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Global Research Progress and Trends on Critical Metals: A Bibliometric Analysis

Alina Butu [1], **Steliana Rodino** [1,2,*] and **Marian Butu** [1,*]

[1] Biotechnology Department, National Institute of Research and Development for Biological Sciences, 060031 Bucharest, Romania
[2] Institute of Research for Agricultural Economy and Rural Development, 011464 Bucharest, Romania
* Correspondence: steliana.rodino@yahoo.com (S.R.); marian_butu@yahoo.com (M.B.)

Abstract: In the perspective of observing the latest worldwide and European strategies toward green transition and delivering a secured access to local resources, the objective of this study was to analyze the research progress on critical materials and, more specific, critical metals and review the future research hot-topics for critical metals. Consequently, a bibliometric analysis for the assessment of the current state of the art research, future trends as well as evolution through time of the critical metals research was performed in the present work. The study included four phases of work: (i) search string selection, (ii) data collection, (iii) data processing, and (iv) data interpretation. A total of 433 publications on critical metals were collected from Scopus database between 1977 and 2023, with an increasing yearly trend and a burst in 2013. The data retrieved showed a significant increase in publications related to the topic in the last 10 years. The results show that research interest is concentrated around six critical areas: (i) bioleaching as an important process of critical metal recovery, (ii) circular economy concepts and recovery of critical metals by urban mining from e-waste, (iii) resource recovery from waste landfills as urban mines, (iv) targeted studies on various critical elements (copper, zinc, gallium, silver, lithium), (v) rare elements as industry vitamins and, (vi) coal deposits and coal ashes as an alternative source of critical metals. This analysis could provide important guidance for further directions on the development of research for recovery of critical metals.

Keywords: circular economy; critical metals; mine waste; recovery; recycle; research trends

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1. Introduction

Currently, the European Union (EU) is in the process of transformation towards a bioeconomy and circular economy. The circular economy model was first announced in 2014 [1]. The circular economy assumes a transition from a linear model based on take–make–dispose to a circular model, in which waste, if it arises, becomes a valuable resource for another production cycle [2,3]. Thus, an optimized model is designed that foresees an innovative approach, namely, make–use–reuse–remake–recycle and again, make [4,5]. Wealth from waste is now considered an opportunity for future practice [6].

Already, the world is experiencing a shortage of various resources that cannot be recreated or replaced. An example, rare earth metals used in everyday electronic devices—tantalum, silver, gallium, and indium, may disappear in the next 20–50 years [7]. At the same time, only 8.6 % of materials are returned to the economy [8].

As the demand for mineral resources is expected to grow due to global competition and the industrialization of developing countries [9], the digitalization of the economies of developed countries [10], and socio-economic disturbances in the process of a profound transformation of the international economic order [11], it is considered that the dependence on critical raw materials may soon replace dependence on oil and gas [12]. A reliable and sustainable supply of both primary and secondary raw materials, especially critical raw materials for key technologies and strategic sectors [4] such as renewable energy, electromobility, digital technologies [10], space and defense, is one of the necessary conditions for achieving national security and independence for every region [8].

The methodology for identifying critical minerals from the total mass of minerals and products of their primary processing is based on an assessment of the significance (demand) of its use in production (important in use) and the degree (probability) of a potential risk in limiting its supply (availability) to the consumer (likelihood of a supply restriction) [4,13,14].

Among critical raw materials, the metals are the object of this paper. The term critical metals has become inextricably linked with the concept of sustainable development. Questions that brought this into discussion are, among others: What kind of sustainability can there be when there is a risk of stability in the supply of raw materials? On the other hand, what will be left for future generations if the resources are depleted? Trying to answer these questions, the present is presenting an overview of worldwide research towards recovery and recycling of critical metals from mine waste as an important source of valuable raw materials.

Formulation of the Research Questions

As the technologies are advancing rapidly, so is the demand for high-tech critical metals. Sustainable sourcing for the critical materials by finding alternative sources of supply, including from recovery and recycling from waste, could be a viable option as it can address the increasing demand with minimum environmental impact. As a result, research on critical metals has gained importance over the years. In this context, for studying the research trend on critical metals, the following research questions were framed:

- What is the trend of research over the years on critical metals?
- Who are the leading countries, authors, and publication sources (number of research articles, top cited) across the world performing research related to critical metals?
- Which are the most relevant keywords used in research studies related to the topic?

As mentioned above, this study is searching to find the answers to these questions using bibliometric analysis.

Therefore, this paper is reporting an overview through publication history, aiming to summarize the research progress related to critical metals and their recovery from secondary sources such as mine tailings, dams, and residues in a circular economy approach.

2. Materials and Methods

For the bibliographic analysis and literature review, the scientific literature on critical metals was studied. For the bibliometric analysis, a total of 433 published articles between 1977 and 2023 were analyzed. These papers were retrieved through the scholarly database of Scopus. Scopus is one of the most trusted and widely used bibliographic databases for bibliometric analysis [15], offering comprehensive coverage of excellent publications in general academic fields, ease of access, and advanced search and filtering features.

The search was carried out in November 2022. The initial search string used in the literature withdrawal included: “critical metals” and “recovery” or “recycling” and “mine” or “mine and waste” or “mine and tailing” or “mine and residue” or “mining and waste” or “mining and residue”. Initially, no language filter and no country filter were applied. The search field was limited to “title”, “abstract”, and “keyword.” Subsequently, the data collection was further demarcated through inclusion and exclusion criteria according to the proposed scope of the analysis to be carried out.

As a first criterion, it was considered appropriate as an eligibility choice to exclude document types from the category of editorial note, erratum, and note (three documents excluded).

For the selection phase, documents in the category of trade journal were excluded, as they were considered to be irrelevant for analysis towards research progress. In the same time, taking into consideration further keywords and contents analysis of the present study, the selection was limited to documents in the English language.

The final database included author, institution, country, keyword, source, category, and citation information from 397 documents that constitute the cornerstone of the processing and data interpretation of the study (Figure 1). The collected data were exported as an Excel file and VOSviewer (version 1.6.18, Center for Science and Technology Studies, Leiden University, Leiden, The Netherlands) software was used for analysis [16] of cooperation networks and keyword co-occurrences of the collected literature data.

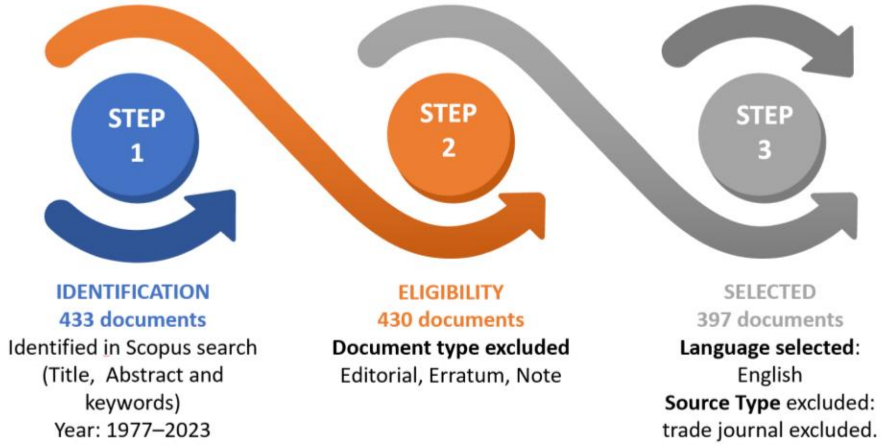

Figure 1. Flow chart describing methodology for collection of publications from SCOPUS database.

3. Results and Discussion

3.1. Scientific Production Analysis

Scientific production analysis was focused on a threefold approach. First, the annual publications and the growth trend were examined, then contributions to the subject as of originating country of the authors affiliation was analyzed, and finally, the most cited publications were examined.

3.1.1. Annual Publications and Growth Trend

The search carried out in the Scopus platform resulted in a total of 397 publications on critical metal recovery from mine tailings with an average of 28.08 citations per document. Among these, the majority were research articles (223, 56.17%), followed by reviews (90, 22.67%), conference proceedings (64, 16.12%), books and book chapters (10, 2.52%), conference reviews (5, 1.26%), and short reports (5, 1.26%). As plotted in Figure 2, during the last 10 years there was a growing interest in research related critical metal recovery from mine tailing. The number of documents increased gradually by 2012. This could be related to the first release of the European critical raw material list in 2011. Other countries (e.g., US, Japan, and Australia) have elaborated analogous reports and lists. Generally, from 2 or 3 publication per year between 1986–2007, the scientific production arrived at up to 71 scientific articles published in 2022, taking into consideration the string search that was used in this analysis (Figure 2).

Approximately half of the scientific publications belong to the period 2019–2022, and this could be correlated with several drivers.

First, in December 2019, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was reported in Wuhan, Hubei Province, China. In January 2022, as the region was highly impacted by COVID-19, China implemented strict restrictive movement policies related to work conditions that triggered disruptions on its international trade, exposing the dependence of the world economy on the supply chain related to metals, plastics, electronics, and other goods for which China is the leading world exporter [17]. Therefore, the reinforcement of the need for sustainable exploitation of local resources and the importance of overcoming the vulnerability of the supply chain for critical materials could be seen as triggered by the COVID-19 crisis.

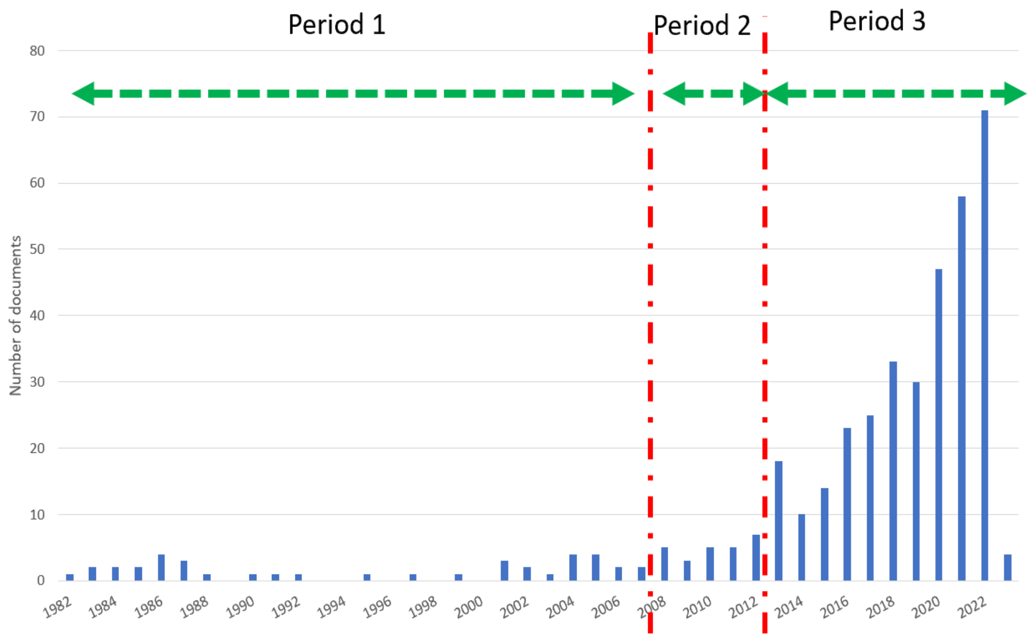

Figure 2. Annual publications and growth trend of identified works extracted from Scopus database.

Second, at the European level, the Green Deal strategy was released as early as 2019. The European Green Deal covers all major aspects of the European economy, taking into account climate and ecological imperatives, according to the new plans contained by the European Commission. One of the key subjects is related to securing a local supply of raw materials. It is, thus, considered that the EU's access to critical raw materials must be supported by an efficient use of resources, thus, involving research development and innovation actions.

Therefore, research towards assuring a secure and reliable supply of critical metals is important not only for the European economy but also for the successful implementation of the European Green Deal.

Finally, the current crisis related to the socio-politic situation of the Russian–Ukrainian conflict has also raised issues on supply chain interruptions related to critical metals.

Therefore, for the regions endangered by supply chain vulnerabilities, the diversification of secondary sources and superior exploitation of known critical raw materials reserves is a must.

A polynomial trend was checked for the assessment of the correlation between the number of documents and the publishing year (Figure 3). For this, documents from 2013 to 2022 were included. While exclusion of the year 2023 was decided on the basis of actual search date, the data before 2013 were excluded taking into consideration the first assessment of the criticality of raw materials in 2014. A good fit of the polynomial curve to the increasing trend of publications was observed, and a high coefficient of determination was obtained (R2 = 0.9662). As already pointed out, as socio-economic context is evolving towards necessity to endure local supply, concerns on the subject may continue to grow in the coming years.

3.1.2. Country Contributions

According to the affiliation of the authors, the contribution to the topic as analyzed by country indicates that a total of 62 countries across the world bring up research related to critical metal recovery from mine waste (Figure 4).

United States stands up for the highest scientific production, with 82 publications on critical metal recovery in English in the Scopus database, accounting for 20.65% of all countries during the analyzed period.

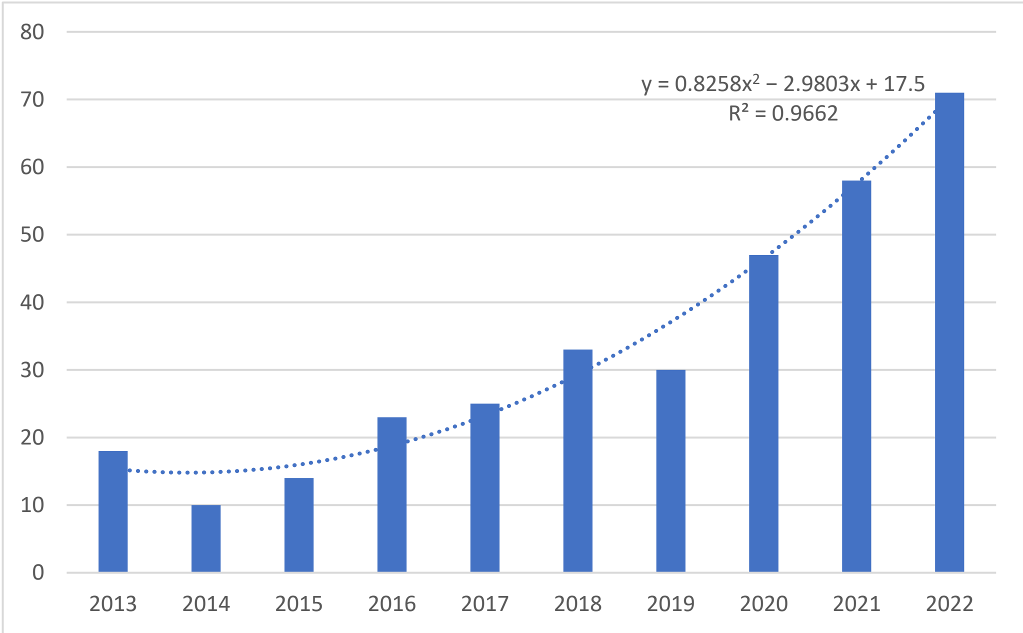

Figure 3. Correlation between yearly number of publications.

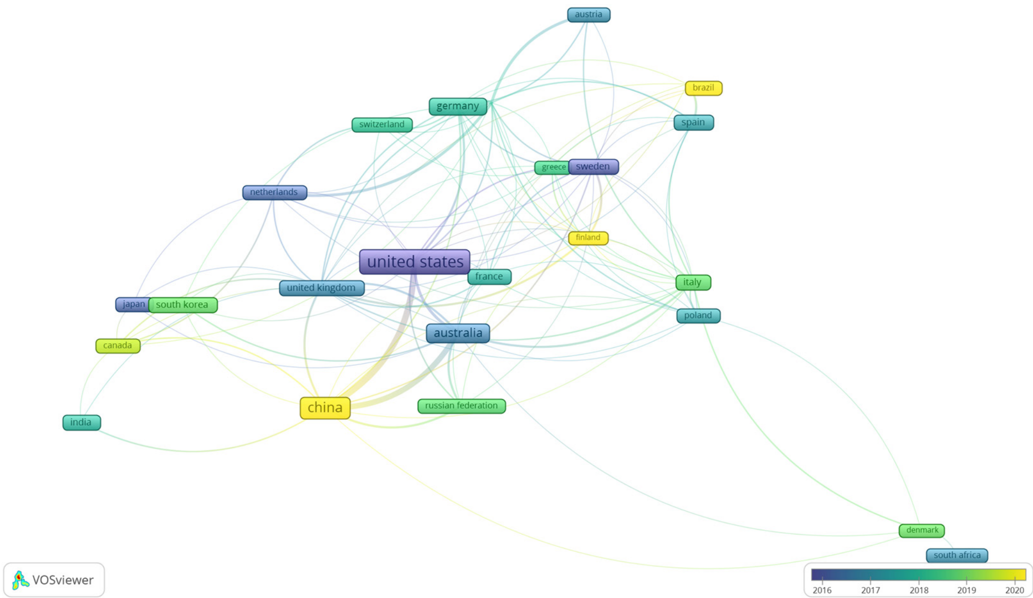

Figure 4. Country distribution of publications related to critical metals.

In fact, the first study that brought into light the concept of critical materials was the criticality matrix elaborated by the National Research Council in 2008. This matrix was built to assess the criticality of a wide range of materials based on demand emerging or increasing, dependence on imported materials, social or environmental pressure, policy measures, and concentration of production [13,18].

While most of the critical raw materials come from China, it is interesting to find that almost 15% of the scientific production on the analyzed topic comes from this country. Australia is in the third place (40 documents, 10.58% of total), followed by most of the European countries, such as Germany, France, United Kingdom, Belgium, Italy, Spain, and Sweden (summarizing 166 documents and a share of 41.81% of the total). Overall, the European research progress on critical metal recovery accounts for over 60% of the analyzed database.

The graphical representation of the contribution by country is shown in Figure 5. The larger the node is, the more publications the corresponding country has produced. The connecting lines between the nodes designate the network of collaborative relationships between the different countries. The closer the distance, the stronger the connection between the countries, suggesting that respective regions have built strong collaboration.

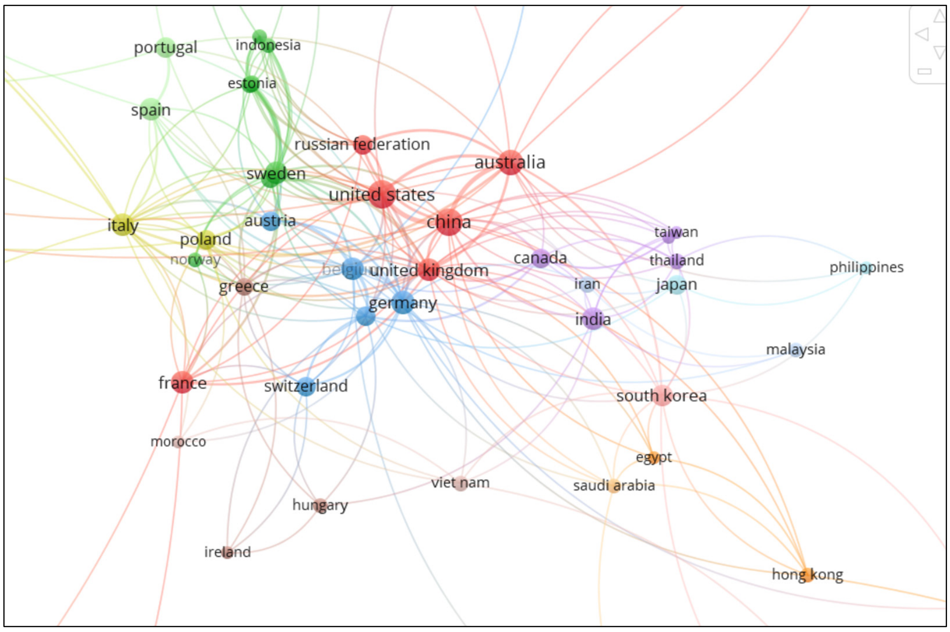

Figure 5. Co-authorship of selected publications.

The co-authorship of the 62 countries is included within 17 clusters (various colors used) with a total of 238 links and a total link strength of 326.

The United States represents the most productive country with the largest association (326 co-authorships), connected to 10 other countries or territories.

When speaking of the citations of the published works by country, the ranking positions change, and if taking into account the first top cited papers by country, three more countries are added to the list (Netherlands with 2081 citations, Switzerland with 386, and Canada with 380). The top cited country's work from the most productive countries is, however, Belgium, with a share of 12% of the total citations (2610 citations) (Table 1).

Table 1. Citations of the published work, by country.

Document Rank	Country	Region	Documents	Share of Total	Citations Rank	Citations	Share of Total Citations
1	United States	North America	82	20.65%	3	2097	9.68%
2	China	Asia	59	14.86%	7	912	4.21%
3	Australia	Australia	42	10.58%	5	1670	7.71%
4	Germany	Europe	26	6.55%	2	2509	11.59%
5	France	Europe	21	5.29%	14	189	0.87%
6	India	Asia	21	5.29%	8	687	3.17%
7	United Kingdom	Europe	21	5.29%	4	1986	9.17%
8	Belgium	Europe	19	4.79%	1	2610	12.05%
9	Italy	Europe	19	4.79%	9	507	2.34%

Table 1. *Cont.*

Document Rank	Country	Region	Documents	Share of Total	Citations Rank	Citations	Share of Total Citations
10	Spain	Europe	19	4.79%	11	405	1.87%
11	Sweden	Europe	19	4.79%	10	503	2.32%
12	South Korea	Asia	18	4.53%	6	1198	5.53%
13	Brazil	South America	14	3.53%	15	78	0.36%
14	Portugal	Europe	12	3.02%	12	315	1.45%
15	Austria	Europe	10	2.52%	13	232	1.07%

This analysis is highlighting the participation of developed countries and their concern for critical metal recovery from mine waste.

3.1.3. Most Cited Publications

The scientific production analyzed (397 articles) returned 11,150 citations.

Most citations (2557) were generated by the 22 articles published in Journal of cleaner production (Figure 6). The second most cited publication was Separation and Purification Technology, which generated 715 citations for the three articles published in 2017, 2022, and 2023. All the three articles were review papers dealing with the selective recovery of rare earth elements from e-waste via ionic liquid extraction [19], critical assessment of chemical route for generation of energy and valuable products coupled with metal recovery [20], and recovery and recycling of lithium [21].

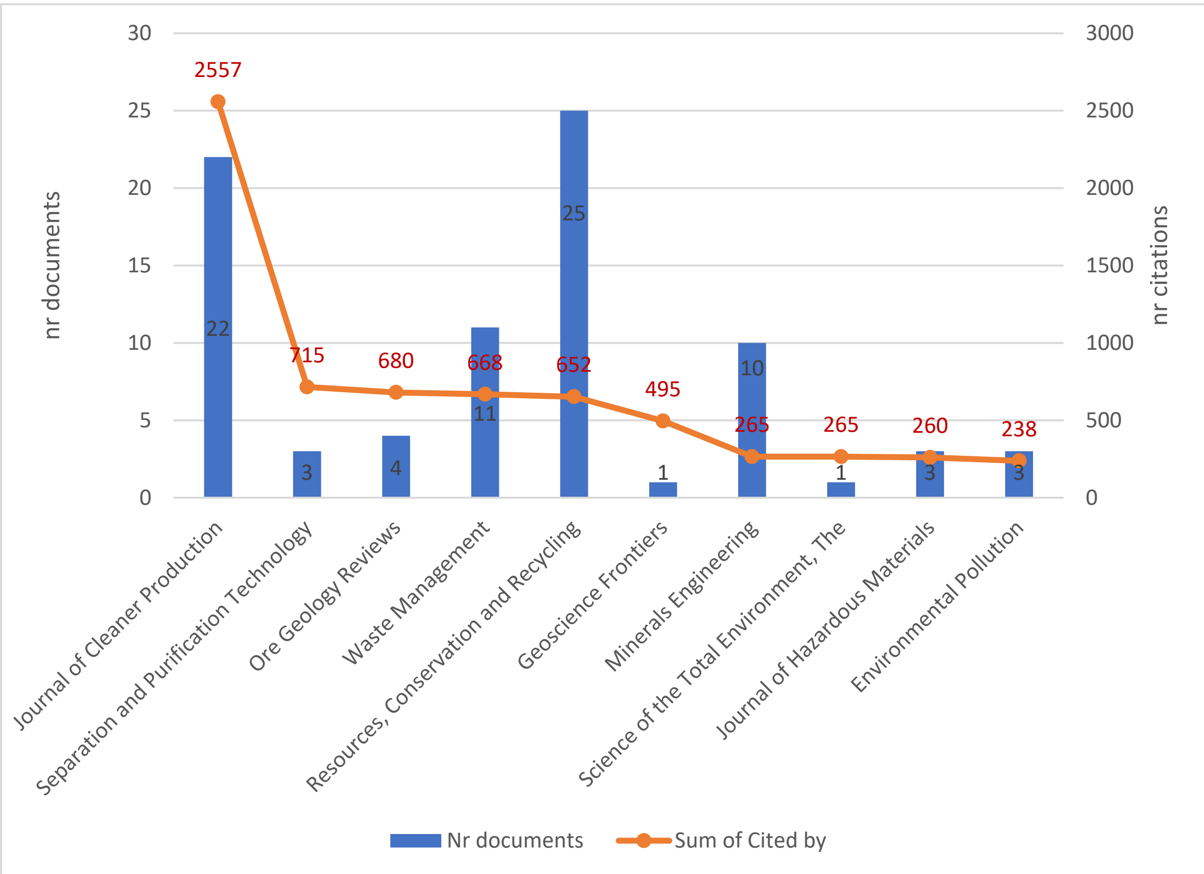

Figure 6. Number of documents by journal and corresponding citations.

In Table 2, the top 10 of the most cited documents are presented, with a total of 4589 citations, representing 41.16% out of the total citations. The top 10 most cited papers are included in the paper type review.

Table 2. The top ten most cited papers by author.

No	Publication Year	Document Title	Authors	Citations Per Article	Journal Title	Citations Per Year
1	2013	Recycling of rare earths: A critical review	Binnemans et al.	1458	Journal of Cleaner Production	146
2	2017	Recovery and recycling of lithium: A review	Swain	712	Separation and Purification Technology	119
3	2013	Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources	Hein et al.	518	Ore Geology Reviews	52
4	2019	Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact	Balaram	495	Geoscience Frontiers	124
5	2015	Towards zero-waste valorisation of rare-earth-containing industrial process residues: A critical review	Binnemans et al.	367	Journal of Cleaner Production	46
6	1992	Potential use of constructed wetlands for treatment of industrial wastewaters containing metals	Dunbabin et al.	265	Science of the Total Environment	9
7	2014	Hidden values in bauxite residue (red mud): Recovery of metals	Liu et al.	257	Waste Management	29
8	2013	Selective extraction and recovery of rare earth metals from phosphor powders in waste fluorescent lamps using an ionic liquid system	Yang et al.	201	Journal of Hazardous Materials	20
9	2019	A critical review on remediation, reuse, and resource recovery from acid mine drainage	Naidu et al.	170	Environmental Pollution	43
10	2014	Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling	Habib et al.	146	Journal of Cleaner Production	16

The study by Binnemans et al. entitled "Recycling of rare earths: A critical review" [22] was the most cited publication, with 1458 citations. This article presents an overview of the state-of-the-art of the challenges and possible solutions associated with the recycling of the rare earths, as encountered during (mainly) lab-scale R&D efforts. Although recognizing the importance of such a research direction, the study does not tackle critical metal recycling from new and landfilled industrial residues (e.g., red mud, phosphogypsum).

The study by Swain (2017) entitled "Recovery and recycling of lithium: A review" [21] was the second most cited publication, with 712 citations. In this study, recovery and recycling of lithium from various primary resources such as different ores, clay, brine, seawater and secondary resources such as the recycling of batteries by different technique were reviewed. The author highlighted the need for Li recovery technology development from low-grade sources and recommended urgency for the alternative recycling method from secondary resources. Moreover, the author concluded that considering the benefits, hydrometallurgical recycling of LIB should be a focus.

The paper by Hein et al. (2013) entitled "Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources" [23] retrieved 518 citations. The authors report on general characteristics of deep-ocean mineral deposits and their distributions and compare the deep-sea ores with land-based resources. Moreover, challenges, potential barriers and enhancers, and major advantages and disadvantages of deep-ocean mining were explored.

REE applications, occurrence, exploration, analysis, recycling, and environmental impact were investigated by V. Balaram, 2019 [24].

The author also investigated deep sea mining as a promising option for the future, however, pointing out that the potential risks and drawbacks associated with this process should be considered before investing in this technology. The deep-sea mining of REE was presented as an attractive option as it would reduce the negative environmental impacts caused by land-based mining. This would also help in reducing the cost associated with the mining process as the extraction from the deep sea would be much cheaper and easier than from the land-based sources. However, deep sea mining also has some drawbacks that need to be addressed. The deep-sea environment is highly fragile and could be damaged by the extraction of REE, thereby leading to the destruction of marine life. Additionally, the extraction of REE from the deep sea is much more difficult and risky than from the land-based sources. This could lead to an increase in the cost associated with the mining process. Moreover, the current technology and infrastructure is not advanced enough to undertake deep sea mining; hence, a significant investment is required to make this possible.

The review highlights that one of the most promising new strategies for the supply of REE is the extraction of rare earth elements from coal-fired ash. This approach involves the recovery of REE from the ash produced from coal combustion and has been investigated in recent years. The potential for recovering REE from coal-fired ash is very attractive as it could provide a large and consistent supply of REE for industry. The process of extracting REE from coal-fired ash involves the physical separation of the REE-bearing minerals from the ash and then the chemical extraction of the REE from these minerals [24].

Another identified strategy for the future supply of REE is the recycling of REE from e-waste, such as end-of-life electronics and electrical equipment. As Balaram summarized, the process of extracting REE from e-waste involves the physical separation of the REE-bearing components from the e-waste and then the chemical extraction of the REE.

In another highly cited review, Bimermans [25] discusses the existing options for the recovery of rare earths from alternative large volume sources such as phosphogypsum, red mud, mine tailings, metallurgical slags, coal and incinerator ash, and waste water streams. Although they contain low concentrations of REEs, these secondary sources could bring back into the economy important amounts of critical metals, as they are largely spread across industry [25].

While studying the natural wetlands as effective sinks for metals, Dubabin and Bowmer (1992) [26] showed that they have a high capacity to store and retain metals due to the complex physical, chemical, and biological processes that occur in these systems. Wetland vegetation takes up and stores metals, and sediments and soils act as sinks to trap metals, including the ones included in the criticality lists. Dunbabin and Bowmer also found that the metal concentrations in the root systems of the affected plants were significantly higher than those in the rhizomes and leaves. This suggests that the roots are the primary sites of metal uptake in plants exposed to contaminated soils. Additionally, they found that the metal concentrations in green leaves were significantly lower than those in non-green leaves, indicating that the green leaves may be serving as a sink for the metals, preventing them from entering the plant's vascular system [26].

Metallurgical processes for aluminum, sodium, iron, titanium, vanadium, scandium, and other valuable element recovery from red mud were investigated by Liu et al. [27]; the authors concluded that bauxite residue or red sludge is a viable option for recovery of scandium resources due to the concentration and availability of scandium. However, red mud is less usable for the extraction by pyrometallurgical method of other trace elements because of substantial energy requirements and environmental pollution.

Another highly cited paper (221 times) reported on selective extraction and recovery of rare earth metals from phosphor powders in waste fluorescent lamps using an ionic liquid system [28]. This study demonstrates the importance of considering the effects of different mineral acids on the leaching of indium from LCD panel glass. The findings suggest that hydrochloric acid should be used for leaching at lower solid to liquid ratios due to its higher leaching efficiency. This study provides valuable insights for the industrial production of indium from LCD panel glass [28].

The processes of acid mine drainage formation were reviewed by Naidu et al. in the paper entitled "A critical review on remediation, reuse, and resource recovery from acid mine drain-age" [29]. Economic implications, prevention of acid mine drainage (AMD) formation, and rehabilitation of affected areas are aspects tackled in this study. As AMD rises as an important alternative source for the recovery of REEs, several treatment processes can lead to obtaining increased quality water for reuse. Nevertheless, there are also bottlenecks that need to be studied, such as increased operation cost, brine management, and the need for membrane pretreatment [29].

While investigating on "Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling", the study of Habib et al. [30] explored the risk of supply constraints for two rare earth elements, namely, neodymium (Nd) and dysprosium (Dy), considering the predicted high demand of Nd and Dy and their forecasted supply in the short-to-long term future. The authors demonstrated that a normal primary supply is unable to meet the forecasted demand of Nd and Dy in their modeled demand scenarios by 2050. Although recycling is unlikely to close the wide gap between future demand and supply by 2050, in the long term, secondary supply from recycling can potentially meet almost 50 % of the demand, i.e., by 2100. It is evident that recycling can play a major role in reducing the geopolitical aspects of supply risk [30].

3.2. Co-Occurrence Keyword Network

The co-occurrence analysis of indexed keywords helps to better understand the research progress and interest of a certain domain. The analysis involves a first step of cleaning and filtering the database of resulting keywords. A total number of 4795 keywords resulted from the selected publications related critical metals. A large number of these keywords had only 1 (3546, 73.95%) or 2 (553, 11.53%) occurrences, while 138 (2.88%) keywords had more than 10 occurrences.

Table 3 presents the top 20 words with the highest link strength and occurrence.

Table 3. The top 20 main words with the highest link strength in selected documents.

Ranking	Keyword	Total Link Strength	Occurrences
1	metal recovery	1406	168
2	recycling	1331	130
3	mining	991	84
4	rare earths	893	78
5	metals	822	77
6	rare earth elements	659	61

Table 3. *Cont.*

Ranking	Keyword	Total Link Strength	Occurrences
7	electronic waste	591	48
8	metal	576	39
9	lanthanide	526	29
10	rare earth element	516	29
11	waste management	515	39
12	copper	513	42
13	recovery	507	50
14	leaching	498	48
15	critical raw materials	434	38
16	controlled study	415	26
17	coal	387	55
18	sustainable development	363	38
19	yttrium	344	19
20	metallurgy	335	27

Figure 7 details the co-occurrence network map of the most frequent keywords in publications related to the topic. Each keyword is represented by a sphere (node), while the lines connecting the spheres show links between the selected keywords to the number of co-occurrences between two keywords.

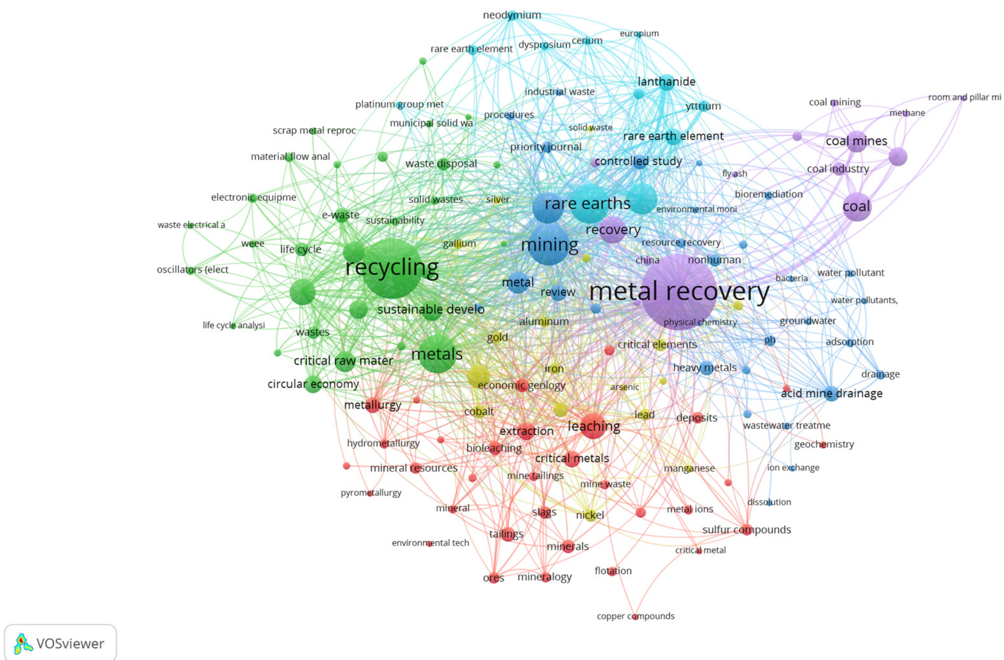

Figure 7. Co-occurrence network map.

The sphere size is related to the number of the keyword's links, and line thickness is proportional.

The co-occurrence maps were designed considering the keywords with at least 10 occurrences, which resulted in 138 keywords. Moreover, these were manually refined by excluding irrelevant words (country names, generic concepts, etc.).

The keyword database revealed six clusters indicated by different colors.

Cluster 1 (red color)

This cluster contains a number of 33 items mainly related to methods for recovery of critical metals from various sources. "Leaching" is the word with most occurrences (48), with a total link strength of 498 and a number of 124 links. Other keywords such as "metallurgy" (27 occurrences), "hydrometallurgy" (16 occurrences), "pyrometallurgy" (10 occurrences), "bioleaching" (23 occurrences), "solvent extraction" (18 occurrences), "extraction" (31 occurrences), and "mine tailing" (16 occurrences) and "tailings" (25 occurrences) are keywords included in this cluster.

Bioleaching uses microbial strains to bio solubilize metal-containing inorganic compounds [31,32]. Due to the shortage of resources and the need to extract critical metals from secondary sources (low-grade tailings; solid or liquid waste) microbial-activity-based methods are developing as innovative alternatives for the supply of critical metals and materials [33–36]. Various process drivers and limitations such as reaction time, pH, temperature, mass transfer rate, nutrient requirement, pulp density, and particle size are important research parameters to take into account [37–41].

Indeed, many strategies for critical material recovery are based on pyrometallurgical processing in combination with hydrometallurgical methods such as leaching, solvent extraction, and precipitation [42–45].

Cluster 2 (green color)

This cluster contains a number of 31 items mainly related to recycling methods for sourcing critical metals from secondary sources. The circular economy concept is very well represented in this cluster by inclusion of waste electric and electronic equipment in the research interest [46,47]. The most used keyword of this cluster is "recycling" with an occurrence of 130 times, a total link strength of 1280, and total links of 129. "Metals" has an occurrence of 77 times, while "electronic waste" is the second most used for this cluster, with an occurrence of 48, 115 links, and a total link strength of 575. Other related keywords are "electronic equipment", "waste electric equipment", "e-waste", and "waste disposal".

With the depletion of primary reserves, the focus is slowly shifting to processing the urban mines, such as electronic (e-)waste [45].

Recovery of critical metals from waste electric and electronic equipment and their recycling in a sustainable circular economy approach in additive manufacturing applications was detailed by Efstratiadis in a recent detailed review [48]. Bioleaching was described as an alternative process with reduced undesirable environmental issues. Bioleaching is involving the use of microorganisms, either bacteria of fungi, in a stirring environment or cultivation without agitation, which eventually proved to be more efficient due to less energy consumption.

Cluster 3 (dark blue color)

The third cluster includes 30 items and is mainly related to mining of critical metals from tailings, dams, and ores. The most important keyword is "mining" (84 occurrences) with the number of links of 131 and a total link strength of 941.

Keywords related to mining are among the most used in this cluster: "metal" (39 occurrences), recovery (50 occurrences), "resource recovery" (16 occurrences).

Generally, it is widely recognized that extracting critical metals from old and abandoned tailings is a reasonable option, as costs associated with mining activity are low due to the fact that ores are partly processed and ground. In the same time, there is a higher possibility to find critical metals at an economically viable concentration than in new ores as the past technologies were less efficient than present ones [49].

Nevertheless, urban mining is an important topic in the analyzed publications. "Resource recovery" from waste landfills as urban mines is a subject of particular interest in the scientific literature. However, "controlled studies" (26 occurrences) are needed for demonstrating the economic efficiency of such processes.

Cluster 4 (yellow color)

This cluster includes 17 items related to critical metals per se. "Copper" is the most used keyword (42 occurrences), with a total link strength of 488 and the number of links of 124. Other keywords are “zinc” (25 occurrences), “iron” (20 occurrences), “gallium” (16 occurrences), “silver” (11 occurrences), and “lithium” (14 occurrences).

Among the existing critical metals, copper is categorized as cross-cutting, being vital in renewable energy and clean storage technologies [50]. Copper is used in rechargeable batteries, electric motors, electrical wiring and connectors, and charging stations, as well as in supporting infrastructures needed to connect renewable energy to the main electrical grid [50,51].

Cluster 5 (indigo color)

The fifth cluster comprises 12 items and includes rare earth elements and related keywords.

“Rare earths” (78 occurrences) and “rare earth elements” (61 occurrences) are the most used keywords in this cluster, closely related to “cerium”, dysprosium”, “europium”, “lanthanide”, “neodymium”, and “yttrium”.

Rare earth metals, or rare earth elements, were given their name not because they are rare in the earth’s crust but because they are rarely found in volumes and quantities sufficient for economically viable extraction. These elements can be found in the earth’s crust as often as nickel, zinc, chromium, and lead. The rare earth elements include 17 elements from the periodic table of Mendeleev: 15 lanthanides (with atomic weights from 57 to 71 in the periodic system), as well as scandium and yttrium. Yttrium with an atomic weight of 39 and scandium are often considered to be in the REM group since they have the same chemical and physical properties and are also found in the same deposits [19,52]. Cerium, yttrium, lanthanum, and neodymium are found most frequently in the earth’s crust [53,54]. All these elements have unique physical and chemical properties. Rare earths are important and the most expensive components of magnetic, optical, and electronic devices that are produced in the defense and aerospace industries: drones, guided missiles, laser guidance devices for satellite communications [28,55].

Cluster 6 (light blue color)

“Metal recovery” is the central keyword of this last cluster. With an occurrence rate of 168 and 168 links, this is one of the most used keywords in the selected publications.

This cluster includes 10 items, most of them related to coal, such as “coal deposits”, “coal industry”, “coal mines”, and “fly ash”.

Extraction and utilization of critical elements from coal and coal ash seems to be an alternative for sourcing critical metals [56]. Literature sources have already demonstrated that critical elements such as uranium, germanium, REEs, yttrium, gallium, and aluminum can be extracted from coal combustions products [56–58]. More research should be performed on finding highly elevated concentrations of critical elements in metals, and the efficient extraction technology should be optimized.

The demand for critical metals in the context of the development of high-tech industries is steadily growing, and ensuring reliable and stable supplies has become an issue. Uncertainties focus on the future supply of such elements, which are critical to production but vulnerable to potential supply disruptions.

The trend towards the transition from carbon energy to renewable energy, which has recently overwhelmed mankind, has sharply shifted the raw material priority of the world industry and economy from hydrocarbons to metals. In an effort to move away from fossil energy sources, the global community is being drawn into a new dependence on other types of raw materials.

Electricity instead of hydrocarbons is a good idea, and there is sound rationality in the energy transition itself. However, humanity, trying to solve the global warming issues, ran with this transition, and now the concern is about how industry and the economy should keep up with it. Solar energy demanded copper, aluminum, and chromium; wind energy—copper and zinc; geothermal—nickel and chromium; hydrogen—nickel and platinoids. Some metals can be mined quickly and are not expected to be in short supply, but others are a problem, including cobalt. An average EV battery requires about 9 kg of cobalt [59]. The production of electric vehicles has received massive support from governments around the world. Europe has set a plan to completely abandon the internal combustion engine in the coming years [60], and in 2021 alone, the price of this element has increased by more than 100% [61], being now one of the most expensive battery components—the price per ton is around $35,000 [62]. Thus, research towards this critical element is expected to increase.

Providing the economy with critical metals occupies an important position for every national security, while being a determining condition for the development of industrial modernization. The global introduction of modern technologies, such as: technologies for creating high-speed vehicles and intelligent control systems for new modes of transport; technologies for new and renewable energy sources, including hydrogen energy; technology for creating new-generation rocket-space and transport equipment, is not possible without critical metals.

As recovery of valuable raw materials from waste is rising, maybe a good research direction is to explore the work implemented on extraction of metals from heavy tonnage waste, such as metallurgical slag. Slag is a waste product from the pyrometallurgical processing of various ores. According to Piatak (2015), based on 150 different studies, the mineralogical and geochemical properties of different types of slag were analyzed and classified in two categories, namely, ferrous and nonferrous slag [63]. The ferrous slag is to be separately studied as historical iron slag and steel and iron slag. The nonferrous slag includes copper slag, zinc slag, lead–zinc slag, and nickel slag. Several studies highlighted the importance of reprocessing waste piles for secondary metal recovery, thus, generating revenues [64,65]. Of course, one of the keys issues to be addressed is that the slag is generally characterized by an uneven distribution of the target components throughout the slag dump [66]. However, the laboratory tests performed by Kasikow et al. demonstrated that a recovery process for large volumes of nickel–cobalt technogenic raw materials is valid to the total volume of slag [66]. On the other hand, bio-assisted extraction of metals from historical slag by use of *Acidithiobacillus thiooxidans* was demonstrated as being technical feasible and, at the same time, economically efficient [65]. Another already in practice example of metal recovery is the modern smelter of Zambian Copperbelt where the historical copper tailing was revisited for extraction of cobalt recovery [64].

In the same line, another in-depth two articles review was put forward by Phiri et al., who investigated the potential for copper slag waste as a resource for a circular economy [67,68]. An overview of copper and cobalt production from ore reserves and of global demand and supply risks for these metals was presented. The mainstream idea has revealed the current knowledge about metallurgical slags, including the chemical and mineralogical characterization of copper slag from 21 major producing countries, metal recovery, and importance for reducing environmental harm. Among others, the authors have pointed out the efficiency of using sulfuric acid as the leaching agent for copper in the process of metal extraction for the recovery of technologically critical elements such as cobalt [68]. The authors have succeeded in demonstrating that the circular economy approach to existing waste has the potential to return economic value by assuring a supply of critical metals while reducing the impacts of metal production on the environment.

A study by Loksin et al. extensively addressed the extraction of critical metals from phosphogypsum. The study pointed that a high efficiency for the purification of phosphogypsum is to complement sulfuric acid leaching with initial water washing [69].

It is, however, important to highlight once again that the criticality of one specific element depends on supply and demand. Obviously, while for the United States, a certain element is critical, for the European Union, for example, it is not considered critical. At the same time, there are common elements for several regions. Although most of the critical elements come from China, even this region registers issues with some raw materials.

Naturally, research paper publications are focused on certain critical metals as a result of the common methods or technologies available for exploitation or recovery.

4. Conclusions and Future Directions

A limitation of this study is that it might have excluded high-quality scientific articles that were deficient in choosing relevant keywords or where the publishing language was other than English. Another limitation is that the topic was researched and evaluated using the Scopus database. Other databases for scientific literature, such as Google Scholar, Web of Science, are for sure important sources for catching existing trends. As a future direction, the search will be extended to include patents databases as well.

Eventually, one of the most important drawbacks when analyzing research on critical materials is that the natural resources are considered a national asset and research related to these might remain unpublished as it must comply with a specific national regulatory framework.

The recent worldwide crisis situations such as the pandemic and military conflicts, have drawn once again attention to the risk of industrial sectors supply disruptions and the need to strengthen the sources of supply with critical raw materials. Therefore, identifying alternative sources through the development of technologies for the recovery of critical metals is of great importance.

This paper involved the use of bibliometric methods to survey scientific publication relating to critical metals and to highlight the dynamics of knowledge production in the field. The concept of critical metals over the past decades has been widely used by economists, policy makers, and scientists in industrialized and rapidly developing countries. They have become common in scientific and technical literature, denoting a material that is practically indispensable for the latest industrial technologies but, at the same time, extremely scarce or vulnerable to supply disruptions. In the scientific literature, the concepts of "scarce" and "strategic" are also used, which have a similar meaning to the concept of "critical" in relation to raw materials. The term "strategic" is more often used in politics and "deficit" in economics. Critical metals are vital to the adoption of new digital and low-carbon technologies, including smartphones, photovoltaics, solar panels, and electric vehicles. They own unique properties that ensure their wide application in various industries.

Using data extracted from Scopus and assessment methods available within VOSviewer, friendly graphical tools showed the relations between publications, taking into consideration various parameters such as keywords, affiliation countries, and citations. Interpretations of work that researchers are producing knowledge in this field were also presented.

By analyzing the co-occurrence of keywords, six areas of research in critical metals recovery were defined: (i) bioleaching as an important process in critical metal recovery, (ii) circular economy concepts and recovery of critical metals by urban mining from e-waste, (iii) resource recovery from waste landfills as urban mines, (iv) targeted studies on various critical elements (copper, zinc, gallium, silver, lithium), (v) rare elements as industry vitamins, and (vi) coal deposits and coal ashes as an alternative source of critical metals.

This paper was envisioned to support scientist who intend to perform a critical metals study by showing criticality research area map as well as research gaps.

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