Research on key cobalt technologies based on patent analysis

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Based on global cobalt technology patents, this paper uses patent data mining and co-occurrence methods to identify technology application trends, key technology areas, key technology layouts, and technology roadmap. According to the development trend, the development of co-cobalt technology is divided into slow and rapid development stages. The conclusion are: 1) In terms of key technologies, E35-V (Cobalt compound) is the long-term R&D focus in the field of cobalt, and X16-B01F1 (Lithium-based) is the most important key technology area at present. 2) China, Japan, the United States, and South Korea are the main contributors to key cobalt technologies, mainly focusing on the R&D layout of L03-E01B5B (Lithium electrode) technology in the field of X16-B01F1 (Lithium-based). 3) Regarding the cooperation relationship between patent applicants, cooperation between groups is relatively close, cooperation between different countries is less, and transnational cooperation is mainly concentrated in developed countries, among which the United States has the most transnational partners. 4) In the field of cobalt's most important electrode material technology LG Chemical Co., Ltd. (Korea) and Sumitomo Metal Mining Corporation (Japan) are the two companies with clear technology lines, while Univ Cent South (China) has a late technology development. Finally, we make suggestions for the development of cobalt technology: focus on core technology for R&D and innovation, actively study the technology status and innovation mode of leading companies, and strengthen the cooperation among different R&D institutions.

KEYWORDS

cobalt, patent layout, key technologies, patent analysis, co-occurrence

1 Introduction

Cobalt is an important emerging key mineral resource. Several countries such as the United States, China, and Japan have now included cobalt in their national strategic mineral inventories, making it a key mineral for global strategic mineral research and assessment (McCullough and Nassar, 2017). The Democratic Republic of Congo is the world's largest producer of cobalt ore reserves and production. Cobalt production in the DRC has been a major global supply for decades. At the same time, China is the largest

producer of refined cobalt globally, followed by Finland and Canada (Dehaine et al., 2021). Cobalt is widely used in high-tech fields such as aerospace, chemical, electronics, medical and high-temperature magnetic alloys (Hayes and McCullough, 2018). In addition to these applications, cobalt is used to manufacture catalysts, desiccants, dyes, pigments, and pharmaceuticals (Sun et al., 2019). At the same time, cobalt is also an important raw material. Due to the rapid development of new energy electric vehicles, the battery industry has become cobalt's most important consumption field (Liu et al., 2020). With the rapid development of strategic emerging industries and the transformation of some clean energy sources, fuel vehicles have gradually shifted to electric vehicles, and the economic value, as well as the demand for cobalt, has multiplied (Campbell, 2019). As a frontier material for future development, cobalt has made breakthroughs in related patent technologies, and the number of global patent applications has increased exponentially. Many enterprises worldwide have started early in the patent development of cobalt-related technologies, but most still lack patent layouts of critical technologies. Enterprises involved in cobalt technology R&D in each country must grasp related technologies' global patent application trends and actively lay out key patent technologies to improve their competitive advantages. Therefore, it is crucial to understand the current global critical technologies of the cobalt industry and their development rules and analyze the technology planning and innovation models of critical technologies in each country to promote the high-quality development and strategic layout of cobalt technology.

Scholars' research on cobalt mainly revolves around two aspects: one is the analysis of cobalt ore resources in terms of reserves, supply, and trade, and the other is the development and application of cobalt-related technologies. Horn et al. (2021) studied three deposit types of cobalt and identified 104 deposits in Europe currently being explored for cobalt, 79 of which are located in Finland, Norway, and Sweden. Fu et al. (2020) found by quantifying the material market of cobalt that with the increase in demand for lithium batteries, the demand for cobalt resources is expected to grow by more than 300% in the next decade, and the future faces a significant risk of supply concentration and mining restrictions of cobalt resources. In addition, some scholars have also studied the flow of cobalt using a trade-related material flow model and found that the supply and demand of cobalt have seen rapid growth, with the Democratic Republic of Congo, the United States, China, and Japan being the major powers in the cobalt trade network (Cullen and Allwood, 2013; Sun et al., 2019). Other studies have used a link predictive analysis model, combined with trade networks, to forecast the international trade relationship of cobalt (Liu et al., 2020). The results show reduced trade stability of cobalt and forecast the next three and 5 years for the countries most likely to trade cobalt ore.

Cobalt is currently being studied in various technological fields of technology and applications, such as catalysts, alloy materials, magnetic materials, medicine, and battery materials. Cobalt can be used as a catalyst to improve energy utilization, and Kim et al. (2020) synthesized cobalt-based catalysts with enhancement by inserting traces of palladium. Kim et al. (2018) also prepared cobalt-based catalysts with different base strengths by controlling the amount of yttrium oxide. Metallic cobalt can also be used with other metals to make alloys to generate high-temperature alloys, magnetic alloys, and anticorrosive alloys (Talapatra et al., 2009; Garcia et al., 2016; Yu et al., 2018; Wang et al., 2022). In medical research, cobalt was found to be a trace element in the human body, and its metabolic level was associated with thyroid hormones (Alkjaer et al., 2005). Lin et al. (2020) found that cobalt compounds can act as antimicrobial agents, promote bone cell growth, and reduce inflammatory responses. Cobalt also has many cutting-edge studies in the field of battery materials. Luo et al. (2022) summarized recent nickel-rich and cobalt-as-cathode materials. He et al. (2015) found that cobalt sulfide can be used not only as a lithium-ion battery electrode material but also as a cathode active material in rechargeable magnesium batteries.

Patent data is the world's largest and most reliable source of technical information and one of the most effective indicators of the current state of technological intellectual property development (Safin and Manteuffel, 2016). Patent analysis methods can be used to identify the state of technological development and current research hotspots and predict future development and competitor innovation trends (Zou et al., 2018). At present, few scholars have conducted an overall overview and analysis of the technology field of cobalt from the perspective of patent technology. Most of the existing patent technology research focuses on the downstream of cobalt, such as lithium-ion battery technology. Lee and Su (2020) used patent analysis methods to analyze lithium-ion battery patent trends using patent metrics and analyzed the technological innovation and similarity of the top six patent assignees. Aaldering and Song (2019) used a data-driven approach combining patent co-classification analysis, link prediction algorithm application, and text mining techniques to highlight the post-lithium-ion battery technology research advances. Malhotra et al. (2021) analyzes the evolution of lithium-ion battery knowledge trajectories over the past 50 years.

From the studies mentioned above, it can be found that previous studies lacked research on the cobalt industry from the perspective of patent analysis, while cobalt belongs to the critical raw materials of the future, and researching key technologies of cobalt is of great significance for countries to carry out technological R&D and strategic layout. As global competition becomes increasingly fierce, science and technology innovation has also become a core indicator of national competitiveness. Improving the level of critical technologies and innovation

FIGURE 1
Research framework.
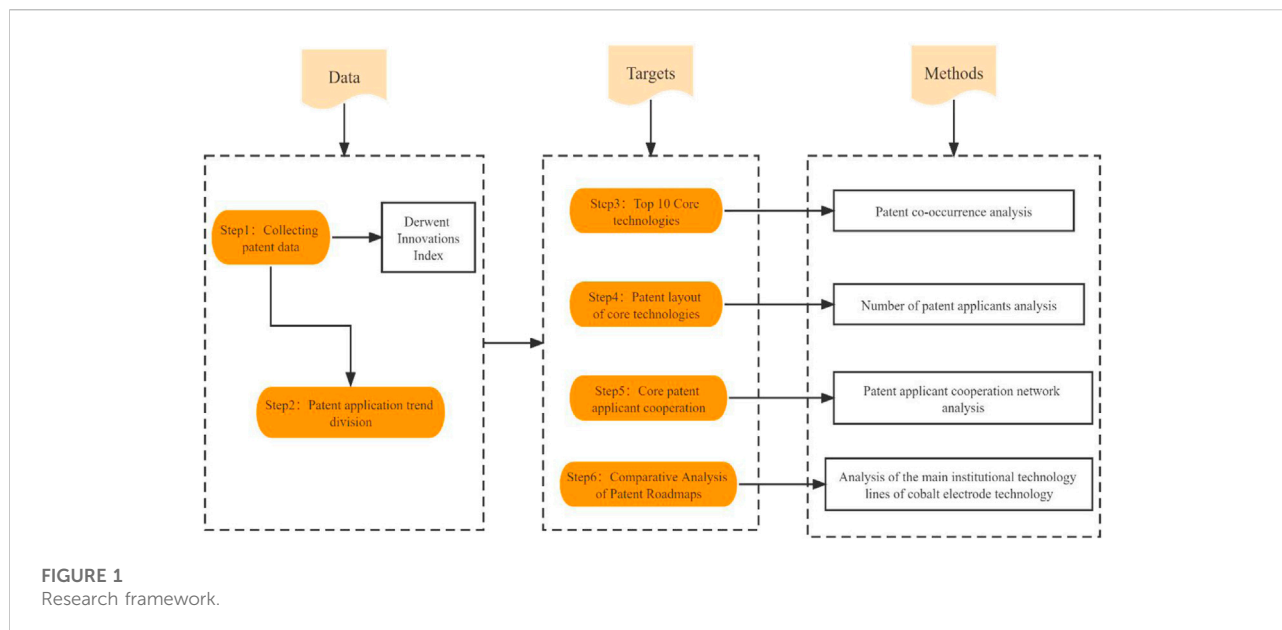
capability has become a significant task at present. Therefore, assessing the R&D trends and the current situation in the field of cobalt key technologies, determining the national competitive posture of key technologies, and clarifying the future key technology R&D directions are of great practical significance for countries to carry out the layout of cobalt key technology R&D and improve their scientific and technological innovation capabilities. Therefore, in order to effectively evaluate the critical technologies of cobalt, this paper takes the patent data of cobalt as the basis, firstly divides the technological development of cobalt into the slow development stage and rapid development stage according to the development trend, then uses patent analysis and co-occurrence analysis to determine the critical technologies of cobalt in each stage, followed by the analysis of the technology layout and cooperation of patent applicants. Finally, patent applicants in cobalt's most important electrode material technology field are selected to analyze the patent technology routes. The rest of this report is organized as follows. Section 2 introduces the research framework and methodology, Section 3 presents the research content, and Section 4 concludes and presents the policy comments of this paper.

2 Research framework and methods

Based on patent data mining methods such as patent analysis and co-occurrence analysis, this paper first delineates the development trend of cobalt patent technology. The key technologies at different development stages are identified, and on this basis, the patent technology layout and the cooperation relationship between patent applicants and patent application countries are analyzed. Finally, the patent applicants

in the most important electrode material technology field of cobalt are selected for the analysis of patent technology routes. The overall analysis framework of this paper is shown in Figure 1, and the whole analysis process is refined into the following six steps.

Step 1: Data acquisition and processing. Patents are an important carrier of technological research and development results and contain 90%–95% of the world's technical information, so technology research based on patent analysis is more scientific and comprehensive (Altuntas and Gök, 2020; Bai et al., 2021). In this study, patent information related to the vital mineral cobalt industry was extracted using the Derwent Innovations Index (DII). The Derwent Patent Database is one of the most authoritative patent databases in the world, containing patent information from over 50 patent-granting institutions worldwide, with a unique classification system and high value-added patent information (Yuan and Li, 2020). The search topics are as follows: (Cobalt metal* OR cobalt ore* OR cobalt salt* OR cobalt compound* OR cobalt mining* OR cobalt oxide* OR cobalt hydroxide* OR cobalt chloride* OR cobalt sulfate* OR cobalt oxalate* OR cobalt carbonate* OR cobalt sulfide* OR lithium cobaltate* OR cobalt smelting and processing* OR cobalt recovery), the data collected span from 1 January 1967, to 1 June 2022, and the number of patent applications searched was 218,267.

Step 2: Classify the development stages according to the patent application trends. The major economies of cobalt patent applications: Japan, the United States, Germany, the United Kingdom, China, and South Korea, are extracted based on patent data, their historical patent application trends, and the
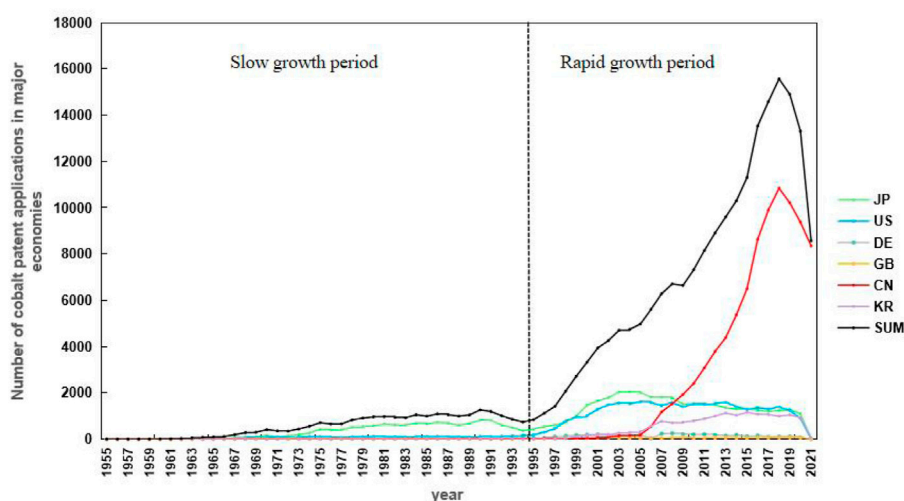
FIGURE 2
Global trends in cobalt technology patent applications by major countries.

global trend of total cobalt patent applications are analyzed. By analyzing the overall trend of patent applications, the development of cobalt technology patents is divided into two stages.

Step 3: Key Technology Identification. The Derwent Innovation Index (DII) database provides information such as the year of patent filing, the country of filing, and the Derwent Manual Code of the patent, which can help us identify key technologies. Based on the Derwent classification codes, experts form Derwent manual codes by hand to refine patent data in technology areas. In this paper, we analyze the co-occurrence of Derwent manual codes in the patent data of the cobalt industry, form a patent co-occurrence network diagram, and make a qualitative judgment on the key technologies of the cobalt industry based on the visualized information. Among them, the key technologies in the cobalt field were identified by combining the number of patent occurrences and the centrality index of social network analysis. On this basis, the number of occurrences of key technologies and the intermediary centrality index was used as horizontal and vertical coordinates, and the mean of the two was used as the origin to establish a right-angle coordinate system to analyze the differences in importance and attention according to the quadrants of key technology distribution. Among them, more occurrences of a patent node indicate that the patent is a current research hotspot (Robinson et al., 2013), while the higher the intermediary intra-centrality index indicates that the node plays a greater role as a bridge in the network.

The formula proposed by Freeman (1978) for the betweenness centrality index is as follows:

$$BC_i = \sum_{s \neq i \neq t} \frac{n_{st}^i}{g_{st}}$$

where: g_{St} = the number of shortest paths from technology field s to technology field t. n_{st} = the number of shortest paths passing through technology field i among the g_{St} shortest paths from technology field s to technology field t.

Betweenness centrality index refers to the number of times a node acts as the shortest bridge between two other nodes. When a node acts as a bridge more often, its betweenness centrality is higher. In patent co-occurrence networks, nodes with high betweenness centrality represent key nodes connecting existing and emerging technologies, and these nodes represent the key technology areas in the network (Freeman, 1978).

Step 4: Technology layout of core patent applicants. Based on the identification of cobalt key technologies, statistics containing information on the application fields of key technologies at different stages, the principal applicants and applicant countries of key technologies are identified based on the number of patent applicants and patent applicant countries in the technology fields. China, Japan, the United States, and South Korea, the major economies of global cobalt patent applications, are selected to compare the number of applications in different key technologies in significant countries. Analyze the gap in the layout of key technologies and R&D strength between countries at different stages. Secondly, a bimodal network is constructed based on the relationship between key technologies and patentees to form a cobalt key technology distribution map of patentees. The important applicants of key technologies are judged by judging the size and color of nodes and the thickness of edges in the network.

Step 5: Cooperation analysis of core patent applicants. Key technology patent applicants are extracted, and an undirected

FIGURE 3
Identification of key cobalt technologies at different stages.
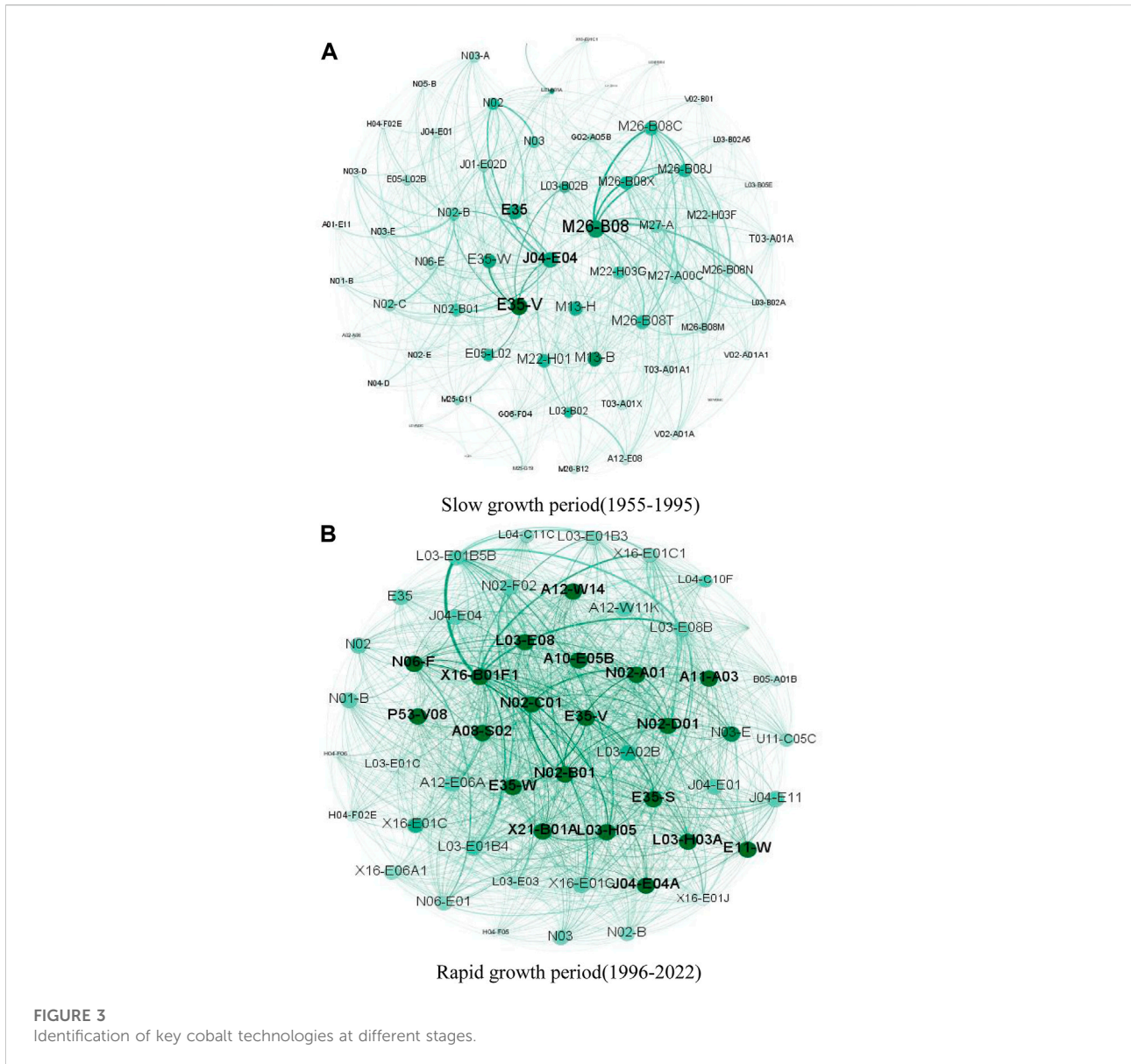
weighted cooperation network of patent applicants with patent applicants as nodes, cooperation relationship as edges, and cooperation time as weights are constructed according to the cooperation relationship between patent applicants. Next, this cooperative network is analyzed by combining the number of nodes, the number of edges, the average clustering coefficient, and the average path length in the social network analysis. The number of nodes and edges represent the size of the network, the average clustering coefficient indicates the closeness of cooperative relationships in the network, and the average path length indicates the average number of steps to form cooperative relationships among patent applicants. Secondly, the cross-country cooperation relationships at different stages are extracted. An undirected weighted cobalt key technology

cross-country cooperation network is constructed, with nodes representing different institutions, node colors representing the countries to which the institutions belong, and edges representing the number of cooperation between different institutions.

The average clustering coefficient formula is as follows (Saramäki et al., 2005):

$$C_i = \frac{2n_i}{k_i(k_i - 1)}$$

$$\bar{C} = \frac{1}{N}\sum_{i=1}^{N}C_i$$

where: k_i = the number of patent applicant partnerships n_i = total number of partnerships

FIGURE 4
Number of occurrences and betweenness centrality cross-coordinates.
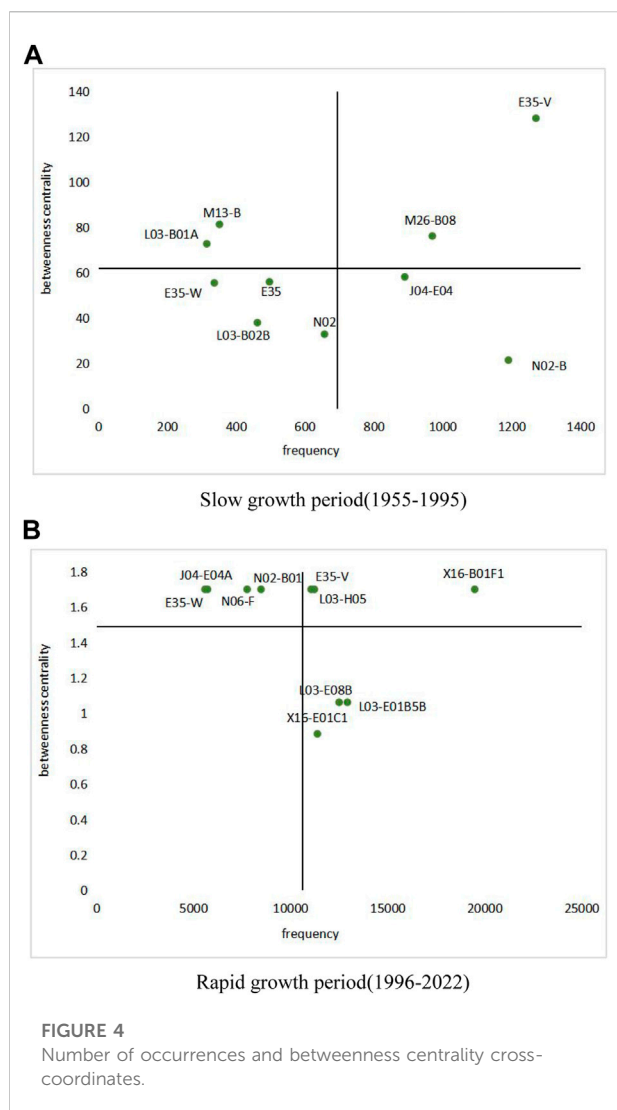
The average clustering coefficient is a coefficient that measures the degree of clustering of nodes in a graph. In a cooperative network of patent applicants when the clustering coefficient is closer to 1, then the closer the cooperative relationship between patent owners is.

The average path length equation is as follows (Watts and Strogatz, 1998):

$$L = \frac{1}{n(n-1)} * \sum_{ij} d_{ij}$$

where:L = average shortest path length between nodes in the network .n = number of technical fields.d_{ij} = the shortest distance between the technical field i and j.

The average path length is the shortest path length between any two nodes, that is, the average number of steps of cooperation between nodes in the patent applicant's cooperation network. The

smaller the average path, the easier it is for patent applicants in the cooperative network to generate cooperative relationships.
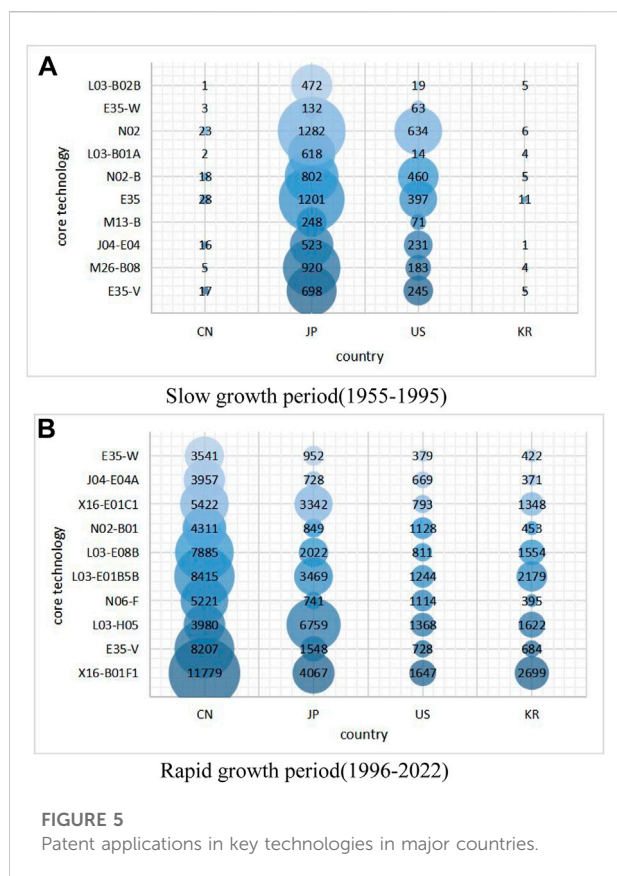
Step 6: Based on the results of the identified cobalt key technology areas, the most important electrode technology areas were selected at present, and then the top three different country patent owners, LG Chem Ltd. (Korea), Sumitomo Metal Mining Co. (Japan), and Univ Cent South (China), were selected. A patent roadmap was created based on patent citation relationships, as well as the number of patent citations and the number of family patents. By analyzing the technology patent roadmaps of different organizations, the technological development paths of the patentees were compared.

3 Results and discussion

3.1 Trend analysis of cobalt patent applications

The global trend of technology applications for cobalt materials is shown in Figure 2. Patent applications for cobalt-related technologies first began around the 1960s, and the number of applications began to show a rapid growth trend after the 21st century. Currently, the countries with a large number of cobalt-related patent applications worldwide are China, the United States, and Japan. The earliest cobalt technology patent was applied for by the United States in 1955, while the earliest patent in China was applied for in 1986, compared with the late start of cobalt industry technology research and development in China. Specifically, the development of global patents related to cobalt technology is divided into two main stages.

The first stage was from 1955 to 1995, a period of slow technological development with few patent applications. In the 1940s, the United States first paid attention to and developed cobalt-based alloys, and at the end of the 1950s, cobalt-based alloys were widely cast and used in the United States. Global patents on cobalt technology were mainly in the hands of Japan and the United States. The second phase, from 1996 to the present, is a period of rapid technological growth, with the total number of patent applications increasing rapidly. Japan and the U.S. still hold many technology patents, but the number of patent applications in China and Korea is also growing rapidly. Due to the global financial crisis in 2008, the growth rate of cobalt industry consumption in many countries was restrained and slowed down. Refined cobalt production and sales in China have surged due to the stagnation of many overseas projects. The rapid growth of cobalt technology patents filed in China has made it the most important country and the main driver of technology development in the cobalt industry. There is an 18-month lag in current patent

A Slow growth period(1955-1995)

core technology	CN	JP	US	KR
L03-B02B	1	472	19	5
E35-W	3	132	63	
N02	23	1282	634	6
L03-B01A	2	618	14	4
N02-B	18	802	460	5
E35	28	1201	397	11
M13-B		248	71	
J04-E04	16	523	231	1
M26-B08	5	920	183	4
E35-V	17	698	245	5

B Rapid growth period(1996-2022)

core technology	CN	JP	US	KR
E35-W	3541	952	379	422
J04-E04A	3957	728	669	371
X16-E01C1	5422	3342	793	1348
N02-B01	4311	849	1128	453
L03-E08B	7885	2022	811	1554
L03-E01B5B	8415	3469	1244	2179
N06-F	5221	741	1114	395
L03-H05	3980	6759	1368	1622
E35-V	8207	1548	728	684
X16-B01F1	11779	4067	1647	2699

FIGURE 5
Patent applications in key technologies in major countries.

applications, so the data for the latter period is for reference only.

3.2 Global cobalt key technology identification analysis

According to the slow and rapid development stages divided in 3.1, the hot patent technology fields with frequencies greater than 200 times and greater than 3,000 times are extracted for co-occurrence analysis, as shown in Figure 3. The nodes in the graph represent the technical field of cobalt, the node size represents the frequency of occurrence of that technical field, and the node color represents the betweenness centrality of the technical field. The edges between the nodes represent the two technical fields that appear in the patent at the same time, and the weights of the edges represent the number of times the two technical fields appear at the same time. The figure shows that the technology nodes of M26-B08, J04-E04, E35, and E35-V in the slow development stage are darker and larger in color. According to the patent codes, we can find that Nickel or cobalt alloys, Catalysts, Compounds of other metals, and Cobalt compounds are the important and hot technology areas of cobalt. There are
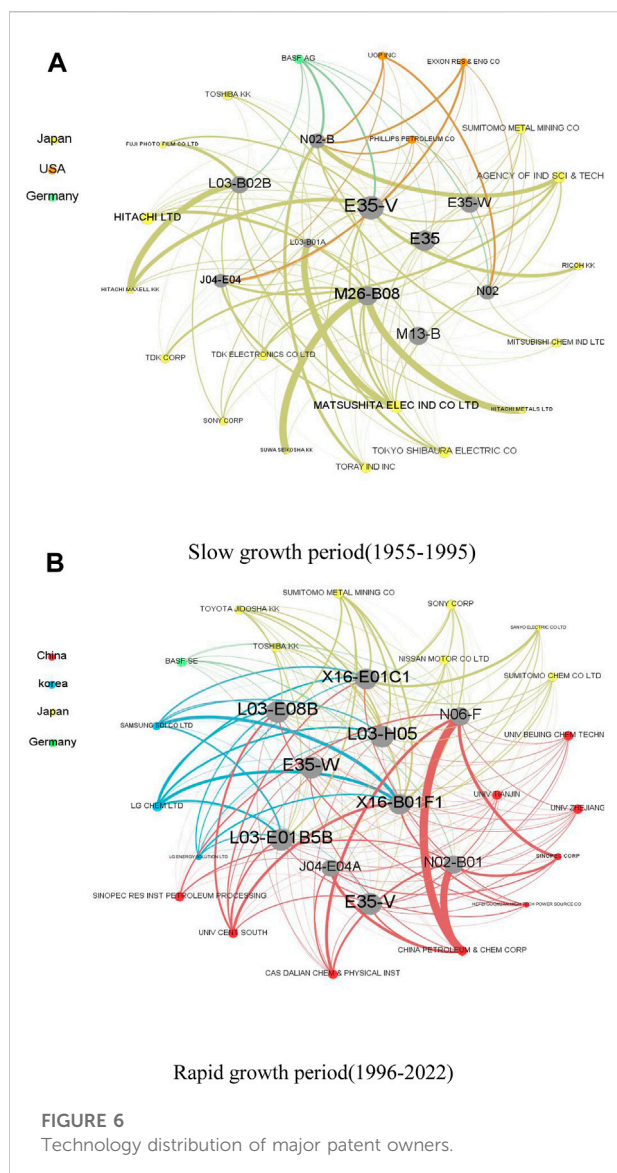
more important and hot technology areas in the second stage, and the technology nodes of A10-E05B, X16-B01F1, L03-E01B5B, and E35-W are larger and darker, indicating that Chemical modification by carbonisation, Lithium-based, Lithium electrodes, Nickel compound, etc. are the hot technology industries of cobalt.

In order to better identify the key technology areas, this paper uses the top 10 Derwent Manual Code ranked by the product of frequency and betweenness centrality in the technology areas to represent the top 10 key technology areas (as Table 1 shows). Based on the identification results and the meaning of the entries of the Derwent manual codes, it can be concluded that the first ranking of cobalt key technology patents in the slow development stage is E35-V (Cobalt compound), M26-B08 (Nickel or cobalt alloy), J04-E04 (Catalysts), M13-B (Coating from solution or suspension of metal compounds), etc. also belong to the key technology area of cobalt in this stage. In the rapid development stage, X16-B01F1 (Lithium-based) replaced E35-V (Cobalt compound) as the top-ranked key technology, and L03-H05(Vehicles), L03-E01B5B (Lithium electrodes), and L03-E08B (Production of electrodes) also became important key technology areas for cobalt in this stage. In 1990, Sony invented the lithium-ion battery, and the demand for lithium cobaltate as one of the anode materials began to increase rapidly, and its related technology patents also became the key technology of the cobalt industry. Cobalt-containing batteries are widely used because of their high energy density, en-vironmental safety, and stable performance.

From the trend of cobalt key technologies over time, it can be found that E35-V (Cobalt compound) ranks first and second in the slow development phase and the rapid development phase, respectively, indicating that Cobalt compound has been the focus of technology research and going in the cobalt industry. x16-B01F1 (Lithium-based) has been ranked first in the rapid growth phase. It has been the top-ranked key technology area so far. From the rapid growth stage, the most important use of cobalt is for lithium-ion batteries as the electrode material for ternary batteries. From the vital technology changes in each phase, catalysts such as J04-E04 (Catalysts) and N06-F (Catalyst support) have been necessary critical technologies for the cobalt industry. E08B (Production of electrodes) has become the new key technology for the cobalt industry.

In order to further analyze the characteristics of critical technologies, we created a matrix for each phase of technology topics with the number of patent occurrences as the horizontal axis and the betweenness centrality as the vertical axis. We took the average of the two as the intersection point of the analysis (as Figure 4 shows).

In the slow development stage, the first quadrant is the quadrant with the high occurrence and high intermediate centrality. E35-V (Cobalt compound) and M26-B08 (Nickel or cobalt alloy) are located in the first quadrant, where E35-V (Cobalt compound) has the highest occurrence and highest

FIGURE 6
Technology distribution of major patent owners.

key technology for this phenomenon is a popular research area, but the relationship with other key technologies is weak.
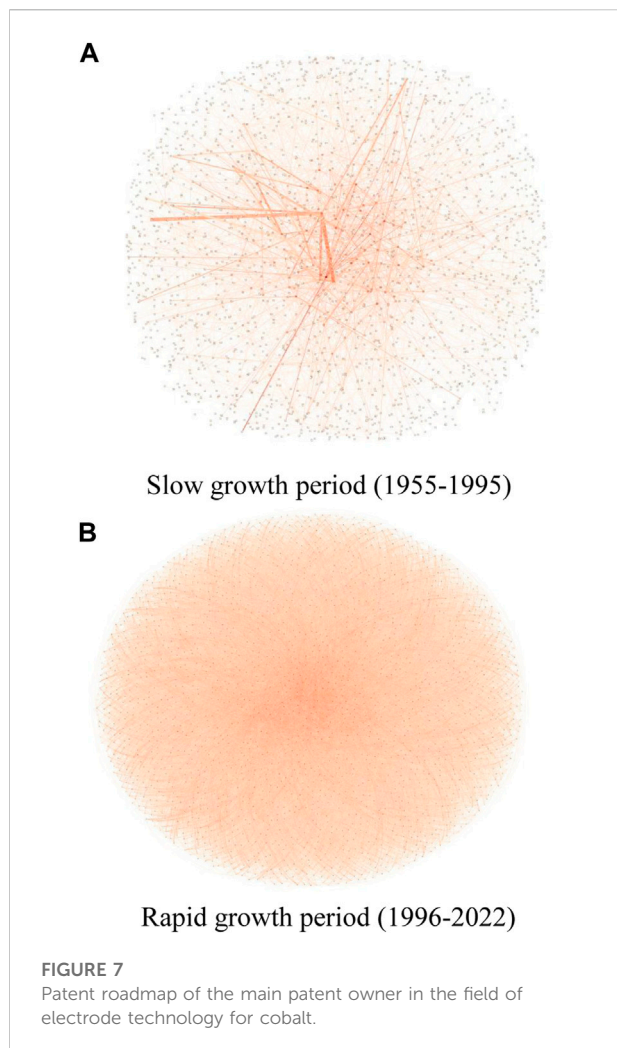
Similarly, the three technology areas in the first quadrant of the rapid development phase are X16-B01F1 (Lithium-based), E35-V (Cobalt compound), and L03-H05 (Vehicles), indicating that these three technologies are the focus of research in the rapid development phase and are in a critical position. Among them, X16-B01F1 (Lithium-based) is the first in the number of occurrences and intermediary centrality, which is the most important key technology in the rapid development stage. There are four technology areas in the second quadrant, namely N02-B01 (Cobalt element or oxide catalyst), N06-F (Catalyst support), J04-E04A (Redox catalysts), and E35-W (Nickel compound), and this quadrant's key technologies are more closely linked to other technologies but are relatively less studied. In the fourth quadrant, L03-E01B5B (Lithium electrodes), L03-E08B (Production of electrodes), and X16-E01C1 (Oxides, complex oxides) are a hot research area but have less connection with other technologies. Among them, the lithium-ion and electrode field is a hot R&D area for cobalt but relatively less connected with other technology fields.

3.3 Patent layout of key technologies

According to the statistics of patent applications for cobalt key technologies, China, Japan, the United States, and South Korea account for 40%, 23%, 16%, and 7% of the global total patent applications for cobalt key technologies, respectively. Therefore, this paper focuses on the technological layout of cobalt critical technologies in China, Japan, the United States, and South Korea at different stages of development. As shown in Figure 5, the size of the bubbles indicates the number of patents filed by each country on crucial technologies. The horizontal coordinates represent countries, and the vertical coordinates represent different key technologies.

As can be seen from the Figure 5, during the slow growth period, Japan has an absolute advantage in the number of patent applications for crucial technologies of cobalt, especially in the fields of E34 (Compounds of other metals) and N02 [Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate] in two technical fields. The U.S. technology areas of N02 [Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate] and N02-B Cobalt—element, (hydr)oxide, inorganic salt, The number of patent applications in N02-B [Cobalt—element, (hydr)oxide, inorganic salt, carboxylate catalyst] is high, while China and Korea are less competitive and have fewer patent applications at this stage. During the rapid growth period, China has an absolute advantage in the number of patent applications for critical technologies and is the most competitive country overall; it is mainly in the patent fields of X16-B01F1 (Lithium-based), L03-E01B5B (Lithium electrodes) and L03-E08B (Production of electrodes). Japan is

intermediate centrality, indicating that it is the focus of R&D in the slow development phase. M13-B (Coating from solution or suspension of metal compounds) and L03-B01A (Variable resistors) are located in the second quadrant, where key technologies play a mediating role in the technology field but are less studied. The third quadrant is the low incidence and low intermediate centrality quadrant, where the key technologies are less important and less studied than the other key technologies, E35-W (Nickel compound), E35 (Compounds of other metals), N02 [Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate] and L03-B02B (Magnetic non-metals) are located in this quadrant. The fourth quadrant is the high occurrence and low intermediate centrality quadrant, where J04-E04 (Catalysts) and N02-B [Cobalt—element, (hydr) oxide, inorganic salt, carboxylate catalyst] are located, and the

FIGURE 7
Patent roadmap of the main patent owner in the field of electrode technology for cobalt.

competitive country. However, Japan has the highest number of applications in the world in L03-H05 (Vehicles).

In order to analyze the layout of different companies in the field of cobalt key technologies, this paper selects the major patent owners whose total patent applications in key technologies in the slow development stage and the rapid development stage exceed 50 and 200, respectively, for comparison, and their patent technology layout is shown in Figure 6. Among them, gray nodes represent key technologies, yellow, orange, green, blue, and red nodes indicate Japanese, American, German, Korean and Chinese patentees, respectively, and the thickness of connecting lines between nodes represent the number of patent applications for key technologies. As seen from Figure 6A, the key technology companies applying for cobalt in the slow development stage mainly originate from Japan, such as HITACHI LTD., MATSUSHITA ELEC IND CO. LTD., TDK ELECTRONICS CO. LTD., etc. The main layout is E35-V (Cobalt compound) and M26-B08 (Nickel or cobalt alloy). PHILLIPS PETROLEUM CO and TDK CORP in the United States are also an essential part of cobalt key technology. Secondly, BASF AG in Germany also has more patents in N02-B [Cobalt-element, (hydr)oxide, inorganic salt, carboxylate catalyst] and E35-V (Cobalt compound).

It can be seen in the rapid development stage that the main origins of companies applying for cobalt key technology are starting to become diversified, mainly China, Korea, Japan, and Germany. Chinese CAS DALIAN CHEM & PHYSICAL INST, CHINA PETROLEUM & CHEM CORP, and UNIV ZHEJIANG are the main contributors to the vital cobalt technology in China, mainly in N02-B01 (Cobalt element or oxide catalyst) and N06-F (Catalyst support). Chinese universities and research institutes are an important part of the global cobalt key technology patentees and have strongly promoted cobalt key technology innovation. In addition, Japan's SANYO ELECTRIC CO. LTD., TOYOTA JIDOSHA KK, and SONY CORP have strong R&D strength in key cobalt technologies, mainly in the field of X16-B01F1 (lithium-based) technology. LG CHEM LTD. and SAMSUNG SDI CO. LTD. of Korea have focused on X16-B01F1 (Lithium-based) and X16-E01C1 (Oxides, complex oxides), and these two companies have the largest number of patents in X16-B01F1 (Lithium-based) technology, so Korea has a certain technological advantage in Lithium-based. BASF SE of Germany has more patents in X16-B01F1 (Lithium-based) and N02-B01 (Cobalt element or oxide catalyst).

second only to China in the number of applications for crucial cobalt technologies, but it overtook China as the world's top filing country in L03-H05 (Vehicles). However, Japan has relatively few applications in catalyst technologies such as N06-F (Catalyst support) and J04-E04A (Redox catalysts). The critical technology applications in the U.S. at this stage are mainly in the fields of X16-B01F1 (Lithium-based) and N02-B01 (Cobalt element or oxide catalyst), and the number of patent applications for N02-B01 (Cobalt element or oxide catalyst) has exceeded that of Japan The number of patent applications for N02-B01 (Cobalt element or oxide catalyst) has surpassed that of Japan and is only surpassed by China. Korea is mainly in X16-B01F1 (Lithium-based) and L03-E01B5B (Lithium electrodes) technologies.

Compared with the slow development stage, the number of applications in China and Korea has increased significantly. Both China and Korea mainly focus on the R&D of X16-B01F1 (Lithium-based) and L03-E01B5B (Lithium electrodes) technology areas. China's total number of patent applications for key cobalt technologies surpasses Japan's, making it the most

3.4 Key technology patent applicant cooperation network

In order to study the cooperative relationship of key technology patent applicants of cobalt, this paper uses Gephi software for the co-occurrence diagram of patent applicants, as shown in Figure 7. In order to understand

FIGURE 8
Cross-border cooperation network for key cobalt technologies.
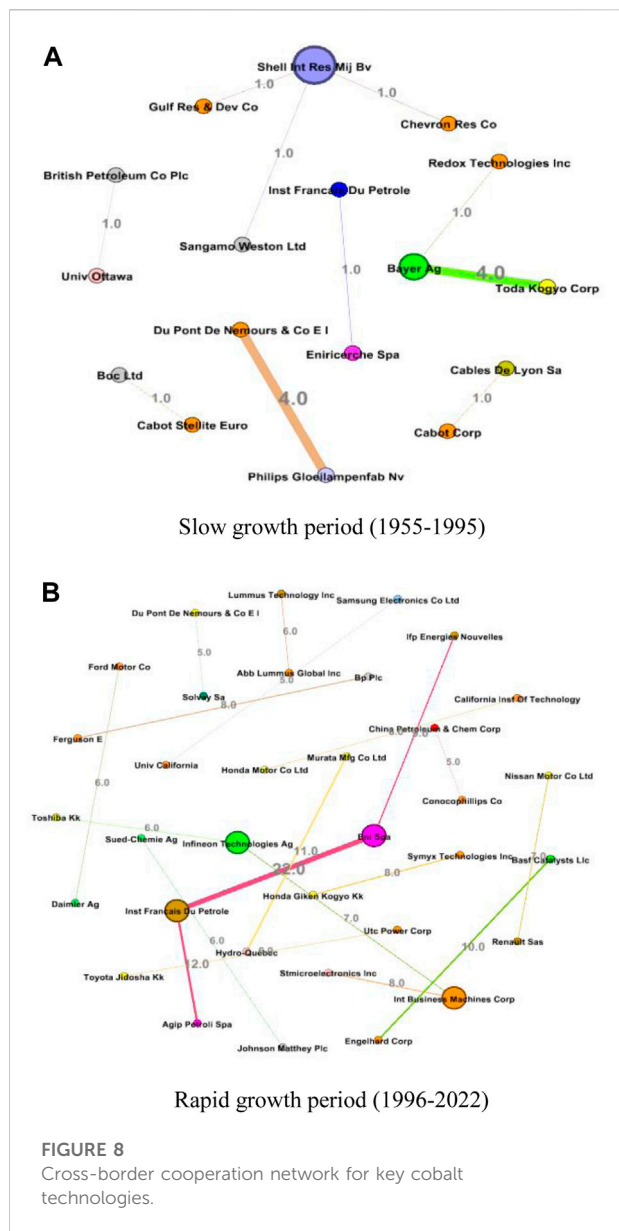
the evolutionary characteristics of the overall cooperative network, the parameters of the overall network characteristics of the cooperative network at different stages are compiled in Table 2 in this paper. It can be seen from the figure that from the slow growth stage to the rapid development stage, the network size expands, and the number of cooperative relationships increases rapidly. The average clustering coefficient and the average shortest path length in Table 2 represent the degree of close cooperation among patent applicants. It can be found that the average clustering coefficient becomes larger and the average path value becomes smaller, indicating that the cooperative relationships among patent applicants are getting closer

and closer. The cooperation network shows the characteristics of large dispersion and small aggregation, with close cooperation among institutions in the same country but less cooperation among institutions in different countries.

In order to deeply analyze the cross-border cooperation relationship of patent applicants, the patent applicants with a high number of cross-border cooperation in both phases are visualized in Figure 8. Different colors in the figure represent the countries from which the organizations come, with yellow representing Japan, orange representing the US, purple representing the Netherlands, green representing Germany, red representing China, blue representing Korea, gray representing the UK, pink representing Canada, rose pink representing Italy, and brown representing France. As seen from the figure, in the slow development stage, US firms engage in more cross-border cooperation, with more frequent cooperation between institutions in the US and the Netherlands. The number of cross-border collaborations by global institutions in the slow development stage is relatively small. In the rapid development stage, cross-border cooperation among patent applicants increased, with the most frequent cooperation between Italy and France. Italy's Eni, Germany's Infineon, and France's Inst Francais collaborate more frequently with other countries. Overall, cross-border cooperation in key cobalt technologies is mainly concentrated in developed countries such as the US, Italy, and the UK, with the US having the most cross-border partners.

3.5 Comparative analysis of major patentees based on patent roadmap

The technology roadmap is an important tool for strategic planning and decision-making, as it can clearly show the pulse and frontier of technology development to relevant organizations through visualization. In this paper, we have selected the critical technology area of cobalt in electrodes and created a patent roadmap based on the patent citation relationship based on the three organizations from different countries with the largest number of related patents, LG Chem Ltd. (Korea), Sumitomo Metal Mining Co. (Japan) and Univ Cent South (China). The critical patents in the patent roadmap are determined based on the frequency of patent citations, key technology areas, and the number of family patents. According to the statistical analysis, in the field of cobalt electrode technology, LG Chem Ltd. (Korea) has 993 patent records, Sumitomo Metal Mining Co. (Japan) has 419 records, and Univ Cent South (China) has 424 records. The patent technology roadmap of the three organizations in the field of electrodes is shown in Figure 9, with the gray part of the figure

FIGURE 9
Collaborative network of patent applicants for key technologies.
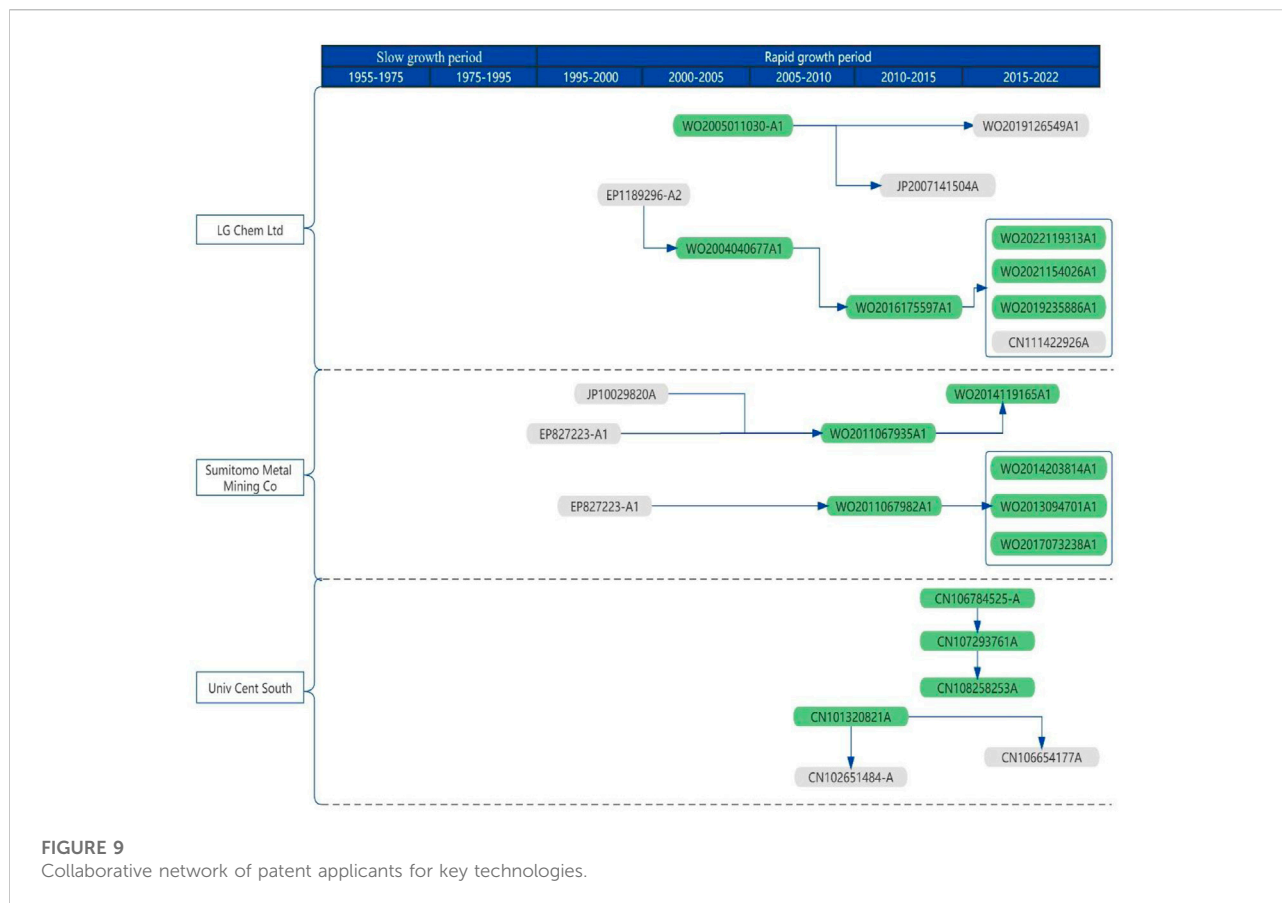
showing the patents of other organizations and the green part showing the patents of their organizations.

LG Chem Ltd. filed a patent WO2004040677A1 on optimized cathode materials for cobalt-containing lithium batteries in 2004, which was cited 71 times. As a result of this technology, the patent WO2016175597-A1 on cathode active material for cobalt-containing lithium-ion secondary batteries was filed in 2016 and was cited 21 times, with 12 family patents. 2005 LG Chem Ltd. filed a patent WO2005011030A1 on anode active material for cobalt-containing lithium-ion secondary batteries, with 22 family patents, and was cited 66 times. On this basis, LG Chem Ltd. and other organizations applied for several patents related to cobalt-containing electrode materials and became the country with the largest number of patents for cobalt electrode materials in the world.

In 2011, Sumitomo Metal Mining Co. applied for WO2011067935A1, "Manufacture of nickel-cobalt-manganese composite hydroxide particles for manufacturing cathode active materials," which has 16 patents in the family and has been cited 76 times. In addition, WO2014119165A1, "Manufacture of nickel-cobalt composite hydroxide for active cathode materials," was filed in 2014 with 29 citations and 16 family patents. Sumitomo Metal Mining Co. Based on this, more related patents have been filed.

In 2008, Univ Cent South applied for patent CN101320821A on the technology of integrated energy storage components for capacitors and lithium-ion batteries, which was cited 32 times, and two family patents. 2017, Univ Cent South applied for CN106784525A on the technology of lithium-sulfur battery diaphragm and graphene preparation, which was cited 47 times.

In general, the core technology of the most popular electrode material for cobalt is receiving attention from various companies. Among them, LG Chem Ltd. (Korea) and Sumitomo Metal Mining Co. (Japan) are two companies with clear technology lines, while Univ Cent South (China) is late in developing its technology. Univ Cent South (China) has more patents for critical technologies, but the quality of core technologies is poorer than the other two organizations.

4 Conclusion and policy implications

4.1 Conclusion

The current research lacks research on cobalt key technologies from the perspective of patent analysis, while cobalt belongs to the key raw materials of the future. There are

TABLE 1 Top 10 key technologies for cobalt.

Rank	Derwent manual code	Category meaning	Frequency	Betweenness centrality
(A) Slow growth period (1955–1995)				
1	E35-V	Cobalt (Co) compound	1270	128.27305
2	M26-B08	Nickel or cobalt alloy	969	76.24981
3	J04-E04	Catalysts	889	58.208617
4	M13-B	Coating from solution or suspension of metal compounds [general]	351	81.39311
5	E35	Compounds of other metals [general]	496	56.00599
6	N02-B	Cobalt—element, (hydr)oxide, inorganic salt, carboxylate catalyst [general]	1190	21.424194
7	L03-B01A	Variable resistors	314	72.818273
8	N02	Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate [general]	656	32.892766
9	E35-W	Nickel (Ni) compound	336	55.550736
10	L03-B02B	Magnetic non-metals [general]	461	38.007232
(B) Rapid growth period (1996–2022)				
1	X16-B01F1	Lithium-based	19480	1.699919
2	E35-V	Cobalt (Co) compound	11214	1.699919
3	L03-H05	Vehicles	11049	1.699919
4	N06-F	Catalyst support	8466	1.699919
5	L03-E01B5B	Lithium electrodes	12917	1.062272
6	L03-E08B	Production of electrodes	12491	1.062272
7	N02-B01	Cobalt element or oxide catalyst	7749	1.699919
8	X16-E01C1	Oxides, complex oxides	11372	0.884227
9	J04-E04A	Redox catalysts	5707	1.699919
10	E35-W	Nickel (Ni) compound	5578	1.699919

gaps in the research on the development trend, patent owners, key technology layout, and technology development route of cobalt key technology, etc. Assessing the R&D trend and current situation in the field of cobalt key technology is of great practical significance for countries to carry out the R&D layout of cobalt key technology and improve their scientific and technological innovation capability. Therefore, this paper divides the development trend into slow development stages and rapid development stages and uses patent analysis and symbiosis analysis to identify key technologies according to the current status of technology development in the global cobalt industry. On this basis, the layout of key technologies in the cobalt industry is analyzed from the perspective of the key technology patent applicants and the countries to which the applicants belong, and the cooperative relationship among the patent applicants is analyzed. Finally, by analyzing the technical routes of the main patent owners in the most critical core technology field of cobalt-electrode material technology, the main conclusions drawn are as follows:

(1) Patent co-occurrence analysis is used to identify critical technologies and important cobalt features at different stages. E35-V (Cobalt compound) belongs to the key technologies that have been the focus of R&D in the cobalt industry, while X16-B01F1 (Lithium-based) is the most important key technology area at present.

(2) The patent layout of cobalt key technologies is analyzed according to the patent applicants and the countries to which they belong. China, Japan, the United States, and South Korea are the main contributors to cobalt key technologies. Each country concentrates on the layout of R&D in the X16-B01F1 (lithium-based) fields L03-E01B5B (lithium electrode) technologies.

(3) Based on the cooperation network of cobalt key technology patent applicants, the cooperation relationship is analyzed. Collaboration networks have become closer over time between patent applicants. Most collaborative relationships are domestic, with fewer patent applicants cooperating across borders. Transnational cooperation in

TABLE 2 Basic parameters of cooperative networks in different stages of cobalt key technologies.

Stage	Number of network node	Number of sides	Average clustering coefficient	Average path length
1955–1995	2141	2497	0.617	6.957
1996–2022	20160	133218	0.637	3.711

cobalt key technologies is mainly concentrated in developed countries such as the United States, Canada, and the United Kingdom, among which the United States has the most transnational partners.

(4) The three organizations with the highest number of relevant patents in different countries were identified according to the key technology areas of electrode materials for cobalt, and a patent roadmap was established based on the patent citation relationship. LG Chem Ltd. (Korea) and Sumitomo Metal Mining Co. (Japan) are the two companies with clear technology lines, while Univ Cent South (China) has a later technology development.

4.2 Policy implications

Identify the key technology areas of cobalt, and analyze the critical technology layout of applicants and applicant countries as well as the cooperation relationship to provide certain reference values for the R&D, innovation, and strategic layout of relevant technologies in this field. Combining the above research findings, the following recommendations are made.

(1) We should strengthen the R&D and innovation of core technologies such as X16-B01F1 (lithium-based) and L03-E01B5B (lithium electrode) around the cobalt industry chain and pay close attention to the new developments in the field of cobalt in recent years. In recent years, cobalt, an important raw material for new energy power batteries, has had a broad market prospect. In the future, we should increase our technological research and development efforts and innovation to expand our technological fields.

(2) Countries should increase support for critical enterprises to promote their research and development of key technologies to gain advantages for international competition. For enterprises with strong international competitiveness, other enterprises can actively learn from the technology status and innovation models of leading enterprises, such as Sony Corporation of Japan and Lg Chemical Co. of Korea. Actively promoting the cooperation of different R&D institutions and building industrial R&D technology innovation alliances, not only limited to the cooperation within the country but also strengthening the transnational partnership, is conducive to accelerating the R&D process to

improve the efficiency of technology achievement transformation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Author contributions

ZH contributed to the study conception, data collection, methodological application, and paper writing. TD was involved in the improvement, revision and refinement of the study.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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