Knowledge graph construction and visualization analysis of coal mine accident safety management research based on CiteSpace and VOSviewer

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Abstract. Although the coal mining industry has implemented mechanization and automation, frequent coal mine accidents still occur, making coal mine safety a primary concern. To gain a comprehensive understanding of global progress in preventing coal mine accidents and managing safety, we utilized the Web of Science database (WOS) as our sample source. With the support of CiteSpace and VOSviewer software, we constructed a knowledge graph depicting publication numbers, research institutions, and keyword clustering to visually analyze coal mine accident prevention and safety management. Our research reveals that this field has undergone three stages of development: initial growth, steady progress, and rapid advancement. Particularly noteworthy is the current golden age of rapid development from 2018 to 2023 which has garnered significant attention from researchers. In terms of author collaboration networks, notable contributors with high publication rates and citation counts include Wu Qiang, Liu Quanlong, et al. Regarding institutional cooperation networks, major research institutions such as China University of Mining & Technology, Shandong University of Science & Technology, and Anhui University are actively engaged in important scientific research related to coal mining. Through keyword clustering analysis based on relevant literature review, it is evident that research on coal mine safety management primarily focuses on high-frequency keywords such as "coal and gas outburst","risk assessment" and "coal miners" By extracting the top nine emergent keywords with high-intensity levels and arranging them chronologically according to their emergence year, the evolution pattern over time was obtained for emergent words. Furthermore, it was observed that emerging keywords like "China", "subsidence" and "workers" have also gained increasing attention during this period.

Keywords: Coal mine safety; Scientific method of measurement; WOS; Safety management; Risk management; Research hotspot.

1. Introduction

Coal, as the largest fossil fuel globally, serves as the primary source of electricity in most countries and plays a crucial role in global energy production[1]. However, frequent coal mine accidents and safety incidents have imposed substantial societal losses due to factors such as the complex occurrences of certain coal seams, mining challenges, insufficient safety awareness among coal mine employees, and illegal mining activities[2,3]. With the advancement of mechanization and intelligence in coal mines, significant improvements have been made in addressing numerous safety issues at the engineering level. However, the academic community has recently begun to focus on an overlooked yet critical factor contributing to coal mine accidents, specifically, the management of coal mine safety, which is essential for effective coal mine safety management. Effective coal mine safety management serves as the foundation and determining factor for successful production[4].

In recent years, numerous scholars have conducted extensive research on coal mine safety management to mitigate the occurrence of accidents. Yang et al. (2022)[4] examined the efficiency of coal mine safety management by employing a sustainable operation index system and environmental risk model. Wang et al. (2023)[3] achieved intelligent and efficient management of coal mine safety accidents through the study of digital twins on coal mine safety management, establishing a scientific and rational coal mine safety cooperative management early warning index system. Ma et al. (2016)[5] established a cooperative management early warning index system for effectively identifying and controlling hazard sources in coal mines using a three-stage semi-

quantitative method. Wu et al. (2022)[6] thoroughly examined the role of intelligent coal mining in promoting coal mine safety. Zhou et al. (2018)[7] developed a B/S software model, referred to as the mine occupational safety and health management and risk control system, which promotes mine occupational safety and health management based on risk early warning and dynamic monitoring, aiming to achieve the objectives of daily management of occupational safety and health, risk identification and assessment, and risk early warning and dynamic monitoring. Li et al. (2015)[8] adopted four test instruments (Sensory and cognitive capacity test, Sixteen-Personal Factor Questionnaire, Symptom Checklist 90 Questionnaire, and the supervisors' evaluation)   to identify unsafe behavior factors. The self-established Questionnaire of Safety Behavior Norms (QSBN) was also used to propose the safety behavior countermeasures of coal mine employees. Melih Iphar et al. (2018)[9] developed a fuzzy logic safety assessment method to enhance the risk assessment process and overcome the uncertainty issues encountered in the classic decision matrix risk assessment method.

Bibliometrics employs mathematical and computational statistical techniques to examine the disciplinary growth process, and the evolution of research focal points, the distribution of institutions and authors, among other aspects. Based on an analysis of author productivity, publication volume, research institutions, cited references, the temporal dynamics of keywords, and their emerging characteristics, it can propose potential directions for the discipline's advancement[10]. Utilizing bibliometric analysis software, data mining visualization can vividly and intuitively represent the subject's development course and evolutionary patterns as knowledge graphs, offering researchers a novel and macroscopic perspective[11].In recent years, with the extensive adoption of bibliometrics, it has become a prevalent tool in diverse fields such as medicine, agriculture, engineering, and science.

The systematic review of the existing research literature within the academic community reveals a wealth of international research on coal mine safety accident management. However, the majority of these studies mainly focus on the development, implementation, and theoretical aspects of coal mine safety management systems. There is a dearth of literature that comprehensively summarizes and categorizes the current research status of coal mine safety accident management, let alone comparative review articles that analyze the state of the art in this field. To fill this gap, this study employs knowledge graph software CiteSpace and VOSviewer to visually analyze the global literature on coal mine safety accident management, constructing a knowledge graph that visualizes the number of publications, research institutions, countries, and other relevant metrics. The resulting dataset is further sorted, summarized, and analyzed through bibliometric and literature research methods, offering a novel perspective on the cutting-edge trends and frontier hotspots in this field. The ultimate goal is to provide a scientific reference for the advancement of coal mine safety management.

2. Data source and processing

2.1 Data source

In order to improve the objectivity and accuracy of the research conclusions, this paper selects Web of Science (WOS), a citation database with great influence in the world, as the data source. The data source and processing results are shown in Table 1.

Table 1 Data sources and processing results

Archive	Web of Science Core set (SCI,SSCI)

Retrieval mode	(TS=(Coal mine) OR TS=(Coal mining) OR TS=(Coal mine accidents)) AND (TS = (Accident Prevention) OR TS = (Safety Management) OR TS = (Security Management) OR TS = (Risk Assessment) OR TS = (Risk Model))
Literature category	Article
Language	English
Time span	January 2013 - January 2023
Search literature	1999 article
Valid literature	1210 article

2.2 Analytical method

CiteSpace, a Java-based literature visualization software, was developed by Professor Chen Chaomei from Drexel University in the United States. Following several years of development and promotion, CiteSpace has emerged as one of the most reliable software products in the field of scientometric visualization[12]. This software enables the presentation and analysis of the structure, pattern, and distribution of scientific knowledge via visualization functions, such as author collaboration, keyword co-occurrence, organizational distribution, and literature integration. As a result, CiteSpace provides valuable guidance for comprehending and mastering the evolving trends and interrelationships within the disciplinary frontier. VOSviewer, another Java-based bibliometric analysis software, was developed by Nees Jan van Eck and Ludo Waltman from the Scientific Research Center of Leiden University in the Netherlands. This software incorporates literature data samples and generates knowledge maps, allowing for the display of the overall external characteristics of the subject area. VOSviewer particularly excels in cluster analysis [13].

To comprehensively explore the realm of coal mine safety accident management and discern its current traits and evolving trends, this study employs CiteSpace 6.2.R4 and VOSviewer 1.6.18 software to construct a knowledge map that encompasses the volume of literature, author distribution, institutional contributions, country-wise research, keyword clustering, as well as their respective shifts over time. Furthermore, by integrating classical literature, an in-depth analysis is conducted on the global landscape of coal mine safety accident management from 2013 to 2023, shedding light on the forefront and trajectory of this field.

3. Results and analysis

3.1 Analysis of annual publication volume

Based on a statistical analysis of data extracted from the Web of Science (WOS), the trend in annual publication volume has been identified. Figure 1 displays the global distribution of annual publications focusing on research related to coal mine accident safety management from 2013 to 2022. The results of the analysis of trends in published documents divide global coal mine safety management research over the past decade into three stages: a slow germination period, a steady growth period, and a rapid development period. It is evident that there has been an overall increasing trend in the number of publications related to research on managing accidents in coal mines over the past ten years.

(1) During the slow germination period (2013-2015), the average annual publication count was 41 articles, representing a decline of two articles compared to the previous year. The reason is that the

coal mine safety problem has not attracted enough attention, and the coal mine safety management is still in the embryonic stage.

(2) The stable growth period (2016-2018) was preceded by a quick transition from the slow germination period. The inaugural increase in the volume of published documents was observed in 2016, a phenomenon potentially linked to the numerous significant coal mine accidents in 2015 that garnered extensive societal concern. Moreover, in 2015, China shuttered over 2,000 small coal mines rife with safety hazards, and concurrently, introduced an updated version of mine safety regulations in 2016.

(3) Rapid Development Period (2019-2022): Following a significant increase in the number of published documents after 2018, an exponential growth trend emerged, indicating a rapid development phase. The number of published articles surged by 6.79 times, from 43 in 2013 to reach its peak at 292 in 2022. This surge reflects intensive research on coal mine safety accident management and marks the beginning of a golden age characterized by rapid development within this field that has attracted widespread attention from researchers. Based on these findings regarding publication volume, it can be anticipated that this topic will continue to be a focal point and research trend for future studies.
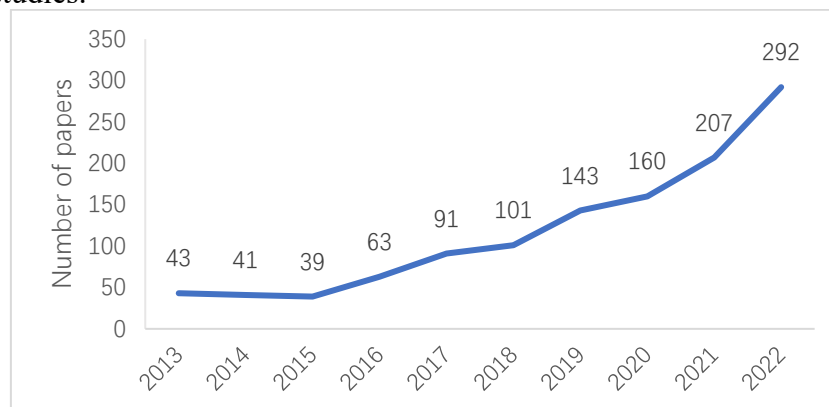
Fig. 1 Number of published papers from 2013 to 2022

3.2 Cooperative network

3.2.1 Collaborative network of authors

Authors of documents to some extent reflect the forefront of scientific research in a specific field. By selecting "author" as the node type in "Co-authorship" within VOSviewer and manipulating the data, we established a lower threshold of five articles and visualized the knowledge graph based on collaborative relationships between authors, as shown in Figure 2. Our analysis included 77 authors, 20 co-authors, and 95 lines within the atlas, accumulating a total connection intensity of 276. Using different colors to represent distinct clusters of author collaboration, the lines connecting each point illustrate their collaborations. Notably, the size of nodes is relative to the number of documents. As depicted in Figure 2, author cooperation exhibits a small-scale cluster cooperation pattern characterized by intensive collaboration within clusters and limited connections between them. The authors' institutions reveal that most clusters consist of researchers from the same institution.
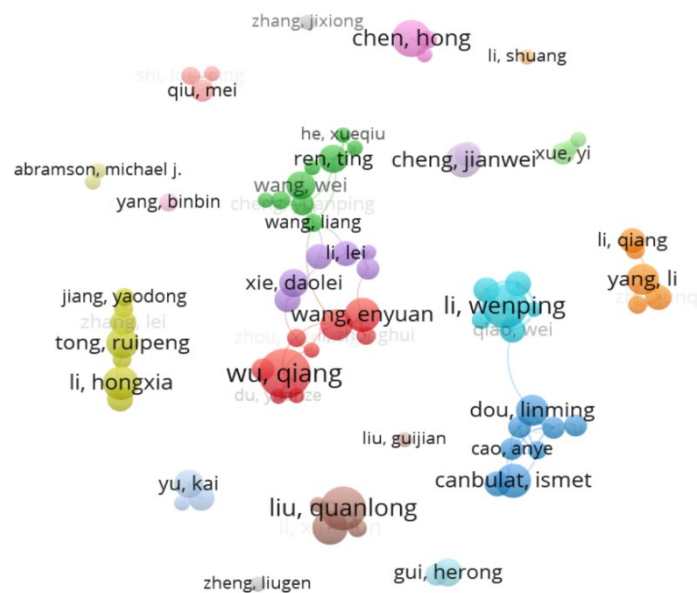
Fig. 2 Author cooperation network diagram

To quantitatively analyze the volume of authors' publications, Table 2 presents information on the top five authors with the highest publication counts. Among them, only one author has published more than 15 articles, and all top five authors have published more than 10 articles. Wu Qiang ranks first with 16 articles, followed by Liu Quanlong and Li Wenping with 14 articles each. The most frequently cited article is by Liu Quanlong (293 citations), followed by Wu Qiang (166 citations) and Cheng Hong (129 citations).

Table 2 TOP5 author publications

Author	Documents	Citations
Wu Qiang	16	166
Liu Quanlong	14	293
Li Wenping	14	89
Cheng Hong	12	129
Wang Enyuan	11	56

3.2.2 Collaborative network of research institutions

The node type is designated as "institution". The knowledge graph is visualized accordingly based on the classification of institutions, as illustrated in Figure 3. Each node represents a scientific research institution, and the size of the node reflects the number of papers published by that institution. The larger the node, the more extensive its publication record. The connections between nodes signify collaborative relationships between scientific research institutions in terms of paper publications. A greater number of connections indicates stronger cooperative bonds between these institutions[14].

Fig. 3 Cooperation network of research institutions

The graph comprises 228 nodes, 313 connections, and a network density of 0.0121. The institutions with a substantial number of publications are primarily associated with research institutes and universities specializing in coal research. These include China University of Mining & Technology, Shandong University of Science & Technology, Anhui University of Science & Technology, Henan Polytechnic University, Xi'an University of Science & Technology, China University of Geosciences, Chinese Academy of Sciences, Liaoning Technical University, and others. Simultaneously, there exist numerous connections among diverse institutions, indicating a relatively close collaboration between them.

To quantitatively analyze the volume of published documents from various institutions, the data of the top 10 research institutions with the highest number of published documents was extracted, as depicted in Table 3.

Table 3 Top 10 research institutions with the number of publications

Number	Institution	Papers
1	China University of Mining & Technology	228
2	Shandong University of Science & Technology	53
3	Anhui University of Science & Technology	42
4	Henan Polytechnic University	21
5	Xian University of Science & Technology	21
6	China University of Geosciences	15
7	Chinese Academy of Sciences	14
8	Liaoning Technical University	14
9	University of Science & Technology Beijing	12
10	Chongqing University	12

Among these research institutions, five have published more than 20 articles each, with two publishing over 50 articles. The China University of Mining & Technology, ranking first, has published 228 articles, nineteen times the number of Chongqing University, ranking tenth. This institution is far ahead of others in terms of research output. It is followed by Shandong University of Science & Technology with 53 articles and Anhui University of Science & Technology with 42 articles.

3.3 Keyword co-occurrence and clustering

3.3.1 Keyword co-occurrence

Authors of research papers extensively summarize keywords. Analyzing keywords from research papers within a specific field can rapidly identify research hotspots and frontiers[13]. After processing the data, the VOSviewer software was configured to display "All keywords" in the "Co-occurrence" feature, resulting in a visual knowledge graph based on keyword classification, as illustrated in Figure 3. The analysis yielded 194 nodes, 6 clusters, and 3535 connections, with a total connection strength of 5778. The size of the nodes, label font size, and label and line visibility in the figure were adjusted to enhance the clarity of the keyword node and its associated connections."

Fig. 4 Keyword co-occurrence analysis map

In the keyword co-occurrence graph, the size of the node label corresponds to the frequency of the corresponding keyword. The co-occurrence relationship between keywords is represented by connections in the co-occurrence network. To enhance the reliability of the keywords, the subject term (coal mine safety accident management) was removed, resulting in the top 5 keywords as follows: China (54), system (32), coal and gas outburst (31), performance (30), and methane (27). As illustrated in the figure, the color of the nodes gradients from dark to light, indicating that the darker color signifies the earlier appearance of the keyword, while the lighter color signifies a later appearance. As observed in the figure, China has been actively engaged in the research field of coal mine safety accident management from the early stages, which is consistent with China's national conditions. Despite being a major coal-producing country and experiencing continuous adjustments in its energy structure in recent years, coal still accounts for over 70% of primary energy, maintaining a crucial role in China's daily life. However, due to complex occurrence conditions and challenging coal seam mining, China has the highest number of coal mine accidents globally[15].

3.3.2 Keyword clustering

The application of cluster analysis serves as an effective method for conducting an in-depth analysis of research hotspots, thereby facilitating a more comprehensive understanding of global trends in coal mine safety accident management. CiteSpace software is employed for keyword clustering, with the clustering type set to "keyword." Subsequently, the primary clustering labels are filtered, and the top 12 clusters with the highest clustering intensity are selected. These results are presented in the form of a visual knowledge graph, as illustrated in Figure 5.

As depicted in the figure, keyword points of various colors congregate to form 12 distinct clusters. Cluster #1 is situated in the central region of the map, functioning as a bridge and link, thereby serving as a crucial foundation for the realization of coal mine safety accident management.
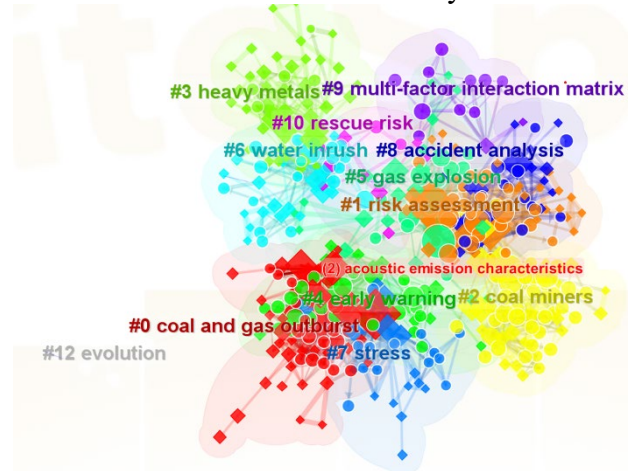

Fig. 5 Keyword cluster analysis diagram

To further investigate the initial appearance time, active period, and emergence of keywords, "Timezone" is chosen for the visualization of the spatial and temporal distribution of keywords, as depicted in Figure 6.

The map comprises 293 nodes, 1485 connections, and a network density of 0.0347. To facilitate a comprehensive understanding of the evolution of high-frequency keywords within a specific time frame (i.e., burst words), the utilization of a red highlighting method is more advantageous for analyzing the development of research hotspots in coal mine safety management across various epochs.

The spatial and temporal distribution map of keywords reveals that the high-frequency keywords and emerging terms primarily encompass six clusters, namely accident analysis, coal spontaneous combustion, heavy metals, coal mining, coal and gas outburst, and coal miners. Notably, on the time zone distribution axis of cluster #0 accident analysis, high-frequency keywords were most prevalent with years distributed over the past decade including topics such as coal mine safety management system intervention effect and interrupted regression model.
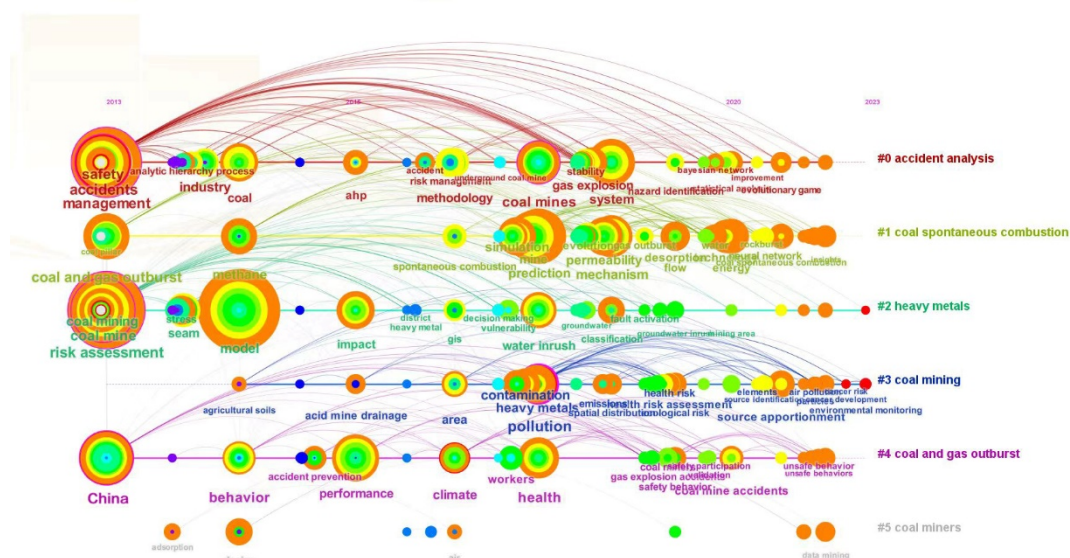

Fig. 6 Keyword time zone distribution

3.4 Frontier analysis

The cutting-edge research domain in scientific exploration is an emerging field[16]. By analyzing the alterations in keyword frequencies and the emergence of new terms, we can delve into the frontiers and development trends of this domain. Utilizing CiteSpace software and leveraging keyword clustering as depicted in Figure 5, we selected "Burtrace" to identify an unexpected term. The outcome of this detection is presented in Figure 7.

Top 9 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	2013 - 2023
subsidence	2014	3.54	2014	2018	
China	2013	5.52	2016	2018	
workers	2017	2.84	2017	2019	
seam	2014	3.25	2018	2019	
association	2018	2.51	2018	2019	
mechanism	2018	3.11	2020	2021	
energy	2020	2.63	2020	2023	
gas	2020	2.51	2020	2021	
source apportionment	2021	2.61	2021	2023	

Fig. 7 Keyword time zone distribution

Among them, the red portion signifies the year in which the keyword attains prominence, i.e., the year of its activation. The eruptive term receives significant attention from researchers at this stage. In the table, the detection information of the top 9 emerging words is derived from tracking and summarizing their emergence intensity, as well as noting the initiation and conclusion of each high-frequency term.

As illustrated in Table 2, research hotspots can be categorized into two time intervals based on the fluctuation trend of published paper numbers: The first interval spans from 2013 to 2019, corresponding to both the gradual growth phase and accelerated development phase in paper numbers. All three keywords with the highest eruptive intensity occur during this stage. The primary focus of research is on China's coal mine safety management and coal seam subsidence. As is also known, the keywords include China (5.52), seam (3.54), and subsidence (3.25), with the starting and ending years primarily ranging from 2014 to 2018.

The interval period 2 spans from 2019 to 2023, corresponding to a rapid increase in the publication rate. Some emerging active keywords remain relevant in present-day research, representing the current focal points that have garnered widespread attention from scholars. At this stage, research emphasis and hotspots primarily revolve around strategies for preventing coal and gas outbursts, production mechanisms in safety management, and resource allocation for accident prevention. This also involves summarizing and analyzing outbreak-related keywords, which mainly encompass four critical terms: mechanism (3.11), energy (2.63), source apportionment (2.61), and gas (2.51).

4. Conclusion

With the assistance of two visualization tools, Citespace and VOSviewer, this study conducts a bibliometric analysis of the literature related to coal mine safety management in China from 2013 to 2023 and comprehensively reviews the evolution of this field. Through examining the publication volume, researchers, institutions, co-occurring keywords, keyword cluster analysis, and evolutionary trends, the following findings are revealed:

(1) Driven by time distribution, research on global coal mine safety accident management has undergone three stages of development: gradual initiation, steady growth, and rapid acceleration. Between 2016 and 2023, the number of articles published in core journals and all journals has surged significantly indicating that the field entered a period of rapid growth in 2016 and ushered in a golden age of accelerated development which attracted widespread attention and appreciation from researchers.

(2) According to the collaborative network of authors, the collaboration community of authors within this field has established several prominent scholars. Among them, Wu Qiang, Liu Quanlong, Li Wenping, Cheng Hong, and Wang Enyuan, the top five authors with the highest number of published papers, all serve as staff members at renowned coal mine safety research institutions.

(3) Based on the institutional cooperation network, eminent institutions actively engaged in coal mine safety accident management globally include China University of Mining & Technology, Shandong University of Science & Technology, Anhui University of Science & Technology, Henan Polytechnic University, Xi'an University of Science & Technology, et al. These are crucial research institutes in the field of coal mine safety.

(4) As it is also known from the induction and analysis of keywords, it is concluded that the main content of global coal mine safety accident management includes high-frequency keywords as well as China, workers, seam, and association. The top 9 keywords with the highest emergent intensity were extracted, and the evolution of emergent words was acquired after reordering according to the emergent year. This provides significant support for exploring the evolutionary path and frontier change trend in this field.

(5) The exploration and evolution of the frontier in this field were analyzed by examining the frequency variations of keywords and the emergence of new terms. Consequently, research hotspots were categorized into two time intervals: 2013-2019 and 2019-2023. The first interval corresponds to the gradual growth phase and the stable development stage in terms of the number of published documents. During this stage, the top three emerging keywords were found to be China, subsidence, and seam, in sequence. The second interval, spanning 2019-2023, represents a period of rapid growth in the number of published documents. This phase is characterized by the involvement of four key terms: mechanism, energy, source apportionment, and gas. The active status of some emerging keywords has persisted to the present day and currently serves as the focal point of contemporary research.

5. Practical value and future prospects

The active and interdisciplinary subject of coal mine safety management undoubtedly still holds great potential for development. Therefore, it is of significant value to examine the research context from a bibliometric and scientometric perspective, which can offer research directions and insights for scholars in this field. To be specific:

(1) This study can help some scholars on coal mine safety management to establish a clear framework for the existing research in this field and understand the development process of this field deeply;

(2) The high-frequency keyword clustering and co-occurrence analysis in this study can offer insights into the central themes and emerging trends of coal mine safety management research, thereby guiding scholars in selecting appropriate research topics;

(3) This study analyzes the core institutions and core authors of coal mine safety management, which can help scholars quickly find the literature they want to refer to in research, and also provide guidelines for relevant scholars to select journals when submitting papers on this topic to a certain extent.

Future research should first integrate literature from multiple databases to ensure comprehensive data selection, actively engage with scholars in the field of coal mine safety management to discern the latest trends and enhance the objective understanding of the field while minimizing the subjectivity of personal analysis and interpretation.

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