M., Viegas, H.M., Salminen, J., Garbarino, E., Orveillon, G., Saveyn, H., Aquilino, V. Llorens, T., Polonio, F., Horckmans, L., d'Hugues, P., Balomenos, E., Dino, G., Feld, M., Madai, F., Janos, F., & Calleja, I.. (2019). *Recovery of critical and other raw materials from mining waste and landfills state of play on existing practices*. Joınt Research Centre (JRC).

Dimov, E., Bakyrdjieva, R., & Stratiev. N. (2020). The mining industry and the recycling of raw materials as an important element of the Bulgarian economy. *Journal of Mining and Geological Sciences, 63*, 289-292.

European Commission (2023). Directorate-general for internal market, industry, entrepreneurship and SMEs, *Study on the critical raw materials for the EU 2023 – Final report.* Office of the European Union

Hool, A., Christoph, H., & Gijsbert. W. (2023). Challenges and opportunities of the European critical raw materials act. *Mineral Economics*, 1-8.

Hristova, T. (2022). The place of the blockchain in the recycling of raw materials. In *2022 8th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE)* (pp. 1-4). IEEE.

Massari, S., & Ruberti, M. (2013). Rare earth elements as critical raw Mümaterials: Focus on international markets and future Strategies. *Resources Policy, 38,* 36-43.

Patil, A., Rudolf, S., & Christian. L. (2022). Opportunities in critical rare earth metal recycling value chains for economic growth with sustainable technological innovations. *Circular Economy and Sustainability.* 3, 1127-1140.

Piotrowski, S. (2023). Critical raw materials in the semiconductor industry: Current challenges and perspectives. *The Third International Scientific Conference: Studies in Changing Bussiness Environment.* Vilnius.

Ruan, S., Song, Y., Cheng, J., & Zhan, C. (2023). Green eco-innovation and supply of critical metals: Evidence from China. *Sustainability, 15*(17), 12730.

Song, Y., Zhouyi, Z., Yijun, Z., & Jinhua. C. (2022). Technological innovation and supply of critical metals: A perspective of industrial chains. *Resources Policy, 79,* 103144.

Watari, T., Nansai, K., & Nakajima, K. (2020). Review of critical metal dynamics to 2050 for 48 elements, resources. *Conservation and Recycling, 155.* 104669.

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