JOURNAL OF THE GEOLOGICAL SURVEY OF BRAZIL

Rare earth elements, sustainability, and ion-adsorption clay: A bibliometric study on global trends and Brazil's prominence

Anna Beatriz Gomes Tetzner[1*], César Henrique Bezerra de Farias[1], Natan Pinheiro de Freitas[1], Alfredo Borges de Campos[1]

[1]Institute of Geosciences - University of Campinas (UNICAMP), Rua Carlos Gomes, 250 – Cidade Universitária, Campinas - SP, CEP: 13083-855[2]Museu Nacional, Departamento de Geologia e Paleontologia, Universidade Federal do Rio de Janeiro, Rua General Herculano Gomes, 1343, Rio de Janeiro, RJ, Brazil, CEP: 20941-360

Abstract

Rare Earth Elements (REE) are critical minerals for the global energy transition and for fulfilling Sustainable Development Goals (SDGs), such as SDG 7 (Clean Energy). However, the traditional supply chain, focused on primary deposits, faces significant geopolitical and environmental challenges. In this context, ion-adsorption clay (IAC) deposits have emerged as the main research route for a more sustainable REE production, aligned with the 2030 Agenda. Despite this relevance, there has been no systematic analysis of the scientific production on this topic in an integrated manner, from the perspective of the entire 2030 Agenda. The objective of this study is to fill this gap by mapping the synergies and trade-offs between global REE-IAC research and the 17 SDGs, and contextualizing this trend with Brazil's emergence as a strategic industrial player. To this end, a bibliometric and systematic review analysis was conducted using the Scopus and Web of Science databases, covering the period from 1973 to 2024. Keyword co-occurrence analysis and thematic clustering were processed using VOSviewer. This analysis was supplemented by a survey of active exploration projects in Brazil, based on technical and governmental reports. The results demonstrate an exponential growth (R^2 = 0.98) in research starting from 2015, the year the SDGs were launched. This period accounts for 91.5% of all historical literature on the topic. The cluster analysis reveals that the intellectual structure of the field is dominated by two pillars: the demand for sustainability (Cluster 1, centered on sdg) and the geological solution (Cluster 2, centered on ion adsorption clay). The research field proves to be mature, actively addressing the challenges of water management (SDG 6, Cluster 8) and toxicity. On the global stage, Brazil stands out as the 5th largest publisher. More importantly, the practical survey identified 24 active IAC projects in the country, including the commercial operation of Serra Verde (GO) and the advanced projects in Poços de Caldas (MG), such as Caldeira and Colossus. It is concluded that the SDGs act as the main driver of innovation in IAC research. Brazil demonstrates a unique convergence between innovation policy (aligned with SDG 9), the global scientific trend, and industrial execution. The country is using IAC deposits as a strategic solution to overcome the environmental challenges of its traditional deposits (associated with Th/U), positioning the country as the main Western hub for REE-IAC production and a strategic supplier for the sustainable energy transition.

Article Information

Publication type: Research Papers
Received 6 November 2025
Accepted 6 January 2026
Online pub. 8 January 2026
Editor : Christophe Renac

Keywords:
Energy Transition
Production Chain
Critical Minerals
Economic Geology
Sustainable Development Goals

*Corresponding author
Anna Beatriz Gomes Tetzner
E-mail address: annab.tetzner@gmail.com

ISSN: 2595-1939
https://doi.org/10.29396/jgsb.2026.v9.n1.2
Open access at jgsb.sgb.gov.br

1. Introduction

The global energy transition towards a low-carbon economy has driven an unprecedented demand for strategic minerals, notably the Rare Earth Elements (REE; Balaram, 2019; Jowitt & McNulty, 2021; Beard et al., 2025). Essential in green technologies such as wind turbines and electric vehicles, the demand for these elements is expected to increase by up to 90% by 2040 (Depraiter & Goutte, 2023; IEA, 2024). This high-demand scenario occurs in a context of high geopolitical risk, given that the global supply chain is massively concentrated in China, which holds the majority of the world's reserves, production, and refining (USGS, 2022; EC, 2023; Grohol & Veeh, 2023; IEA, 2024; Silva et al., 2024; Lins et al., 2025; USGS, 2025). To navigate these vulnerabilities, it is essential to distinguish between 'criticality' — the intersection of economic importance and supply risk — and the pursuit of 'strategic autonomy,' which drives policy frameworks like the EU's Critical Raw Materials Act to ensure security of supply through diversified and resilient value chains (EC, 2023).

Driven by the need for such strategic resilience, global exploration has pivoted toward new sources, particularly ion-adsorption clay (IAC) deposits (Collerson et al. 2025), the central theme of this work. These regolith-hosted deposits are formed through the supergene weathering of diverse parent lithologies, such as granites (Sanematsu and Kon, 2013), metamorphic rocks (Huang et al., 2021), and syenites (Ntomb et al., 2024; Wang et al., 2024). Due to the unique enrichment processes in the weathering crust, IAC deposits currently account for more than 20% of global REE production and, crucially, for approximately 95% of the world's production of Heavy Rare Earth Elements (HREE), which are vital for the manufacturing of high-performance permanent magnets (Zhou et al. 2020; Collerson et al. 2025).

The growing attractiveness of IAC deposits lies in their operational and environmental advantages compared to traditional hard-rock deposits. In these deposits, REE ions are adsorbed onto the surface of clay minerals, allowing their recovery through a simple ion-exchange leaching process with saline solutions at room temperature (Moldoveanu and Papangelakis, 2025). This method avoids the use of harsh acids and energy-intensive beneficiation processes, resulting in lower costs, less waste generation, and, consequently, a lower environmental impact, configuring a more sustainable production alternative when compared to primary deposits (Wall et al., 2017; Estrade et al., 2019). However, sustainability must be treated as a conditional outcome of mining practices rather than an inherent property of ion-adsorption clays (Yang et al., 2013). While the IAC extraction route is strategically aligned with the energy transition due to its lower carbon footprint, environmental trade-offs such as leaching, water contamination, and land degradation are well-documented concerns, especially in historical operations in Southern China and Southeast Asia (Yang et al., 2013). Therefore, ensuring that IAC production effectively contributes to a green economy requires the identification of environmental hotspots and the application of rigorous Life-Cycle Assessment (LCA) to mitigate local impacts (Bailey et al., 2020; Zapp et al., 2022).

Such advantages align the exploitation of IAC deposits directly with the Sustainable Development Goals (SDGs), established by the UN as a global action plan for challenges such as climate change and environmental degradation (UN, 2015). Although the literature often highlights the positive contributions of REE production to SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities) (Bonfante et al. 2021), the value chain of IAC deposits has much broader interactions. Research advancement on this source touches upon multiple aspects of the 2030 Agenda, from industrial innovation (SDG 9) to water management (SDG 6) and responsible consumption (SDG 12), indicating a systemic and complex relationship that goes beyond the final applications of the product. The synergy between IAC mining and the 17 SDGs is far from static. In practice, it demands a constant negotiation between the drive for economic and technical efficiency and the ethical weight of environmental impacts tied to extracting critical minerals (Yang et al., 2013; Bailey et al., 2020).

Despite this relevance, a critical gap is identified in the literature: although IAC deposits are increasingly recognized for their sustainable potential, analyses of this relationship tend to be piecemeal or focused on specific objectives, such as SDG 7 (Energy) or SDG 9 (Innovation). There is, however, no systematization that analyzes the scientific production on the topic in an integrated manner from the perspective of the complete set of 17 SDGs. Therefore, the central objective of this study is to fill this gap through an integrated analysis of scientific publications on IAC-type deposits, correlating the advancement of knowledge with the entirety of the 2030 Agenda. This study maps the synergies and the trade-offs between global REE-IAC research and the 17 SDGs, providing a systemic overview of how these minerals act as critical drivers for sustainable development (Bonfante et al., 2021). By identifying how technological development impacts sustainable progress, this scientific contribution delivers a robust framework to support public policies that prioritize strategic autonomy and high-standard mineral exploitation in Brazil and worldwide.

2. Materials and Methods

To analyze the scientific landscape regarding REE deposits of the IAC type, a systematic and bibliometric literature review was conducted. The procedure was structured in three stages: (1) definition of the search strategy and data collection; (2) application of inclusion and exclusion criteria for document selection; and (3) data extraction and analysis (Figure 1).

2.1. Data Sources and Search Strategy

Data collection was performed in October 2025, using the Scopus (Elsevier) and Web of Science (Clarivate Analytics) databases. The choice of these two databases is justified by their broad coverage of the global scientific literature, rigorous indexing, and advanced search functionalities, being widely considered the standard for bibliometric analyses (Butu et al., 2023). The search was conducted using the following keywords and Boolean operators: ("rare earth elements" OR "REE") AND ("ion-adsorption clay" OR "IAC") AND ("sustainable development goals" OR "SDG"). The initial search returned 851 publications. The databases were unified using the Xplore Dados tool.

2.2. Screening and Selection Criteria

The initial dataset was subjected to a screening process, including duplicate removal, a temporal filter, and inclusion and exclusion criteria by document type to ensure the relevance and quality of the final portfolio. The identification of duplicates for exclusion was performed automatically, using DOI as the distinction criterion, ensuring the uniqueness of each document in the database, resulting in 20 excluded files. Next, files with a publication year registered as 2025 (ahead of print publications) were removed to maintain consistency with the defined analysis period. Finally, the selection was refined based on document type. Only “Research Articles” (Articles) and “Review Articles” (Reviews) were included. Other publication types, such as “Editorials”, “Notes”, “Errata”, “Conference Abstracts”, and “Letters to the Editor”, were excluded as they did not align with the scope of analyzing primary scientific production.

2.3. Data Extraction and Analysis

The final set of publications, after applying all criteria, was exported containing complete information on authorship, affiliation, year, source, keywords, and citations. Data analysis was performed with the aid of the VOSviewer software (version 1.6.20), a tool for constructing and visualizing bibliometric maps (Van Eck & Waltman, 2010). Keyword co-occurrence networks were generated to identify the main research themes, and co-authorship networks were generated to analyze country collaboration. Descriptive statistical analyses and the creation of complementary graphs were performed using Microsoft Excel software.

3. Results

3.1. Analysis of Scientific Production

The analysis of scientific production was structured in three stages. Initially, the temporal evolution of publications and the geographical distribution of contributions were examined, based on the authors’ country of affiliation and the journals that published the most. Next, the intellectual structure of the field was analyzed through keyword co-occurrence networks. Finally, the global scientific landscape was contextualized with the national reality, through a survey of active rare earth exploration projects in Brazil.

3.1.1 Temporal Evolution of Scientific Production

The analysis of the bibliometric portfolio (Figure 2), comprising 811 documents (articles and review articles), reveals the evolution of interest in the topic between 1973 and 2024. The time series can be segmented into three distinct periods, reflecting different research phases.

The first period, from 1973 to 2006, is characterized by scarce and inconsistent research activity. It begins with the first indexed publication in 1973 (n=1) and accumulates only 35 publications over more than three decades, with an average of approximately 1 article per year. The second period, from 2007 to 2014, shows initial growth. In the 7 years comprising this period, there is a consolidation of interest in the topic. Scientific production became continuous and growing, starting with 5 publications in 2008 and reaching a first peak of 19 publications in 2013. A total of 65 articles were published in this phase, indicating the field was gaining momentum.

The third period, from 2015 to 2024, is marked by exponential growth in scientific production. The year 2016, with 24 publications (n=24), acts as an inflection point, initiating a growth trajectory that intensifies from 2018 (n=21). The magnitude of this phase is evidenced by the fact that 80.4% of all identified literature on the topic, 651 out of 810 articles, were published in this period. The last four years (2021-2024) alone account for 63.8% (n=517) of all publications in the time series, culminating in the most productive year, 2024, with 182 articles. The moving average visually corroborates this transition, from an almost zero base to a phase of rapid acceleration, reaching a value of 163 in 2024.

The exponential nature of this growth is illustrated in detail in Figure 3. The regression analysis demonstrates that an exponential curve, defined by the equation $y = 9.914e^{(0.2964x)}$, fits the annual data with a very high degree of precision. This is confirmed by a coefficient of determination (R^2) of 0.9851. An R^2 value so near to unity provides strong statistical evidence for how quickly and consistently the scientific community has ramped up its focus on this field over the past ten years.

This value, very close to 1, statistically validates the rapid and continuous acceleration of the scientific community’s interest in the topic during this last decade.

3.1.2. Contribution by Country

According to author affiliation, Figure 4 details the contributions by country/organization, considering a minimum of 5 publications. China is the absolute leader in scientific production, with 128 documents and 5,096 citations. Following are the United States (n=45 documents; 3,160 citations) and Australia (n=42 documents; 2,480 citations), followed by India (n=23, 627 citations). Brazil appears as the fifth country with the highest number of publications on the topic (n=17); the relevance of this production is underscored by the number of citations received, totaling 800, indicating that national research is actively consumed and referenced by the global scientific community. Other countries with relevant contributions (n>10) include France (n=16), the United Kingdom (n=14), Canada (n=12), Russia (n=11), and Spain (n=10).

3.1.3. Most Cited Journals

Figure 5 presents the 10 journals with the highest cumulative number of citations for their articles on the topic, highlighting the channels of greatest scientific influence. The journal *Ore Geology Reviews* emerges as the source of greatest combined impact and productivity, leading the list with 41 documents that have accumulated a total of 2,809 citations.

A relevant observation is the presence of journals that, despite not having a large volume of articles, show extremely high impact, suggesting the publication of seminal articles or comprehensive reviews. Noteworthy are the *International Journal of Coal Geology* (3 documents, 1,195 citations) and *the Japanese Journal of Applied Physics* (1 document, 1,052 citations).

The significant impact of this single publication in the Japanese journal is attributed to the seminal review by Kishi et al. (2003) on the development of multilayer ceramic capacitors (MLCCs). The study addresses the challenge of replacing noble metals with nickel electrodes, establishing a predictive model where the ionic radius of rare earth dopants determines their site occupation in the $BaTiO_3$ lattice. This control is fundamental to maintaining the reliability and insulation resistance of the components, providing the theoretical basis for the miniaturization of electronics with dielectric layers thinner than 2 μm.

The list of the 10 most cited journals also reveals the strong interdisciplinary connection of the topic with sustainability and the energy transition. High-impact, broad-scope journals, such as Journal of Cleaner Production (9 documents, 833 citations), Renewable & Sustainable Energy Reviews (8 documents, 817 citations), and Science of the Total Environment (7 documents, 752 citations), feature prominently. Completing the list are journals focused on geosciences and engineering, such as Minerals Engineering (12 documents, 1,158 citations), Chemical Geology (15 documents, 1,053 citations), and Hydrometallurgy (11 documents, 961 citations).

3.2. Keyword Co-occurrence Network

The co-occurrence analysis of Author Keywords is a bibliometric technique that helps to understand the structure, progress, and main research interests in a given domain. The analytical process required a prior step of cleaning and normalizing the keyword database extracted from the publications. A total of 4,117 keywords were obtained from the selected publications. Of these, 4,036 terms were observed to have a frequency of less than 5 times, a value corresponding to 98% of the total. In contrast, a core of 81 keywords had a frequency of 5 or more occurrences, this being the set of terms used for the present analysis.

Table 1 details the 10 most frequent terms of this thematic core, their occurrences, and their total link strength. The analysis allows for the identification of two key terms for the study: "ree" (rare earth elements) with a total of 407 occurrences, and "sdg" (Sustainable Development Goals) with 122 occurrences. This frequency validates the strong intersection between the two themes in the studied dataset.

To identify the intellectual structure of the research field, a clustering analysis was performed on the keyword co-occurrence network, using the VOSviewer clustering algorithm. This method groups terms that frequently appear together, indicating research sub-themes. The analysis identified 10 main thematic clusters (Figure 6).

The analysis of the cluster content allows for the identification of the following thematic nuclei

Cluster 1 (Red): Sustainability Framework and SDGs. This is the largest thematic cluster, grouping all the central terms of the 2030 Agenda, such as "sdg" (n=122), "sustainability" (n=36), "sustainable development" (n=19), "circular economy" (n=16), and "climate change" (n=10). It also includes the disaggregation into specific SDGs, such as sdg 2 (Zero hunger), 3 (Good health and well-being), 4 (Quality education), 7 (Affordable and clean energy), 11 (Sustainable cities and communities), 12 (Responsible consumption and production), and 14 (Life below water).

Cluster 2 (Green): Geology and Genesis of IAC Deposits. This cluster focuses on geological aspects, containing terms such as "ion adsorption clay" (n=29), "weathering" (n=17), "regolith hosted deposits" (n=15), "geochemistry" (n=15), "kaolinite" (n=5), "halloysite" (n=9), and "south china" (n=13), indicating the key geographical region for the study of these deposits.

Cluster 3 (Blue): Rare Earth Elements and Impacts. This cluster is anchored on the term 'ree" (n=407) and connects it to terms like "recovery" (n=21), "heavy metals" (n=9), "toxicity" (n=8), and "uranium" (n=9), reflecting research on REE recovery and the penalty elements (impacts) associated with them.

Cluster 4 (Yellow): Processing and Extractive Metallurgy. This group is focused on the chemical extraction processes, including "leaching" (n=10), "adsorption" (n=38), "ion exchange" (n=8), "solvent extraction" (n=13), and "precipitation" (n=6).

Other smaller clusters reveal frontier topics related to specific applications and impacts. Cluster 7 (Orange) focuses on applications and life cycle, addressing "electric vehicles" (n=7), "e-waste" (n=7), and "life cycle assessment" (n=5). Cluster 8 (Brown), in turn, connects directly to Cluster 1 (SDGs), focusing on "sdg 6" (n=16), "water quality" (n=5), and "groundwater" (n=6).

3.3. Overview of REE Exploration Projects in Brazil

To contextualize the global scientific research with the national practical reality, a survey of active Rare Earth Element projects in Brazil was conducted. The search was carried out on official websites of exploration companies and subsequently confirmed in their technical reports (such as Preliminary Economic Assessment - PEA), with the initial objective of identifying projects focused on ion-adsorption clay (IAC) type deposits.

The survey indicates sector growth in Brazil, with strong participation from international companies and increasing valuation in the financial market (*Melfi et al.*, 2016; Heider and Siqueira, 2024), while also reporting the development of new extraction and processing technologies, particularly focused on ionic clays, aimed at improving energy efficiency and reducing environmental impact.

Currently, the country has 37 active rare earth projects distributed across several states (Figure 7), 24 of which are focused on ionic clays. Minas Gerais leads with 18 initiatives, including the Caldeira (Meteoric Resources) and Colossus (Viridis Mining) projects in the Poços de Caldas Alkaline Complex (PCAC). Goiás stands out for its more advanced-stage projects: Pela Ema (Serra Verde), in commercial operation since 2024, and Carina (Aclara Resources), which inaugurated its pilot plant in 2025. Other states such as Bahia (Monte Alto and Campo Grande), Amazonas (Ema and Apuí), and Piauí (Corrente) also have relevant initiatives, demonstrating the geographical diversity of Brazil's REE potential.

4. Discussion

The bibliometric analysis and the project survey reveal a transformation in the REE sector over the last decade, driven by a convergence of geopolitical, economic, and, above all, sustainability forces. The following discussion integrates the presented results to interpret global trends and Brazil's emerging strategic role.

4.1. The 2015 Milestone: Sustainability as a Driver of Global Research.

The most significant result of the temporal analysis (Section 3.1.1) is the exponential growth in rare earth research starting from 2015 (Figure 2). This surge in publications aligns with the UN's launch of the SDGs in 2015, a strong indicator that the global sustainability agenda has shifted from a peripheral concern to the primary catalyst for research in the field.

The keyword analysis (Section 3.2) corroborates this hypothesis, as Cluster 1 is formed by words like "sdg", "Sustainability", and "2030 agenda". The second cluster, formed by terms referring to economic geology, such as "regolith hosted deposits" and "geochemistry", places ion-adsorption clay deposits in the spotlight for achieving the SDGs, given that these deposits account for more than 20% of global REE production and approximately 95% of the global production of heavy rare earths (Zhou et al. 2020; Collerson et al. 2025). In this type of deposit, recovery and beneficiation are simpler due to the REE ions being adsorbed onto the surface of clay minerals (Sanematsu and Watanabe, 2016), thereby transforming it into a strategic alternative to the demand for mining aligned with the 2030 Agenda.

4.2. The Structure of the Research: Genesis, Processing, and Impact Assessment

The analysis of publication journals and thematic clusters demonstrates that research on IAC is correlated on two parallel fronts; Figure 8 illustrates this dynamic. On one hand, "ion adsorption clay" is strongly linked to the terms of its own cluster (Green), which define the Genesis and Geology of the deposit, including terms like "geochemistry", "weathering", "regolith hosted deposits", "kaolinite", and "south china". The formation of these regolith-hosted deposits is governed by a complex mineral-system framework, where the distribution and concentration of REEs are primarily constrained by the composition of the parent rock and the intensity of chemical weathering (Sanematsu and Watanabe, 2016; Li and Zhou, 2020; Russo et al., 2025). IACs are formed through the supergene weathering of diverse parent lithologies, such as granites (Sanematsu and Kon, 2013), metamorphic rocks (Huang et al., 2021), and syenites (Ntomba et al., 2024; Wang et al., 2024). The geochemical process initiates with the breakdown of primary REE-bearing minerals, typically silicates or phosphates, releasing REE ions into soil solutions during weathering (Sanematsu and Kon, 2013; Li and Zhou, 2020; Russo et al., 2025). These ions migrate through the regolith profile and are subsequently adsorbed onto the negatively charged surfaces of secondary clay minerals, such as kaolinite and halloysite, through ion-exchange mechanisms (Li and Zhou, 2020; Russo et al., 2025). The vertical evolution of the weathering crust is decisive for the economic viability of these deposits, as specific horizons become selectively enriched in Heavy Rare Earth Elements (HREE; Zhou et al., 2020). This demonstrates the research effort to understand where and how these deposits form, with a focus on Chinese geological provinces, which host the majority of these deposits (Van Gosen et al., 2017).

On the other hand, the same "ion adsorption clay" node projects directly to Cluster 5 (Purple), connecting to the entire vocabulary of Processing and Extractive Metallurgy, such as "leaching", "adsorption", "ion exchange", "precipitation", and "solvent extraction". This connection emphasizes that while the ion-exchange leaching process with saline solutions occurs at room temperature and avoids harsh acids, research is heavily focused on optimizing reagent consumption to ensure that the process maintains its operational advantage (Moldoveanu and Papangelakis, 2025). Equally important is the connection with Cluster 4, which links IAC deposits to REE ("ree", "lanthanide") and penalty elements like "uranium", bringing up critical issues of "toxicity" and "heavy metals". This link reflects the documented reality that sustainability is a conditional outcome; if not properly managed, the leaching of IACs can lead to severe environmental trade-offs, such as groundwater contamination and land degradation, as seen in historical operations in Southern China (Yang et al., 2013). Finally, the connection with Cluster 7 (Light Green), specifically with "LCA", demonstrates that the research has advanced to a maturation phase where the "green" potential of IACs must be rigorously quantified to identify environmental hotspots and validate them as a truly sustainable alternative to traditional primary deposits (Bailey et al., 2020; Zapp et al., 2022).

The multidisciplinary nature of the topic is reflected in the analyzed publication channels. Research focused on genesis and geology (Cluster 2) finds its main vehicle in high-impact geosciences journals, such as *Ore Geology Reviews and Chemical Geology*. In parallel, studies on processing and metallurgy (Cluster 5) are predominantly published in elite engineering journals, such as *Hydrometallurgy and Minerals Engineering*. The high frequency of citations in journals with an environmental scope, such as Journal of Cleaner Production and Science of the Total Environment, also corroborates the importance of impact assessment and risk mitigation (Clusters 4 and 8).

4.3. Convergence in Brazil: Strategic Policy, Innovation, and Commercial Vanguard

In this global scenario, Brazil emerges with a unique prominence. The geographical analysis (Figure 4) positions the country as the fifth largest global scientific contributor. REEs are classified by the federal government as "future-bearing" substances and priorities in the Plan for Science, Technology, and Innovation for Strategic Minerals (MME, 2011; MCTIC, 2018). As detailed in official documents, this plan was conceived in direct alignment with the SGDs, aiming to use REEs as vectors for national development. The strategy seeks to add value to mineral commodities, promote innovation, and position the country competitively in the global market. This is reflected in the contribution to a broad set of objectives, including SDG 7, by providing vital inputs for the energy transition (wind turbines, electric vehicles); SDG 9 (Industry, Innovation, and Infrastructure), by materializing targets 9.5 and 9.b of strengthening research and adding value; and SDG 12 (Sustainable Production), by seeking routes with lower waste generation. The development of this supply chain is therefore seen as fundamental for economic growth (SDG 8) and for increasing Brazilian participation in high-technology exports (SDG 17).

The result of this strategic policy is the synergy observed in the field projects (Section 3.3), where the promotion of innovation (SDG 9) meets industrial practice. The advancement in research on the unique geology of IAC deposits in alkaline complexes, such as those at Poços de Caldas (Guarino et al., 2021), is not a purely academic exercise. On the contrary, this research attracted significant international private capital (Meteoric Resources and Viridis Mining) and fostered university-industry partnerships, resulting in the Caldeira and Colossus projects (Brasil Mineral, 2024b). This demonstrates the precise execution of target 9.5 (“strengthen scientific research”), transforming frontier geological knowledge into technological capacity and attracting foreign investment.

In practice, Brazil’s current trajectory follows the exact path that global research highlights as essential for the future of the sector. The country is applying this innovation to develop an REE source that is intrinsically more aligned with the pillars of sustainability, notably SDG 12 (Sustainable Production), by aiming for lower waste generation, and at the same time bypassing the main technological and environmental bottleneck (Th/U management) of national primary deposits. The commercial operation of the Pela Ema project (Serra Verde) since 2024 (Brasil Mineral, 2024a) and Aclara’s pilot plant (2025) in Goiás are concrete proof that the country is converting the global scientific trend into industrial reality. By prioritizing value-added products (SDG 9.b) and improving the national trade balance (SDG 17), Brazil is carving out a role as the primary REE-IAC production hub outside of Asia, an evolution that directly addresses the global demand for a more secure and diversified mineral supply.

The integration of Brazil into this high-technology value chain is underpinned by the global demand for components such as the MLCCs previously detailed (Section 3.1.3), as well as fuel cells, wind turbines, and traction motors (EC, 2023), which require precise control of REE dopants to ensure electronic reliability, efficiency, and miniaturization. More than just a boost to local industry, Brazil’s push into IAC research and exploration represents a direct effort to diversify a market currently centered in China. As China controls most global reserves and refining capacity (Beard et al., 2025), Brazil’s scientific and geological progress is an important step toward breaking this concentration and securing the global supply chain.

As highlighted by the National Council for Scientific and Technological Development (CNPq), the race for REEs is essentially a race for scientific-technological dominance; therefore, by mastering the extraction and processing of these elements, Brazil will transcend the role of a mere ore exporter. Advancing this sector will help stabilize the national trade balance while turning Brazil into a major participant in the effort to diversify global supply chains. This transition moves the world toward a more balanced market, ensuring that technological independence is no longer restricted to a single nation (CNPq, 2025).

4.4. The Systemic Relationship with the SDGs: Synergies and Trade-offs

The cluster analysis reveals that the connection between REE-IAC and sustainability is systemic and complex. Cluster 1 groups several SDGs, reflecting the multiple facets of this mining. The simpler beneficiation of IAC (Moldoveanu and Papangelakis, 2025) contributes positively to SDG 12, by reducing waste generation (target 12.5). It is important to recognize that sustainability is not an intrinsic feature of ion-adsorption clays. Instead, it should be viewed as a result that depends on the specific mining methods and environmental standards applied during extraction (Yang et al., 2013).

While the IAC extraction route is strategically aligned with the energy transition due to its lower carbon footprint, environmental trade-offs such as leaching, water contamination, and land degradation are well-documented concerns. Historical operations in Southern China, characterized by surface mining and heap-leaching, resulted in severe local environmental damage where the production of just 1 ton of rare-earth oxide generated 2,000 tons of tailings and 1,000 tons of contaminated wastewater (Yang et al., 2013). These practices required massive remediation efforts, with costs in regions like Ganzhou estimated at 38 billion RMB — a figure that drastically outweighs the industry’s annual profits.

To ensure that IAC production effectively fulfills its promise of being a “green” alternative, the identification of environmental hotspots is essential (Zapp et al., 2022). Meta-analyses of LCA studies demonstrate that the chemical extraction and solvent separation stages are the primary drivers of environmental impact. Although IACs avoid energy-intensive roasting, they present toxicity risks that must be managed, particularly regarding the subestimation of natural radioactivity (NORM). Sources like Thorium-232 can present an environmental impact up to six times higher than reported in standard LCAs (Bailey et al., 2020). This contribution to SDG 12 is significant when considering that while REEs are essential for SDG 7 and SDG 11 as key components of clean energy technologies, the process of obtaining them generates conflicts such as complex management of radioactive tailings.

IAC deposits, therefore, represent a strategic route as they mitigate the main productive conflict (waste) of traditional deposits. Nevertheless, the scientific community maintains significant attention on SDG 6 (Clean Water), as evidenced by Cluster 8 (“water quality”) and Cluster 4 (“toxicity”). The field has clearly matured, with research now pivoting toward advanced solutions like phytoremediation with organic amendments to mitigate environmental footprints. Recent studies by Janot et al. (2025) show that REEs have a high affinity for organic phases, which reduces their bioavailability and toxicity in post-mining environments, aligning innovation (SDG 9) to ensure the protection of water resources and terrestrial ecosystems (SDG 15).

The integration of the IAC value chain into the 2030 Agenda necessitates a lifecycle perspective that encompasses the principles of the circular economy, fulfilling Target 7.a and SDG 11. While technological readiness for rare-earth magnet recycling has progressed, practical recovery from the ‘urban stock’ still faces significant economic barriers and low global recycling rates (Depraiter & Goutte, 2023; Ormerod et al., 2023). In this context, the first rare-earth supermagnet recycling laboratory in the Southern Hemisphere is expected to begin operations by late 2026 in Poços de Caldas, southern Minas Gerais, as a result of a partnership between Viridis Mining and Ionic Rare Earths Limited, with Ionic contributing proprietary technology for the separation of rare-earth oxides from materials (Brasil Mineral, 2024c; Assis, 2025). Bridging the gap between primary extraction from IACs and secondary recovery is essential to achieve Target 12.5, ensuring that demand for green technologies does not result in an unmanaged burden of electronic waste.

Notably, the convergence observed in Brazil between IAC research and national strategic goals materializes the commitments to SDG 9, 12, and 17 (MCTIC, 2018). This development aligns with Target 9.5, aiming to increase R&D spending to 2.00% of the GDP and strengthen scientific research by reaching 3,000 researchers per million inhabitants. Through Target 9.b, Brazil seeks to support domestic technology and industrial diversification, adding value to commodities. These efforts are intrinsically linked to Target 12.5, prioritizing the substantial reduction of waste through recycling and reuse, and Target 17.11, which focuses on increasing national exports and global development partnerships. By integrating advanced processing with circular strategies, the IAC sector can reduce the global environmental footprint while fostering strategic autonomy through resilient value chains (Ormerod et al., 2023).

5. Conclusion

The present analysis has demonstrated, through an integrated bibliometric methodology, that the research landscape for REE has been fundamentally reconfigured since 2015. This study significantly advances the initial mapping of Brazil's REE potential conducted by Heider & Siqueira (2024) by identifying a fundamental paradigm shift within the scientific community. Our analysis reveals that research has moved beyond a narrow focus on mineral extraction toward the systemic management of social and environmental impacts, a transition explicitly catalyzed by the 2030 Agenda. The exponential growth in publications since 2015 confirms that the SDGs now act as the primary catalyst for innovation in the sector (Cluster 1), positioning ion-adsorption clay (IAC) deposits (Cluster 2) as the preferential geological route for a production model aligned with global sustainability standards.

The intellectual structure of the field reveals a mature research area that no longer treats sustainability as an inherent property of the deposit, but as a conditional outcome of rigorous technological and ethical management. It was demonstrated that critical challenges, such as water quality (SDG 6) and toxicity (Cluster 4), have been moved to the forefront of the scientific agenda, treated as central drivers for innovation (SDG 9) and LCA. Furthermore, the integration of circular economy principles, including magnet recycling and waste reduction (SDG 12), has emerged as an essential requirement to ensure that the REE-IAC supply chain provides a truly "green" alternative to traditional primary deposits (Ormerod et al., 2023; Bailey et al., 2020).

Finally, the study highlights that Brazil occupies a vanguard position in this global transition. The country demonstrates a unique convergence between political strategy, scientific demand, and industrial execution, with 24 active IAC projects transitioning from frontier knowledge to commercial reality. By prioritizing the IAC route, Brazil is not only overcoming the technological and environmental bottlenecks associated with traditional Th/U-bearing deposits but is also positioning itself as the primary Western hub for sustainable REE production. In alignment with the perspective of the CNPq, this progress signifies that the race for REEs is essentially a race for scientific-technological dominance. Therefore, by mastering the extraction and processing of these elements, Brazil transcends the role of a mere ore exporter, acting strategically to rebalance the global geopolitical scale and diversify a highly concentrated supply chain. This study provides the strategic groundwork for aligning mineral policy with the high environmental standards required by the global energy transition. By grounding these policies in SDG 9 and Target 9.b, nations can foster a more equitable market where technological independence is no longer a monopoly, but a shared global reality.

Acknowledgements

ABGT would like to thank the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES) for the research grant, process 88882.329724/2014-01. The authors would like to thank the JGSB reviewers for their guidance and suggestions that contributed to improving the communication and scientific content of the manuscript.

Authorship credits

Author	A	B	C	D	E	F
ABGT	■	■	■	■	■	
CHBF	■		■	■	■	
NPF		■			■	
ABC					■	■

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

References

Assis, F.. 2025. MG terá o primeiro laboratório de reciclagem de ímãs de terras raras do Hemisfério Sul. G1. https://g1.globo.com/mg/sul-de-minas/noticia/2025/09/14/mg-tera-o-primeiro-laboratorio-de-reciclagem-de-imas-de-terras-raras-do-hemisferio-sul.ghtml

Balaram, V. 2019. Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. Geoscience Frontiers, 10(4), 1285–1303. https://doi.org/10.1016/j.gsf.2018.12.005

Bailey, G., Joyce, P. J., Schrijvers, D., Schulze, R., Sylvestre, A. M., Sprecher, B., ... & Van Acker, K. (2020). Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. Resources, Conservation and Recycling, 155, 104675. https://doi.org/10.1016/j.resconrec.2019.104675

Beard, C.D., Marquis, E., Smith, M.P., Li, M.Y.H., Estrade, G., Goodenough, K.M. (2025). Ion Adsorption Mineralisation in Regolith-Hosted REE Deposits. In: Bowell, R.J., Butt, C.R.M. (eds) Geology, Geochemistry and Formation of Supergene Mineral Deposits in Deeply Weathered Terrain. Mineral Resource Reviews. Springer, Cham. https://doi.org/10.1007/978-3-031-75733-4_14

Brasil Mineral. 2024a. Mineração Serra Verde inicia produção comercial em Minaçu. https://www.brasilmineral.com.br/noticias/mineracao-serra-verde-iniciaproducao-comercial-em-minacu

Brasil Mineral. 2024b. Viridis adquire novas áreas para expandir projeto Colossus. https://www.brasilmineral.com.br/noticias/viridis-adquire-novas-areas-para-expandir-projeto-colossus

Brasil Mineral. 2024c. Viridis faz joint venture de tecnologia com a Ionic Rare Earths. https://www.brasilmineral.com.br/noticias/viridis-faz-joint-venture-de-tecnologia-com-a-ionic-rare-earths

Butu, A., Rodino, S., & Butu, M. 2023. Global research progress and trends on critical metals: A bibliometric analysis. Sustainability, 15(6), 4834. https://doi.org/10.3390/su15064834

Collerson, K. D., Dimitrakopoulos, R., & Greville, G. 2025. A meaningful metric to compare the value and prospectivity of clay-hosted regolith rare earth element deposits. Ore Geology Reviews, 178, 106582. https://doi.org/10.1016/j.oregeorev.2024.106582

Depraiter, L., & Goutte, S. 2023. The role and challenges of rare earths in the energy transition. Resources Policy, 86, 104137. https://doi.org/10.1016/j.resourpol.2023.104137

Estrade, G., Marquis, E., Smith, M., Goodenough, K., & Nason, P. 2019. REE concentration processes in ion adsorption deposits: Evidence from the Ambohimirahavavy alkaline complex in Madagascar. Ore Geology Reviews, 112, 103027. https://doi.org/10.1016/j.oregeorev.2019.103027

European Commission – EC. (2023). Critical raw materials. Single-Market-Economy.ec.europa.eu; European Commission. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

Grohol, M., & Veeh, C. (2023). Study on the Critical Raw Materials for the EU 2023. Publications Office of the European Union.

Guarino, V., Lustrino, M., Zanetti, A., Tassinari, C. C., Ruberti, E., De'gennaro, R., & Melluso, L. 2021. Mineralogy and geochemistry of a giant agpaitic magma reservoir: The Late Cretaceous Poços de Caldas potassic alkaline complex (SE Brazil). Lithos, 398–399, 106330. https://doi.org/10.1016/j.lithos.2021.106330

Heider, M., & Siqueira, D. F. 2024. Novos potenciais das terras raras no Brasil. In the Mine. https://www.inthemine.com.br/site/novos-potenciais-das-terras-raras-no-brasil-argilas-ionicas/

Huang, Y., He, H., Liang, B., Bao, Z., Tan, W., Ma, L., Zhu, J., Huang, J., & Wang, H. 2021. Characteristics and genesis of ion adsorption type REE deposits in the weathering crusts of metamorphic rocks in Ningdu, Ganzhou, China. Ore Geology Reviews, 135, 104173. https://doi.org/10.1016/j.oregeorev.2021.104173

International Energy Agency. 2024. Global critical minerals outlook 2024. https://www.iea.org/reports/global-critical-minerals-outlook-2024

Janot, N., Huot, H., Rivard, C., Perrin, M., Noirault, A., Tang, Y. T., ... & Montargès-Pelletier, E. (2025). Localization and speciation of Rare Earth Elements in mine tailings from ion-adsorption clay deposits, Southern China: Insights from microfocused X-ray fluorescence spectroscopy. Journal of Hazardous Materials Advances, 17, 100609. https://doi.org/10.1016/j.hazadv.2025.100609

Jowitt, S. M., & McNulty, B. A. 2021. Battery and energy metals: Future drivers of the minerals industry? Seg Discovery, 124, 11–18. https://doi.org/10.5382/2021-127.fea-01

Kishi, H., Mizuno, Y., & Chazono, H. (2003). Base-metal electrode-multilayer ceramic capacitors: past, present and future perspectives. Japanese journal of applied physics, 42(1R), https://doi.org/10.1143/JJAP.42.1

Li, M. Y. H., & Zhou, M. F. (2020). The role of clay minerals in formation of the regolith-hosted heavy rare earth element deposits. American Mineralogist, 105(1), 92-108. https://doi.org/10.2138/am-2020-7061

Lins, F. A. F., Vera, Y. M., & Dourado, M. D. L. 2025. Brasil é o segundo em reservas de terras raras no mundo. Brasil Mineral. https://www.brasilmineral.com.br/noticias/brasil-e-o-segundo-em-reservas-de-terras-rarasno-mundo

Ministry of Mines and Energy – MME. 2011. Plano Nacional da Mineração 2030: Geologia, mineração e transformação mineral [National Mining Plan 2030: Geology, mining, and mineral transformation]. Brasília, DF: Secretariat of Geology, Mining and Mineral Transformation. Available at: https://www.gov.br/mme/pt-br/assuntos/secretarias/geologia-mineracao-e-transformacao-mineral/publicacoes-1/plano-nacional-de-mineracao-2030.

Ministry of Science, Technology, Innovations and Communications – MCTIC. 2018. Plano de ciência, tecnologia e inovação para minerais estratégicos: 2018-2022 [Science, technology, and innovation plan for strategic minerals: 2018-2022]. Brasília, DF: Secretariat of Technological Development and Innovation.

Melfi, A. J., Misi, A., Campos, D. D. A., & Cordani, U. G. (Eds.). 2016. Recursos minerais no Brasil: Problemas e desafios. Academia Brasileira de Ciências.

Moldoveanu, G., & Papangelakis, V. G. 2025. Rare earth recovery from ion-adsorption clays by ion exchange leaching. In S. Seetharaman (Ed.), Treatise on process metallurgy: Volume 2B (pp. 529–543). Elsevier. https://doi.org/10.1016/B978-0-443-40294-4.00045-1

National Council for Scientific and Technological Development – CNPq. 2025. As várias faces da questão terras raras e a corrida pelo domínio científico-tecnológico [The various faces of the rare earths issue and the race for scientific and technological dominance]. Official CNPq Portal. Available at: https://www.gov.br/cnpq/pt-br/assuntos/noticias/destaque-em-cti/as-varias-faces-da-questao-terras-raras-e-a-corrida-pelo-dominio-cientifico-tecnologico

Ntomb, Y. D., Bondje, L. M. N. B., Mandeng, E. P. B., Wadjou, J. W., Bidzang, F. N., & Ngos III, S. 2024. Major and trace elements behaviour in three weathering profiles developed on syenitic rocks in Ina pluton (syenitic set of Linté, Central Cameroon). Journal of African Earth Sciences, 216, 105315. https://doi.org/10.1016/j.jafrearsci.2024.105315

Ormerod, J., Karati, A., Baghel, A. P. S., Prodius, D., & Nlebedim, I. C. 2023. Sourcing, refining and recycling of rare-earth magnets. Sustainability, 15(20), 14901. https://doi.org/10.3390/su152014901

Russo, S. C., González-Álvarez, I., Cocker, H. A., & McCoy-West, A. J. 2025. The fundamentals of rare earth element ion-adsorption clay deposits: A mineral systems approach for exploration. Journal of Geochemical Exploration, 107845. https://doi.org/10.1016/j.gexplo.2025.107845

Sanematsu, K., & Kon, Y. 2013. Geochemical characteristics determined by multiple extraction from ion-adsorption type REE ores in Dingnan County of Jiangxi Province, South China. Resource Geology, 63(4), 313–330. https://doi.org/10.9795/bullgsj.64.313

Sanematsu, K., & Watanabe, Y. 2016. Characteristics and genesis of ion adsorption-type rare earth element deposits. https://doi.org/10.5382/Rev.18.03

Silva, G. F., Silva, A. D. R., & Souza Gaia, S. M. (Orgs.). 2024. An overview of critical and strategic minerals of Brazil. Serviço Geológico do Brasil.

United States Geological Survey. 2022, February 22. U.S Geological Survey releases 2022 list of critical minerals. https://www.usgs.gov/news/national-news-release/us-geological-surveyreleases-2022-list-critical-minerals

United States Geological Survey. 2025. Mineral commodity summaries 2025. https://doi.org/10.3133/mcs2025

Van Eck, N., & Waltman, L. 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Van Gosen, B. S., Verplanck, P. L., Seal, R. R., II, Long, K. R., & Gambogi, J. 2017. Rare earth elements. In K. J. Schulz, J. H. DeYoung, Jr., R. R. Seal, II, & D. C. Bradley (Eds.), Critical mineral resources of the United States—Economic and environmental geology and prospects for future supply (Cap. O, pp. 1–31). U.S. Geological Survey.

Wall, F. 2021. Rare earth elements. In S. Elias & D. Alderton (Eds.), Encyclopedia of geology (pp. 680–693). Academic Press.

Yang, X. J., Lin, A., Li, X. L., Wu, Y., Zhou, W., & Chen, Z. (2013). China's ion-adsorption rare earth resources, mining consequences and preservation. Environmental Development, 8, 131-136. https://doi.org/10.1016/j.envdev.2013.03.006

Zapp, P., Schreiber, A., Marx, J., & Kuckshinrichs, W. (2022). Environmental impacts of rare earth production. MRS bulletin, 47(3), 267-275. https://doi.org/10.1557/s43577-022-00286-6

Zhou, M. F., Li, M. Y. H., Wang, Z., Li, X. C., & Liu, J. 2020. The genesis of regolith-hosted rare earth element and scandium deposits: Current understanding and outlook to future prospecting. Chinese Science Bulletin, 65, 2265–2279. http://dx.doi.org/10.1360%2FTB-2020-0350 \

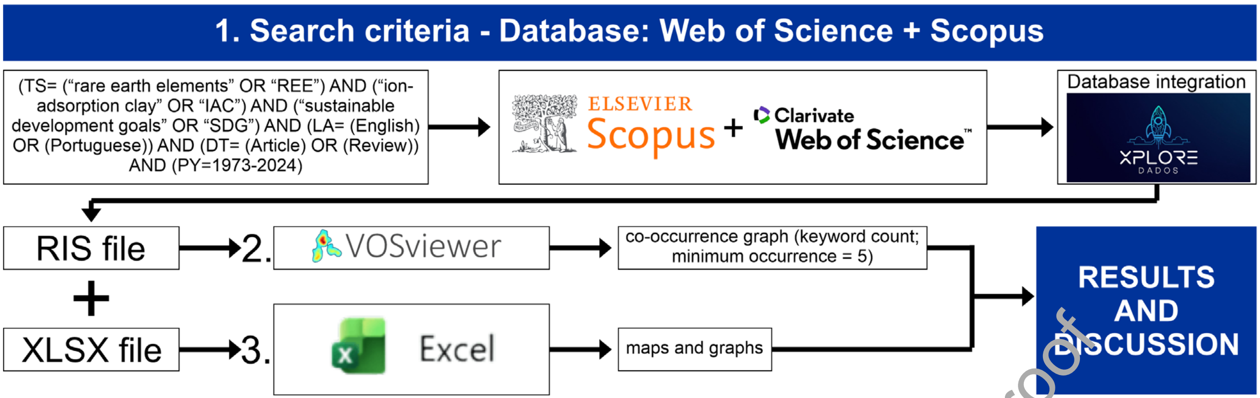

FIGURE 1. Flowchart of the methodological procedures used to obtain the results.

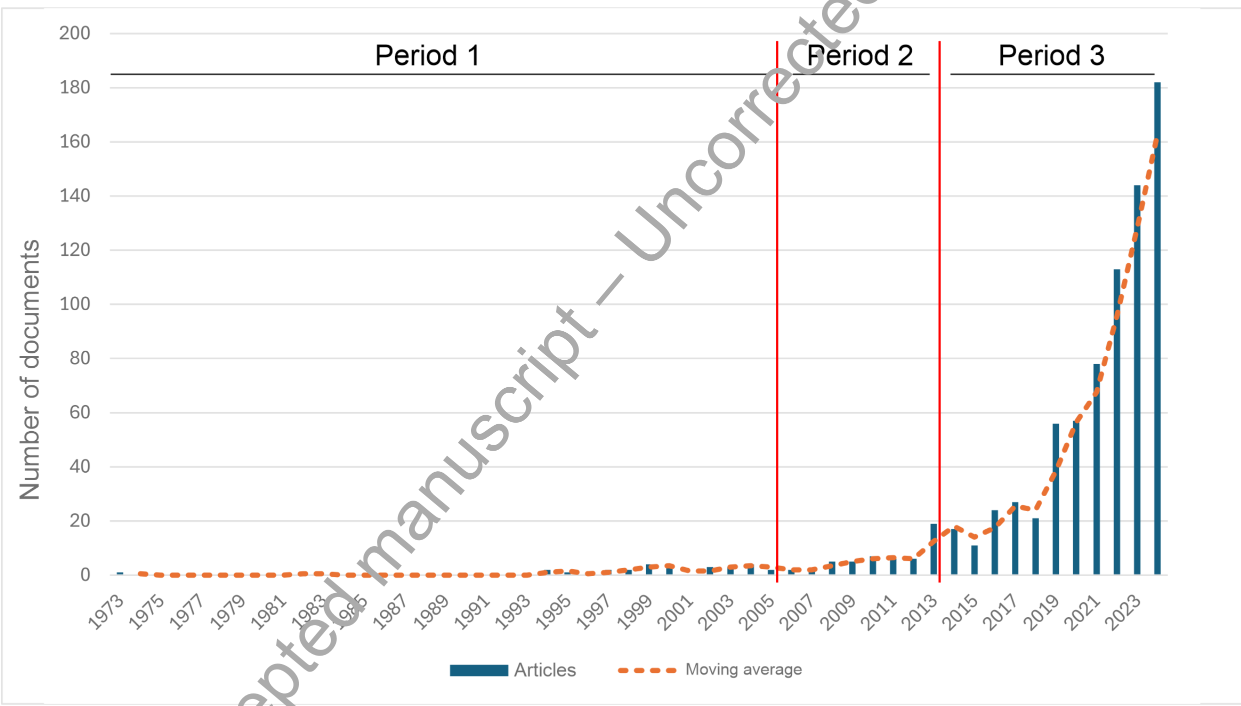

FIGURE 2. Annual publications and growth trend of works extracted from the Scopus and Web of Science databases.

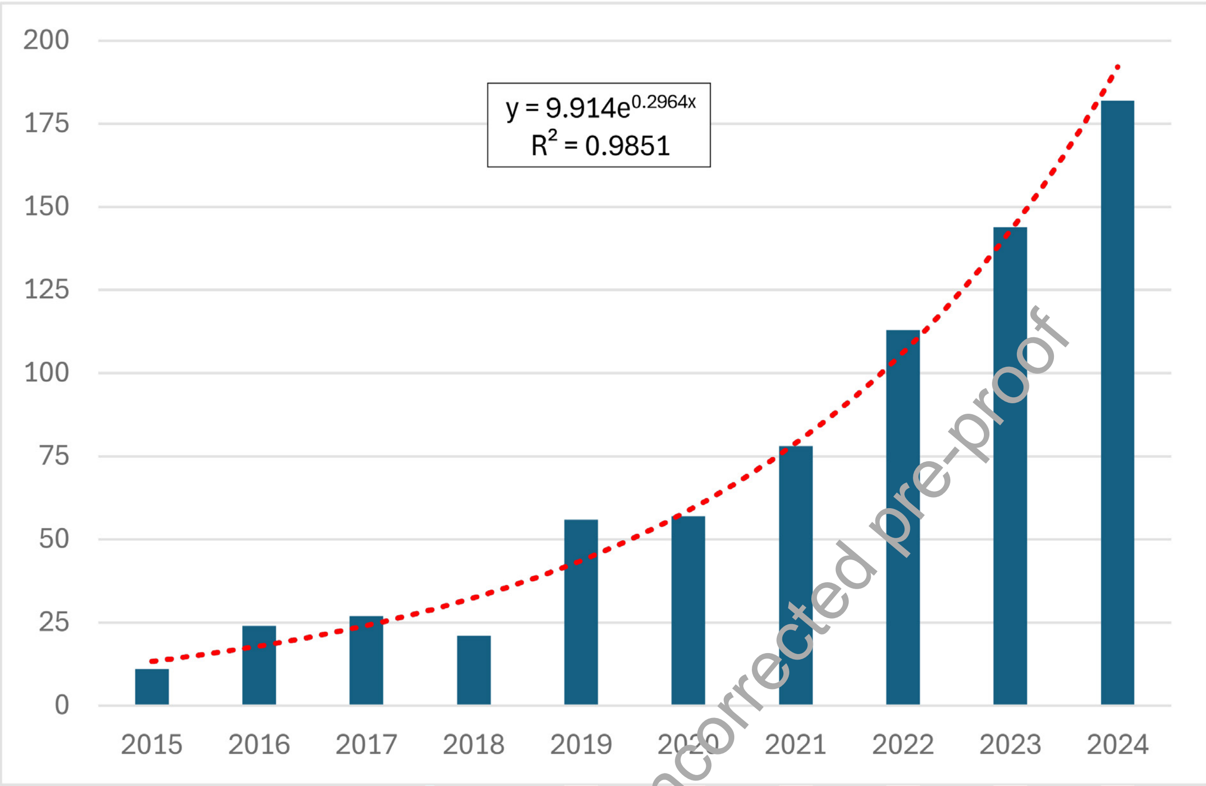

FIGURE 3. Correlation between year and number of publications.

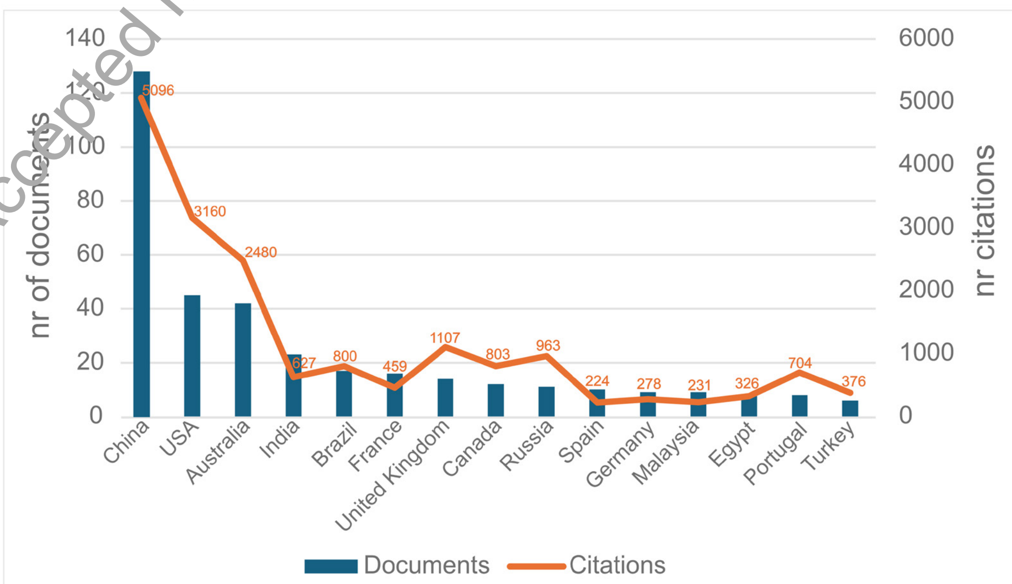

FIGURE 4. Number of works and citations published by country.

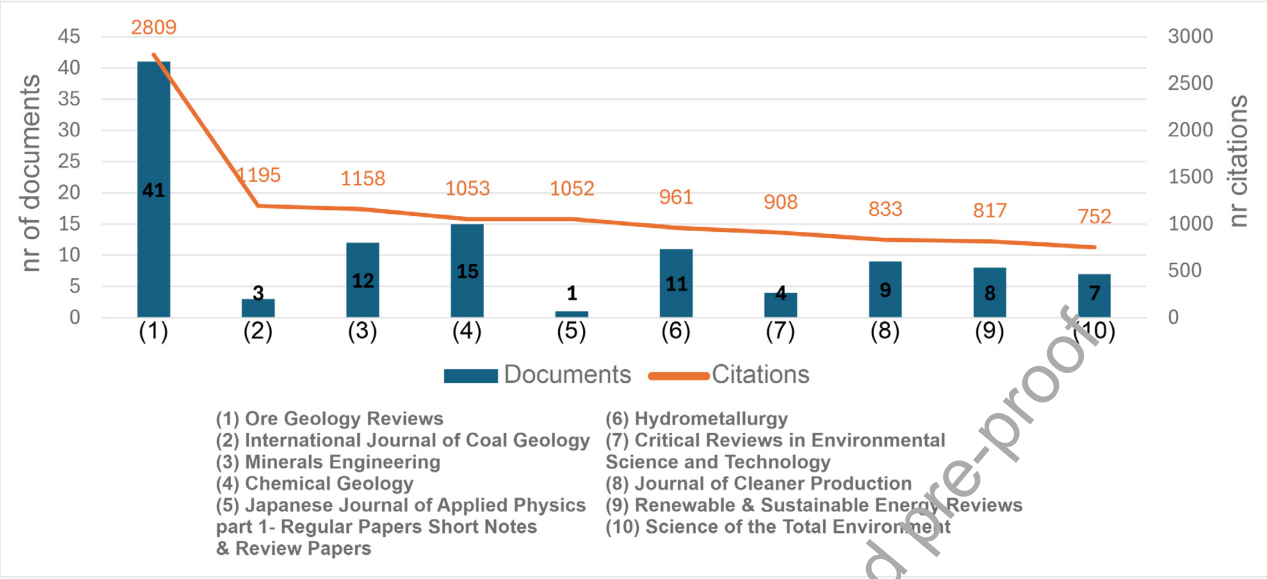

FIGURE 5. Number of documents and citations related to journals.

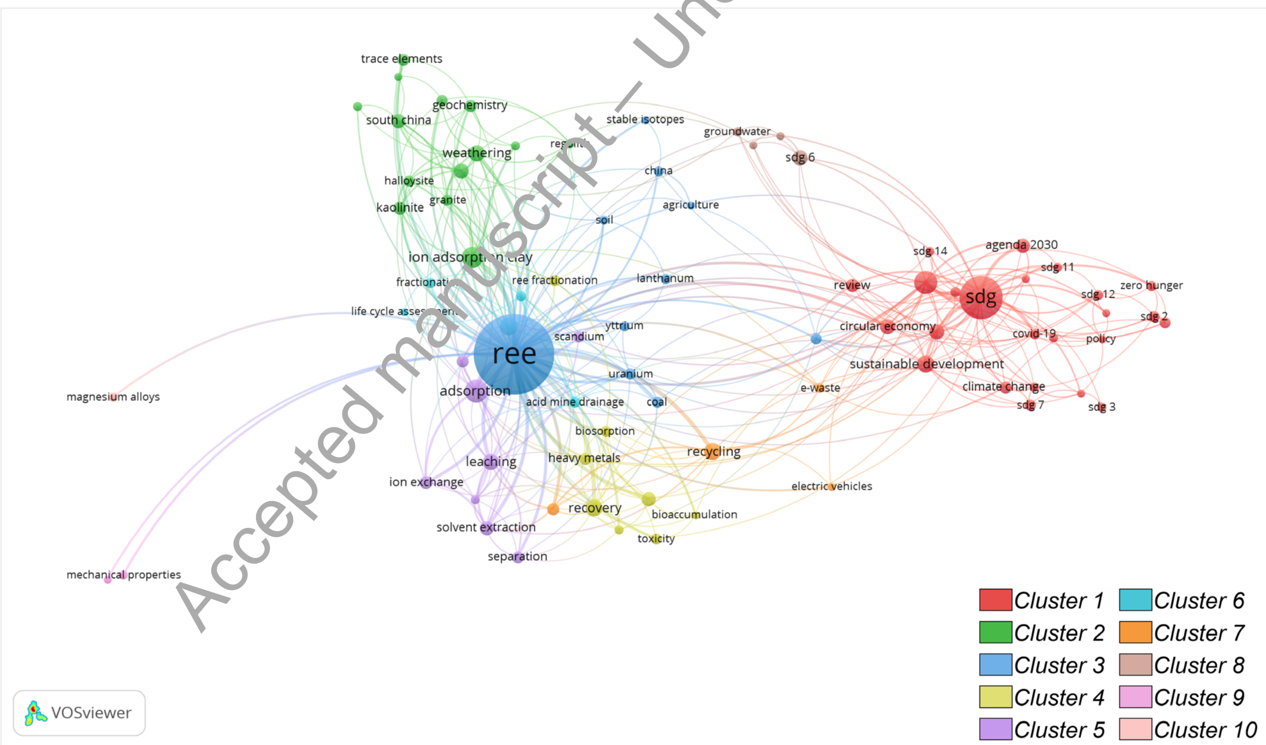

FIGURE 6. Term co-occurrence map.

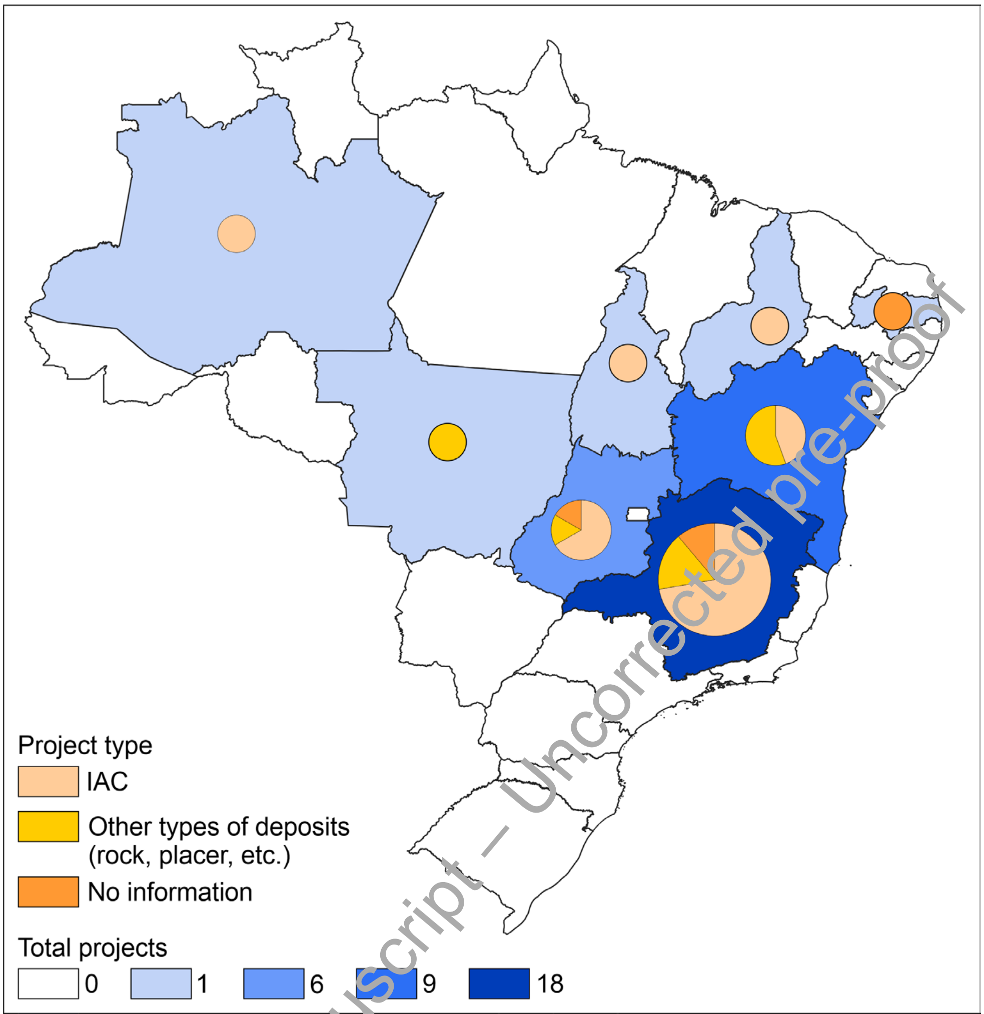

FIGURE 7. Distribution of projects involving rare earths in the national territory.

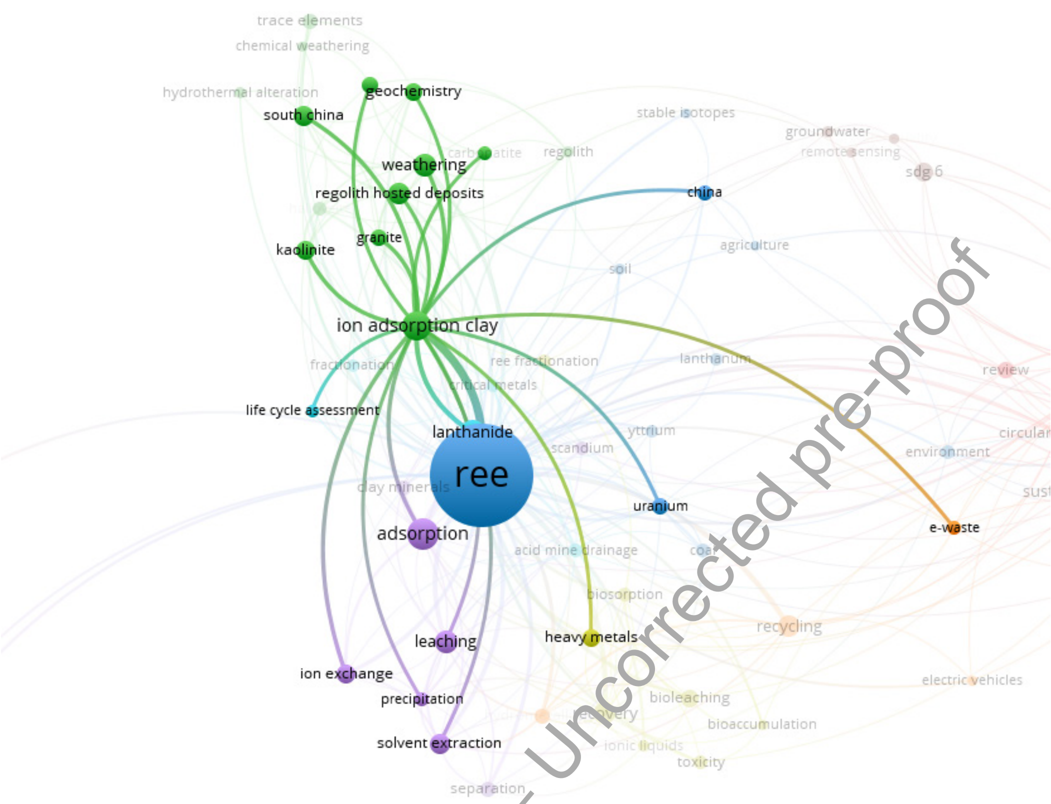

FIGURE 8. Terms directly related to "ion adsorption clay"

TABLE 1. Top 10 most cited terms, their occurrence, and total link strength

	Keyword	Occurrences	Total link strength
1	ree	407	411
2	sdg	122	119
3	adsorption	36	63
4	sustainability	36	61
5	ion adsorption clay	29	51
6	lanthanide	21	33
7	recovery	20	36
8	recycling	19	36
9	sustainable development	19	31
10	leaching	17	38