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A BIBLIOMETRIC ANALYSIS OF RESEARCH TRENDS IN RARE EARTH ELEMENT (REE) SEPARATION TECHNOLOGIES

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Abstract:

The escalating worldwide requirement for Rare Earth Elements (REEs), propelled by their indispensable applications in clean energy technologies, electronics, and advanced manufacturing, has intensified research into efficient and sustainable separation technologies. Despite substantial scientific progress, the expanding volume of literature has created challenges in identifying dominant research trends, key contributors, as well as newly emerging thematic developments within this area. This study seeks to bridge this gap by offering an extensive bibliometric examination of REE separation technologies. A systematically compiled dataset was extracted from the Scopus database through the use of advanced search strategies built around two core terms, namely "rare earth element" and "separation technology." The dataset comprises 1,193 publications spanning the period from 2018 to May 2026. Data cleaning as well as refinement were carried out through OpenRefine, whereas performance analysis and visualization of scientific mapping were conducted using VOSviewer and the Scopus analytical tools. The results demonstrate a pronounced upward trajectory in yearly publication output, with a sharp increase observed after 2021, indicating growing global research interest. China, the United States, and Germany stand out as the principal contributors when assessed through publication volume and citation influence. Meanwhile, keyword co-occurrence mapping identifies dominant themes such as Solvent Extraction (SX), adsorption, and hydrometallurgical processes, alongside emerging topics including green separation technologies and membrane-based systems. Collaboration network analysis further highlights increasing international research partnerships, particularly among technologically

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advanced economies. To conclude, this study delivers a structured synthesis of the knowledge framework and the shifting research landscape surrounding REE separation technologies, yielding meaningful insights for researchers, policymakers, as well as industry stakeholders to guide future research directions, funding priorities, and innovation strategies in support of sustainable resource development.

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Keyword:
Rare Earth Element, Separation Technology

Introduction

The isolation of Rare Earth Elements (REEs) underpins supply chains for clean energy, electronics, and defense, yet remains one of hydrometallurgy's most difficult problems due to the highly similar physicochemical properties of neighboring lanthanides. Growing demand, geopolitical concentration of mining, and the shift toward secondary resources have driven intense innovation in separation technologies and a broad, interdisciplinary research landscape (Z. Chen et al., 2021; Opare et al., 2021; Ouardi et al., 2023; Traore et al., 2022). Conventional industrial flowsheets—leaching, multistage Solvent Extraction (SX), and precipitation—are being reassessed against requirements for higher selectivity, lower environmental impact, and economic viability across increasingly complex feedstocks from ores, industrial effluents, and end-of-life products (Judge & Azimi, 2020; Liu & Chen, 2021; Merroune et al., 2024; Neves et al., 2021).

Across this landscape, SX continues to function as the principal industrial purification step for both light and heavy REEs, applied after acid leaching of primary and secondary resources (Judge & Azimi, 2020; Liu & Chen, 2021; Neves et al., 2021; Opare et al., 2021). Classical multistep Liquid–Liquid Extraction (T-LLE) circuits achieve high throughput but require 40–50 stages to separate elements with low separation factors, generate large volumes of flammable organic solvents and contaminated aqueous waste, and struggle with achieving ultra-high purities and stable operation (Bailey et al., 2020; Ding & Azimi, 2024). Moreover, recent reviews classify an expanding family of SX systems—organophosphorus extractants, Ionic Liquids (ILs), aqueous two-phase systems, deep eutectic solvents, and Non-Aqueous Solvent Extraction (NASX)—aimed at improving efficiency, selectivity, and sustainability (Bailey et al., 2020; Gholami et al., 2025; Merroune et al., 2024; Neves et al., 2021). For heavy REEs, advanced LLE and solid–liquid processes have been optimized to balance extraction capacity, separation efficiency, and impurity control, with non-aqueous flowsheets demonstrating high-purity grouping of HREEs in drastically fewer stages than conventional circuits (Gholami et al., 2025; Liu & Chen, 2021). Parallel efforts in impurity removal use tailored precipitation, SX, and Ion Exchange (IX) steps to manage critical contaminants such as Alumunium (Al), Iron (Fe), Thorium (Th), and Uranium (U), which strongly influence downstream separation performance and product specification (Judge & Azimi, 2020).

Beyond SX, a wide range of complementary separation routes is being systematically developed. IX has re-emerged, particularly for secondary resources and sulfate media, due to its high selectivity, relatively simple equipment, and potential for greener operation when combined with optimized resins and process designs (Liu & Chen, 2021; Ouardi et al., 2023; Traore et al., 2022). Reviews stressed IX as an efficient, economical option for upgrading dilute or heterogeneous feeds, even though long cycle times and low solution concentrations limit productivity (Bailey et al., 2020; Ouardi et al., 2023). Membrane-based strategies—including polymer inclusion membranes, liquid membranes, nanocomposite and imprinted membranes, as well as metal-organic framework-based structures—aim to couple extraction and separation in a compact, low-waste format (Bashiri et al., 2022; L. Chen et al., 2018; Pathapati et al., 2023). Mechanistically, these systems rely on complexation within the membrane, adsorption on engineered active sites, or size-/charge-based rejection of REE complexes (Bashiri et al., 2022; L. Chen et al., 2018). In contrast, non-liquid membranes offer improved stability and the prospect of task-specific recognition. On the other hand, reviews highlighted that practical REE applications remain at early stages, with scale-up, long-term stability, and precise selectivity engineering as central research needs (Bashiri et al., 2022; Kujawa et al., 2023; Pathapati et al., 2023). Electrochemical methods, especially electrodialysis with advanced ion-exchange membranes, are also being modeled and optimized to achieve selective separation (e.g., Dy from Nd/Pr). This demonstrates the trade-offs between voltage, energy consumption, and separation performance and suggests alternative membrane configurations to improve efficiency (Ding & Azimi, 2024).

Conceptually oriented state-of-technology and bibliometric reviews map the knowledge structure of REE separation research across techniques, media, and application fields. Analyses indicate that SX, leaching, as well as plasma-based methods constituted the three most extensively investigated separation technologies between 2015 and 2020, with chemistry, engineering, and metallurgy dominating the disciplinary landscape (Opare et al., 2021). Across more than 40 research fields, acid- and base-driven leaching, often involving ILs or salts, emerges as the central enabling step for REE mobilization prior to downstream separation (Opare et al., 2021; Traore et al., 2022). Comprehensive comparative reviews integrate precipitation, crystallization, redox control, adsorption, SX, IX, and membrane processes, emphasizing that no single method alone can universally meet requirements for purity, cost, and environmental performance. Instead, hybrid and sequential flowsheets tailored to specific feedstocks are increasingly viewed as the way forward (Z. Chen et al., 2021; Liu & Chen, 2021; Pathapati et al., 2023; Traore et al., 2022). At the same time, sustainability-focused work examines “greener” solvents (deep eutectic solvents, ILs, aqueous two-phase, as well as cloud-point systems) and agromining via hyperaccumulator plants, aligning REE recovery with circular-economy and low-impact goals (Gholami et al., 2025; Neves et al., 2021; Opare et al., 2021).

In conclusion, the evolution of REE separation technologies reflects a shift from reliance on large multistage SX circuits toward a diversified portfolio of hybrid, selective, and sustainability-oriented processes. The knowledge structure is increasingly interdisciplinary, integrating hydrometallurgy, membrane science, electrochemistry, and green solvent design,

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and recognizing the importance of impurity control and secondary resources (Bailey et al., 2020; Liu & Chen, 2021; Opare et al., 2021). Future directions highlighted across recent reviews include: (i) advancing non-aqueous and environmentally benign SX systems, especially ILs and deep eutectic solvents, while solving adjacent REE selectivity and solvent regeneration; (ii) designing robust, scalable membrane and membrane-assisted processes with task-specific recognition and long-term stability; (iii) optimizing IX and electrochemical routes for high-purity separation at lower energy and chemical consumption; and (iv) integrating these technologies into flexible flowsheets that accommodate variable ores, wastes, and recycling streams (Bailey et al., 2020; Merroune et al., 2024; Ouardi et al., 2023). Together, these trends point toward REE separation platforms that are not only more efficient and selective but also better aligned with the environmental and resource-security imperatives driving global REE demand.

Research Question

1. What are the temporal trends in the volume of scholarly publications on REE separation technologies from 2018 to May 2026?
2. Which key publications have shaped the development of REE separation technology research as indicated by citation-based metrics?
3. What conceptual structures and evolving research themes can be identified in REE separation technology using keyword co-occurrence analysis?
4. How do country-level co-authorship networks reveal the structure and intensity of international collaboration in REE separation technology research?

Methodology

Bibliometric analysis entails the organized identification, systematic structuring, and quantitative evaluation of bibliographic information obtained from academic publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). In addition to conventional descriptive measures, including publication outlets, chronological patterns, and prominent contributors (Y. C. J. Wu & Wu, 2017), bibliometric methodologies have progressively expanded to integrate more sophisticated procedures such as document co-citation analysis, which helps reveal the underlying intellectual architecture of a given research domain. Conducting a robust literature review requires an iterative, transparent process that involves the careful construction of search terms, exhaustive extraction of relevant records from databases, and comprehensive analytical evaluation. This methodical framework supports the development of a dependable body of evidence while simultaneously strengthening the overall validity and reliability of the resulting insights (Fahimnia et al., 2015).

In this investigation, priority was given to high-impact scholarly works in order to encompass meaningful contributions to both the conceptual and theoretical advancement within the field. To maintain consistency and ensure the precision of the dataset, Scopus served as the principal database for bibliographic extraction (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). In alignment with accepted academic conventions, the inclusion criteria were limited exclusively to peer-reviewed journal articles, with books and lecture materials deliberately omitted to maintain methodological rigour (Gu et al., 2019). Drawing on the extensive coverage of Scopus, relevant publications published between 1947 and May 2026 were systematically compiled for further examination.

Data Search Strategy

The bibliometric data were obtained from Scopus through a structured and transparent search strategy. The search string was defined as detailed in Table 1. This formulation ensured that the retrieved publications were confined to core subject areas directly relevant to technologies for REE separation. The initial search yielded a total of 1193 records.

Subsequently, a systematic screening process was conducted in accordance with the selection criteria specified in Table 2. The inclusion criteria comprised publications written in English, classified within the domains of Chemistry, Materials Science, Chemical Engineering, and Engineering, and limited to journal articles. Conversely, non-English publications, studies outside the specified subject areas, and non-article document types were excluded.

The combined application of the search strategy and the screening criteria ensured the development of a focused, high-quality dataset, consequently strengthening the dependability and overall robustness of the ensuing bibliometric analysis.

Table 1: The Search String

Scopus	TITLE-ABS-KEY ((“rare earth element*” OR “rare earth metal*” OR REE OR lanthanide*) AND (“separation process” OR “separation technology” OR separation OR extraction OR recovery OR purification OR leaching OR “solvent extraction” OR “ion exchange” OR adsorption OR membrane OR hydrometallurgy) AND (technology* OR innovation)) AND PUBYEAR > 2017 AND PUBYEAR < 2027 AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (SUBJAREA , “MATE”) OR LIMIT-TO (SUBJAREA , “CHEM”) OR LIMIT-TO (SUBJAREA , “CENG”) OR LIMIT-TO (SUBJAREA , “ENVI”) OR LIMIT-TO (SUBJAREA , “ENGI”)) AND (LIMIT-TO (LANGUAGE , “English”))

Table 2: The Selection Criterion is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Subject	Chemistry, Material Science, Chemical Engineering and Engineering, Environmental Science	Others
Document Type	Article	

Data Analysis

VOSviewer is an extensively used bibliometric mapping application created by Nees Jan van Eck and Ludo Waltman at Leiden University (van Eck & Waltman, 2010, 2017). It is purpose-built for the visual representation and quantitative exploration of scientific knowledge frameworks, providing sophisticated capabilities for building network structures, grouping related items into clusters, and producing density-based visual maps. The program facilitates the analysis of a wide range of bibliometric linkages, including co-authorship networks, co-citation patterns, as well as keyword co-occurrence relationships, thereby enabling an in-depth examination of research domains. With its interactive user interface and ongoing methodological and technical refinements, it supports the efficient processing of large datasets, the computation of bibliometric indicators, customization of visual outputs, and integration of heterogeneous data inputs, collectively enhancing its role as a powerful tool for scholarly analysis.

A key advantage of VOSviewer is its ability to convert intricate bibliometric interconnections into clear, easily interpretable visual formats. The tool is particularly effective in network-based analyses, where it supports the identification of thematic clusters, the detection of keyword co-occurrence patterns, and the production of density visualizations that reveal zones of concentrated scholarly activity. Its accessible, user-centred interface also enables both beginners and advanced researchers to methodically examine the intellectual structures and emerging trends within a field. Note that continuous software development further ensures methodological adaptability, enabling the analysis of various data types, including authorship, citation, and collaboration networks.

In the present study, bibliographic data comprising publication year, article title, authorship, source journals, citation metrics, as well as keywords were extracted in PlainText format from Scopus for the period spanning 2018 to May 2026. The resulting dataset was processed and examined using VOSviewer version 1.6.20. By implementing VOS mapping alongside clustering procedures, bibliometric networks were generated and analyzed in a structured manner. Unlike Multidimensional Scaling (MDS), VOSviewer utilizes a mapping strategy that arranges items in a reduced-dimensional space so that the spatial separation between any pair of items corresponds to the extent of their relational similarity (van Eck & Waltman, 2010). Although it shares conceptual foundations with MDS (Appio et al., 2014), the VOS methodology incorporates normalization techniques tailored specifically for co-occurrence datasets. More precisely, the association strength between items i and j is expressed as:

$$AS_{ij} = \frac{C_{ij}}{W_i W_j},$$

in which C_{ij} represents the observed co-occurrence frequency between items i and j, while $W_i$and W_j denote the total occurrence counts of items i and j, respectively. This indicator captures the proportional link between empirical co-occurrence and the expected frequency under an assumption of statistical independence, thereby providing a more reliable normalization for network construction and interpretation (Van Eck & Waltman, 2007).

Result and Discussion

There are five research questions being discussed in this section.

RQ1: What Are the Temporal Trends in The Volume of Scholarly Publications on REE Separation Technologies From 2018 To May 2026?

The publication pattern presented in Table 1 demonstrates a pronounced and consistent rise in studies on REE separation technologies from 2018 (70 publications) to a peak in 2025 (277 publications), followed by a partial count for 2026 (139 publications). The gradual increase between 2018 and 2020 reflects a baseline growth phase, likely driven by rising global awareness of REE criticality in electric vehicles, clean energy technologies, as well as high-performance electronics. The more pronounced growth from 2021 onwards (110 to 178 publications by 2024) suggests an acceleration phase linked to intensified policy attention and supply chain concerns, particularly after disruptions highlighted during the COVID-19 period. Other than that, governments and industries began prioritizing resource security and technological independence, which translated into increased funding, collaborative research, and innovation in separation techniques, including IX, SX, as well as membrane technologies. This aligns with broader trends in strategic materials research, where critical minerals are increasingly embedded within national innovation and industrial policies (Alonso et al., 2012; Binnemans et al., 2013).

The sharp surge in 2025 (277 publications) can be interpreted as a maturity or expansion phase of the research field, in which accumulated investments, established research networks, and emerging pilot-scale developments converge to yield a higher volume of outputs. This peak may also reflect intensified interdisciplinary integration, combining chemical engineering, materials science, and sustainability perspectives, as well as growing interest in environmentally friendly and economically viable separation methods. The apparent decline in 2026 (139 publications) should be interpreted cautiously, as it may reflect incomplete annual data rather than a genuine reduction in research activity. Overall, the trend demonstrates a transition from exploratory research to more structured, application-oriented innovation, consistent with the evolution of technological innovation systems, in which knowledge production increases alongside policy support, industrial demand, and technological readiness (Hekkert et al., 2007; Humphries, 2013).

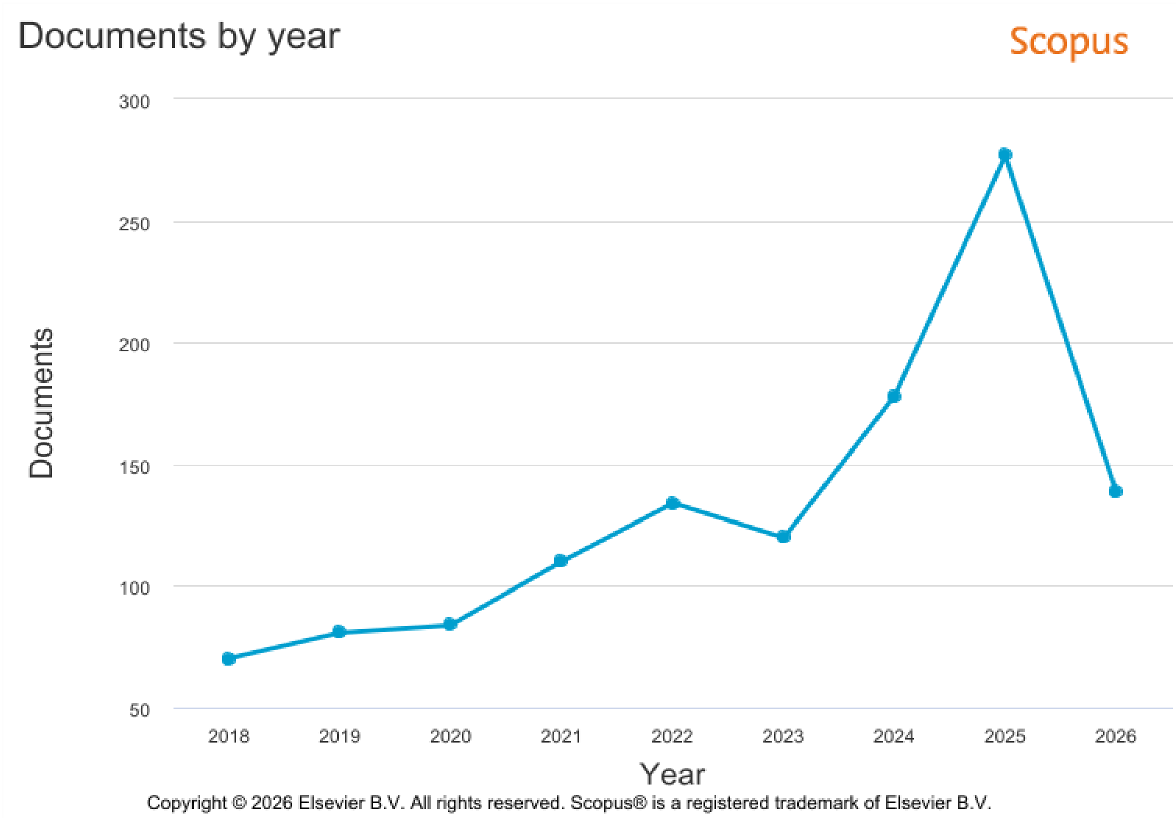

Figure 1: Trend of Research in REE Separation Technology by Years

Table 3: Publication Percentage (%) by Year

Year	Documents	Percentage
2026	139	11.65
2025	277	23.22
2024	178	14.92
2023	120	10.06
2022	134	11.23
2021	110	9.22
2020	84	7.04
2019	81	6.79
2018	70	5.87

RQ2: Which Key Publications Have Shaped the Development of REE Separation Technology Research as Indicated by Citation-Based Metrics?

Table 4 indicates that the most highly cited articles are dominated by recent (post-2018) reviews and interdisciplinary studies, with strong emphasis on sustainability, resource recovery, and advanced materials. For instance, *Recent advances on hydrometallurgical recovery of critical and precious elements from end-of-life electronic wastes - a review, and electronic waste as a secondary source of critical metals: Management and recovery technologies* demonstrate high citation counts because they address global concerns on circular economy and critical material supply risks. These papers function as comprehensive references that integrate technological, environmental, and policy dimensions, making them highly valuable across multiple disciplines. The prominence of journals such as Critical Reviews in Environmental Science and Technology and Resources, Conservation and Recycling further supports the argument that high-impact publications are those positioned at the intersection of environmental sustainability and resource engineering. Hence, this trend suggests that citation impact is no longer driven solely by technical novelty in separation chemistry, but increasingly by relevance to global sustainability agendas and policy-driven research priorities.

Furthermore, Table 4 reveals a diversification of research themes beyond conventional SX into emerging domains such as bio-based separation, adsorption materials, and socio-environmental analysis. Highly cited works, including *Lanmodulin: A Highly Selective Lanthanide-Binding Protein from a Lanthanide-Utilizing Bacterium and Green and robust adsorption and recovery of Europium (III) with a mechanism using hybrid donor conjugate materials,* illustrate growing interest in biologically inspired and green separation technologies, which align with ESG and sustainable innovation frameworks. At the same time, articles such as *the social and environmental complexities of extracting energy transition metals* achieve high citations by addressing governance, environmental risks, and societal implications, expanding the scope of REE research beyond purely technical domains. This shift can be justified by the growing importance of interdisciplinary knowledge in informing policy and investment decisions, particularly for critical materials such as REEs. From a technology management perspective, the results imply that impactful research is closely linked to its ability to address systemic challenges—combining technological feasibility, environmental responsibility, and policy relevance—rather than focusing solely on process optimization.

Table 3: Most Cited Author

No	Authors	Title	Year	Source title	Cited by
1	Sethurajan et al. (2019)	Recent advances on hydrometallurgical recovery of critical and precious elements from end of life electronic wastes - a review	2019	Critical Reviews in Environmental Science and Technology	356
2	Rahman et al. (2020)	Green and robust adsorption and recovery of Europium(III) with a mechanism using hybrid donor conjugate materials	2023	Separation and Purification Technology	316
3	Dong et al.(2021)	Lanmodulin: A Highly Selective Lanthanide-Binding Protein from a Lanthanide-Utilizing Bacterium	2018	Journal of the American Chemical Society	288
4	Lee et al. (2018)	Selective Adsorption of Rare Earth Elements over Functionalized Cr-MIL-101	2018	ACS Applied Materials and Interfaces	247
5	F. Wu et al. (2022)	Utilization path of bulk industrial solid waste: A review on the multi-directional resource utilization path of phosphogypsum	2022	Journal of Environmental Management	248
6	Işıldar et al. (2018)	Electronic waste as a secondary source of critical metals: Management and recovery technologies	2018	Resources, Conservation and Recycling	279
7	Cotruvo (2019)	The Chemistry of Lanthanides in Biology: Recent Discoveries, Emerging Principles, and Technological Applications	2019	ACS Central Science	260
8	Lèbre et al. (2020)	The social and environmental complexities of extracting energy transition metals	2020	Nature Communications	382

No	Authors	Title	Year	Source title	Cited by
9	Maddalena et al. (2019)	Inorganic, organic, and perovskite halides with nanotechnology for highlighting yield x- and γ-ray scintillators	2019	Crystals	246
10	P. Wu et al. (2021)	Recent Progress of Thermocatalytic and Photo/Thermocatalytic Oxidation for VOCs Purification over Manganese-based Oxide Catalysts	2021	Environmental Science and Technology	323

RQ3: What Conceptual Structures and Evolving Research Themes Can Be Identified in REE Separation Technology Using Keyword Co-Occurrence Analysis?

Figure 2 reveals a highly centralized keyword network dominated by the core term REE, which exhibits the greatest frequency of occurrences (324) alongside the highest total link strength (421), thereby underscoring its function as the intellectual anchor of the research field. Surrounding this core, process-oriented clusters such as Leaching, Adsorption, and SX form a tightly interconnected network, reflecting the technological emphasis on hydrometallurgical separation pathways. The relatively high link strength of "recycling" (139) and "recovery" (94) suggests that recent research is increasingly integrating separation technologies with secondary resource utilization. This clustering pattern implies that the field is no longer confined to primary extraction but is transitioning towards resource efficiency and circular material flows, driven by supply risks and geopolitical dependencies associated with REEs. The co-occurrence of "hydrometallurgy", "ion exchange", and "ionic liquids" further demonstrates methodological convergence, in which conventional and emerging techniques are hybridized to improve selectivity and efficiency.

In addition, Figure 2 highlights an emerging sustainability-oriented cluster characterized by keywords such as Circular Economy, Life Cycle Assessment, and "critical raw materials", which exhibit moderate occurrences but strong linkages. This indicates a shift in research priorities from purely technical optimization towards system-level evaluation and policy relevance. The presence of application-specific terms such as "NdFeB magnets", "electronic waste", and "urban mining" reflects the growing importance of end-of-life product recovery as an alternative source of REEs. Moreover, niche but rising themes such as "machine learning", "deep eutectic solvents", and "metal-organic frameworks" suggest the early-stage integration of digitalization and advanced materials into separation processes. The dispersion of these keywords across clusters suggests an interdisciplinary expansion of the field, with chemical engineering, environmental science, and data-driven optimization converging. Overall, the network structure in Figure 2 demonstrates a maturing research landscape that balances process innovation with sustainability imperatives and resource security considerations.

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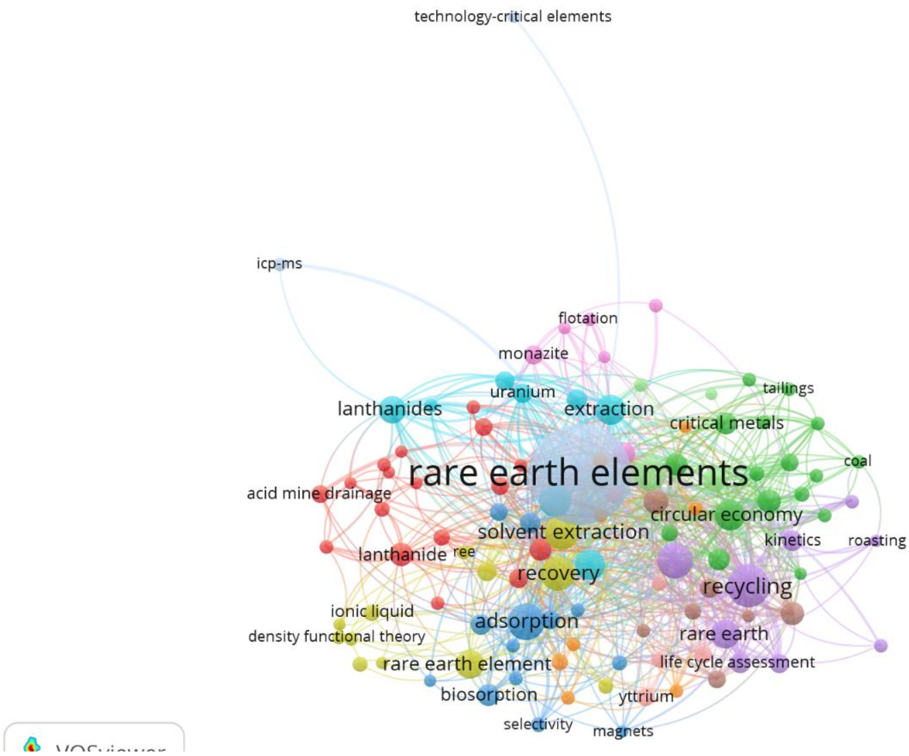

Figure 2: Network Visualization Map of Keywords' Co-Occurrence

RQ4: How Do Country-Level Co-Authorship Networks Reveal the Structure and Intensity of International Collaboration in REE Separation Technology Research?

Figure 3 demonstrates a highly uneven but strategically interconnected global collaboration structure, dominated by China as well as the United States, as the major knowledge producers in rare earth research. China leads significantly in both publications (411) and citations (7478), supported by the highest total link strength (109), indicating not only research volume but also extensive international collaboration. This dominance is structurally consistent with China's control over global REE supply chains and its long-term investment in upstream and downstream technologies. The United States, while producing fewer documents (223), maintains strong citation impact (5413) and high connectivity (84), reflecting its role in high-quality research and strategic partnerships. European nations, including the United Kingdom, Germany, as well as France, exhibit disproportionately high total link strengths relative to their publication counts, suggesting that they function as key collaboration hubs within the network. This indicates a distributed innovation model in Europe, where cross-border research integration compensates for lower domestic resource endowments.

In contrast, emerging and resource-rich nations, including Brazil, India, as well as South Africa, exhibit a moderate publication output but comparatively lower total link strengths, implying weaker integration into global knowledge networks despite their geological potential. Malaysia, with 17 publications and modest link strength (17), reflects an early-stage participation in the global REE research ecosystem, likely constrained by limited Research and Development (R&D) scale and international collaboration platforms. However, the presence of countries such as Australia and Canada—both with strong mining sectors—demonstrates a closer alignment between resource endowment and research output when supported by institutional capacity and international partnerships. The relatively low connectivity of countries like the Russian Federation, despite a higher number of publications, suggests more domestically oriented research systems. Overall, Figure 3 illustrates that global REE investigation is influenced not merely by the distribution of resources but also by geopolitical considerations, collaborative intensity, and the maturity of national innovation systems, with highly connected countries exerting greater influence on knowledge diffusion and technological direction.

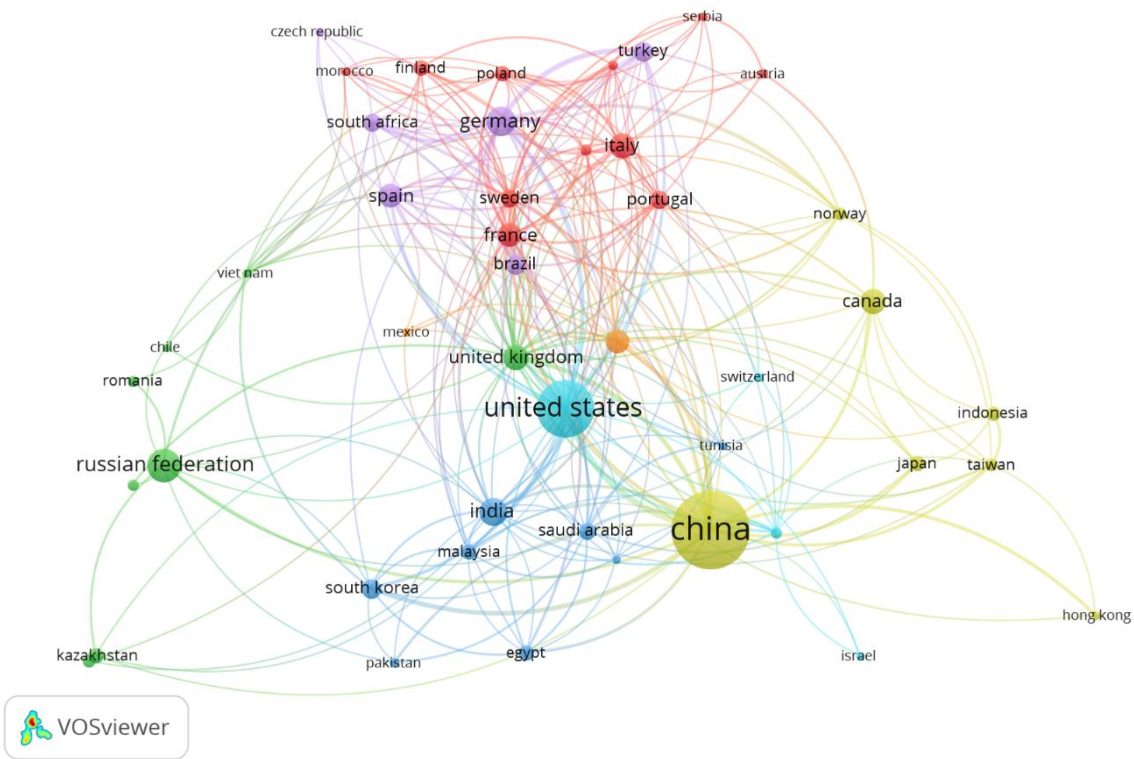

Figure 3: Country-Level Co-Authorship Networks

Conclusion

This study aims to examine the progression and organization of research on REE separation technologies through a bibliometric framework, concentrating on publication growth, influential studies, thematic evolution, and global collaboration patterns. The study aims to address key questions related to how research output has changed over time, which works have shaped the field, what major themes are emerging, and how international collaboration is structured within this domain.

The findings demonstrate a steady and ongoing rise in research output between 2018 and May 2026, with a more rapid expansion observed after 2021, indicating stronger global attention towards REE supply challenges and technological advancement. Examination of highly cited works indicates that the most impactful studies are increasingly interdisciplinary, combining technical, environmental, and sustainability perspectives. Keyword analysis indicates that traditional separation approaches, such as SX, adsorption, and hydrometallurgical processes, remain dominant, while newer directions, including green technologies, circular economy concepts, and advanced materials, are gaining importance. In addition, collaboration patterns reveal that research output is concentrated among a few leading countries with strong interconnections, while participation from other regions remains relatively limited.

This study advances the field by providing a systematic synthesis of research trends as well as knowledge development in REE separation technologies. It provides a new understanding of how the field is evolving from conventional process optimization towards more integrated and sustainability-oriented approaches. The findings may support decision-making in research planning, funding allocation, and innovation strategies, especially in aligning technological development with environmental and resource considerations.

However, certain limitations exist. The analysis is based on a single database alongside a predetermined set of keywords, which may result in the omission of pertinent studies. Moreover, the focus on quantitative indicators also limits deeper evaluation of technological effectiveness and industrial application. Future studies may consider integrating multiple data sources, applying qualitative assessment, and examining links between research output and real-world implementation.

In conclusion, bibliometric analysis is an effective tool for understanding research development and identifying gaps in REE separation technologies. The observed trends indicate a gradual shift towards more sustainable, interdisciplinary, and application-oriented research, highlighting the need for continued efforts to support innovation and strengthen global research collaboration in this critical field.

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