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TOWARDS SUSTAINABLE DEVELOPMENT IN THE EUROPEAN UNION: A CRITICAL RAW MATERIALS PERSPECTIVE

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ABSTRACT: Sustainability is a key goal of the European Union, which is seen as a global leader of change in tackling climate change, as well as building green economic sustainability, leading to greater social prosperity. A milestone of sustainable development to support the European Union in achieving climate neutrality is the European Green Deal. Its initiatives aim to build a competitive and innovative EU economy while respecting and protecting the environment. According to current priorities, the European Union aims to become the first climate-neutral continent by 2050, thanks to critical raw materials. The purpose of this article is to analyse and assess the impact of critical raw materials on the sustainability of the European Union. The study uses a scoping review methodology and statistical analysis based on the Shapiro-Wilk test and Spearman correlation coefficient. The results show that critical raw materials are important for achieving sustainable development and implementing the EU economy towards climate neutrality. This paper contributes to the literature on sustainability. It can also provide important information for policymakers to understand how to shape green policies in the context of the strategic importance of critical raw materials in the transformation of an eco-innovative economy.

KEYWORDS: critical raw materials, sustainable development, European Green Deal, European Union

Introduction

Sustainable development is a concept that is gaining more and more attention as a new trend in socio-economic development around the world (Hopwood et al., 2005). There is growing interest in both politics and industry to support a sustainable economy in the context of ever-changing conditions for social and economic development. The need to decouple economic growth from negative environmental impacts is increasingly being emphasised. The growing importance of sustainable development, as well as the circular economy, the assumptions of which have been fully accepted by individual entities, requires a number of actions (Mancini et al., 2015). The implementation of the European Green Deal by the European Union in 2019, which is a kind of roadmap covering a number of policies, should be considered part of these actions (Smol et al., 2020; Stilwell, 2021). The European Union aims to become the first climate-neutral continent by 2050. The implementation of the European Green Deal by the European Union is intended to lead to the development of clean technologies, reduction of pollutant emissions, environmental protection and investments in R&D (Smol et al., 2020).

However, clean and environmentally friendly technologies require the consumption of significant amounts of mineral resources. Access to mineral resources remains crucial for individual economies, as it has a huge impact on their competitiveness and innovation (Smol & Kulczycka, 2019). Minerals, including critical raw materials, also contribute to the integration of sustainable development and the implementation of many policy initiatives, including the European Green Deal (Guzik et al., 2021). Critical raw materials can be defined as those of economic and strategic importance for the European economy, but the continuity of supply is high risk (Ferro & Bonollo, 2019; Karali & Shah, 2022). The global economy needs a continuous and uninterrupted supply of critical raw materials to enable it to function properly while contributing to the transformation to an eco-innovative and low-carbon economy (Christmann, 2021; Hofmann et al., 2018; Hund et al., 2020; Melfos & Voudouris, 2012).

Research on critical raw materials remains fragmented and tends to focus on selected aspects. For the European Union, research on critical raw materials focuses on their economic importance (Hofmann et al., 2018), supply risk (Løvik et al., 2018; Martins & Castro, 2020), recycling (Yuksekdag et al., 2022), assessment of the (sustainable) life cycle (Hackenhaar et al., 2022), as well as their mapping and production possibilities (de Oliveira et al., 2021; Melfos & Voudouris, 2012). Looking more broadly at the issue under study, there are also analyses of individual mineral resources classified as critical raw materials. This applies in particular to those raw materials that are used in technological innovations, such as lithium-ion batteries, photovoltaic cells, or wind turbines (Alessia et al., 2021; León & Dewulf, 2020; Petranikova et al., 2020; Rachidi et al., 2021; Song et al., 2019).

Research shows that critical raw materials play a significant role in the transformation of the eco-innovative economy and progress in moving towards a resource-efficient circular economy (Christmann, 2021; Hofmann et al., 2018; Karali & Shah, 2022; Melfos & Voudouris, 2012). This is favoured by the use of critical raw materials in many technological innovations, the implementation of which is to contribute to achieving a low-emission and climate-neutral economy. This article provides new insights into the impact of critical raw materials on sustainability. The purpose of this article is to analyse the impact of critical raw materials on the sustainable development of the European Union. On this basis, the following research questions will be answered: What is the role of critical raw materials in the sustainable development of the European Union? What factors limit and support the impact of critical raw materials on the sustainable development of the European Union? The study was based on secondary data that was analysed using the scoping review method and statistical analysis based on the Shapiro-Wilk test and the Spearman correlation coefficient. The article refers to the European Union, for which sustainable development remains one of the fundamental goals leading to the further development of the EU countries (Grzebyk & Stec, 2015).

In the next section, we provide a literature review on the role of critical raw materials for sustainable development. The next section explains the research sample selection and data collection and the method of data analysis. This is followed by the results of the study, and the final section contains a discussion and concluding remarks.

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Literature review

Access to mineral resources, including critical raw materials, remains crucial for the global economy, contributing to the development of modern technologies, as well as the competitiveness and innovation of individual countries (Ferro & Bonollo, 2019; Hofmann et al., 2018; Mancini et al., 2015). However, the importance of critical raw materials is extremely important in the context of a low-carbon and eco-efficient economy (Mancini et al., 2015; Mateus & Martins, 2021). Even more so, critical raw materials support the reduction of pollutant emissions, energy efficiency, production and storage of renewable energy, and electric mobility (Mateus & Martins, 2021). This is crucial as the European Union strives to achieve goals such as reducing its environmental impact, dematerialisation and the security of supplies of mineral resources (Mancini et al., 2015; Mateus & Martins, 2021).

The literature review on the impact of critical raw materials on the sustainable development of the European Union was carried out in accordance with the scoping review approach. The applied method enables replication of the research, as well as a wide and detailed review of the literature. The key aspect in the case of a scoping review is the appropriate selection of keywords identifying the literature leading to the achievement of the research goal (Arksey & O'Malley, 2005). For this article, the following keywords are defined: critical raw material*, CRM*, sustainable*, European Union, EU and Europe. In order to achieve the research goal and select appropriate literature for analysis, the following research questions were asked:

What is the role of critical raw materials in the sustainable development of the European Union?

What factors limit or support the impact of critical raw materials on the sustainable development of the European Union?

Inclusion and exclusion criteria were developed for a literature review based on the scoping review method. In order to reflect the review's focus on current knowledge, the review focused on 2010-2022 literature. This period was dictated by the fact that the first list of critical raw materials for the European Union was announced in 2011. Other inclusion criteria included Economics and the Social Sciences as well as articles from peer-reviewed journals and review articles. Book chapters and conference materials were excluded from the review. Moreover, only texts in English were included in the literature review. Electronic journal databases, Scopus and Science Direct, were used to search for relevant materials. Table 1 provides a complete list of the inclusion and exclusion criteria that were applied in the scoping review.

Table 1. Inclusion and exclusion criteria used in the literature review

Selection steps for the literature review	Comments	No.
Items identified during the initial browsing of databases	SCOPUS and Science Direct databases were used	106
Application of inclusion and exclusion criteria	Inclusion and exclusion criteria included: a) publications that appeared in 2010-2022 b) Economics and Social Sciences c) articles and review articles d) publications in English	21
Duplicates removed	No duplicates were found among the articles remaining after the inclusion and exclusion criteria had been applied	21
Title and Abstract review	At this stage, 14 articles were removed: 13 articles made little reference to the issue under study, and 1 article focused on the technological aspect	21
Full-test review	The low contribution item was deleted	7

In total, 106 articles were identified after applying key search terms. The inclusion and exclusion criteria presented above were then considered, and 13 articles in Scopus and 8 articles in Science Direct were identified. No duplicates were found among the results obtained. The review of the titles and abstracts revealed 13 articles that had little relevance to the issue under study. One article was also excluded, which made specific reference to critical raw materials focusing on the technological area. However, these articles do not contribute significant insights to assessing the sustainability

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impact of critical raw materials. Based on the established inclusion and exclusion criteria, seven articles were finally identified for inclusion in the analysis. The next step was to obtain full-text versions of the articles included in the study. Subsequently, each of these articles was reviewed, and one low-contribution article was removed on this basis. Ultimately, six articles were included in the study. During the analysis of the articles, particular attention was paid to observations regarding the aim of our study: determining the impact of critical raw materials on the sustainable development of the European Union.

Based on the literature that was selected as part of the scoping review, it appears that the researchers focused on the analysis of the criticality of European resources with regard to sustainable development, assessment of the supply of critical raw materials, analysis of trends in the extraction of mineral resources in Europe and the issue of import, the potential of the mining life cycle and product life cycle in the European Union in the context of value chains as well as sustainable resource management.

The complexity of the issue of critical raw materials, taking into account the economic, social and ecological dimensions of sustainable development, was taken into account in studies by Arendt et al. (2020). They used the SCARCE method (approach to enhance the assessment of critical resource use on the country level) to study and assess the criticality of resource use in the EU-28, Iceland, Norway and Switzerland, with the reference year being 2015. The study covered 42 raw materials (31 metals, 2 non-metals, 2 metalloids and 4 fossil fuels), and they considered 11 supply risk categories (including trade barriers, political stability, and price fluctuations) and 6 vulnerability categories (including economic importance, substitutability, import dependency) as determinants of criticality. The analysis showed that the most critical raw materials included gallium, rare earth metals, and tantalum (all of which are classified as critical raw materials in the European Union). The authors of the study emphasised that this is related to the high economic importance of these raw materials, low substitutability, use in technological innovations, trade barriers, or high consumption of primary resources. Moreover, researchers captured the social and environmental aspects of resource use. They stressed that the use of resources must be consistent with sustainable development. In addition to the availability of resources for present and future generations, the availability of raw materials, as well as social and environmental factors, should therefore be taken into account during the processes of extraction, processing and use of resources. The conducted analysis determined the compliance of the tested raw materials with social and environmental standards. In the case of social standards, factors such as human rights violations, geopolitical risk and small-scale mining were taken into account. The lowest positions in the ranking were obtained by tantalum and cobalt, which are classified as critical raw materials in the European Union. In turn, environmental standards have addressed such factors as climate change, water scarcity and the sensitivity of the local biosphere. In the case of compliance with environmental standards, the lowest scores were given to platinum and niobium, which are also critical raw materials. An interesting conclusion from these studies is also the fact that European supply risk is no different from global supply risk.

Christmann also pointed out the essence of the mining industry's influence on ecological and social factors (Christmann, 2021). In the article, she emphasised that the mining sector has a negative impact on the natural environment despite many efforts made by various entities. Christmann (2021) noted that the mining sector contributes to 16% of global CO_2 emissions to the atmosphere and generates about 50 billion tonnes of solid waste annually. At the same time, demographic growth, urbanisation, the development of the middle class and the drive to move towards a low-carbon economy are constantly increasing the demand for mineral resources. The European Union, which is a significant importer of mineral resources, including critical raw materials, thus contributes to increasing its environmental footprint beyond its borders. Dependence on the import of critical raw materials may consistently increase, resulting from the development of innovation and competitiveness of the EU economy. Even more so, the production of electricity from renewable energy sources and electromobility are of key importance to the European Union. In addition, the list of critical raw materials for the European Union has been constantly expanding since 2011. In 2011, only 14 resources were classified as critical, while in 2020, 30 resources were included in the list of critical raw materials. Moreover, Christmann (2021) emphasised the reluctance to explore and extract mineral resources in the European Union, as well as political disapproval due to fears of potential social conflicts. Hence, the article points out that greater circulation of resources is needed, which can be achieved through

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recycling, efficient production of mineral resources, and eco-design of product activities. At the same time, recycling rates for many raw materials, including critical raw materials, remain at a very low level (<10%).

The pursuit of a low-emission economy, as well as the dependence of the European Union on the import of mineral resources used in many key technologies, was also spotlighted in research by Mateus and Martins (2021). They noticed that the orientation towards an environmentally efficient economy stimulates a high dependency on the demand for mineral resources, including critical raw materials. Eco-innovations, digitisation of the economy and the development of modern technologies lead to an increase in the consumption of critical raw materials. Hence, changes in the management of primary and secondary sources and the use of mineral resources are extremely important, as well as value chains based on mineral resources related to the mining and production life cycle. Improving the link between the mining and product life cycles is necessary to ensure the security of supply. In addition, changes in production chains and the development of sustainable procedures contribute to dematerialisation and building a low-carbon economy. At the same time, the European Union is not able to ensure complete independence and self-sufficiency in the field of critical raw materials because global raw material supply chains are subject to market tensions and geopolitical factors.

The importance of dematerialisation, resource efficiency, as well as promoting a circular economy was also highlighted in studies by Mancini et al. (2015). The article compares three approaches: "mass"-based accounting (i.e. material flow analysis); "impact assessment", which is based on the Life Cycle Assessment methodology; and "resource criticality", based on an assessment of critical raw materials for the EU economy. The aim of the study was to evaluate current resource analysis methodologies to support raw materials policy. The study also analysed trends in the extraction of mineral resources in Europe and the import of mineral resources over the last 10 years. The results of the analysis showed that the choice of methodology influences the prioritisation of resources. However, the authors indicated that the policy objectives of raw materials should be based on an assessment of their potential economic, social, and environmental impacts. They also emphasised that the priority of the European Union is to improve the efficiency of resource management and that resource assessment may be crucial from the point of view of other EU policies, including those related to eco-innovation and competitiveness (Urbaniec & Tomala, 2021). In addition, resource efficiency will enable the identification of resources of key importance to the EU economy, the use of which should be optimised through consumption reduction, recycling and substitutability.

In turn, Santillán-Saldivar et al. (2021) focused on the importance of recycling and extended the Geopolitical Supply Risk method (GeoPolRisk) to integrate a supply risk assessment of critical raw materials as a complement to the environmental Life Cycle Assessment (LCA) as part of the Life Cycle Sustainability Assessment (LCSA). They tested their method on 13 key raw materials for the EU's information and communication technology (ICT) sector. The authors of the study checked whether recycling reduces the risk of raw material supply. Research results have shown domestic recycling has the potential to mitigate supply risk, especially when imports are based on stable trading partners. Thus, this study contributes to the consideration of circular economy strategies for critical raw materials.

The circular economy concept, resource efficiency and critical raw materials have been studied by Peiró et al. (2020). The aim of their study was to discuss how the circular economy strategy is incorporated into European product policy. The authors emphasised that the concept of a circular economy was accepted by both individual governments and industry. In addition, the European Union has identified the following objectives for the circular economy and mineral resources: reducing environmental impact, reducing waste, and extending the lifetime of goods. The implementation of these goals is based on material efficiency or environmental requirements. The standards also cover the use of critical raw materials and consider such issues as the viability of products made of critical raw materials, recycling, and reuse of components and/or materials in products.

Research Methodology

Research sampling and data collection

The aim of the article is to analyse the impact of critical raw materials on the sustainable development of the European Union. In addition, factors limiting and supporting the impact of critical raw materials on the sustainable development of the European Union will be listed.

This study uses data on critical raw materials from 2020 when the European Union published a new list of critical raw materials. In order to determine the impact of critical raw materials on the sustainable development of the European Union, the statistical analysis was based on the following indicators related to critical raw materials:

- Supply Risk,
- Economic Importance,
- Import Reliance,
- End-of-life Recycling Input Rate.

In addition, based on the data on critical raw materials from 2020, the statistical analysis also examined critical raw materials in terms of the life cycle stages of materials (raw materials) for critical raw materials.

The list of indicators relevant to the analysis of critical raw materials is taken from the Study on the EU's list of Critical Raw Materials Report 2020 (European Commission, 2020). The list is presented in Table 2 together with the description of individual indicators.

Table 2. Description of indicators included within the statistical analysis

Indicator	Description of the indicator
Supply Risk, SR	the risk of disruptions in the supply of a given material, one of the two main parameters when assessing the criticality of the raw material (apart from the economic importance)
Economic Importance, EI	the importance of the raw material for the economy; next to Supply Risk, it is the main parameter for assessing the criticality of the raw material
Import Reliance, IR	this indicator takes into account the actual EU supply (net imports divided by the sum of domestic production plus net imports) and the level of dependence on imports in the calculation of supply risk
End-of-life Recycling Input Rate, EoL-RIR	production of secondary material from post-consumer functional recycling (old scrap) transferred for processing and production and replacing the primary material input
Stage	refers to the life cycle stage of the material for which the criticality assessment has been performed: extraction (E) or processing (P)

Source: authors' work based on European Commission (2020).

Given the research objective, the critical raw materials were grouped in accordance with the division proposed in the annual World Mining Data publication, departing from the classification proposed by the European Union. Table 3 below lists the critical raw materials according to the proposed division.

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Table 3. Inclusion and exclusion criteria used in the literature review

Group	Critical raw materials included in a given resource group
Precious metals	PGMs (Iridium, Palladium, Platinum, Rhodium, Ruthenium)
Iron and ferro-alloy metals	Cobalt, Niobium, Tantalum, Titanium, Tungsten, Vanadium
Non-ferrous metals	Antimony, Bauxite, Beryllium, Bismuth, Gallium, Germanium, Indium, Lithium, Scandium, HREEs*, LREEs**
Industrial metals	Baryte, Borate, Fluorsphar, Natural graphite, Phosphate rock
Mineral fuels	Coking coal
Critical raw materials not classified in any of the above groups	Hafnium, Magnesium, Natural rubber, Phosphorus, Silicon metal, Strontium

* HREEs – heavy rare earth elements include Dysprosium, Erbium, Europium, Gadolinium, Holmium, Lutetium, Terbium, Thulium, Ytterbium, Yttrium.
** LREEs – light rare earth elements include Cerium, Lanthanum, Neodymium, Praseodymium, Samarium.

Data analysis method

Quantitative research methods were used in this study. The study focused on the impact of critical raw materials on the sustainability of the European Union, driven by the European Union's ambitious goal to pursue climate neutrality. In addition, critical raw materials are of enormous economic importance and play an important role in the development of technological innovations. Due to the lack of normality in the distribution of the analysed variables (checked with the Shapiro-Wilk test), the correlations between them were analysed using the Spearman correlation coefficient. A significance level of 0.05 was adopted in the analysis. Thus, all p values below 0.05 were interpreted as showing significant relationships. Statistical analysis was performed in the R program, version 4.2.1 (R Core Team, 2022).

The conducted research meets the following research criteria: reliability and validity. Selected research methods made it possible to increase the validity of research results and verify the impact of critical raw materials on the sustainable development of the European Union. Taking into account the second criterion for the evaluation of the research methodology, reliability, the methods used to support similar research and enabled their replication. In addition, the research used publicly available and reliable secondary data on critical raw materials and sustainable development. The applied research methods also made it possible to answer these research questions: What is the role of critical raw materials in the sustainable development of the European Union? What factors limit and support the impact of critical raw materials on the sustainable development of the European Union?

Results of the research

First, the analysed variables were distributed for all critical raw materials. None of the analysed variables had a normal distribution (p values from the Shapiro-Wilk tests are lower than 0.05), so all correlation coefficients present in the analysis will be Spearman's rank coefficients.

Table 4. Distribution of analysed variables

Parameter	Shapiro-Wilk test
Supply Risk (SR)	p<0.001
Economic Importance (EI)	p=0.002
Import reliance (IR) [%]	p<0.001
End-of-life Recycling Input Rate (EoL-RIR) [%]	p<0.001

Subsequently, the general relationship between Supply Risk (SR) and Economic Importance (EI) was examined, which is presented in Table 5 and Figure 1. It can be observed that the relationship between Supply Risk and Economic Importance turned out to be statistically insignificant (p > 0.05). However, in view of the development of renewable energy and electromobility, as well as the implementation of further technological innovations, the economic importance of many critical raw materials, including rare earth elements, natural graphite, cobalt, lithium, niobium and silicon metal will increase (Lewicka et al., 2021), especially since the necessity to mobilise significant amounts of critical raw materials will be necessary (Hache et al., 2019; Luderer et al., 2019; Pommeret et al., 2022).

Table 5. The relationship between Supply Risk (SR) and Economic Importance (EI)

Variables	Spearman`s correlation coefficient	p
Supply Risk (SR) & Economic Importance (EI)	0.007	p=0.967

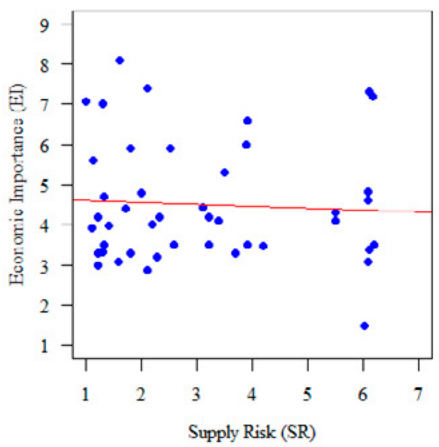

Figure 1. The relationship between Supply Risk (SR) and Economic Importance (EI)

Table 6 shows the Spearman correlation coefficients (column "r") in the material groups. The table is sorted from the strongest (highest absolute value r) to the weakest (lowest absolute value r) correlation. The strongest correlation is, therefore, in the "Precious metals" group. It is worth emphasising that none of these correlations is statistically significant (all p are higher than 0.05) and that sometimes these correlations are counted on very small groups. Moreover, in the case of examining the relationships in the subgroups, the Mineral fuels group was omitted, with only one sample: coking coal.

Table 6. Relationships between Supply Risk (SR) and Economic Importance (EI) in subgroups

Group of materials	N	r	p
Precious metals	5	-0.7	p=0.233
HREEs	7	0.445	p=0.317
Iron and ferro-alloy metals	6	0.429	p=0.419
Non-ferrous metals (excl. LREEs and HREEs)	9	0.385	p=0.306
Industrial metals	5	-0.359	p=0.553
Non-ferrous metals (incl. LREEs and HREEs)	21	0.303	p=0.182
LREEs	5	0.154	p=0.805
Critical raw materials not classified in any of the above groups	6	-0.029	p=1

Table 7 shows the Spearman correlation coefficients (column "r") for the breakdown of critical raw materials by material (raw material) life cycle stage for which the criticality assessment was performed in the case of the relationship between Supply Risk (SR) and Economic Importance (EI). The relationship in Extraction is slightly stronger, but in both groups, the relationships are statistically insignificant. To justify the results indicating statistically insignificant relationships between

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supply risk (SR) and economic importance (EI) in the table given, several factors can be taken into account. The chosen statistical method, in this case, Spearman correlation, assumes a monotonic relationship between the variables but not necessarily a linear one. If the relationship between SR and EI is not strictly monotonic, this may weaken the correlation coefficient and lead to statistically insignificant results. Furthermore, contextual factors not included in the analysis, such as specific market dynamics or external influences, may also affect the relationship between SR and EI.

Table 7. Relationships between Supply Risk (SR) and Economic Importance (EI) in subgroups by material life cycle stage

Stage	N	r	p
Extraction	14	-0.14	p=0.633
Processing	30	-0.068	p=0.721

Next, the relationship between Import reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR) was investigated. Table 8 and Figure 2 show that this relationship is significant (because $p<0.05$) and positive, so the higher the IR value, the higher the EoL-RIR value, and vice versa, the higher the EoL-RIR value, the greater the IR value. Statistically significant correlations reinforce the validity of the observed relations.

Table 8. Relationship between Import reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR)

Variables	Spearman`s correlation coefficient	p
Import reliance (IR) & End-of-life Recycling Input Rate (EoL-RIR)	0.366	p=0.017

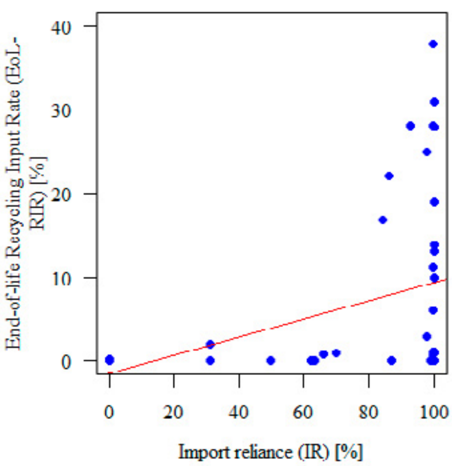

Figure 2. Relationship between Import reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR)

The next step was to check the above relationship in subgroups. The strongest relationship was found in the group "Critical raw materials not classified in any of the above groups" (Table 9). In turn, the only significant relationship is in the group "Non-ferrous metals (incl. LREEs and HREEs)". This group is much larger than the others; therefore, it is easier to show a significant dependence. For HREEs and LREEs, the correlation cannot be calculated because for each material of these groups, IR = 100%. In the case of examining the relationships in the subgroups, the Mineral fuels group was again omitted with only one sample: coking coal.

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Table 9. Relationships between Import reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR) in subgroups

Group of materials	N	r	p
Critical raw materials not classified in any of the above groups	6	0.657	p=0.156
Precious metals	5	-0.516	p=0.373
Iron and ferro-alloy metals	6	-0.5	p=0.5
Non-ferrous metals (incl. LREEs and HREEs)	21	0.494	p=0.023
Industrial metals	5	0.224	p=0.718
Non-ferrous metals (excl. LREEs and HREEs)	9	0.211	p=0.586
HREEs *	7	---	---
LREEs *	5	---	---

* IR = 100% for each group member.

The table below summarises the Spearman correlation coefficients (column "r") in the breakdown of critical raw materials by material (raw material) life cycle stage, for which the criticality assessment was carried out in the case of the relationship between Import reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR) (Table 10). The use of Spearman correlation coefficients indicates that the analysis considered non-linear relationships between IR and EoL-RIR. This is important as it allows for capturing any potential monotonic relationships, even if they are not strictly linear.

Table 10. Relationships between Import reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR) in subgroups by material life cycle stage

Stage	N	r	p
Extraction	14	0.453	p=0.12
Processing	30	0.284	p=0.135

As in the case of the relationship between Supply (SR) and Economic Importance (EI), the relationship between Import Reliance (IR) and End-of-life Recycling Input Rate (EoL-RIR) is stronger at the Extraction stage, but in both dependence groups are statistically insignificant.

Discussion and conclusions

The objective of this article was to analyse and evaluate the impact of critical raw materials on the sustainable development of the European Union. The literature review shows that critical raw materials are becoming an important element in implementing sustainable development. The study of critical raw materials is necessary in view of the bottleneck in the supply of these raw materials, as well as their importance for the economy and technological progress. However, the environmental context and the need to develop technological innovations that will enable the transformation of the EU economy to a low-carbon and climate-neutral economy should not be forgotten. Hence, one of the trends is to clarify the role of critical raw materials in the context of the sustainable development model.

The results of the analysis showed that critical raw materials are one of the key factors influencing the sustainable development of the European Union. From the European Union's perspective, it is crucial to achieve climate neutrality and to fully implement a sustainable development model in which social and environmental issues will be important in addition to economic performance. Accordingly, there is an increasing emphasis on the development of technological innovations in the

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energy and electromobility sectors, thus observing the growing economic importance of critical raw materials. As a result, it will be essential to maintain a continuous supply of these raw materials.

Various indicators were analysed as part of this study. Only the relationship between import dependency (IR) and the end-of-life recycling participation rate (EoL-RIR) shows significance. This means that the higher the IR value, the higher the EoL-RIR value and, conversely, the higher the EoL-RIR value, the higher the IR value.

In line with the assumptions of the European Green Deal and the circular economy, the European Union aims at a more efficient use of resources and the recycling of raw materials (Smol et al., 2020). At the same time, it remains dependent on the import of mineral resources, including critical raw materials. The development of technological innovations, including those in the field of electromobility or renewable energy, affects the importance of critical raw materials. Thus, the limited availability and dependence on imports of these raw materials may pose a serious challenge in terms of further development and implementation of technological innovations (Helbig et al., 2016). This is important because the European Union imports 98-99% of rare earth metals from China, 98% of borate from Turkey, 85% of niobium from Brazil, 71% of platinum from South Africa, and 68% of cobalt from the Democratic Republic of the Congo. All these raw materials are used in renewable energy and electromobility sectors (Lewicka et al., 2021).

To justify results indicating statistically insignificant relations between selected indicators, various factors can be taken into account. Among others, contextual factors not included in the analysis, such as specific market dynamics or external influences, may also affect these results. Therefore, the consideration of additional factors may help to explain the statistically insignificant relationship between supply risk and EI indicators at different stages of the life cycle of critical raw materials.

Our research provides comprehensive insights that can be useful to decision-makers responsible for implementing sustainable development at both the level of the European Union and its individual member states. Sustainable development is the goal of all actors, which means that more and more attention is being paid to the tools that support these developments.

The results presented in this article have their own research limitations. The literature review and research contained answers to the research question, which made it possible to achieve the aim of the article – to present the impact of critical raw materials on the sustainable development of the European Union. However, the main caveat to the research carried out is that the analysis relates only to the European Union and ignores other developed economies. This is even more true given the differences between individual countries in terms of recognising specific mineral resources as critical. An example is manganese, which has not been included as a critical raw material in the European Union. However, in the United States, manganese is classified as a critical raw material (Karali & Shah, 2022). In addition, the study was based only on the most recent data on critical raw materials that were published in 2020. Gathering relevant data for analysis was a significant challenge, so there is still a need for further research on this topic.

It is worth expanding the area of analysis as soon as new data becomes available. This would significantly increase understanding of the impact of critical raw materials on sustainable development. An important aspect seems to be the preparation of a comparative analysis that would capture this topic from the perspective of the lists of critical raw materials that were published in 2011, 2014 and 2017, respectively. It would make it possible to check how critical raw materials have influenced the sustainable development of the European Union over the years. This is all the more important because the next review and evaluation of critical raw materials will be carried out next year. Additionally, another interesting topic remains the study of the role of critical raw materials in implementing sustainable development in other countries, especially in developed economies. It seems extremely interesting to examine this thread in the case of China, which is also an important producer of many raw materials classified as critical.

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The contribution of the authors

Conceptualization, J.T. and M.U.; literature review, J.T.; methodology, M.U.; formal analysis, M.U.; writing, J.T. and M.U.; conclusions and discussion, J.T. and M.U.

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References

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. International Journal of Social Research Methodology, 8(1), 19-32. https://doi.org/10.1080/1364557032000119616

Alessia, A., Alessandro, B., Maria, V.-G., Carlos, V.-A., & Francesca, B. (2021). Challenges for sustainable lithium supply: A critical review. Journal of Cleaner Production, 300, 126954. http://dx.doi.org/10.1016/j.jclepro.2021.126954

Arendt, R., Muhl, M., Bach, V., & Finkbeiner, M. (2020). Criticality assessment of abiotic resource use for Europe–application of the SCARCE method. Resources Policy, 67, 101650. http://dx.doi.org/10.1016/j.resourpol.2020.101650

Christmann, P. (2021). Mineral resource governance in the 21st century and a sustainable European Union. Mineral Economics, 34(2), 187-208. https://doi.org/10.1007/s13563-021-00265-4

de Oliveira, D. P., Filipe, A., Gonçalves, P., Santos, S., & Albardeiro, L. (2021). Critical Raw Materials Deposits Map of Mainland Portugal: New Mineral Intelligence in Cartographic Form. The Cartographic Journal, 58(3), 222-232. http://dx.doi.org/10.1080/00087041.2021.1977882

European Commission. (2020). *Study on the EU's list of critical raw materials (2020). Final Report.* https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en

Ferro, P., & Bonollo, F. (2019). Materials selection in a critical raw materials perspective. Materials & Design, 177, 107848. http://dx.doi.org/10.1016/j.matdes.2019.107848

Grzebyk, M., & Stec, M. (2015). Sustainable development in EU countries: concept and rating of levels of development. Sustainable development, 23(2), 110-123. http://dx.doi.org/10.1002/sd.1577

Guzik, K., Galos, K., Kot-Niewiadomska, A., Eerola, T., Eilu, P., Carvalho, J., & Raaness, A. (2021). Potential benefits and constraints of development of critical raw materials' production in the EU: Analysis of selected case studies. Resources, 10(7), 67. https://doi.org/10.3390/resources10070067

Hache, E., Seck, G. S., Simoen, M., Bonnet, C., & Carcanague, S. (2019). Critical raw materials and transportation sector electrification: A detailed bottom-up analysis in world transport. Applied Energy, 240, 6-25. http://dx.doi.org/10.1016/j.apenergy.2019.02.057

Hackenhaar, I., Alvarenga, R. A., Bachmann, T. M., Riva, F., Horn, R., Graf, R., & Dewulf, J. (2022). A critical review of criticality methods for a European Life Cycle Sustainability Assessment. Procedia CIRP, 105, 428-433. http://dx.doi.org/10.1016/j.procir.2022.02.071

Helbig, C., Wietschel, L., Thorenz, A., & Tuma, A. (2016). How to evaluate raw material vulnerability-An overview. Resources Policy, 48, 13-24. http://dx.doi.org/10.1016/j.resourpol.2016.02.003

Hofmann, M., Hofmann, H., Hagelüken, C., & Hool, A. (2018). Critical raw materials: A perspective from the materials science community. Sustainable Materials and Technologies, 17, e00074. https://doi.org/10.1016/j.susmat.2018.e00074

Hopwood, B., Mellor, M., & O'Brien, G. (2005). Sustainable development: mapping different approaches. Sustainable Development, 13(1), 38-52. http://dx.doi.org/10.1002/sd.244

Hund, K., La Porta, D., Fabregas, T. P., Laing, T., & Drexhage, J. (2020). *Minerals for climate action: The mineral intensity of the clean energy transition.* Washington, D.C.: World Bank. https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf

Karali, N., & Shah, N. (2022). Bolstering supplies of critical raw materials for low-carbon technologies through circular economy strategies. Energy Research & Social Science, 88, 102534. https://doi.org/10.1016/j.erss.2022.102534

León, M. F. G., & Dewulf, J. (2020). Data quality assessment framework for critical raw materials. The case of cobalt. Resources, Conservation and Recycling, 157, 104564. https://doi.org/10.1016%2Fj.resconrec.2019.104564

Lewicka, E., Guzik, K., & Galos, K. (2021). On the possibilities of critical raw materials production from the EU's primary sources. Resources, 10(5), 50. https://doi.org/10.3390/resources10050050

Løvik, A. N., Hagelüken, C., & Wäger, P. (2018). Improving supply security of critical metals: Current developments and research in the EU. Sustainable Materials and Technologies, 15, 9-18. http://dx.doi.org/10.1016/j.susmat.2018.01.003

Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R. C., Popp, A., van den Berg, M., van Vuuren, D., & Hertwich, E. G.

(2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. Nature Communications, 10(1), 5229. https://www.nature.com/articles/s41467-019-13067-8

Mancini, L., Benini, L., & Sala, S. (2015). Resource footprint of Europe: Complementarity of material flow analysis and life cycle assessment for policy support. Environmental Science & Policy, 54(1), 367-376. https://doi.org/10.1016/j.envsci.2015.07.025

Martins, F. F., & Castro, H. (2020). Raw material depletion and scenario assessment in European Union – A circular economy approach. Energy Reports, 6, 417-422. https://doi.org/10.1016/j.egyr.2019.08.082

Mateus, A., & Martins, L. (2021). Building a mineral-based value chain in Europe: the balance between social acceptance and secure supply. Mineral Economics, 34(2), 239-261. https://link.springer.com/article/10.1007/s13563-020-00242-3

Melfos, V., & Voudouris, P. C. (2012). Geological, mineralogical and geochemical aspects for critical and rare metals in Greece. Minerals, 2(4), 300-317. https://doi.org/10.3390/min2040300

Peiró, L. T., Polverini, D., Ardente, F., & Mathieux, F. (2020). Advances towards circular economy policies in the EU: The new Ecodesign regulation of enterprise servers. Resources, Conservation and Recycling, 154, 104426. http://dx.doi.org/10.1016/j.resconrec.2019.104426

Petranikova, M., Tkaczyk, A., Bartl, A., Amato, A., Lapkovskis, V., & Tunsu, C. (2020). Vanadium sustainability in the context of innovative recycling and sourcing development. Waste Management, 113, 521-544. https://doi.org/10.1016/j.wasman.2020.04.007

Pommeret, A., Ricci, F., & Schubert, K. (2022). Critical raw materials for the energy transition. European Economic Review, 141, 103991. https://doi.org/10.1016/j.euroecorev.2021.103991

R Core Team. (2022). *R: A Language and Environment for Statistical Computing.* Vienna: R Foundation for Statistical Computing.

Rachidi, N. R., Nwaila, G. T., Zhang, S. E., Bourdeau, J. E., & Ghorbani, Y. (2021). Assessing cobalt supply sustainability through production forecasting and implications for green energy policies. Resources Policy, 74, 102423. https://doi.org/10.1016/j.resourpol.2021.102423

Santillán-Saldivar, J., Cimprich, A., Shaikh, N., Laratte, B., Young, S. B., & Sonnemann, G. (2021). How recycling mitigates supply risks of critical raw materials: Extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. Resources, Conservation and Recycling, 164, 105108. https://doi.org/10.1016/j.resconrec.2020.105108

Smol, M., & Kulczycka, J. (2019). Towards innovations development in the European raw material sector by evolution of the knowledge triangle. Resources Policy, 62, 453-462. https://doi.org/10.1016/j.resourpol.2019.04.006

Smol, M., Marcinek, P., Duda, J., & Szołdrowska, D. (2020). Importance of sustainable mineral resource management in implementing the circular economy (CE) model and the European Green Deal Strategy. Resources, 9(5), 55. https://doi.org/10.3390/resources9050055

Song, J., Yan, W., Cao, H., Song, Q., Ding, H., Lv, Z., Zhang, Y., & Sun, Z. (2019). Material flow analysis on critical raw materials of lithium-ion batteries in China. Journal of Cleaner Production, 215, 570-581. https://doi.org/10.1016/j.jclepro.2019.01.081

Stilwell, F. (2021). From green jobs to Green New Deal: What are the questions? The Economic and Labour Relations Review, 32(2), 155-169. https://doi.org/10.1177/10353046211009774

Urbaniec, M., & Tomala, J. (2021). Eco-innovation measuring in European and Asian countries: a comparative analysis. Economics and Environment, 79(4), 70-86. https://doi.org/10.34659/2021/4/28

Yuksekdag, A., Kose-Mutlu, B., Siddiqui, A. F., Wiesner, M. R., & Koyuncu, I. (2022). A holistic approach for the recovery of rare earth elements and scandium from secondary sources under a circular economy framework – A review. Chemosphere, 293, 133620. https://doi.org/10.1016/j.chemosphere.2022.133620

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W KIERUNKU ZRÓWNOWAŻONEGO ROZWOJU UNII EUROPEJSKIEJ: ROLA KRYTYCZNYCH SUROWCÓW MINERALNYCH

STRESZCZENIE: Zrównoważony rozwój jest kluczowym celem Unii Europejskiej, która jest postrzegana jako globalny lider zmian w zakresie przeciwdziałania zmianom klimatu, a także budowania ekologicznej równowagi gospodarczej prowadzącej do większego dobrobytu społecznego. Kamieniem milowym zrównoważonego rozwoju, który ma wesprzeć Unię Europejską w osiągnięciu neutralności klimatycznej, jest Europejski Zielony Ład. Inicjatywy podejmowane w ramach Europejskiego Zielonego Ładu mają na celu budowanie konkurencyjnej i innowacyjnej gospodarki UE z poszanowaniem środowiska naturalnego. Zgodnie z założeniami Europejskiego Zielonego Ładu, Unia Europejska do 2050 roku ma stać się pierwszym kontynentem neutralnym klimatycznie dzięki krytycznym surowcom mineralnym. Celem niniejszego artykułu jest analiza i ocena wpływu krytycznych surowców mineralnych na zrównoważony rozwój Unii Europejskiej. W badaniu wykorzystano metodologię przeglądu zakresu i analizę statystyczną opartą na teście Shapiro-Wilka i współczynniku korelacji Spearmana. Wyniki pokazują, że surowce krytyczne są ważne dla osiągnięcia zrównoważonego rozwoju i wdrożenia gospodarki UE w kierunku neutralności klimatycznej. Niniejszy artykuł stanowi wkład do literatury na temat zrównoważonego rozwoju. Może również dostarczyć ważnych informacji dla decydentów politycznych, aby zrozumieć, jak kształtować zieloną politykę w kontekście strategicznego znaczenia surowców krytycznych w transformacji ekoinnowacyjnej gospodarki.

SŁOWA KLUCZOWE: krytyczne surowce mineralne, zrównoważony rozwój, Europejski Zielony Ład, Unia Europejska

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