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Research article

An international comparative study of rare earth research from the perspective of bibliometrics

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A R T I C L E I N F O

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A B S T R A C T

Rare earth refers to a type of strategic resource. Countries worldwide have invested considerable money in relevant research. This bibliometric study was to evaluate the global situation of published rare earth research to discover rare earth research strategies in a wide range of countries. In this study, 50,149 SCI papers related to rare earth were collected. In addition, we divided the above papers into 11 main research fields according to discipline and keyword clustering, and divided the above theoretical cultures into different industry fields according to the keywords of the above papers. After that, the research directions, research institutions, funding, and other aspects of rare earth research in numerous countries were compared. The result of this study suggests that China's rare earth research has been generally in the leading position worldwide, whereas there are still some problems in the discipline layout, strategic strategies, green development, and fund support. Other countries place a greater focus on areas regarding national security strategies (e.g., mineral exploration, smelting, and permanent magnetism).

1. Introduction

Rare earth has been extensively used in numerous fields for its excellent optical and electromagnetic characteristics. Notably, it has high application value and is a vital national strategic resource in high-tech electronic products, defense and military industry, aerospace, and other national strategic areas. The supply center of global rare earth resources has changed twice in history. Brazil, India, and Australia were important sources of rare earths before the 1960s. Later, with the discovery of the Mountain Pass rare earth mine in California, the United States turned out to be the world's largest supplier of rare earths. Moreover, China's rare earth industry gradually occupied a leading position in the market through the discovery and exploitation of rare earth resources in China in the 1980s. At present, nearly 90% of the world's rare earth supply originates from China. Given the strategic characteristics of rare earth, the world's major economic powers have launched fierce competition around the rare earth industry over the past few years. For instance, in 2007, the Ministry of Education, Culture, Science and Industry of Japan proposed the "rare metal alternative materials plan", and continued to take measures in the areas of rare earth resource reserves, source diversity, functional alternative materials, and so forth [1]. In 2009, the American Magnetic Materials Association (USMMA) proposed that rare earth is a crucial material related to national security [2]. Rare earth was listed as the "critical material strategy" by the U.S. Department of Energy in 2010 [3]. From 2011 to 2015, the US Department of Defense has conducted five studies on rare earth materials [1]. In 2012, the US Department of

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Energy set up the Key Materials Institute (CMI), which began to focus on the research of important materials (e.g., rare earth) and launched the REACT project (Rare Earth Alternatives in Critical Technologies). The REACT project will identify low-cost and source abundant rare earth replacement materials, or more efficient rare earth magnets, especially in fields (e.g., electric vehicle (EV) motors and wind turbines) where magnets have been extensively employed [4]. In 2016, China issued the Development Plan of Rare Earth Industry (2016–2020), proposing to expand high-end application research of rare earth based on innovation-driven development. China proposes to boost the development of rare earth magnets, luminescent materials, hydrogen storage materials, ultra-high purity rare earth metals and compounds, smelting and preparation technology of high-performance rare earth alloys, as well as green production of the rare earth industry (e.g., significantly reducing the emission intensity of major pollutants and increasing smelting and separation capacity and recovery rate) [5]. Since then, with the escalation of Sino-US trade frictions, the White House of the United States issued Executive Order EO13817 in December 2017, comprehensively improving the security guarantee strategy for key minerals represented by rare earth, suggesting the important role of rare earth in the game of great powers [6]. In May 2020, U.S. Republican Senator Cruz submitted the "Onshoring Rare Earths Act" to the House of Representatives, requiring the U.S. Department of Justice to purchase rare earth minerals and key elements from the United States and establish special funds for the development of the above-mentioned materials [7]. In June 2021, the United States Senate passed the "Innovation and Competition Act" to formulate a research investment plan of nearly 250 billion dollars, with a dedicated rare earth chapter, to increase investment in innovative technology research and development in the field of rare earth in the country [7]. Subsequently, the production of rare earth in overseas countries tended to be increased. The data from the United States Geological Survey (USGS) suggested that the production of rare earths in the United States was increased from 18,000 tons in 2018–43,000 tons in 2021. Myanmar has increased from 19,000 tons in 2018–26,000 tons in 2021. Thailand has increased from 1000 tons in 2018–8000 tons in 2021 [8]. However, mined ore should often be transported to China for processing since there is insufficient smelting and separation technology. Supply chain security is still not ensured. Accordingly, the United States and Japan have begun to develop smelting technologies, and the European Union has vigorously conducted research and development of rare earth recovery technologies and provided industrial support. For instance, the European Union announced investment in the SUSMAGPRO project to investigate the sustainable recovery, reprocessing, and reuse of rare earth permanent magnets [9]. As revealed by the above efforts, rare earths have progressively aroused the attention of major global economies, and various innovative policies and funds have been continuously invested. Thus, analyzing and evaluating the status and trends of rare earth related research in various countries is of great significance for improving the layout of scientific research, improving the performance of scientific research output, and laying emphasis on formulating scientific and technological policies.

Papers have been confirmed as the vital outputs of scientific research. It is a very common means to use papers to conduct research, evaluation, and analysis, and find scientific research layout, trend, and advantages of a wide range of countries and institutions. There are also many papers involving rare earths, representative papers include: Song et al. (1999) carried out classified statistics and analysis of rare earth papers from 1990 to 1998 in the two major journals of rare earth study, and expounded the research progress and situation of rare earth science and technology in China [10]. Wu et al. (2014) used CNKI database to study the situation and trend of rare earth economic research in China based on the method of bibliometrics. The results show that more than 8200 papers on rare earth economic issues have been published by 2012. However, rare earth articles are published in economic journals, and there have been rare high-quality and cited papers [11]. Xu (2017) took the author keywords in the research papers published in the Web of Science database from 1985 to 2015 as the knowledge unit, and conduct knowledge metrological analysis in the field of rare earth research using the knowledge map analysis software Sci2 Tool, and analyzed and detected the frontier in the field of rare earth research [12]. Liu et al. analyzed the literature regarding rare earth research in terms of the number of papers, author groups, issuing institutions, keywords, emerging words, and timelines using CiteSpace based on knowledge mapping analysis methods, with CNKI literature as the data source. On that basis, they attempted to discuss the evolution trend and development hotspots of domestic rare earth export research [13]. Based on Scopus database and Scival scientific research management analysis platform, Shi et al. (2021) searched the scientific and technological literature published on rare earth materials from 2015 to 2020, and analyzed the research status and hotspots of rare earth optical functional materials [14]. Opare et al. (2021) compared the current status and future development directions of rare earth element separation technologies using papers published in the Web of Science database over the past decade through the qualitative analysis and the classical bibliometric analysis. Their results have suggested that the most mature separation technologies comprise leaching, solvent extraction, and plasma technology. The most extensively employed fields cover chemistry Engineering, and metallurgy, and stress is placed on the importance of multidisciplinary research in achieving more effective solutions [15]. Klingelhofer et al. (2022), based on the Web of Science database, used quantitative analysis to study the impact of rare earth elements on the environment and health in the application and production process. The study found that only some high-income countries have conducted relevant research, mainly focusing on electric vehicles, wind turbines, and permanent magnets, as well as gadolinium and cerium dioxide nanoparticles for magnetic resonance imaging [16]. Makhija et al. (2022) used 1315 documents published on Scopus and Web of Science databases for bibliometric analysis, and used the bibliometrix-R software package to visualize the identified documents. They studied and discussed core publications, keyword analysis, and cluster mapping analysis [17]. As revealed by existing research, rare papers have adopted the paper data to evaluate the scientific research direction and output efficiency of entire rare earth field. Most papers still employed the paper citation data for cutting-edge trend analysis or quantitative analysis for a specific field.

Our main goal is to analyze the status and trends of rare earth related research in major countries worldwide using bibliometric methods, and observe the research focus, scientific research layout, highly cited papers, key research, and development institutions, and the use of scientific research funds in a wide range of countries through comparison. In combination with policies issued by some countries, the effects of scientific research outputs will be further discussed.

To investigate the above objectives in depth, the following problems should be addressed. As mentioned above, rare research has conducted the quantitative analysis of scientific research output using overall rare earth research paper data. Accordingly, more extensive data should be used for evaluation and analysis, insights should be gained into the development process of rare earth research, and the main participating countries and institutions in rare earth research identified and analyzed. However, the rare earth industry involves different application fields (e.g., exploration, mining, smelting, processing, and magnets), as well as light-emitting materials. Thus, how to effectively classify papers and analyze them in different categories is the key to research. Because some research belongs to basic research and some belongs to applied research, different applied research serves different industries. For instance, the rare earth industry chain can be divided into specific applications such as upstream mining and smelting, midstream alloys, oxides, downstream permanent magnets, optics, and catalysts. However, there are significant differences between disciplines and industrial applications, so classification by discipline often does not achieve the desired results. Using the divided data for comparative research between a wide range of countries, we can find the advantages of the respective country, such that the purpose of this paper can be more effectively achieved.

The rest of this study is organized as follows. In the next section, the existing research on rare earth is briefly introduced, and the development process of using bibliometrics is summarized to evaluate research. In the third section, data resources and research methods are introduced. The fourth section is the results of this study. We first give a general description of the paper data. Then the papers are classified twice, and the advantages of the respective country were determined. Furthermore, an international comparison is drawn on major scientific research institutions and funds. In the last section, the discussion, conclusions and future research directions are presented.

2. Literature review

2.1. Rare earth

The research on rare earth mainly started from mid 1990s. From the perspective of research content, it mainly includes the development of China's rare earth industry, international competitiveness of rare earth industry, and the impact factor analysis of external trade environment on the rare earth industry. For the trend and development of China's rare earth industry, previous papers have mainly focused on the loss of resource, environmental damage, overcapacity of China's rare earth industry [18,19]. In general, the international competitiveness of the rare earth industry refers to the ability of a specific country's rare earth industry to grasp the global market value and sustain the profitability in a specific international industrial chain. The main purpose of the research on the international competitiveness of rare earth industry is to answer why China cannot effectively transform its resource advantages into market advantages. Numerous scholars have compared the international technological innovation from specific rare earth technologies (e.g., metal materials and luminescent materials). While some scholars adopted more commonly used competitiveness comparison models, such as Porter Diamond model, SWOT model, to evaluate the international competitiveness of rare earth industry of a wide range of countries [20–23]. The study of external trade environment has become a hot topic since China lost the WTO case in the early 2010s. Some studies believed that China's rare earth industry should establish a unified market supervision system, strategic reserve system, strengthen the application of legal means, establish industry leading enterprises, and establish an export quota system to cope with the external trade environment [24–27].

2.2. Bibliometrics

Bibliometrics refers to a discipline that investigates the distribution structure, quantitative relationships, change patterns, and quantitative management of literature information using mathematical, statistical, and other quantitative research methods, and further explores certain structures, characteristics, and laws of science and technology. Papers are vital outputs of scientific research. Mining and quantitative analysis using paper data, including countries, institutions, authors, keywords, journals, and other objects, can present the overall trend, distribution, and hot spot changes in different research fields. It is a very common means for conducting research, evaluation, and analysis, and discovering the advantages and disadvantages of a wide range of countries and institutions. As early as the beginning of the 20th century, people began to conduct quantitative research on literature, whereas bibliometrics was not established as an independent discipline. Until 1969, Alan Pritchard, a famous British information scientist, first proposed to replace the name of "statistical bibliography" with the term "Bibliometrics" [28]. The emergence of this term marks the formal birth of bibliometrics. Bibliometrics refers to a measurement technique that evaluates and predicts the establishment and development trend of science and technology with statistical methods, with a wide variety of external characteristics of scientific and technological documents as the research object. The classic literature in history comprises the history of comparative anatomy. For instance, a statistical analysis of the literature, published in Science Progress in 1917 by F T. Cole as the first author, has been considered the earliest work of bibliometric research. This is the first relatively complete metrological study of the history of science and technology in the modern sense. It counted 6436 publications on animal anatomy in European countries from 1543 to 1860, and drew a time distribution curve of the number of publications [29]. The development process of comparative anatomy is indicated by this curve. Since then, Lotka's Law, Zipf's Law, and Scientific Citation Index have laid a foundation for bibliometrics [30]. Subsequently, the main areas of bibliometrics research have been developing with the continuous emergence of new measurement indicators (e.g., impact factors) and the development of information technology and the networking of information. At present, bibliometric methods use a wide variety of techniques (e.g., co-citation analysis, bibliographic coupling, and co-author and co-keywords analysis), and they have been the critical means to evaluate the research status and discover the frontier trends.

3. Materials and methodology

3.1. Data source

In this study, SCIE database in Web of Science (WoS) database was selected as the data source. SCIE database, as the largest and most comprehensive academic resources database, contains the most influential core academic journals in various field including geoscience, geochemistry, natural science, and engineering technology. Besides, SCIE database is the most important data source for bibliometric analysis. In the field of rare earth research, the above-described papers [12,15–17] also used SCIE databases for quantitative analysis. All research papers involving rare earth and related elements should be considered, such that the retrieval strategy is: TS=(((rare * earth) or (rare earth) or (rare * earth material *) or (rare * earth element *)) AND (La or Ce or Pr or Nd or *Pm* or Sm or Eu or Gd or Tb or Dy or Ho or Er or Tm or Yb or Lu)), and the type of paper is constrained to 'research paper'. Rare earth has been extensively employed in industry since the 1990s, and international research has become increasingly popular in the same period. As indicated by the data [12], the number of international SCI papers in 1991 has been increased by nearly two times over the number of the previous year, such that the publication time of this study was limited to 1991–2021. The data were acquired in September 2022, and a total of 50,149 pieces of data were retrieved.

3.2. Research design

Fig. 1 illustrates the basic framework of this study. First, a general analysis was conducted on the global rare earth research, which comprised the overall development trend of papers, country analysis, and analysis of the characteristics of the research disciplines. On that basis, the current status, trends, and the main disciplines of rare earth research were determined. This is also the most routine part of bibliometric analysis research [31]. Notably, the judgment order of corresponding author country and first author country was adopted in this study to define the country of origin of SCI papers since cooperation has become a very significant feature in the field of

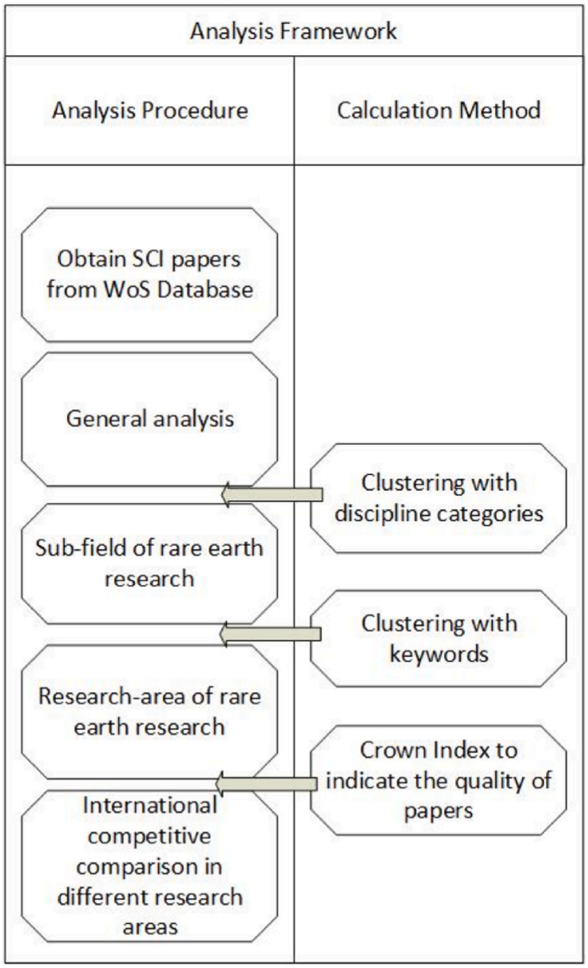

Fig. 1. Analysis framework of this study.

scientific research. Second, since rare earth technologies comprise upstream exploration and mining, midstream smelting and purification, downstream product applications, and recycling and reuse, involving a wide variety of technologies (e.g., geological science, marine science, intermediate oxide and metal smelting technology, luminescent materials technology, magnetic materials technology, environmental protection technology, and recycling technology), all SCI papers will be clustered. Literature clustering has been widely used to classify rare earth research [32–34]. Zhou et al. (2021) used the Fast Unfolding clustering method to divide text information into various fields of the rare earth industry [1]. In this study, two consecutive clustering methods, discipline clustering and keyword clustering, are used. The main reasons are presented as follows: 1. The number of articles varies significantly. China has a great advantage in SCI papers. Moreover, the difference in the size and positioning of institutions may also lead to the imbalance of research direction and the number and strength of papers; 2. There is a big gap between disciplines. Rare earth research covers basic sciences such as materials, physics, chemistry, and geosciences, as well as considerable disciplines focusing on application, such as metallurgy, geology, mining, chemical engineering, electricity, and optics. The research intensity of different disciplines is also different. The above two reasons make it easy to regard the overall intensity of the research as low, but the field focusing on application is mistaken as not the trunk, but the "side branches" are ignored in cluster analysis. This situation can be avoided using the above-mentioned two consecutive clustering methods. The first step in the clustering process refers to the formation of a larger clustering result. In the second step, the sub clusters generated in the previous clustering step serve as input, and the relevant clustering algorithm is adopted to cluster again. In general, the result of the second step of clustering conforms to the termination condition, i.e., no clustering division will be performed if the target feature value is less than a certain threshold value and the clustering effect is slight [35–38]. Thus, this study first conducts cluster analysis through discipline categories, and first classifies disciplines that are close to each other. Next, it uses the same algorithm to cluster the keywords in the respective discipline field, and maps the clustered keywords with disciplines to discover the core technology fields. Lastly, according to the clustering results, we compared countries, and found the advantages of countries in rare earth research from the number, quality, key institutions, funding, and other aspects.

The main clustering methods are as follows.

3.2.1. *Clustering with discipline categories*

The community detection problem should divide total nodes into different sub-community with densely connected nodes, whereas nodes of various communities' area unit are solely sparsely connected. The precise formula of the optimization problem is difficult to know. Consequently, many algorithms are planned to work out affordable and smart partitions moderately and quick. The rummage around for quick algorithms has aroused nice interest over the past few years because of the increasing handiness of enormous network datasets. There are several community detection algorithms: the splitting algorithm detects links between communities and removes them from the network [39–41], the aggregation algorithm recursively merges similar nodes/communities [42], and the optimization method follows the maximization of the objective function [43–45]. In general, the quality of partitions generated by the above methods is measured with the so-called modularity of partitions. The modularity refers to a scalar value ranging from −1 to 1. Compared with links between communities, it measures the density of links within a community [40,46]. Under a weighted network (a weighted network is a network with a weight on its link), it is defined as:

$$Q = \frac{1}{2n}\sum_{i,j}\left[B_{ij} - \frac{k_i k_j}{2n}\right]\varphi(c_i, c_j) \tag{1}$$

where B_{ij} denotes to the number of the edge between node i and node j, $k_i = \sum_j B_{ij}$ expresses the sum of the edges linked to node i, c_i denotes the sub-network for which node i is allocated, the function φ is 1 if $c_i = c_j$ and 0 otherwise, and $n = \frac{1}{2}\sum_{ij} A_{ij}$.

In this study, the WoS discipline categories of all paper data were retrieved using Excel vba to determine the co-occurrence times of any two discipline codes, and the Fast Unfolding method [47] was adopted to calculate the Q value.

3.2.2. *Clustering with keywords*

After the classification of disciplines was completed, the papers in the respective subdivided field can be clustered again with keywords. This study uses the keyword field "Keywords Plus" in the WoS data for clustering. The keywords in the WoS database are data service labels, which are more standardized than the author's keywords and are more effective in building the knowledge map. The clustering method is the consistent with that in 3.2.1.

3.2.3. *Indicator for paper quality*

Key research institutions are not only the main body of scientific research, but also a crucial support for national scientific research strength. Besides quantitative indicators such as the number of documents issued, the quality of papers is a vital manifestation of the scientific research level of institutions. In this study, the crown index is used to measure the overall level of the organization's papers. The Crown Index is proposed by the Science and Technology Research Center of Leiden University (CWTS) to measure the relative influence of an institution in a certain discipline field relative to the world average scientific research level [48]. Its calculation is shown in formula (2):

$$\frac{CPP}{FCSm} = \frac{Number\ \ Citation_{ij} / Number\ \ Papers_{ij}}{Number\ \ Citation_{j} / Number\ \ Papers_{j}} \tag{2}$$

Where Number $Citation_{ij}$ is the number of citations of papers in field j of institution i, Number $Papers_{ij}$ is the number of papers in field j of institution i, Number $Citation_j$ is the number of citations of all papers in field j worldwide, and Number $Papers_j$ is the total number of papers in field j worldwide.

3.3. Analytic software

As mentioned above, the preprocessing of SCI paper data mainly includes extraction and co-occurrence calculation of disciplines and keywords, which is completed using MS Excel Vba. The co-occurrence results will be input into the clustering and visualization software Gephi to complete the clustering of disciplines and keywords and then generate clustering images. The analysis of results (e.g., the classification of SCI paper, calculation of the Crown Index and other statistic work) is largely conducted using MS Excel Vba.

4. Results

4.1. Number of publications

As science and technology has been leaping forward, rare earth has been extensively employed in industry. At the same time, due to the discovery of many rare earth minerals in China in the 1980s, and China's significant breakthroughs in mining, smelting, separation, and extraction fields, gradually developing to supply 90% of the world's rare earth resources, many rare earth economic and trade events and disputes are correlated with China. Accordingly, the trend of global rare earth research mainly changes with China's development of rare earth. The Chinese total sales volume worldwide has grown rapidly from less than 15,000 tons in 1990–40,000 tons in 1995 [49]. Driven by supply and demand, the trend of accelerating research on rare earth was followed. As depicted in Fig. 2, the number of SCI papers began to grow linearly from the early 1990s. By 2004, the peak of the new century, the world rare earth trade had reached 267,000 tons, nearly 300 times more than that in 1990 [50]. The research trend also continued to grow after entering the new century. During this period, China continued to supply considerable rare earth products. By 2000, the number had exceeded 70, 000 tons. China has also become the largest supplier of rare earth worldwide. Since then, China's rare earth output has reached 120, 000 tons at its peak, accounting for 90% of the world's rare earth output. China's massive export of rare earth will inevitably trigger vicious competition for export opportunities in the country. In this case, in 2009, the Ministry of Industry and Information Technology prepared the Development Plan of Rare Earth Industry for 2009–2015 and the Development Policy of Rare Earth Industry, drawing a red line for rare earth exports: in the next six years, China's total rare earth export quota would be controlled in 35,000 tons/year [22]. Since then, the price of rare earth has fluctuated significantly for a short time. In 2011, the price has increased by 7 times compared with the previous year. Many developed countries have begun to arrange special research projects related to rare earth. Thus, the growth rate of rare earth research papers has accelerated since 2016 after several years of development. With the involvement of rare earth elements in the Sino US trade friction in 2018 and the official listing of rare earth and other rare metals as national key metals by the US Department of the Interior [23], the research on rare earth has been growing rapidly, suggesting the necessity of this study.

4.2. Top countries

The following data are counted according to the correspondence author, so the number is different from that given in the WoS database. As depicted in Fig. 3, China has the largest number of papers in the field of rare earth, accounting for nearly 30% of the world. Notably, the domestic rare earth industry has developed rapidly after 2000, and the number of papers has increased significantly, followed by the United States (10%), Japan (8%), Germany (7%), India (6%), France (5%), and Russia (5%). From the time dimension of paper output, China's rare earth related papers also began to grow rapidly since 2000 when China served as the largest supplier of rare earth worldwide. In 2006, China's Outline of the National Medium- and Long-term Science and Technology Development Plan (2006–2020) listed rare earth technology as the vital support direction, and the number of papers has been rising continuously. Since

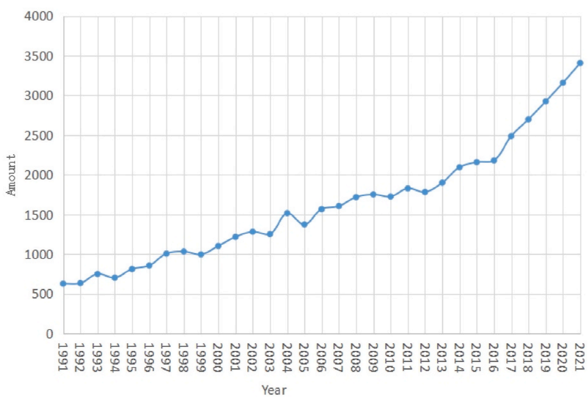

Fig. 2. Number of SCI papers worldwide.

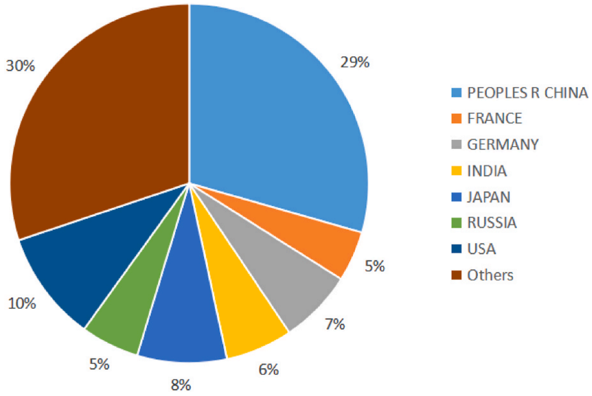

Fig. 3. Proportion of SCI papers by country.

China's rare earth supply has accounted for nearly 90% of the world's total in 2010, the price fluctuation at that time gave the greatest stimulus to our rare earth research. The research efforts have slowed down as the price fell back. In October 2016, the Ministry of Industry and Information Technology issued the Rare Earth Industry Development Plan (2016–2020), stipulating that China should significantly improve the level of scientific and technological innovation in high-end rare earth functional materials, devices and green development in the "13th Five Year Plan", and the related rare earth field has entered the accelerating trend again as shown in Fig. 4. In contrast to other major research source countries, the number of papers on rare earth research tended to increase with the large supply and wide application of rare earth after 2000; throughout its development, however, the output of papers has always been relatively stable without significant changes. The possible reason for this result is that the supply of rare earth has always been stable. Although there are fluctuations, the market is stable. For instance, the 2012 report of the US Department of Defense on the potential supply threat of rare earth highlighted by GAO (the US Government Accountability Office) suggests that the supply of rare earth is sufficient. Accordingly, for the above rare earth using countries, the research has maintained a certain intensity, whereas there is no corresponding fluctuation. Some minor fluctuations mainly stem from political and economic disputes between relevant countries and China. For instance, Japan experienced a small peak in 2006. The main reason is that since 2004, there has been a dispute between China and Japan over the East China Sea issue, and China has suspended its rare earth exports to Japan. In 2010, Japan, the United States, Germany, and other countries showed another small upsurge in rare earth research. The main reason was that China set export quotas that year. Later, with China's failure in the WTO, national research gradually declined. After 2017, as global supply chain risks have aroused rising attention, and the supply of rare earths has been monopolized for a long time, and rare earths are widely used in future industries (e.g., electric vehicles and new energy), the number of scientific research papers in a wide range of countries has been elevated.

4.3. Disciplinary characteristics of rare earth research

In industrial research, industrial chain analysis is an effective method to judge the comparative advantage and competitive advantage of enterprises and industries in a wide range of countries or regions. In terms of scientific research, the analysis of discipline dimensions can also help us understand the scientific research direction of various countries, especially in today's era when interdisciplinary integration is common, and thus form our own unique international scientific research competitiveness. This study uses the WoS discipline category (field WS) indicator in SCIE database, which includes 151 discipline subcategories expanded based on five

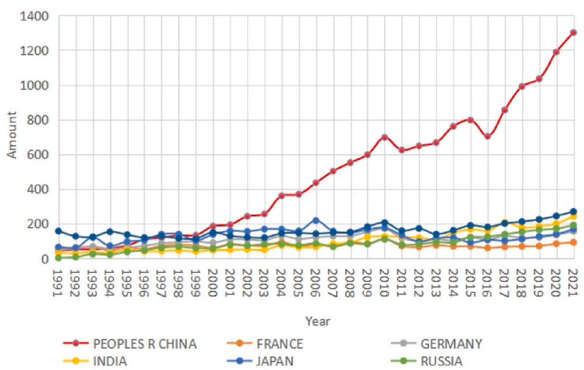

Fig. 4. SCI papers of major rare earth research countries.

major categories of life sciences and biomedicine, natural sciences, applied sciences, arts and humanities, and social sciences. The results are presented in Fig. 5. In terms of disciplines concentrated by the Rare Earth Institute, they mainly focus on "materials science, multidisciplinary", accounting for 15%–20% all the time, followed by "chemistry, physical", "physics, applied", "metallurgy and metallurgical engineering", "physics, condensed matter", "geoscience, multidisciplinary", "geochemistry and geophysics", "chemistry, multidisciplinary", "optics", etc. In terms of development and change, all disciplines have basically maintained a stable research effort. Only "physics, condensed matter" and "chemistry, physical" have declined, while "geosciences, multidisciplinary" has shown a significant upward trend since 2012, indicating that multidisciplinary geological and mineral research is a research hotspot in the exploration of rare earth resources. Based on the discipline overview, the following will be integrated and classified again to find and compare the hot spots and trends of rare earth research in various countries.

4.4. *Cluster results of rare earth research fields*

The WoS discipline categories of 50,149 papers were preprocessed using Excel vba to obtain the co-occurrence times of any two technical codes, and the Q value was calculated using the Fast Unfolding method [47] to identify the communities of the respective discipline. The Q value is obtained as 0.551, within the better range of community clustering recommended by the algorithm [47]. The results are presented in Fig. 6. In general, the main disciplines can be assigned to three groups, primarily covering "materials science, multidisciplinary" materials research direction (blue). To be specific, basic science research (e.g., materials science research, basic chemistry research) and applied technology research (e.g., optics, metallurgical engineering, membrane application, material testing research) are involved. The research direction of environment and geology (purple) places a focus on "environmental science" and "geoscience, multidisciplinary", which comprises "engineering, environmental", "engineering, chemical", and so forth. Other small scale applied research (gray) focuses on "chemistry, analytical", "nuclear science and technology", etc. Furthermore, as revealed by the specific contents represented by the above three discipline categories, their division is relatively rough, such that the respective discipline category should be subdivided again, i.e., each large community is subdivided again through Fast Unfolding algorithm to get more sub communities (sub discipline categories). The results are listed in Table 1. As depicted in the table, research regarding rare earth can be classified into six categories. To be specific, category 1 primarily comprises "materials science, multidisciplinary", "chemistry, physical", "metallurgy and metallurgical engineering" and other disciplines that are relatively basic or widely studied in rare earth research. Category 2–6 involve the upstream exploration and mining of rare earth and other major applications. For instance, Category 2 covers the exploration and mining of rare earth, including "geochemistry and geophysics", "mineralogy" and "geology" that are biased towards the foundation, and "mining and mineral processing" with stress on applications.

After the classification of disciplines is completed, the technical points of the respective subdivided field can be clustered by the same algorithm. The WoS keyword Keywords Plus was adopted in this study to cluster technical points. The WoS keyword Keywords Plus refers to a trademark of data service, which is more standardized than the author's keyword and more effective in building the knowledge map. The results are listed in Table 2. To be specific, discipline field 1 is the most basic and extensive discipline in rare earth research, such that it contains the most sub research fields (e.g., rare earth oxide research, luminescence research, alloy research, physical and chemical properties research, and magnetic research). Second, the field of geography and mineral resources (e.g., rare earth geology and mineral research and rare earth geology and mineral/ocean research). In the other three subdivisions, the research scale is relatively small, such that subdivision is stopped. Subsequently, the keywords in the respective research field are compared to

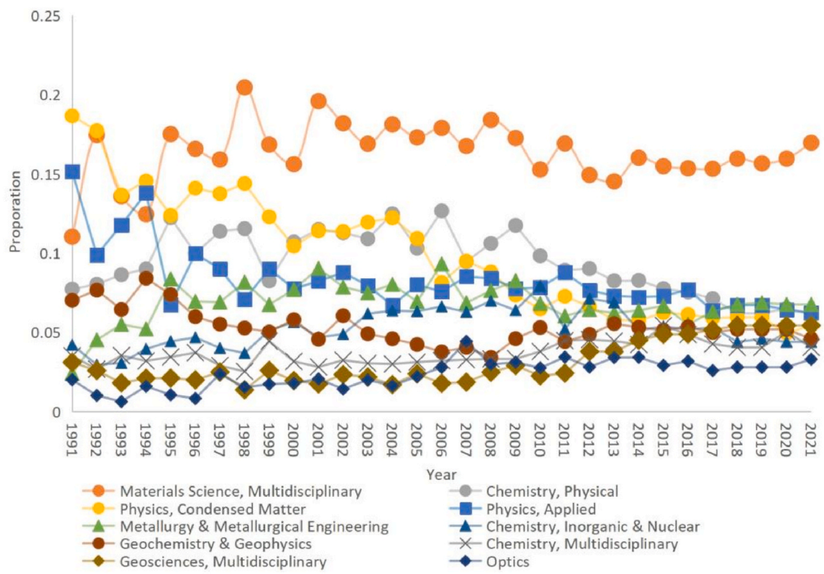

Fig. 5. Proportion of major disciplines in rare earth field.

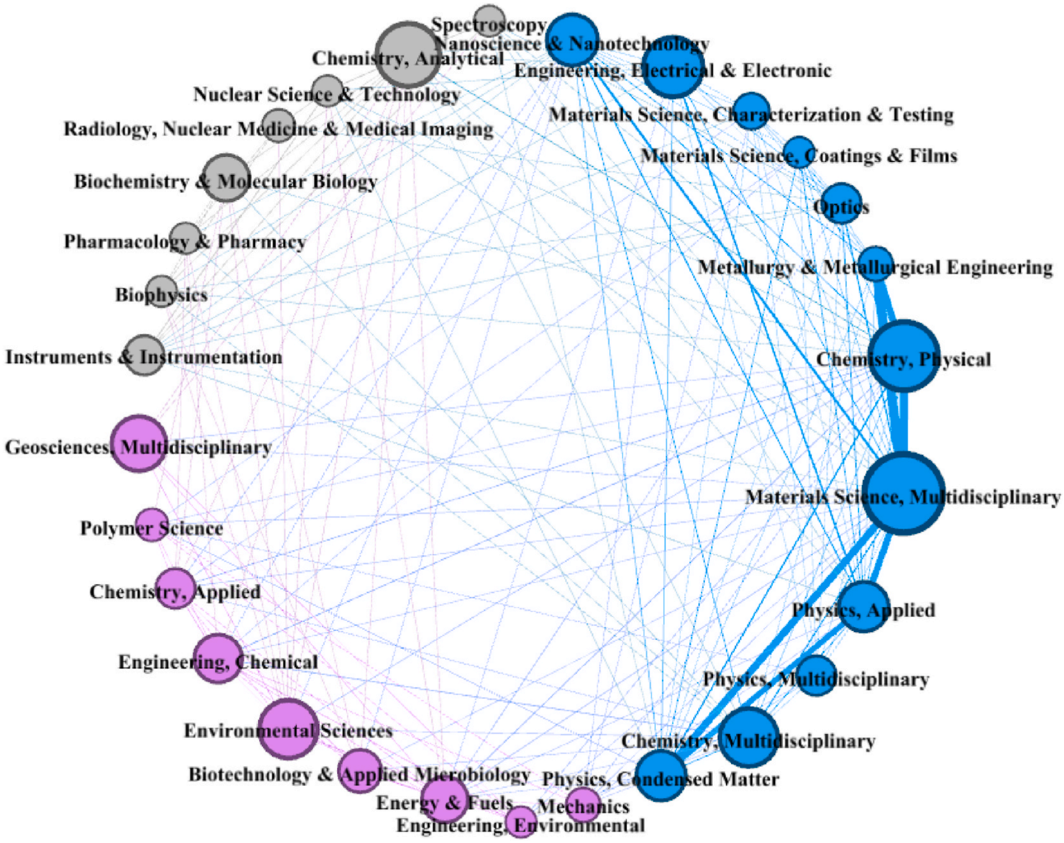

Fig. 6. WoS discipline category clustering of research regarding rare earth.

Table 1
WoS discipline clustering results of research regarding rare earth (the top four communities in each sub-field).

No.	Sub-field	WoS Discipline			
1	Basic research field	Materials Science, Multidisciplinary	Chemistry, Physical	Metallurgy & Metallurgical Engineering	Chemistry, Analytical
2	Geography and mineral resources	Mineralogy	Geochemistry & Geophysics	Mining & Mineral Processing	Geology
3	Nuclear technology	Nuclear Science & Technology	Physics, Nuclear	Instruments & Instrumentation	Chemistry, Inorganic & Nuclear
4	Chemical industry	Engineering, Chemical	Electrochemistry	Chemistry, Applied	Energy & Fuels
5	Environmental field	Environmental Sciences	Engineering, Environmental	Water Resources	Green & Sustainable Science & Technology
6	Biochemical medicine	Biochemistry & Molecular Biology	Endocrinology & Metabolism	Biophysics	Pharmacology & Pharmacy

remove some keywords with less common features. The feature keywords in the respective research field are listed in the fourth column of the table.

4.5. Research trend of different countries

The 50,149 papers retrieved in this study are classified according to the WoS discipline categories and research fields given in Tables 1 and 2. For papers involving multiple WoS discipline codes or multiple research field codes, this study is merged according to the corresponding subdivisions containing the most discipline classification/research field codes, and the results are shown in Fig. 7. In terms of overall quantity, rare earth, as an excellent material modification element, mainly focuses on the basic research of material science, which is mainly reflected in the research of rare earth luminescence technology (code 12) and rare earth magnetic technology (code 15). There are nearly 7500 papers in the field of magnetic technology, and more than 6500 papers in the field of luminescence technology; Second, they are: rare earth geology and mineral research (code 21), rare earth chemical properties research (code 14), rare earth alloy research (code 13). The number of research papers in the above three areas is 2000–4500; The few research fields are:

Table 2
Clustering results of research directions related to rare earth.

Sub-field	Code	Research area	Characteristic keywords
1	11	Study on Rare Earth Oxides	OXIDE、OXIDATION、CATALYSTS、RARE-EARTH-OXIDES、DECOMPOSITION LOW-TEMPERATURE、DENSITY-FUNCTIONAL THEORY、CERIA、STABILIZATION
	12	Study on rare earth luminescence	RARE-EARTH IONS、LUMINESCENCE、OPTICAL-PROPERTIES、SPECTROSCOPY、ENERGY-TRANSFER、PHOTOLUMINESCENCE、THIN-FILMS、SPECTROSCOPIC CHARACTERIZATION、VIBRATIONAL-SPECTRA、LANGMUIR-BLODGETT-FILMS
	13	Study on rare earth alloys	MICROSTRUCTURE、MECHANICAL-PROPERTIES、CERAMICS、YTTRIUM、CRYSTALLIZATION、STRENGTH、TRANSFORMATION、DEFORMATION、THERMAL-STABILITY、ALLOY
	14	Study on Physicochemical Properties of Rare Earth	CRYSTAL-STRUCTURES、LIGANDS、REACTIVITY、STRUCTURAL-CHARACTERIZATION、MOLECULAR-STRUCTURE、METAL-ORGANIC FRAMEWORKS、POLYMERIZATION、PRECURSORS
	15	Study on Rare Earth Magnetism	PERMANENT-MAGNETS、MAGNETIC-PROPERTIES、NEUTRON-DIFFRACTION、SINGLE-CRYSTALS、ELECTRONIC-STRUCTURE、INTERMETALLIC COMPOUNDS 、ANISOTROPY
2	21	Study on rare earth geology and mineral resources	PETROLOGY、CONTINENTAL-CRUST、GREENSTONE-BELT、MASS-SPECTROMETRY、GEOCHEMISTRY、ROCKS、MANTLE
	22	Rare Earth Geology and Mineral Resources/Marine Research	MID-ATLANTIC RIDGE、EAST PACIFIC RISE、ABYSSAL PERIDOTITES、BACK-ARC BASIN、MIDOCEAN RIDGES、SOUTHWEST INDIAN RIDGE
3	31	Rare earth NMR study	RARE-EARTH NUCLEI、HIGH-SPIN STATES、EXCITED-STATES、DEFORMED-NUCLEI、ISOTOPES、TRANSITION-PROBABILITIES、NUCLEAR-MAGNETIC-RESONANCE、SOLID-STATE NMR 、MAS-NMR、SPIN RELAXATION
4	41	Study on Separation and Recovery of Rare Earth	ADSORPTION、SEPARATION、SOLVENT-EXTRACTION、RECOVERY、URANIUM、THERMODYNAMICS、CATIONS METAL-IONS
5	51	Study on Environmental Protection of Rare Earth	HEAVY-METALS、TOXICITY、SOIL、ACCUMULATION、OXIDATIVE STRESS EXPOSURE、MINING AREA、WASTE、SOLVENT-EXTRACTION、POLLUTION、CONTAMINATION
6	61	Research on rare earth biochemical medicine	PLANTS、CELLS、SUPEROXIDE-DISMUTASE、RESPONSES PROTEIN、APOPTOSIS LEAVES、NEPHROGENIC SYSTEMIC FIBROSIS、URINE、LIQUID-CHROMATOGRAPHY、PHARMACEUTICAL DOSAGE FORMULATIONS、EXAFS SPECTROSCOPY

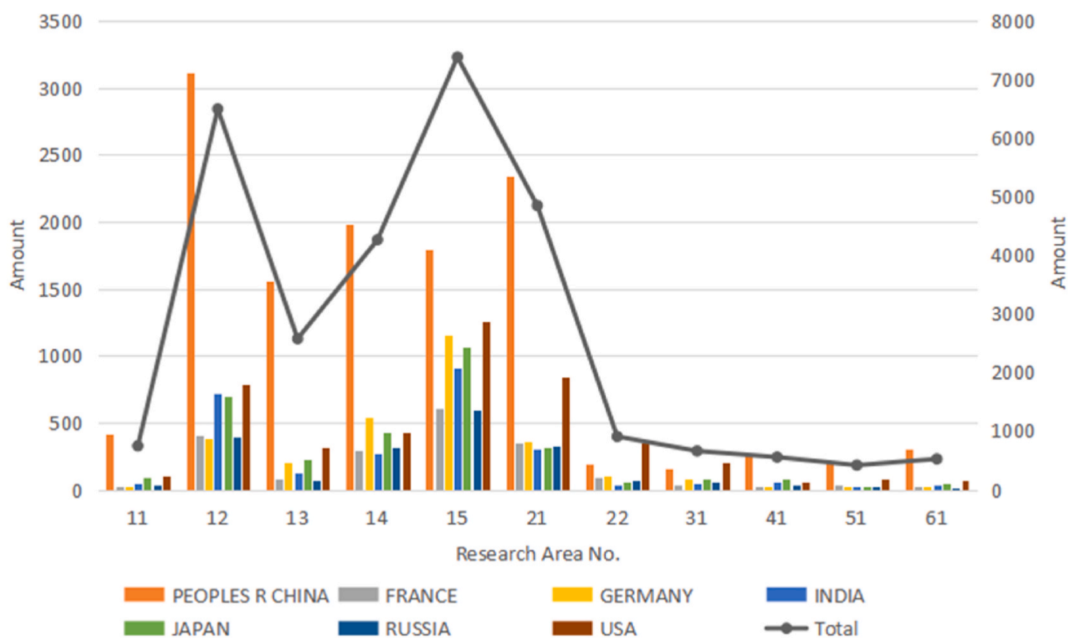

Fig. 7. Comparison of papers in various research areas of major rare earth research countries.

rare earth oxide research (code 11), rare earth geology and mining/marine research (code 22), rare earth nuclear magnetic resonance research (code 31), rare earth environmental protection research (code 51), rare earth biochemical medicine research (code 61) and rare earth separation and recycling research (code 41). There are generally no more than 1000 research papers in the above fields. In terms of countries, China is in a dominant position in rare earth research, with the most significant advantages in rare earth luminescence technology research (code 12), rare earth alloy research (code 13), rare earth chemical properties research (code 14) and rare earth geology and mineral research (code 21). In the above research fields, China has over 1500 papers, especially more than 3000 papers in luminescence technology research and geological and mineral technology research, far ahead of other countries (basically within 500 papers except for a few countries). Notably, China has proposed the green development of rare earth industry, whereas the relevant research (code 51) is still weak in the number of papers. In rare earth research in other countries, rare earth magnetic research (code 15) is generally valued by all countries, with a high number of papers issued. Permanent magnets are important materials for the future low-carbon society. For instance, using neodymium iron boron magnets can significantly reduce the amount of magnetic material used, reduce the volume and weight of the motor, and significantly improve the efficiency of electrical and mechanical energy conversion. Compared to ordinary permanent magnets, the energy efficiency is increased by more than 10%–15%. Thus, countries attach great importance to it. While other research fields have different priorities, including the United States in geological and mineral research (code 21 and 22), Japan in luminescence research (code 12), and Germany in rare earth physicochemical properties research (code 14). The main reason why the United States stands out in the field of geological and mineral research is that it has considerable rare earth resources. According to the data from the United States Bureau of Geology and Mineral Resources, the United States has 2.3 million tons of rare earth reserves, an increase of 28% in comparison with the previous year. The main intention of the United States is to establish itself and break China's monopoly on rare earth resources. Accordingly, the focus should be placed on geological and mineral research and restore domestic rare earth minerals. Japan's and Germany's respective layouts in luminescence research and physicochemical property research are primarily correlated with their advantageous industries, and Japan's imaging technology in the electronic information industry is globally leading. Germany serves as a major exporter of automobiles and mechanical equipment, consuming a large amount of rare earth resources. Currently, it is committed to the research on rare earth substitutes. Thus, in-depth research on the unique physical and chemical properties of rare earth and finding alternative products are critical to work.

This study calculates the average growth rate of papers published by countries in various research fields in the past 10 years (2012–2021) to examine their development trend. The results are shown in Fig. 8. In terms of countries, China's growth in the traditional research field of large-scale rare earth is relatively slow, while the most rapid growth is in the field of rare earth separation and recycling (code 41) and environmental protection (code 51), which basically reflects the industrial goal of improving rare earth separation efficiency and ecological green development proposed during the 13th Five Year Plan period. Other countries with relatively rapid growth are Japan's rare earth recycling research (code 41), oxide research (code 11). In the United States, there is oxide research (code 11), biochemical medicine research (code 61), etc. As early as 2008, Japan passed the Basic Environmental Plan to recycle rare earth resources. The method of recovering rare earth elements from waste electronic parts developed by Litem Co., Ltd. Can recover 3000 tons of rare earth materials every year. In the direction of rare earth oxide purification, Japan is the critical source country of technology besides China, and the United States also should transfer rare earth to China for processing every year, such that it is of great strategic significance for the above two countries to improve their oxide research strength. India has significantly increased the number of publications in a considerable number of fields, which comprise oxide research (code 11), rare earth alloy research (code 13), rare earth separation and recycling (code 41), as well as environmental protection (code 51). Under trade frictions between China and the United States, India has implemented a strategy of expanding product exports and intensifying competition for investment in the manufacturing industry chain, taking the opportunity to stimulate India's economic and trade interests and revitalize India's manufacturing industry. In a study commissioned by the Indian Ministry of Science and Technology, the Indian Energy, Environment and Water Council suggested that rare earth resources will take on critical significance in nurturing India's domestic manufacturing industry to support the government's low-carbon plan. Accordingly, the entire rare earth industry chain has received widespread attention in India. The research focus of France is also placed on rare earth alloy research (code 13), rare earth geological and mineral research (code 21), and rare earth geological and mineral/marine research (code 22). In general, scientific research and research efforts primarily focus on the acquisition and processing of rare earth resources. In recent years, Germany has experienced a decline in rare earth nuclear magnetic resonance research (code 31), mainly due to a significant decline in the research output of the Helmholtz Institute, a research institution in this field. Since Helmholtz refers to a nationally funded research institution, it is speculated that Germany place major stress on the recovery and replacement of rare earth materials. For instance, the German Fraunhofer

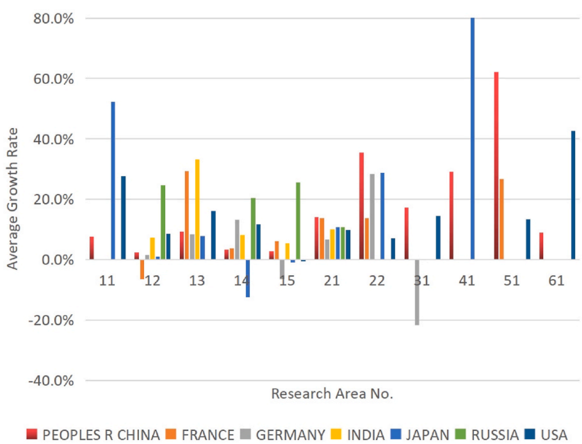

Fig. 8. Comparison of growth trend of papers in various research areas of major rare earth research countries.

Research Institute started the "Critical Rare Earth" project to conduct large-scale research from motor magnets, rare earth element recovery, and the search for alternatives. Thus, the national budget may be reduced for rare earth nuclear magnetic resonance research. In terms of research field, the number of papers issued by various countries in rare earth magnetic research (code 13) and rare earth geology and mineral research (code 21) is increasing, suggesting the common trend of their research and development. Rare earth resources take up a vital strategic position, and China is controlling the main supply of global rare earth resources and the processing of intermediate products. Other countries must consider supply chain security issues. Accordingly, the layout in the above two aspects is the most, suggesting that rare earth materials are crucial components in the industrial system, and rare earth resources are valued by countries as original guarantees.

As a crucial part of scientific evaluation, highly cited papers refer to those papers that have been cited in the forefront of the discipline within the specified statistical time. The above papers, to a certain extent, represent the research progress of the discipline, which is of great significance. In this study, highly cited papers over the past decade that were marked in SCIE database are selected as research objects and then classified in accordance with countries and research fields, (Table 3). The number of highly cited papers in China is the highest, reaching 58, over half of the global total. However, the above highly cited papers are mainly concentrated in rare earth luminescence (code 12), physical and chemical properties (code 14) and geological and mineral research (code 21), rare earth magnetic research (code 15), China's traditional advantageous fields (e,g., alloy research (code 13), separation and recycling (code 41) and green environmental protection research (code 51)) that have been mentioned in the rare earth industry development plan, whereas China's highly cited articles are still blank. Among other countries, the United States has more highly cited papers in the field of geological and mineral research, and Japan has made breakthroughs in rare earth resource recovery. For instance, the United States proposed to extract rare earth from the deep-sea polymetallic nodules; Nissan has developed an effective method for recovering rare earths from waste motor components, which can recover 98% of the rare earths used in motors. The recovery time and cost have also been reduced to about half of those of previous methods.

4.6. Key research institutions

4.6.1. General overview

The number of papers issued by major rare earth research institutions crown coefficient is shown in Fig. 9. In terms of quantity, the Chinese Academy of Sciences (CHINESE ACAD SCI) has an absolute advantage, with more than 2000 papers, and the Russian Academy of Sciences (RUSSIAN ACAD SCI) has more than 1000 papers. Later, many institutions have published between 200 and 500 papers; In terms of quality, University of Tokyo (UNIV TOKYO) in Japan has the highest crown coefficient of 1.89. In addition, University of Nanjing (UNIV NANJING), University of Science and Technology China (UNIV SCI&TECH CHINA) Peking University (PEKING UNIV), Jilin University (JILIN UNIV) and China University of Geosciences (CHINA UNIV GEOSCI) exceeded the average (1.00), while the Russian Academy of Sciences (RUSSIAN ACAD SCI) with a high number of papers has a low crown coefficient, Only 0.47; From the perspective of countries, China's scientific research institutions have reached the international leading level in rare earth research, and have obvious overall advantages in terms of quantity and quality. In other countries, the Russian Academy of Sciences is in the lead in terms of quantity, and in terms of quality, except for the leading University of Tokyo (UNIV TOKYO), Germany's University of Munster (UNIV MUNSTER), France's National Center for Scientific Research (CNRS). The crown coefficients of Osaka University (OSAKA UNIV) and Tohoku University (TOHOKU UNIV) are mostly between 0.8 and 1.0. The research of the University of Tokyo in Japan placed a major focus on the exploration and extraction of rare earth resources. For instance, in 2018, the research team of the University of Tokyo reported that over 16 million tons of rare earth resources were stored on the seabed around the easternmost of Minami Torishima Island of Japan. Osaka University primarily conducted the research on magnets and rare earth substitutes, whereas Munster University in Germany leads the world in research on the application of rare earths to superconducting technology.

The time dimension was regulated to nearly 10 years (2012–2021), and the number of documents issued by major rare earth research institutions crown coefficient is present in Fig. 10. Notably, the overall distribution of major rare earth research institutions in terms of quantity, quality and country is consistent with that before. It is noteworthy that China has significantly improved the quality of rare earth research over the past decade. The crown coefficient of relevant institutions in China has increased. To be specific, while the Chinese Academy of Sciences (CHINESE ACAD SCI) continues to maintain considerable advantages, its crown coefficient has increased from 1.26 to 1.63. Moreover, India's rare earth research represented by Bhabha Atomic Energy Research Center (BHABHA ATOM RES CTR) and Indian Institute of Technology (INDIAN INST TECH) shows a significant upward trend. In the period of rare earth

Table 3
High cited papers of major rare earth research countries in recent 10 years.

Country	Research Area											Total
	11	12	13	14	15	21	22	31	41	51	61	
Peoples R China		32		9	2	15						58
France						1	2	1				4
Germany		3		3								6
India		4		2								6
Japan					2				1		1	4
Russia				1								1
USA		7	3		3	7	3				1	24

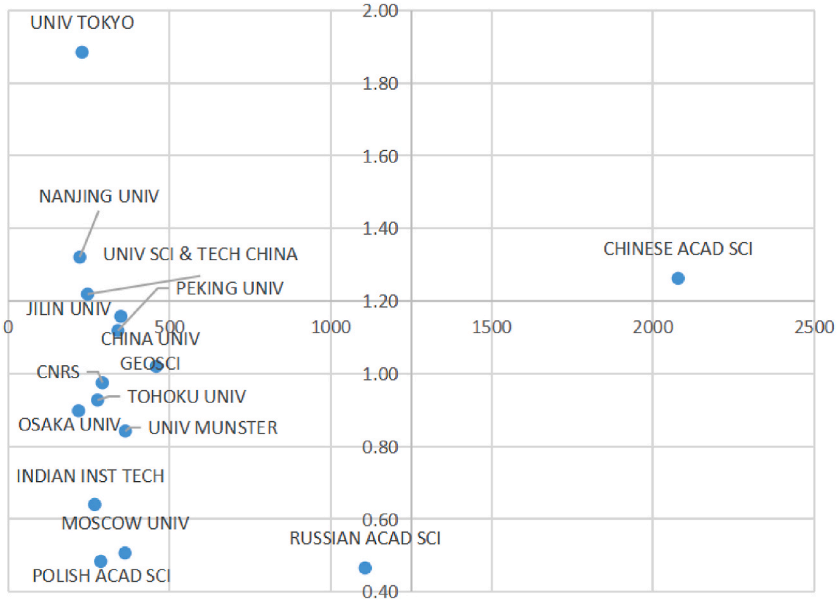

Fig. 9. Number of documents issued by major rare earth research institutions Crown coefficient.

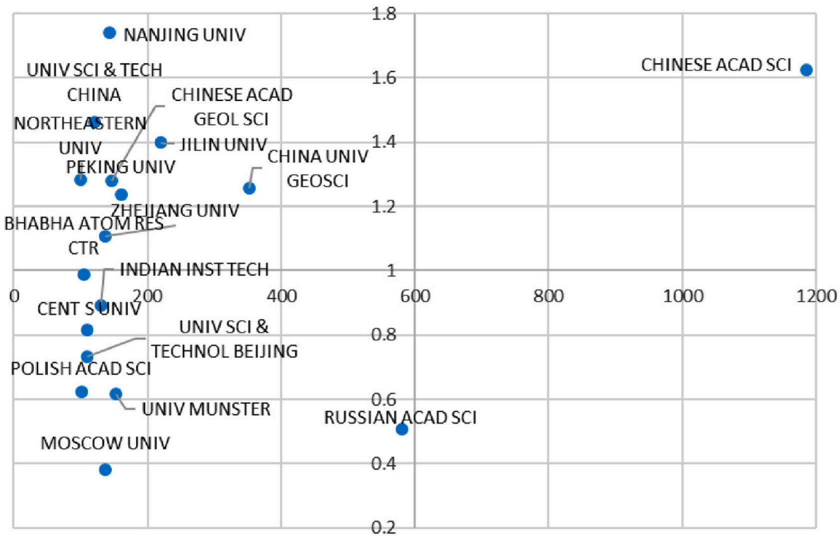

Fig. 10. Number of documents issued by major rare earth research institutions in recent ten years (2012–2021) - Crown coefficient.

price fluctuation in 2010, India announced its plan to restart rare earth production. As a long-term strategy, it is expected to make up for the market gap caused by the decline of China's rare earth exports. India has currently become the second largest rare earth producer worldwide. Permanent magnetic materials, light-emitting materials and hydrogen storage technology are one of the critical products of rare earth, and Baba Atomic Energy Research Center and Indian Institute of Technology are the major institutions in India to study the above two technologies, suggesting that India pays attention to rare earth mining while deserving continuous attention to the extension of the industrial chain.

4.6.2. Analysis of key research institutions in different research directions

The main research institutions were selected in accordance with the above 11 research fields, as listed in Table 4. The respective research field is divided into two groups as follows. The first group is the leading institution of document volume, and the other group is the leading institution of crown coefficient. In the field of geological and mineral research at the upstream of the rare earth industry chain, the number of key institutions is out of proportion to the total number though China leads in the total number of documents issued. Except for the traditional advantageous institutions, such as the Chinese Academy of Sciences (CHINESE ACAD SCI), the China

Table 4
Key institutions in different fields of rare earth research.

Research area	Key Institution						
11	CHINESE ACAD SCI	BEIJING UNIV CHEM TECHNOL	ZHEJIANG UNIV TECHNOL	KYOTO UNIV	RUSSIAN ACAD SCI	SHANGHAI UNIV	NANCHANG UNIV
	CHINESE ACAD SCI	SHANGHAI UNIV	NANCHANG UNIV	ZHEJIANG UNIV TECHNOL	KYOTO UNIV	BEIJING UNIV CHEM TECHNOL	RUSSIAN ACAD SCI
12	CHINESE ACAD SCI	RUSSIAN ACAD SCI	CHANGCHUN UNIV SCI & TECHNOL	TONGJI UNIV	JILIN UNIV	LANZHOU UNIV	BHABHA ATOM RES CTR
	FUDAN UNIV	UNIV GHENT	HARBIN ENGN UNIV	CHINESE ACAD SCI	SHANGHAI JIAO TONG UNIV	BHABHA ATOM RES CTR	NATL INST MAT SCI
13	CHINESE ACAD SCI	SHANGHAI JIAO TONG UNIV	CENT S UNIV	NANJING UNIV AERONAUT & ASTRONAUT	HARBIN INST TECHNOL	CHONGQING UNIV	NORTHEASTERN UNIV
	ZHEJIANG UNIV	MONASH UNIV	UNIV TEHRAN	BEIJING UNIV TECHNOL	CHINESE ACAD SCI	CENT S UNIV	NANJING UNIV AERONAUT & ASTRONAUT
14	CHINESE ACAD SCI	RUSSIAN ACAD SCI	ZHEJIANG UNIV	ANHUI NORMAL UNIV	LANZHOU UNIV	NANKAI UNIV	UNIV CALIF IRVINE
	CHINA UNIV MIN & TECHNOL	PEKING UNIV	UNIV RENNES 1	KIT	CHINESE ACAD SCI	NANKAI UNIV	HENAN UNIV
15	RUSSIAN ACAD SCI	CHINESE ACAD SCI	UNIV MUNSTER	MOSCOW MV LOMONOSOV STATE UNIV	IOWA STATE UNIV	UNIV DELAWARE	INDIAN INST TECHNOL
	NATL INST MAT SCI	CHINESE ACAD SCI	NORTHEASTERN UNIV	IOWA STATE UNIV	TOHOKU UNIV	ZHEJIANG UNIV	CNRS
21	CHINESE ACAD SCI	CHINA UNIV GEOSCI	CHINESE ACAD GEOL SCI	RUSSIAN ACAD SCI	JILIN UNIV	NANJING UNIV	PEKING UNIV
	UNIV HONG KONG	JACOBS UNIV BREMEN	GUMUSHANE UNIV	UNIV SCI & TECHNOL CHINA	NANJING UNIV	CHINESE ACAD SCI	US GEOL SURVEY
22	CHINESE ACAD SCI	CHINA UNIV GEOSCI	CHINESE ACAD GEOL SCI	RUSSIAN ACAD SCI	AUSTRALIAN NATL UNIV	NANJING UNIV	UNIV DURHAM
	UNIV WISCONSIN	JAPAN AGCY MARINE EARTH SCI & TECHNOL	UNIV NACL AUTONOMA MEXICO	JILIN UNIV	UNIV DURHAM	AUSTRALIAN NATL UNIV	UNIV MUNSTER
31	BROOKHAVEN NATL LAB	CHINESE ACAD SCI	PEKING UNIV	RUSSIAN ACAD SCI	UNIV WISCONSIN	MCMASTER UNIV	UNIV COLOGNE
	UNIV VIENNA	UNIV ZARAGOZA	EUROPEAN SYNCHROTRON RADIAT FACIL	UNIV WISCONSIN	RUSSIAN ACAD SCI	BROOKHAVEN NATL LAB	UNIV COLOGNE
41	CHINESE ACAD SCI	RUSSIAN ACAD SCI	TSINGHUA UNIV	UNIV TEHRAN	KYUSHU UNIV	ATOM ENERGY AUTHOR	CHINA UNIV GEOSCI
	TOHOKU UNIV	KATHOLIEKE UNIV LEUVEN	KYOTO UNIV	KYUSHU UNIV	POLITECN TORINO	TSINGHUA UNIV	NATL MET LAB
51	JIANGNAN UNIV	CHINESE ACAD SCI	UNIV MONTREAL	UNIV PALERMO	SOOCHOW UNIV	JAN KOCHANOWSKI UNIV HUMANITIES & SCI	NANJING NORMAL UNIV
	WAGENINGEN UNIV	KATHOLIEKE UNIV LEUVEN	TSINGHUA UNIV	UNIV QUEENSLAND	UNIV SOUTHERN DENMARK	CSIC	JIANGNAN UNIV
61	CHINESE ACAD SCI	JIANGNAN UNIV	NANJING NORMAL UNIV	INNER MONGOLIA UNIV	LANZHOU UNIV	UNIV TOKYO	RTM NAGPUR UNIV
	PEKING UNIV	WUHAN UNIV	LANZHOU UNIV	UNIV TOKYO	CHINESE ACAD SCI	JIANGNAN UNIV	SOOCHOW UNIV

University of Geosciences (CHINA UNIV GEOSCI), the Chinese Academy of Geological Sciences (CHINESE ACAD GEOL SCI), Peking University (PEKING UNIV), and Nanjing University (NANJING UNIV), all of them are foreign institutions, suggesting that foreign countries have invested heavily in rare earth exploration and mining over the past few years. For instance, the United States Geological and Mineral Survey (US GEOL SURVEY) and some countries have recently discovered rare earth minerals and joined the research team (e.g., Türkiye's GUMUSHANE UNIV). Moreover, the deep-sea resources of rare earth have become the focus of many foreign research institutions (e.g., the Japan Ocean Science and Technology Center (JAPAN AGCY MARINE EARTH), and the University of Wisconsin (UNIV WISCONSIN)). Although the enrichment of rare earth elements in the ocean is not new, the submarine geological survey will be promoted in 2019 with Japan's completion of the evaluation of rare earth deposits in the offshore Minami Torishima Island in 2016 [51]. Japanese marine research and development institutions and comprehensive industrial technology research institutes will accurately estimate the content of rare earth mud and plan to launch trial production in 2022. On that basis, the research on rare earth deep-sea resources will become a hotspot in the future. In July 2019, the White House of the United States released the Energy Resource Governance Initiative (ERGI), with an aim to build an international resource governance system led by the United States and other western countries to ensure their supply. China's relevant institutions are outstanding in terms of research quantity and quality of results in the field of rare earth industry chain processing (oxide research and alloy research). For instance, in the field of oxide research and alloy research, China's relevant institutions (e.g., the Chinese Academy of Sciences (CHINESE ACAD SCI), Shanghai University (SHANGHAI UNIV), Nanchang University (NANCHANG UNIV), Central South University (CENT S UNIV), and Shanghai Jiao Tong University (SHANGHAI JIAO TONG UNIV)) have been taking the lead. China is currently the largest exporter of rare earth, as well as the largest importer. The main reason for this result is that China outperforms other countries in rare earth primary processing. Most rare earth ores should be transported to China for purification and refining and then exported to downstream manufacturers in a wide variety of industries for product manufacturing. For instance, the rare earth raw ore mined in Mountain Pass should be transported to China for primary processing and then transferred back to the United States. In the application fields in the middle reaches of the rare earth industry chain (e.g., luminescence research, physical and chemical properties research, and permanent magnet research), China shows significant advantages in luminescence research and permanent magnet research, while foreign institutions (e.g., the University of Delaware (UNIV DELAWARE), Iowa State University (IOWA STATE UNIV), the University of Munster (UNIV MUNSTER) in Germany, Tohoku University (TOHOKU UNIV) in Japan) have strong competitiveness in the field of permanent magnet research. It is noteworthy that Ames Laboratory of the US Department of Energy (DOE), set up in Iowa State University (IOWA STATE UNIV), exhibits strong strength in the number and quality of papers. Permanent magnets take on great significance in the future industry. The energy density of a permanent magnet motor is increased with the energy density of the magnet. To continuously expedite technological progress, the United States Department of Energy has developed the Vehicle Technologies Program (VTP) to focus on reducing the rare earth content of electric motors in the next decade. In the permanent magnet motors of existing hybrid electric vehicles, the rare earth content is about 3–5 g of rare earth materials per kW of rated peak power. In future electric vehicle (EV) applications, full electric propulsion of large-scale vehicle platforms may require the provision of 100 kW (continuous)/200 kW (peak) motors. The above-mentioned vehicles will use larger, high-performance motors. The VTP project aims to develop advanced electric vehicle motors, eliminate, or significantly reduce the rare earth content, making it lower than 10% of existing permanent magnet motors (not exceeding 0.33 g/kW). Besides being extensively employed in fields (e.g., civil electric motors), permanent magnet materials are also essential materials for high-end weapons (e.g., guided bombs, cruise missiles, and Joint Strike Fighter (JSF)). The Department of Defense (DOD), the Government Accountability Office (GAO), and RAND have repeatedly mentioned the significance of permanent magnetic materials for the U.S. economy and military. Thus, the research on permanent magnetic materials will become increasingly intense in the future. A wide range of countries have different areas of advantage in other relevant papers with relatively small paper scales. In the field of rare earth separation and recycling, China has an advantage in separation technology, while Japan and Belgium are leading in recycling technology. For instance, Hitachi Metal started the recycling business of Nd-Fe-B sintered magnet processing debris (waste) in 2015, and the University of Leuven in Belgium (KATHOLIEKE UNIV LEUVEN) is developing the use of ionic liquids to recover rare earth from waste fluorescent lamps. Other countries are also stepping up research and industrialization of rare earth resource recovery. For instance, the French company Carester was established in 2019 and plans to build a factory to extract and recover rare earth from permanent magnets, with a proposed investment of 56 million euros. In 2021, the company has successfully completed financing. In 2022, the French government will invest another 15 million euros in a recovery fund to accelerate the development of the rare earth recycling industry. Rare earth nuclear magnetic resonance research mainly involves the application of rare earth in medical and detection fields such as nuclear magnetic resonance. Because the equipment in this field is mainly from European and American manufacturers, Europe and the United States have absolute advantages in research. China has taken the lead in the number of papers in the field of environmental protection research. For instance, Jiangnan University (JIANGNAN UNIV) has shown a certain degree in rare earth ecological governance, and Soochow University (SOOCHOW UNIV) has shown a certain degree in radioactive pollution control. However, in terms of quality, European and American research institutions still rank first, Including Wageningen University (WAGENINGEN UNIV), University of Leuven (KATHOLIEKE UNIV LEVEN), and University of Southern Denmark (UNIV SOUTHERN DENMARK). The above-described research institutions have strong cooperative relationships, such as Wageningen University, Institute of Ecological Environment Netherlands (NIOO-KNAW), and the University of South Denmark, which have close cooperative relationships in the field of rare earth element ecological environmental protection. Thus, the overall strength is strong. In the field of rare earth biochemical medicine research, relevant institutions in China have obvious advantages, such as Peking University (PEKING UNIV), Jiangnan University (JIANGNAN UNIV), Nanjing Normal University (NANJING NORMAL UNIV), etc.

4.7. Fund support analysis

4.7.1. General overview

The science fund takes on great significance in ensuring discipline construction. It can directly provide financial guarantee for human and material resources while expanding and deepening the direction of discipline development. It is also a crucial reference index for information personnel to obtain the latest academic trends and master the trend of discipline development. Fig. 11 shows the funding trend of rare earth related papers. In terms of time, the funding of rare earth papers started in 2007. If considering other time factors such as the time interval, rare earth research funds mainly started around 2005, and then increased rapidly. Moreover, the trend is basically the same as the graph trend of the number of papers issued, which not only shows that rare earth funding has a trend of increasing year by year, but also shows that it is more obviously stimulated by external factors. In terms of countries, it is similar to the distribution of papers. As depicted in Fig. 12, China's SCI paper funding accounts for the highest proportion worldwide, close to 40%, followed by the United States (9%), India (5%), Germany (5%), Russia (5%), Japan (5%) and other countries. In addition, nearly 30% of the funded papers come from countries not listed in the figure, which indicates that considerable countries have provided funding support in the field of rare earth research, but the number of papers issued is low, and no fixed research force has been formed. As mentioned above, due to the overall stability of the supply of rare earth resources, most countries have not previously formed linked funding.

4.7.2. Funding direction and effect analysis

In this study, the proportion of funding from different research directions was represented by the proportion of papers funded by different research directions. From the proportion of research fields supported by the Fund, as presented in Fig. 13, the proportion of funding for rare earth luminescence research, rare earth physicochemical properties research, rare earth magnetic research and rare earth geology and mineral research is high, followed by rare earth alloy research, and the proportion of funding for other research directions is low. In terms of countries, China has the largest support for luminescence research, close to 25%, followed by geological and mineral research (nearly 20%), and alloy research, physical and chemical properties research and magnetic research (nearly 10–15%). Compared with China, the most significant difference between other countries lies in the research on rare earth magnetism. The proportion of China's fund in this field is about 12%, whereas that of other countries is more than 20%, up to 30%. Besides the research on rare earth magnetism, India's funding for luminescence research (about 30%), Germany's research on rare earth physicochemical properties (about 22%), and the United States' funding for rare earth geology and mineral research (about 19%) are significant as well. Due to their industrial characteristics and strategic objectives, the United States and Germany have focused on the field of geological and mineral research and the study of rare earth physicochemical properties. India's research on selective luminescence has primarily relied on two key institutions with a preliminary research foundation, i.e., Bhabha Atomic Energy Research Center (BHABHA ATOM RES CTR) and the Indian Institute of Technology (INDIAN INST TECH). The research of the above-mentioned two institutions originated from atomic energy engineering technology, and it is similar to rare earth luminescence research. Accordingly, they receive more funding in the field of luminescence.

The average trend of fund changes in recent 10 years is shown in Fig. 14. In terms of research field, only the rare earth geology and mineral research field has witnessed an increase in the amount of fund support from all countries, suggesting that the rare earth resource guarantee represented by rare earth geological exploration and research is the main direction of a wide range of countries' funding. In addition, research in numerous rare earth intermediate fields (e.g., alloy research and magnetic research) also has a general growth trend in various countries. In terms of specific countries, China has seen the fastest growth in environmental protection research on rare earth. In addition, funds for rare earth separation and recycling have witnessed a relatively rapid growth, basically consistent with the guiding direction of green development and improving separation and recycling efficiency proposed by China's "13th Five Year Plan" for rare earth. Japan's average growth in rare earth alloys exceeded 80%. In the disclosed Japanese Rare Earth Strategy 2030, permanent magnet and hydrogen storage were clearly identified as Japan's future development direction, both need high-quality alloy technology. Shin-Etsu Chemical and Showa Denko built rare earth alloy factories in China from 2012 to 2013 to satisfy the growing demand [52]. Furthermore, Japan has become the critical rare earth alloy producer worldwide except China, suggesting the significance of rare earth alloys to Japan.

With reference to the calculation method of institutional crown coefficient, this study calculates the ratio of the number of citations of the papers supported by the fund of each research direction to the overall average, to investigate the effect of the fund support of the respective country in the past 10 years. The calculation results are presented in Fig. 15. The citation frequency of papers supported by the Russian Foundation is the lowest, nearly consistent with the previous analysis of the crown coefficient of institutions, i.e., the rare

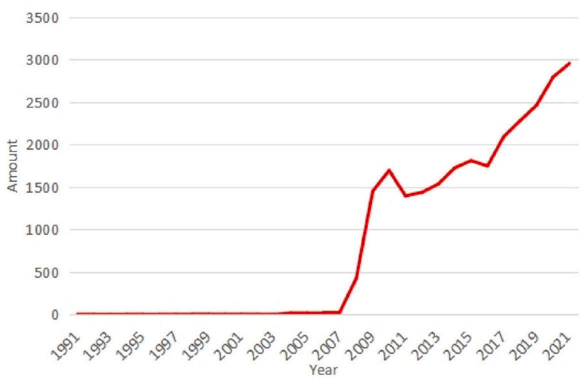

Fig. 11. Number of papers supported by the rare earth research fund.

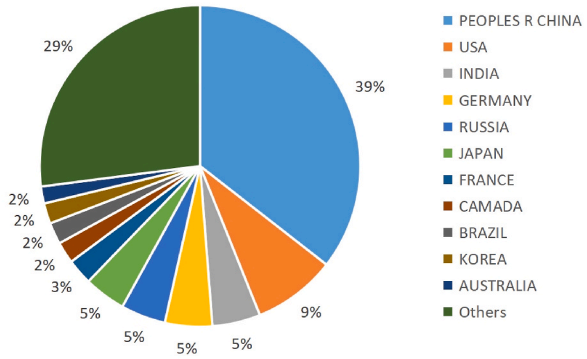

Fig. 12. Number of articles supported by the rare earth research fund.

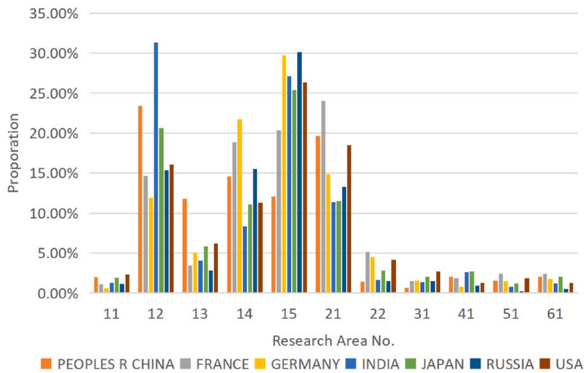

Fig. 13. Proportion of papers supported by the rare earth research fund.

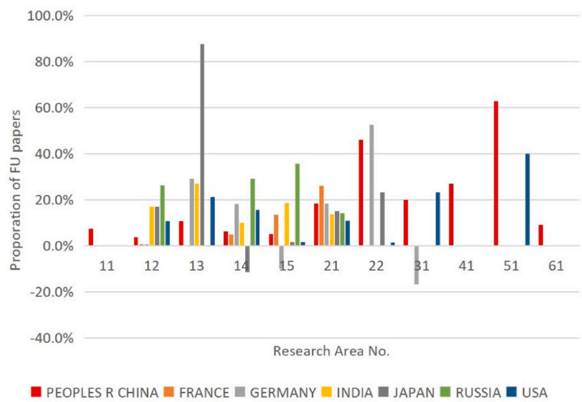

Fig. 14. Trends of papers supported by the rare earth research fund.

earth research in Russia is largely concentrated in the Russian Academy of Sciences and Moscow University, whereas the current research capacity of the above two institutions is not high. India's research institutions, a new force in rare earth research, are similar to those of Russia. They have been conducting relevant research mainly relying on two leading institutions, the Bhabha Atomic Energy Research Center, and the Indian Institute of Technology. Although the crown coefficient is average (nearly 1), the short history of rare earth research in India has not significantly improved India's overall research strength, which is manifested by the relatively low effect of fund support. China's fund support effect is at the middle level, leading in some research fields (rare earth compound purification, rare earth geology, and mineral research). However, the crown coefficient of major research institutions in China is high, suggesting that China's rare earth funds are scattered, and there are considerable interveners besides some R&D institutions, leading to the lack of overall fund use effectiveness; The use of funds in Japan, Germany and the United States is high. For instance, Japan and Germany are the most prominent in the field of rare earth separation and recycling and rare earth alloy research, with significant strategic goals. The

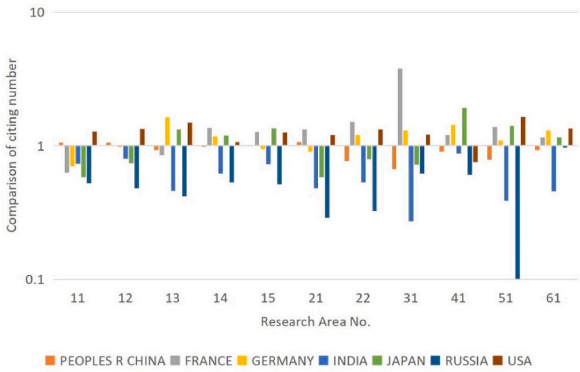

Fig. 15. Comparison of citations of papers supported by the rare earth research fund in recent 10 years.

overall research level of rare earth research in the United States is the highest. Although the distribution is uneven due to the choice of the industrial chain, it their technical reserves and technical strength remain at the international leading level.

5. Discussion, conclusion and future research directions

5.1. Discussion

In this study, the characteristics of rare earth research conducted in a wide range of countries are discussed. Since the beginning of this century, as China has undertaken the supply of global rare earth resources, China has received the highest scientific research investment and output in the field of rare earth resources. However, with the increasingly prominent strategic position of rare earth resources, innovation in rare earth resources has aroused rising attention. It is noteworthy that after the WTO rare earth dispute and the Sino-Japanese rare earth dispute, rare earth research has become a strategic goal for China and other countries. Notably, after the trade friction between China and the United States in 2018, rare earths have become a concern of all parties once again. Currently, with supply chain security becoming a new focus, major countries worldwide are expediting the layout of research in various aspects of rare earth, and the output of papers is continuously rising, and the output of rare earth scientific research has reached a higher level.

This study is based on the rare earth research field unit constructed by SCI paper information, and conducts international comparison on research directions, research institutions, funding and other aspects of rare earth research in various countries. Through the SCIE database, we collected 50,149 papers related to rare earth. In addition, we divide the above papers into 11 main technical fields according to topic clustering. Then, the characteristics of a wide range of countries were analyzed in different fields. Moreover, the crown coefficient is used to analyze the paper quality and research priorities of various scientific research institutions, as well as the funding direction of various countries in the field of rare earth. The current situation, development characteristics and trends of rare earth research worldwide are obtained.

The bibliometric analysis using the paper data is a vital means to understand the research status and explore the development trend. And most of the existing rare earth industry research based on paper information is to analyze the technological superiority or technological evolution of a wide range of countries in specific technologies or product segments through paper data [53]. Even the analysis of a full range of papers is often carried out from the single dimension of discipline, and the actual application of the papers is usually ignored, thus causing possible miscalculation. As far as we know, this study is the first time to try to use the method of twice clustering to obtain different rare earth research fields, while also having disciplinary characteristics. Through this study, policy managers and decision-makers can obtain the research priorities and future layout of the world's major rare earth research contributors. Accordingly, they may be able to gain more insights into where the focus of current research is, and what areas should increase research investment, to gain advantages in the competition of the rare earth industry in the future.

5.2. Conclusion

Base on the analyses above, the following conclusions have been drawn:

First, original achievements have been confirmed as a driving force of industrial progress, and they take on great significance in ensuring competitive advantage. Moreover, existing research on rare earth has fluctuated with political events. The Sino Japanese East China Sea dispute and the WTO's decision on China's rare earth export quotas have stimulated the research on rare earth. In the future, major countries worldwide will deploy their key minerals to ensure supply chain security. Thus, the input and output of rare earth research will be increased. It is noteworthy that China has firmly grasped the intermediate links of the industrial chain in the fields of rare earth minerals, rare earth alloys, and rare earth oxides. Against the backdrop of the decoupling between China and the United States, Western countries will definitely increase research investment in the above fields, give play to the advantages of multidisciplinary cooperation, and break through China's monopoly. Moreover, despite China's leading number of papers in several fields (e.g., rare earth oxide purification, rare earth alloy technology, and rare earth separation technology), relevant original achievements have been rare. Accordingly, in the above-described fields, China also needs to maintain its innovation efforts and create more original results, to maintain its leading edge for a long time.

Secondly, the research on rare earth magnetism and substitutes is a field vigorously developed by various countries. From the perspective of the proportion of publications and funding trends, rare earth magnetic materials are also a key research field actively promoted by various countries. Magnetic materials are one of the important supports for new energy technologies. For instance, Japan has explicitly listed rare earth magnetic materials as the key application objects of rare earth in the future. The European Commission's goal is that by 2030, 10% of the EU's demand for key raw materials will be met through its own mining operations, 40% from local processing, and 15% from EU recycling capacity. In the latest key materials strategy of the US Department of Energy, rare earth magnetic materials have also been listed as a key area of concern. The estimation suggests that as new energy technologies have been widely employed, the use of key metals represented by rare earths will be increased tenfold by 2050. In some aspects, competition among countries has begun to take shape. For instance, in the current largest consumption of neodymium iron boron rare earth permanent magnet materials, all core patents are held by Japanese and American companies. Thus, the research on rare earth magnetism and substitutes should be the core of the competitiveness of the future national rare earth industry, and the key to transforming rare earth from reserves and technological advantages to national strategic advantages. To be specific, in the field of basic research, the core functional mechanisms of rare earth elements (e.g., magnetism, catalysis, and fluorescence) should be explored, while cooperating with high-value application research that adapts to terminal application needs, including rare earth magnetic materials (i.e., permanent magnet motors), rare earth luminescent materials (i.e., LED display devices), rare earth alloy materials (i.e., key aerospace components), and drawing on the experience of China's rare earth industry in optimizing product structure and industrial layout.

Third, the scientific research layout and the research scale have been small in some research fields of rare earth, comprising green development fields (e.g., rare earth ecological and environmental protection) and fields regarding medicine and health. The above-mentioned areas have not aroused wide attention since they have not covered competition between countries. As China is the main upstream producer of rare earth industry, it has issued more documents than other countries. However, from a horizontal perspective, China's research scale in the above-described areas is also relatively small. Even though China's rare earth research papers have leapt to the top worldwide since 2000, and the current annual publication volume is five times that of the second place, the distribution of research directions is uneven, and the repeatability is relatively high [54]. Moreover, there is a situation of "many, small, and scattered" on the research level, with weak research institutions and low quality of scientific research output. Some institutions in the Netherlands, Belgium, and Denmark have exhibited significant research capabilities through collaborative research. Accordingly, in several fields where there is not much scientific research layout or research scale, ways of enhancing scientific research capabilities can be explored through joint research.

Fourth, from the perspective of fund data, numerous countries have invested in the field of rare earth. However, from the perspective of vital research institutions, it has been primarily concentrated in a few countries. Thus, the key to increasing the effectiveness of fund use is to continuously invest in crucial directions and core scientific research institutions. In rare earth research, China has formed several research institutions with large scale and strong strength in their respective core fields. However, for fund use validity, China remains at the middle international level, with large investment and wide distribution, whereas the results are uneven. In contrast, scientific research funds can clearly reveal the achievement level of the United States and the strategic direction of Japan, the research direction is also relatively concentrated. On that basis, it is imperative for countries to focus on funding advantageous research institutions with scientific research funds and draw upon core institutions to expedite the research in areas (e.g., magnets that are highly competitive). In small-scale green/characteristic research fields (e.g., rare earth material recovery and environmental protection governance), research centers can be established, and large-scale plans and projects can be set up to expedite the implementation of joint efforts based on multiple scientific research institutions.

5.3. Future research directions

This study has some limitations that should be acknowledged. First of all, our research focus is on papers in the field of rare earth. The quality of papers in a wide range of countries varies significantly. In some countries, such as China, papers are mainly from research institutions sponsored by the state, and the number of papers is the main indicator for the above institutions to evaluate their own researchers, and this policy has been implemented for a long time, so the number of papers is massive, however the quality is incredibly low. Second, clustering is performed automatically through the network community approach, which cannot guarantee accuracy. In particular, the clustering in this study forms 11 small research directions, but there must be more detailed division in some fields, which will lead to deviation in the calculation results.

To avoid the above limitations, the future research should first design of the value calculation method for the SCI papers to guarantee more accurate raw data. Second, we can improve the clustering accuracy and make the results closer to practical innovation.

Author contribution statement

Wen Xiao: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Lei Zhou: Analyzed and interpreted the data; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ping Yang: Contributed reagents, materials, analysis tools or data; Performed the experiments.

Na Yan: Analyzed and interpreted the data; Wrote the paper.
Chen Wei: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data underlying the study are third-party data downloaded from Thomson Reuters' Web of Science database (www.webofknowledge.com). Full details for search criteria are described in the Materials and Methods section of the paper.

The authors did not have any special access privileges that others would not have.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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