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FUTURE PROSPECTS OF RARE EARTH ELEMENTS IN COAL AND COAL ASH: BASED ON MAPPING OF GLOBAL RESEARCH (1973-2023)

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Keywords

Coal,
Rare Earth Elements,
REEs,
Bibliometric Analysis.

Abstract

As industrial activities continue to expand, there is a growing demand for Rare Earth Elements (REEs). However, REE resources are rapidly depleting, leading to a search for alternative sources. Notably, REEs are found in significant quantities in coal, a fossil fuel with substantial global reserves and active extraction operations. Some countries, particularly China, extract REEs from coal, indicating its potential as an alternative REE source soon. The increasing number of academic research studies on this topic further underscores its importance. This study aims to analyze global academic research on REEs in coal and coal ash from 1973 to 2023 using bibliometric analysis to identify future trends. Data from the WoS database was utilized to ensure objective and comprehensive results. The research encompassed various aspects such as document type, country of origin, co-authors, institutions, citations, keywords, journals, and WoS categories. The findings suggest that coal could emerge as a significant REE source with sustainable and environmentally conscious practices, potentially forming a widespread business network.

KÖMÜR VE KÖMÜR KÜLÜNDEKİ NADİR TOPRAK ELEMENTLERİNİN KÜRESEL ARAŞTIRMALARIN HARİTALANMASINA DAYALI GELECEK GÖRÜNÜMÜ (1973-2023)

Anahtar Kelimeler

Kömür,
Nadir Toprak Elementleri,
NTE,
Bibliometrik Analiz.

Öz

Gelişen endüstriyel faaliyetler ile NTE'lere (Nadir Toprak Element) olan ihtiyaç da aynı oranda artmaktadır. NTE kaynakları hızla tükenmekte ve alternatif kaynak arayışları ortaya çıkmaktadır. Global çapta büyük rezerve sahip ve aktif olarak işletilmekte olan fosil kökenli yakıt kaynaklarından biri olan kömürde de NTE'ler azımsanmayacak oranda bulunmaktadır. Çin başta olmak üzere bazı ülkeler kömürden NTE üretimi yapmaktadır. Kömürün önümüzdeki yıllarda önemli bir alternatif NTE kaynağı olması muhtemeldir. Konu ile ilgili çok sayıda akademik araştırma yapılıyor olması da bunun bir göstergesidir. Bu çalışma 1973-2023 yılları arasında kömür ve kömür külündeki NTE'ler ile ilgili global çapta yapılan akademik araştırmaların bibliyometrik analiz ile irdelenmesi, gelecek beklentilerin saptanması amacıyla yapılmıştır. Çalışmada objektif ve kapsamlı sonuçların elde edilebilmesi adına WoS veri tabanından çekilen veriler kullanılmıştır. Yapılan araştırmalar doküman türü, ülke, ortak yazar, enstitü, atıf, anahtar kelimeler, dergi, WoS kategorisi gibi çok yönlü olarak incelenmiştir. Kömürün sürdürülebilir ve çevresel yaklaşımlarla NTE kaynağı olarak yaygın bir işletme ağına sahip olması muhtemeldir.

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Highlights

- REEs, which can be enriched in coal and coal ash, are emerging as potential sources of essential elements.
- Bibliometric analysis is employed to quantitatively evaluate the literature and identify research trends on a given topic.
- The future trend in the field of REEs will involve every country aiming to leverage the environmental and ecological benefits while providing economic contributions.

Graphical Abstract

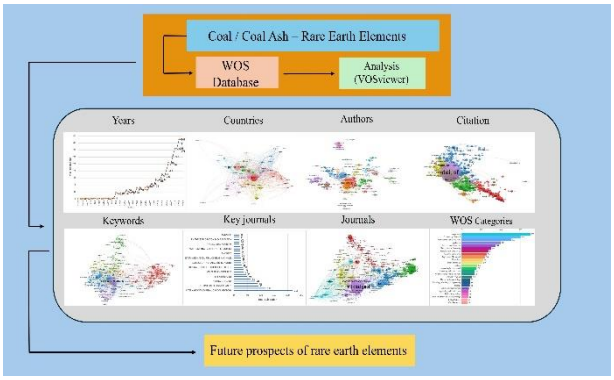

Figure. Distribution of REEs in coal by publications, countries, authors, citations, keywords, journals based on VOSviewer

Purpose and Scope

Rare earth element (REE) reserves are about to be depleted due to expanding usage. Therefore, coal has been investigated as an alternative REE source. The analysis of scientific data is critically important for assessing international activity, predicting future trends, guiding researchers, identifying study topics, and enhancing visibility. This study aims to assess the status, focus, and trends of research on REEs in coal and coal ash by analyzing publications, authors, countries, and journals by implementing VOSviewer.

Design/methodology/approach

In this study, bibliometric analysis was used to obtain more objective and comprehensive results compared to traditional literature reviews. All databases in Web of Science (WoS) were used as data sources for bibliometric analysis. An advanced search formula TS (Topic) = (coal* OR lignite) AND ("rare earth element*" OR REE* OR REY*) was used to identify scientific studies. For network analysis of the publications retrieved from the WoS databases, freely available software VOSviewer 1.6.20 package program was utilized for constructing and visualizing bibliometric networks.

Findings

Since research on REEs in coal began in 1973, the field experienced slow development until 1990, after which interest rapidly increased in 1991. To date, the number of studies on REEs in coal and ash has grown annually. The simultaneous rise in REE studies and the use of technological products and industrial activities indicates that academic research is progressing in parallel with sector needs. Notably, James C. Hower and Shifeng Dai have made significant and impactful contributions to this field. This study reveals that the USA and China have high productivity in terms of total publications. The future trend in this field will involve each country that uses coal as fuel and generates waste material to determine their REE enrichments, protect the environment and ecology, and leverage the economic benefits.

Originality

No comprehensive study has been identified that evaluates current trends and future prospects of REEs in coal and coal ash through bibliometric analysis. This study provides researchers with crucial insights into the trends and hotspots of REEs in coal and coal ash and can guide future studies.

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1. Introduction

Coal is amongst one of the most important energy fuels in the world, meeting a significant portion of the electrical energy demand (Steckel et al., 2015). Coal is a sedimentary rock comprising water, minerals, organic matter, and most trace elements, making it not only an energy provider but also the repository of the broadest array of elements in nature. These elements in coal are pivotal in shaping the depositional environment's properties (Finkelman et al., 2019), impacting coal extraction, combustion, ash disposal, environmental and human health effects, and utilization of valuable by-product raw materials (Dai et al., 2012; Finkelman, 2004; Karadirek, 2023). Despite the widespread presence of rare earth element (REE) deposits globally, economic viability is declining, necessitating the exploration of alternative sources to meet future REE demands (Balaram, 2023).

REEs, which can be enriched in coal and coal ash (Bullock et al., 2018; Dai and Finkelman, 2018; Zhao et al., 2018), are emerging as potential sources of critical elements. Comprising 17 elements, including the lanthanide groups, scandium, and yttrium, REEs are vital in small quantities for enhancing the quality in high-tech products (Şahiner et al., 2017). In our technology-driven world, the dependence on REEs is escalating, with coal, recycling, and marine sediments being alternative sources for these elements (Balaram, 2023). The production of REEs holds significant national importance. For instance, the USA heavily relies on imported REEs. Utilizing coal and coal ash as sources for REEs would reduce dependency on foreign markets, offering a more economical solution. Considering the current consumption rate, the USA could potentially access a 1000-year supply of REEs by processing untouched coal and its by-products (Alvin et al., 2017).

Bibliometric analysis, widely employed across disciplines, delineates the distribution pattern of scientific data within specific subjects, fields, institutions, and countries, enabling quantitative analysis of academic literature through mathematical and statistical techniques (Peng et al., 2018). Yang et al. (2018) conducted a study mapping trace elements in coal and ash, enhancing our understanding of these elements' characteristics.

This study, which is prompted by the increasing significance of REEs, aims to delineate the international outlook of REEs in coal and coal ash through bibliometric analysis (scientific mapping techniques combined with literature network analysis) using data from the Web of Science (WoS) database. The examination of scientific data holds crucial scientific importance in gauging international activity, and future trends, guiding researchers, identifying study topics, and enhancing visibility. Accordingly, scientific studies from 1973 to 2023 were assessed based on WoS categories, publication distribution by year, countries, authors, institutions, journals, most cited works, co-authors, common keywords, bibliography matches, and co-citations in coal and coal ash.

2. Material and Method

This study employed bibliometric analysis, recognized as a method for evaluating research outcomes and gaining a comprehensive view of current scientific output, providing more objective and comprehensive results than traditional literature reviews. All databases in Web of Science (WoS) served as the data source for bibliometric analysis. An advanced search formula TS (Topic) = (coal* OR lignite) AND (“rare earth element*” OR REE* OR REY*) was utilized to identify scientific studies. The timeframe includes 1973–2023 (data retrieval last updated on 31 December 2023), yielding 3920 records. Each publication was evaluated, resulting in the removal of duplicates and materials unrelated to REEs. This study specifically focused on publications concerning REEs within coal and coal ash.

For network analysis of the publications retrieved from the WoS databases, freely available software VOSviewer 1.6.20 package program (van Eck and Waltman, 2010) was utilized for constructing and visualizing bibliometric networks. The program visualizes items in the form of labels and circles, with circle size indicating the item's weight. The colors in the network visualization denote clusters of similar elements, calculated by the program, whereas the distance between items signifies the strength of associations among articles (Yuan et al., 2021).

3. Result and Discussion

3.1. General Distribution of Publications by Type, Year and Countries

A total of 3920 publications across 7 subcategories have been identified in relation to the study topic of REEs in coal and coal ash over the past 50 years. Among these, "Article" comprises the largest share, accounting for 87.9% of the total publications (3446 records). This is followed by "proceeding paper" at 9.6%, "review article" at 5.2%, and "book chapters, meeting abstracts, and other publications" with shares of less than 1% (Table 1).

Table 1. The distributions of document types of rare earth elements in coal and coal ash

DOCUMENT TYPE	RECORD COUNT	FRACTION %
Article	3446	87.9
Proceeding paper	377	9.6
Review article	203	5.2
Book chapters	39	1.0
Meeting abstract	29	0.7
Other publication	57	1.4

Figure 1 illustrates the publication trends for REEs in coal and coal ash from 1973 to 2023. The highest number of publications occurred in 2021 and 2022, totaling 341, while the lowest number of publications was recorded between 1973 and 1990 (<4). During the period from 1991 to 2009, a relatively steady number of publications were released, but starting from 2010, there was a notable upward trend with over 100 publications per year. Although there was a slight decline in the number of publications in 2023, the overall trend indicates a continuous increase in published works.

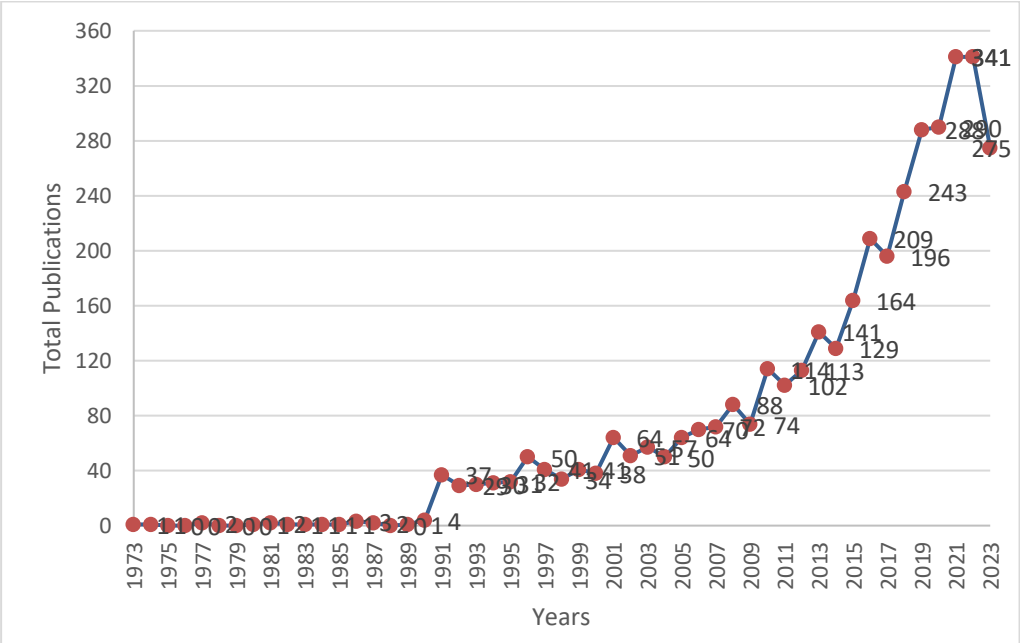

Figure 1. The distribution of publications of rare earth elements in coal and ash by years

The leading countries in conducting research on REEs in coal and coal ash are the United States (1179) and China (1006), as indicated in Table 2. They are followed by Australia (300), the UK (239), Russia (230), Germany (202), India (201), Canada (193), France (153), Spain (119), Japan (116), Poland (105), and several other countries with fewer than 100 publications. Table 2 outlines the top 20 most productive countries in this field. The current trend in global research on REEs in coal and coal ash suggests a significant influence from the USA and China in driving the publication numbers.

The co-author network analysis of publications focused on identifying and interpreting the most influential countries and their connections. Figure 2 reveals that the USA and China, as the two most productive countries, are central to this network. In analyzing studies from these nations, it became evident that they have numerous collaborations with other countries. Particularly noteworthy is the extensive network of co-publications involving the USA, covering a wide range of countries. This indicates both a high volume of publications and a strong level of collaboration.

The USA has been found to have joint publications with countries that also have a substantial publication output, such as China, Australia, Canada, Germany, France, India, Spain, England, and Russia. Additionally, collaborations involving the USA span across continents, highlighting its global engagement in this research domain. Authors affiliated with institutions in the USA predominantly focus on research related to Chinese coals, reflecting the collaborative efforts between authors from the USA and China.

Table 2. The most productive countries/regions of rare earth elements in coal and coal ash

RANK	COUNTRIES/REGIONS	TOTAL PUBLICATIONS	FRACTION (%)
1	USA	1179	30.08
2	Peoples R China	1006	25.66
3	Australia	300	7.65
4	England	239	6.10
5	Russia	230	5.87
6	Germany	202	5.15
7	India	201	5.13
8	Canada	193	4.92
9	France	153	3.90
10	Spain	119	3.04
11	Japan	116	2.96
12	Poland	105	2.68
13	South Korea	76	1.94
14	Italy	72	1.84
15	Iran	65	1.66
16	Netherlands	61	1.56
17	Türkiye	59	1.51
18	Brazil	58	1.48
19	South Africa	56	1.43
20	Sweden	54	1.38

The second circle explosion was in China. A significant collaboration exists between China and the US in joint studies. While there are similarities between China and the USA in the joint country network analysis, the network does not appear as extensive as that of the USA (Figure 2). This suggests that both countries engage in a substantial number of joint publication studies. China's second most prominent collaboration is with Australia. Although not as robust as the collaborations with the US and Australia, China also has strong network ties with Russia and the UK.

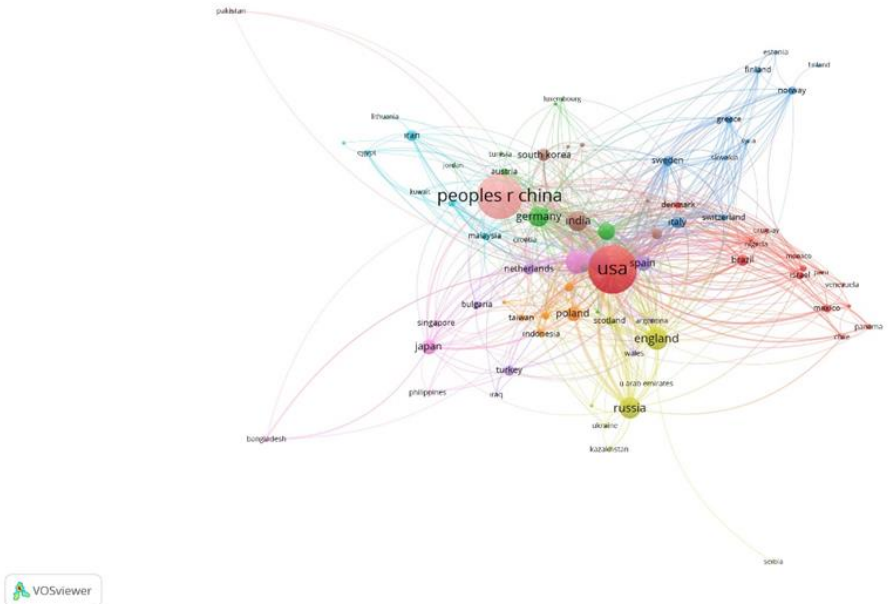

Figure 2. The co-operation network of the countries of REEs in coal and coal ash

Australia and the UK exhibit the most extensive network distribution among Australia, Canada, the UK, and Russia. Canada, in comparison, has a narrower network spread. Despite Russia having a high number of publications, its network distribution is limited, indicating a lack of collaboration with other countries in its studies.

3.2. Co-occurrence and Co-citations Analysis of Authors

For the co-author network analysis of published articles on REEs in coal and coal ash, criteria were set with a minimum of 3 documents authored and a minimum of 3 citations per author. Among the total 12.419 authors mentioned in the analyzed dataset, 669 authors met these criteria, representing approximately 5% of the total authors. The analysis revealed the largest group of linked authors, comprising 362 individuals organized into 25 clusters [with 1801 links and a total link strength of 4478]. Each of the 25 clusters contains between 1 and 32 co-authors, distinguished by different colored clusters.

The results from the co-occurrence analysis reveal a partial collaborative relationship among the authors (Figure 3). Notably, among authors contributing significantly to publications on REEs in coal and coal ash, Hower JC stands out with 103 links and a total link strength of 432, based on 100 publications. Similarly, Dai SF shows prominence with 87 links, a total link strength of 482, and 93 publications (Table 3). These authors share a specialization in coals commonly used in China. Authors with over 30 publications include French D (39 publications), Zhao L (35 publications), Graham IT, and Querol X (34 publications), along with Ward CR (32 publications) (Table 3). The top two authors demonstrate publications with substantial impact, evident from the prominent bursts in their respective nodes within the graph (Figure 3), indicating a relatively close collaboration.

Table 3. The most productive 20 contributors to REE in coal and coal ash

Authors	Record count	Fraction %
Hower JC	100	2.55
Dai SF	93	2.37
French D	39	0.99
Zhao L	35	0.89
Graham IT	34	0.87
Querol X	34	0.87
Ward CR	32	0.82
Finkelman RB	29	0.74
Li J	29	0.74
Nechaev VP	29	0.74
Wang XB	27	0.69
Arbuzov SI	26	0.66
Eble CF	24	0.61
Hsu-kim H	23	0.59
Zhang WC	23	0.59
Zhou CC	23	0.59
Zhuang XG	22	0.56
Seredin VV	21	0.54
Pan JH	20	0.51
Chekryzhov IY	19	0.48

French D, ranking third in terms of publication count, exhibits a strong author network, although not as robust as Dai SF and Hower JC. French D's research encompasses the origin of critical element enrichment, metal enrichment in coal, bio-geochemical evolution of coals and critical elements, as well as studies on REEs focusing on age, environment, origin, mineralogy, and isotopes.

On the other hand, Zhao L. does not demonstrate as extensive an author network as French D and typically collaborates with the same group of authors in their studies, many of whom have a high number of publications. Zhao L., a researcher specializing in fly ash, volcanic ash, mineralogy, critical elements, REEs, trace element enrichments, age, and environment interpretations, primarily focuses on Chinese coals in their work.

Granham IT shares similarities with his co-authors, particularly Zhao L., although their impact and reach differ. In contrast, Querol X, despite having the same number of publications as Granham IT, pursues distinct research directions from the top 5 authors in the field. While the first four authors collaborate closely, Querol X has no shared publications with them and works with an entirely different set of authors. One notable collaborator is Li J. (with 29 publications), with whom Querol X has conducted research across sites in China, Turkey, Brazil, Vietnam, and other countries. Their research focuses on REEs enrichments, trace element enrichments, coals used in power plants, and fly ash analysis. Nechaev VP, Finkelman RB, and Ward CR also have an equal number of publications. Among them, Ward CR and Finkelman RB exhibit widespread distribution in their author networks.

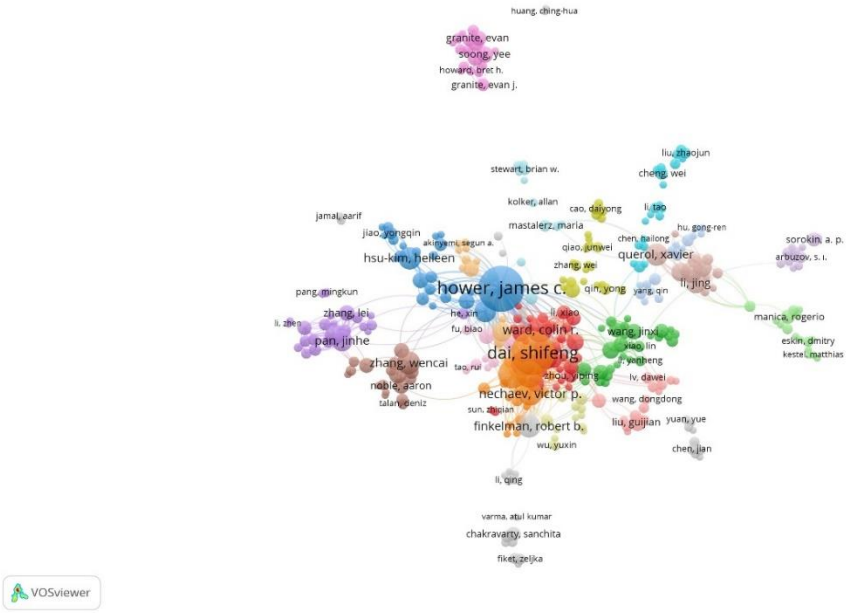

Figure 3. Co-occurrence network analysis of articles in the context of authors

The co-citation author network analysis reveals two distinct groups of authors (Figure 4). One group appears weakly connected, while the other is tightly clustered and interconnected. In the analysis results, a prominent purple cluster in the center signifies Dai SF as the most cited author, despite not being the most prolific in terms of number of publications. Dai has garnered citations from a diverse range of authors, indicating broad recognition within the field. One of Dai SF's highly cited work is a re-view paper covering the abundance, genetic types, effects on human health, and industrial applications of Chinese coal (Dai et al., 2012). In contrast, although Hower JC has the most citations, their network connections are not as extensive as Dai SF's. This suggests that Hower JC's studies are cited primarily within specific study groups or contexts.

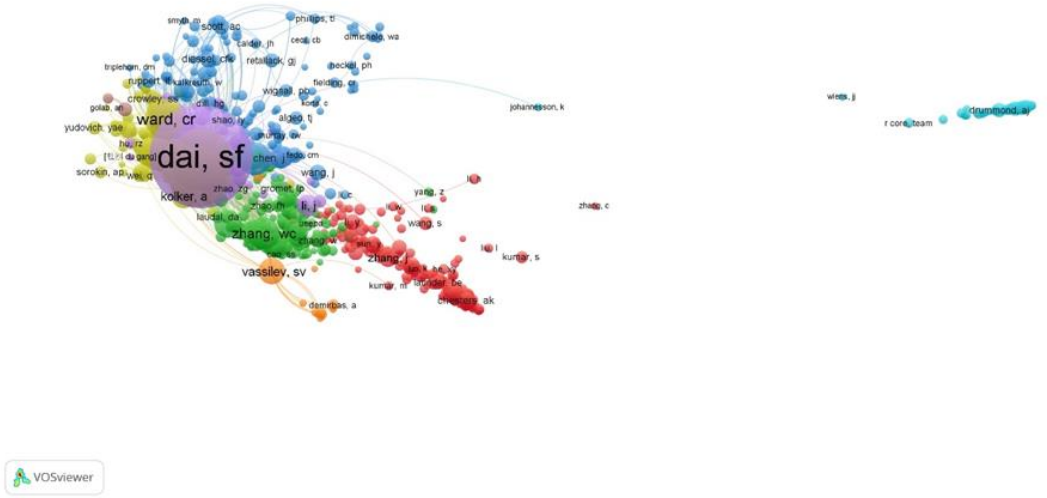

Figure 4. Co-citation network analysis of articles in the context of cited authors

3.3. Co-occurrence Analysis of Keywords

Identifying the keywords and their relationships provides crucial insights into interpreting the study's subjects. A minimum of five keywords (with a minimum occurrence of 5 times each) were selected to conduct keyword network analysis within articles authored on REEs in coal and coal ash. The total number of keywords in the analyzed dataset was 9136, with 348 authors meeting the threshold. The analysis revealed that the largest linked word group comprised 346 items and 10 clusters, with 2291 links and a total link strength of 3800.

Following the network analysis using keywords, the overall representation is depicted through clusters in four distinct colors (Figure 5). Among these groupings, the purple and blue clusters are predominant. Notably, the keywords "Rare Earth Element" and "Coal" emerge as the most frequently utilized terms in the studies. Delving into the connections of these two key terms enables us to interpret the publications concerning this subject.

Among the keywords in the networks established with REE, fly ash, coal, coal waste, bottom ash, and red mud refer to coal samples. Studies on rare earth elements (REEs) in coal have primarily focused on identifying enrichments extracted from coal fly ash, bottom ash, and coal waste. Other keywords such as yttrium, scandium, lanthanides, and critical metals denote the materials investigated in the research. Keywords like leaching, bioleaching, acid leaching, physical separation, and adsorption symbolize the methods utilized. Additionally, keywords like coal by-products and coal combustion indicate that research has been conducted on coal by-products and REEs enriched during coal combustion.

Another crucial keyword is coal. Through detailed analysis, it was found that volcanic ash in coal, trace elements, oil shale, and clay minerals like lignite, maceral, and kaolinite were the focus of research. It is evident that investigations have been conducted on uranium, lithium, germanium, thorium, and carbon isotopes within these products. Strong correlations exist among acid mine drainage, depositional environment, organic association, geochemistry, mineralogy, and coal. Notably, China and Turkey are the most extensively researched areas in this context.

When examining the few keywords prominently highlighted in yellow at the center, it becomes clear that key terms such as lanthanides, enrichment, trace elements, and pyrite are the focus of research concerning the environment or peat, employing methods such as XRD and ICP-MS.

On the right side of the figure, an independent grouping of these keywords appears in red. This grouping primarily relates to the methodological aspects of the studies, revealing the utilization of methods such as fragmentation/coalescence, numerical simulation, fluid dynamics, two- and multi-phase heat flow, and modeling.

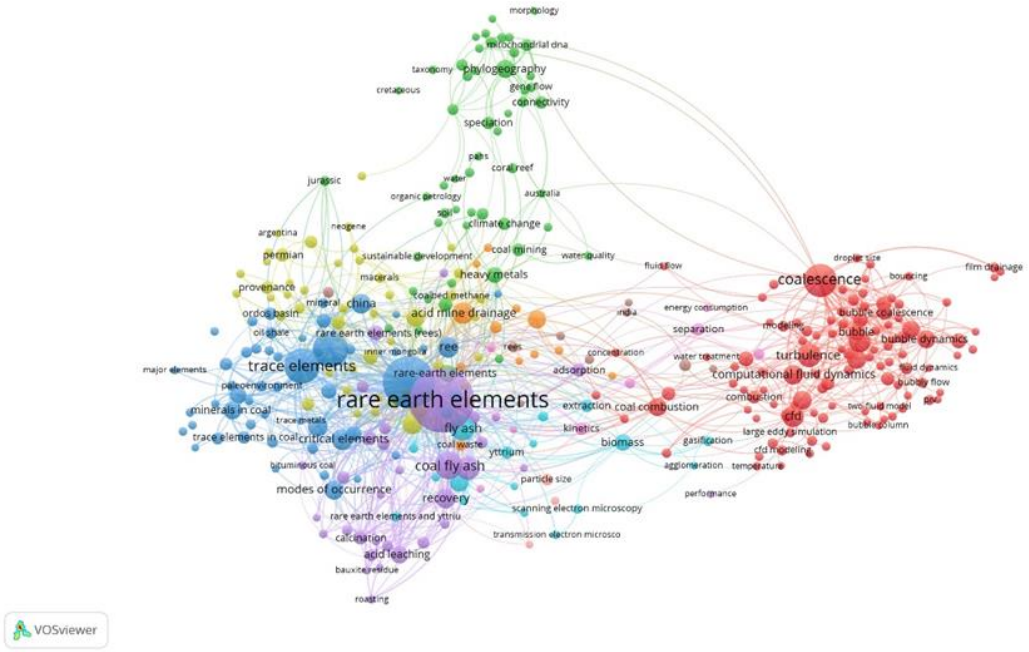

Figure 5. Network analysis of publications by keywords

3.4. Co-citations Analysis of Journals

The International Journal of Coal Geology (218 publications) stands out as the top journal for REE research in coal and coal ash. Additionally, the Journal of Fluid Mechanics (118 publications), Physics of Fluids (90 publications), Energy & Fuels (88 publications), and others also contribute significantly to this field (Figure 6). While the publication count is substantial, it's crucial to assess these publications through bibliometric analysis to gauge their recognition and validity comprehensively.

In network analysis, journals with a widespread indicate that they receive citations from various studies. While the prominent circles of journals only suggest that their citation numbers are high, their connections can be scrutinized in detail to identify the citations they receive from diverse studies.

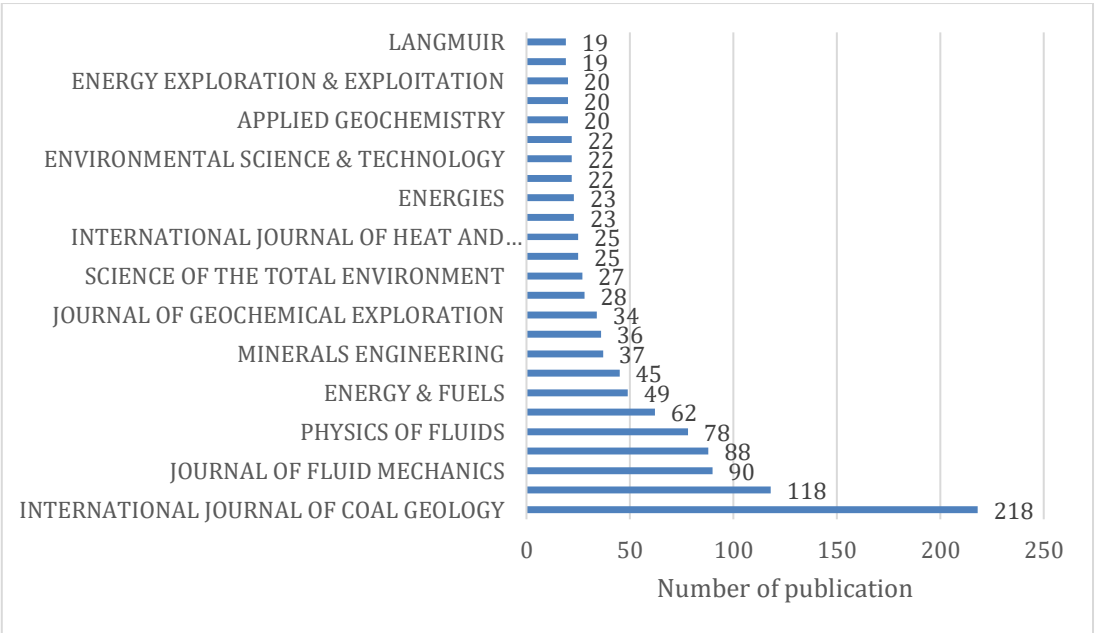

Figure 6. Distributions of output in key journals of rare earth elements in coal and ash in 1973–2023

In this study, co-citation analysis was carried out in journal format. To perform journal network analysis within the citation context, a minimum of twenty sources (with a minimum citation count of 20) were selected. The total

number of sources in the analyzed dataset was determined as 43.414, with 1.020 sources meeting the threshold. The largest linked source group comprised 1.000 items and 6 clusters, with 15.090 links and a total link strength of 5.367.388.

Among the six identified clusters, the International Journal of Coal Geology (in purple) emerged as the most cited journal, creating a burst in the center (Figure 7). This journal not only has a high number of publications but also exhibits the widest network spread. It features numerous highly cited studies on REE research in coal and coal ash. Among the top five most cited studies, three of these studies focus on Chinese coals. One is a review discussing Yttrium's role in REEs within coal, while another explores the future prospects of coal as a critical element source.

Another prominent journal is Fuel (in blue), which although not as widely distributed as the International Journal of Coal Geology, still shows a significant spread. The most cited study in Fuel pertains to the phase-mineral and chemical composition of biomass ash. Journals like Nature and Science share a similar distribution pattern to Fuel. In contrast, the Journal of Fluid Mechanics (in green) ranks second in references but lacks extensive network spread, indicating citations primarily from within the same journal's publications.

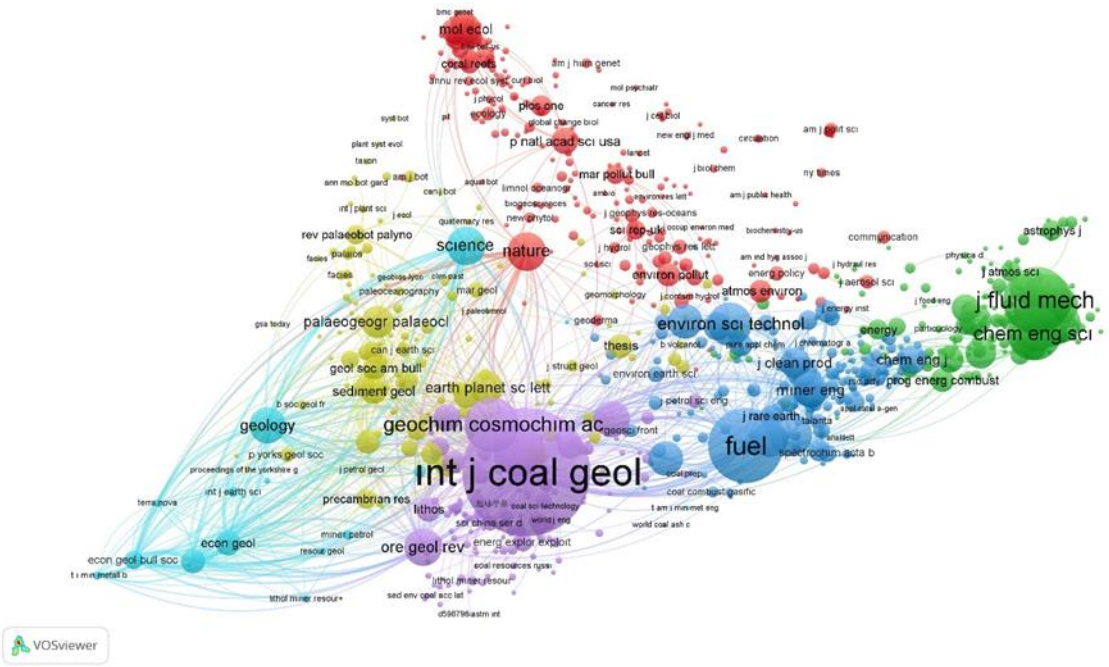

Figure 7. Network analysis distribution of journals publishing on REE studies in coal and coal ash

3.5. Distribution of WoS Categories

The classification of WoS categories offers an advantage by providing information on the subject distribution of academic outputs and enabling insightful comments. In this context, WoS categories related to REEs in coal and coal ash were analyzed. The WoS categories in the top four classifications are Energy & Fuels (17.93%), Engineering, Chemical (15.36%), Geosciences, Multidisciplinary (12.93%), and Mechanics (10.15%) that encompass more than half (54%) of the total articles (Figure 8).

Studies on REEs in coal and coal ash have predominantly been conducted within the realms of environmental research and earth sciences, including environmental sciences, environmental engineering, ecology, green sustainable science and technology, water resources, geological and mineral research encompassing mining mineral processing, geochemistry, geophysics, mineralogy, geology, multidisciplinary research involving chemistry, material science, multidisciplinary science, engineering, physical chemistry, marine freshwater biology, evolutionary biology, and methodological research such as physics, fluids, plasmas, thermodynamics, metallurgy and metallurgical engineering.

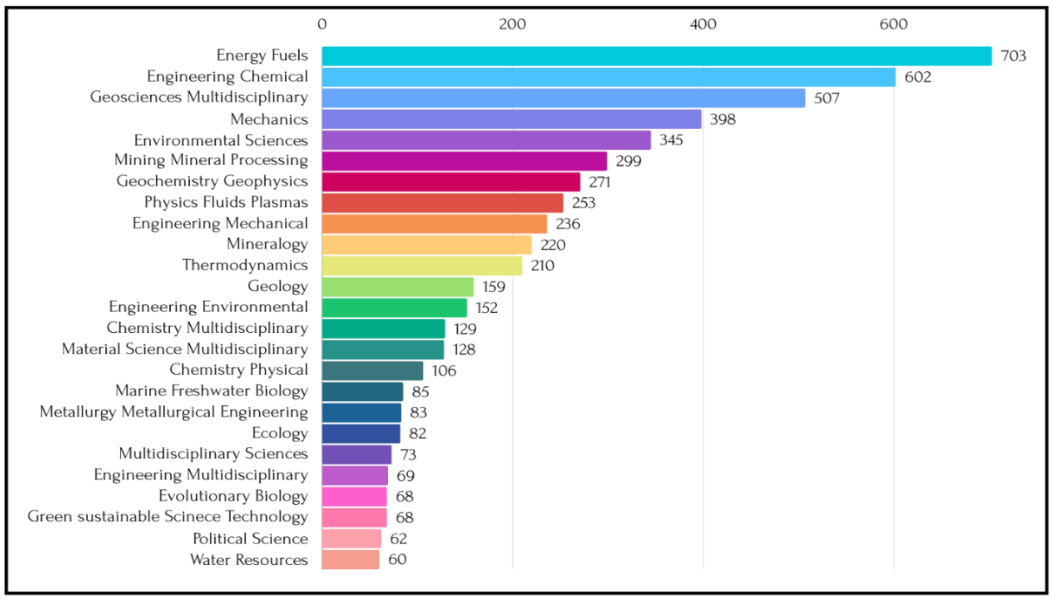

Figure 8. Distribution of WoS categories

3.6. Research Tendencies and Study Focus

It is estimated that a significant portion of the REE reserve will be depleted by 2030 given current operations (Yalcin Erik, 2022). Consequently, researchers are exploring alternative sources of REEs. Coal stands out as one of the important resources for REE production.

The countries with the most intensive REE research in coal and coal ash are the USA and China. One of the significant reasons for this is the abundance of coal reserves in these nations. The USA holds 29% of the world's coal reserves, followed by Russia at 20.6%, Australia at 18.9%, and China at 18%. China leads in world coal consumption at 71.4%, while the United States ranks third, accounting for 7% after India (Global Power Plant, 2024). Globally, there are 121 billion tons of REE reserves identified, with China being the largest producer (Ober, 2017). This aligns with the concentration of academic research in China on this topic.

China, Japan, the USA, Germany, and France are among the top consumers of REEs. Of particular interest here is the USA. Despite being one of the world's leaders in coal reserves and consumption, the production of REEs is not as high in the USA. The substantial number of academic studies conducted in the country is an indication that research in this field is ongoing. Another country facing a situation similar to the USA is Russia. Russia boasts 18 billion tons of coal reserves (Şahiner et al., 2017) and holds a prominent position in academic research on the subject. However, it has not achieved comparable success in REE research studies. On the other hand, Brazil, with 22 billion tons of coal reserves, ranks at the top globally. It comes second only to China in REE production (Şahiner et al., 2017). Despite not leading in terms of coal reserves like Canada, Germany, France, England, and Spain, Brazil's engagement in REE studies indicates that the issue extends beyond coal reserves alone. The fact that countries are exploring alternative REE resources suggests proactive measures against potential decreases in REE resources in the future.

There are numerous researchers who have conducted studies on REEs in coal and coal ash. Discussing the research of Hower JC, the most prolific author, and Dai SF, the second most published and cited author, is crucial for understanding the past and gaining insights into the future of this field. Hower JC embarked on his first study on this subject in 1996 and has since been consistently involved in research. The study of Hower et al. (1999) on REE anomalies of coals in Eastern Kentucky stands out as the most cited publication. His research primarily focuses on China and the USA. He extensively analyzed fire clay coal deposits regarding REEs and also investigated fly ash, mineralogy, and REE enrichments. Dai SF and Hower JC have collaborated on 43 studies since 2011, with a majority of their research focusing on Chinese coals. Their work encompasses topics such as fly ash, volcanic ash, REE enrichment in coal waste, and REE mineralogy. Through their studies, it is apparent that the emphasis should be placed on REE production from coal fly ash, bottom ash, and volcanic ash. This emphasis provides important insights for researchers currently engaged in or planning future research, as well as for countries aiming to enhance REE production.

Their contributions to REE research in coal and coal ash are significant, particularly through their studies, including review articles, on REE investigations in peat areas, the organic relationships of non-mineral elements

in coal, coals of various ages, and coals from different geographical regions.

Generally, the widespread use of keywords such as fly ash, coal waste, and bottom ash in publications supports the emphasis on REE production from these sources. This emphasis is particularly crucial for the utilization and disposal of fly ash and bottom ash wastes generated in thermal power plants. With the growing demand for energy, there has been a corresponding increase in coal fly ash waste. Research conducted in Poland, the second-largest coal consumer in Europe, has revealed that fly ash is a promising raw material for REE (Franus et al., 2015), given that a significant portion of global electricity generation relies on coal. For countries like China, the USA, Russia, and India, which are expected to remain reliant on coal for a considerable time, the utilization of critical elements holds both economic and environmental importance (Dai and Finkelman, 2018).

Despite the presence of alternative energy sources, the reliance on coal-based energy remains unchanged. This leads to the global production of significant amounts of coal fly ash, posing serious ecological threats during disposal and storage (Gollakota et al., 2019). In light of these findings, countries utilizing coal as a fuel and generating waste material from it should assess REE enrichment. They must then develop policies to safeguard the environment and ecology while also leveraging the economic benefits offered by REE contributions.

4. Conclusions

Bibliometric analyses were conducted using data from the WoS database for REE studies in coal and coal ash. The majority of these studies, 87.9%, fall under the Article document type. Dai SF stands out as one of the most cited authors with extensive research on REE in coal and coal ash, including both literature reviews and field studies. Hower JC has also made significant contributions to this field.

The study extensively analyzed the joint network analyses of authors collaborating with Hower JC and Dai SF, revealing strong bursts in their networks. While Hower JC received the highest number of citations, the International Journal of Coal Geology had the highest number of publications. Notably, a majority of the publications were published by the USA (30.08%) and China ranking second (25.66%) in publication output.

Upon analyzing the distribution of WoS categories, studies in energy, environmental sciences, mining, geosciences, multidisciplinary fields, chemistry, and geochemistry stood out categorically.

Keywords play a crucial role in discerning the focus of studies. In this study, a detailed examination was conducted on keywords and their interconnections. Keywords were broadly categorized into element-based investigations, field studies, and methodologies. The analysis revealed a concentration of studies on keywords like fly ash, bottom ash, coal waste, and red mud. Additionally, elements such as Yttrium and Scandium, abundant in coal and coal ash, along with lanthanides and critical metals, were frequently utilized as keywords.

The first study on this subject dates back to 1973, with approximately 50 years of studies analyzed until the end of 2023. Upon examining the data annually, it was noted that the number of publications remained consistently low until 1990, after which it showed an upward trend. The growth rate increased notably after 2010, indicating a significant rise in publications related to REEs in recent years. This trend aligns with the increased utilization of REEs in technological products and industrial activities, reflecting the progressive nature of academic studies in response to sectoral demands. The widespread adoption of REEs over the past five decades also corresponds to the year of the first publication in this area.

The utilization of REEs in electrical, electro-optical, and magnetic applications is extensive. With the rapid global advancement in technological activities, the use of REEs has expanded across various sectors. Main sectors where they are prominently employed include satellite and communication technologies, the defense industry, and medical products.

The use of fossil fuels remains widespread globally, with coal being a primary energy source in many countries, especially for electricity generation. China stands out as one of the leading consumers of coal, with significant production and reserves. Following breakthroughs in science and technology since the 1980s, China has emerged as a major competitor to the USA and European nations in technological product manufacturing. This dual focus on coal and technological advancements has led China to early exploration of REEs, as evidenced by academic publications.

China and the USA are among the top countries conducting REE research in coal and coal ash, often collaborating on joint academic studies. Notably, the research efforts of the USA often center on China, which leads in coal reserves. The study suggests that the USA may soon face a shortage of REEs and should explore alternative sources,

including coal. This trend is mirrored in other technologically developing countries without coal reserves, indicating a potential future use of coal as an REE source alongside its energy role. Given these factors, it is likely that REE studies will increase in the USA in the coming years. Moreover, the presence of academic studies in countries without coal reserves hints at coal's potential dual role as an REE source and energy fuel in the future.

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Conflict of Interest

No conflict of interest was declared by the author.

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