

Visualization Analysis of Knowledge Graph of Coal Mine Risk Early Warning

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Abstract

To systematically reveal the development landscape and evolving trajectories of coal mine risk early warning research in China, this study combines CiteSpace-based visual analytics with bibliometric methods. A total of 688 core journal articles published in the CNKI database from 2001 to 2025 were used to construct a domain knowledge graph. The analysis examines publication trends, journal distribution, author and institutional collaboration networks, keyword co-occurrence, and burst-keyword evolution. The results show that domestic research has progressed through three phases—initial exploration, rapid expansion, and fluctuating stabilization. A stable set of core journals (e.g., Coal Mine Safety and Coal Technology) and influential authors (e.g., Jiang Fuxing and Zhang Qinghua) has gradually emerged, while overall collaboration remains limited and relatively dispersed. Four major research clusters are identified: early-warning systems, gas early warning, rock burst early warning, and coal spontaneous combustion early warning, with spontaneous combustion, indicator gases, and graded early-warning frameworks becoming prominent frontiers in recent years. Burst-keyword evolution further indicates a shift from macro-level hazard identification toward multi-source data fusion and intelligent early-warning technologies, alongside increasing integration with IoT, big data, and artificial intelligence. Overall, coal mine risk early warning research in China is moving toward more refined, intelligent, and system-oriented development, providing scientific support for smart mine construction and modernized coal mine safety governance.

Keywords

Coal Mine; Risk Early Warning; CiteSpace.

1. Introduction

As China's primary energy source, coal accounts for about 60% of total primary energy consumption and more than 70% of primary energy production, giving it an irreplaceable strategic role in energy security, industrialization, and economic development. Nevertheless, coal mining remains a high-risk industry: despite substantial safety improvements, major and exceptionally serious accidents still occur sporadically, posing threats to human life and social stability.

With increasing mining depth, more complex geological conditions, and the widespread adoption of intelligent mining technologies, traditional passive safety management based on experience and post-event handling can no longer meet modern safety requirements. Improving coal mine safety therefore requires a shift from "passive response" to "active prevention" by establishing scientific systems for risk identification, monitoring, and early warning to enable dynamic recognition and real-time response to potential hazards.

Against this backdrop, this study applies CiteSpace-based visual analytics and bibliometric methods to systematically examine 2001–2025 coal mine risk early warning literature in the CNKI database and to construct a domain knowledge map^[1-5]. By analyzing publication trends, core authors and institutions, and high-frequency keywords, the study identifies research trajectories, hotspots, and evolutionary patterns, providing evidence to support future research directions.

Overall, the knowledge-map analysis offers a comprehensive overview of the field, clarifies frontier directions for researchers, and provides decision support for safety management departments in building risk prevention and control systems, thereby promoting the continued advancement of coal mine safety toward informatization, intelligence, and systematization.

2. Bibliometric Analysis

2.1 Data Sources and Research Methods

To comprehensively understand the development process and trends of coal mine risk early warning research in China, this study uses the CNKI database as the primary data source and conducts a retrieval with the subject terms “(coal mine or mine) and (risk) and (early warning)” over the period from 2001 to 2025. The data were restricted to literature indexed by SCI, EI, CSSCI, core journals, and CSCD, yielding a total of 738 publications. After manual screening to remove invalid samples such as conference notices and news reports, 688 valid articles were finally retained and exported in RefWorks format.

By combining bibliometric analysis methods with the CiteSpace software, quantitative and visual analyses were conducted on the temporal distribution of publications, author and institutional distributions, and keyword co-occurrence, in order to reveal the current research status, hotspots, and development trends in this field.

2.2 Distribution of Publication Volume

Publication volume is an important indicator for measuring the maturity and dominant research directions of a specific research field within a given period, as it not only reflects the degree of academic attention but also, to some extent, reveals the evolution of research themes and the concentration of research forces^[6-9]. Fig. 1 illustrates the annual distribution of publications related to coal mine risk early warning from 2001 to 2025. Overall, the number of publications in this field exhibits a general trend of slow growth, followed by rapid increase, and then fluctuation and stabilization, indicating that coal mine risk early warning research has undergone a complete evolutionary process from initial exploration to systematic development. Specifically, the development process from 2001 to 2025 can be roughly divided into three stages.

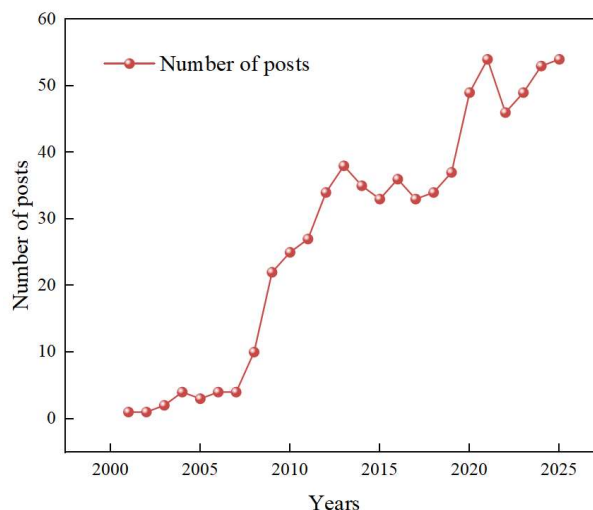


Fig. 1 Statistics of publication volume from 2001 to 2025

From 2001 to 2006, the field was in its initial stage, during which the safety management concept of coal mine risk early warning had not yet formed a systematic theoretical framework, and related studies mainly focused on macro-level issues such as accident emergency response and safety supervision, lacking systematic research on risk identification, assessment, and dynamic early warning. Due to limited informatization and relatively underdeveloped monitoring technologies at that time, scholars tended to conduct discussions from the perspectives of accident cases or experience-based management, resulting in a relatively small number of publications, fragmented research outcomes, and an immature theoretical system.

From 2007 to 2021, the field entered a period of rapid growth, as national attention to coal mine safety production continued to increase and policies and regulations such as the Work Safety Law and Mine Safety Regulations were progressively improved, making coal mine risk early warning a research hotspot in the field of safety science. Research priorities shifted from single-accident prevention to multidimensional risk prevention and control as well as systematic management. Meanwhile, bibliometric data show a rapid rise in publication volume during this stage, reaching a peak around 2015, with the highest annual output of 54 articles. Studies in this period exhibited diversified characteristics, covering monitoring and early warning technologies for typical hazards such as coal spontaneous combustion, gas outbursts, and rock bursts, and also featuring early exploratory research based on big data, the Internet of Things, and artificial intelligence, which laid the foundation for the establishment of a theoretical system for coal mine risk early warning.

From 2021 to the present, the field has entered a period of fluctuation, as coal mine risk early warning research moved into a phase of adjustment and deepening after rapid growth. Although the number of publications has shown slight fluctuations compared with the peak period, the quality and depth of research have improved significantly, and research themes have shifted from qualitative to quantitative approaches and from experience-based to intelligent methods. Research in this stage places greater emphasis on model construction, data fusion, and multi-source information collaborative early warning, with a focus on the development of intelligent and visualized monitoring systems for coal mine safety. It can be anticipated that, with the advancement of smart mine construction and the in-depth application of artificial intelligence and big data analytics, research in the field of coal mine risk early warning will continue to develop toward standardization, systematization, and intelligence, with the disciplinary framework becoming increasingly mature and stable.

2.3 Distribution of Journals by Field

Based on the statistical results, a total of 688 core journal articles related to coal mine risk early warning were retrieved between 2001 and 2025, distributed across 59 Chinese core journals. Overall, the research outputs are relatively concentrated among journals, indicating that academic research in this field has formed a certain stable pattern and core dissemination channels. Table 1 presents the statistical results of journals with a publication frequency of five or more articles, which together published 564 papers, accounting for 82.0% of the total sample, demonstrating a high degree of concentration and academic dependence of coal mine risk early warning research within specific journals.

Among them, Coal Mine Safety is the most representative core journal in this field, having published 99 related papers over the past 25 years, accounting for 14.4% of the total. This journal has long focused on topics such as coal mine safety production, risk management, and disaster prevention and control, serving as an important academic platform for coal mine safety science research in China, and its high publication volume reflects its authoritative status in academic exchanges on coal mine safety. Following closely is Coal Technology, which has published 85 articles, accounting for 12.4%, mainly featuring research related to coal mining technologies, automated monitoring, and applications of early warning systems. Journals such as Coal Science and Technology, Industry and Mine Automation, Mining Safety and Environmental Protection, and Coal Engineering have each published more than 35 related articles, and these journals possess strong professional influence in

coal mine safety, automation control, and information technology research, jointly constituting the core academic publishing platforms in the field of coal mine risk early warning. Their research topics span the entire chain from fundamental theoretical studies to intelligent sensing, risk assessment, and the construction of risk management systems, reflecting the comprehensive and technology-oriented characteristics of research in this field.

Table 1. Statistics of Journals by Publication Output (Frequency ≥ 5)

Journal	Articles
<i>Coal Mine Safety</i>	79
<i>Coal Technology</i>	70
<i>Coal Science and Technology</i>	57
<i>Industry and Mine Automation</i>	55
<i>Mining Safety and Environmental Protection</i>	38
<i>Coal Engineering</i>	37
<i>Journal of China Coal Society</i>	29
<i>China Coal</i>	24
<i>China Safety Science Journal</i>	17
<i>Coal Mining Machinery</i>	13
<i>Journal of Safety Science and Technology</i>	11
<i>China Mining Magazine</i>	10
<i>Journal of Rock Mechanics and Engineering</i>	8
<i>Journal of Mining and Safety Engineering</i>	7
<i>Mining Research and Development</i>	7
<i>Coal Mining Technology</i>	6
<i>Metal Mine</i>	5
<i>Journal of Xi'an University of Science and Technology</i>	5

Overall, coal mine risk early warning research has formed a core group of journals represented by *Coal Mine Safety* and *Coal Technology*, exhibiting features such as concentrated research themes, stable publication channels, and significantly enhanced academic influence. This not only indicates that the research system in this field has become increasingly mature, but also suggests that coal mine safety and risk early warning studies are gradually forming a systematic and networked academic dissemination framework, laying a solid foundation for subsequent interdisciplinary research.

2.4 Author and Institutional Analysis

2.4.1 Analysis of Publishing Authors

Disciplinary advancement relies on the contributions of researchers, who, as an intrinsic driving force, are capable of promoting the development of a field. By examining individual authors and research teams, it is possible to analyze and interpret the work of influential researchers and their patterns of collaboration, thereby facilitating the development of coal mine risk early warning research in China and reducing the occurrence of coal mine accidents.

An analysis conducted using the CiteSpace software produced the author distribution shown in Fig. 2. According to the software's calculations, the network contains 240 nodes, 288 links, and a density

of 0.01. These results indicate that the sample literature involves 240 authors, among whom 288 cooperative relationships exist. Moreover, the density of the author co-occurrence knowledge network is relatively low, at only 0.01. The findings suggest that most authors are working in relatively independent publication stages, with limited connections and collaboration, and only a small number of authors maintain small-scale cooperative relationships.

This low-density author network reflects that coal mine risk early warning research is still in a phase of gradual formation of an academic community. On the one hand, research topics exhibit diversification and specialization, leading to a dispersion of scholarly focus. On the other hand, differences among universities and research institutes in research directions, technical approaches, and data sources also constrain deep collaboration among authors to some extent. Nevertheless, several small but highly intensive collaborative groups can still be observed within the network, whose members have formed relatively stable research alliances through long-term cooperation and play an important role in advancing the field.

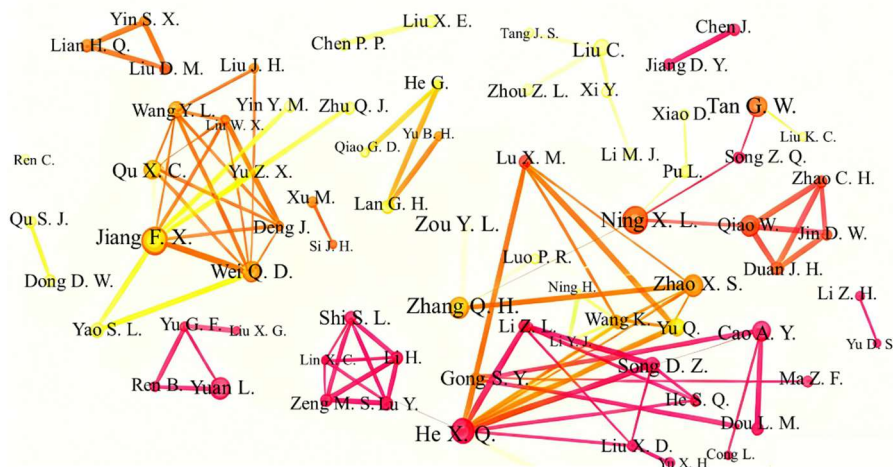


Fig. 2 Visualization map of publishing authors in the field of coal mine risk early warning

Table 2. Statistics of Key Authors' Publications

Key Author	Publications	First Publication Year
Jiang Fuxing	14	2010
Zhang Qinghua	11	2011
Zou Yunlong	10	2011
Ning Xiaoliang	10	2015
He Xueqiu	9	2012
Qu Xiaocheng	9	2011
Zhao Xusheng	8	2010
Tan Guowen	8	2010
Dou Linming	6	2016
Song Dazhao	5	2020
Gong Siyuan	5	2020
Shi Shiliang	5	2020
Li Mingjian	5	2010

In terms of publication output, Table 2 identifies 13 prolific authors with more than five papers each. Jiang Fuxing (14) and Zhang Qinghua (11) rank first and second, indicating strong academic influence. Jiang Fuxing's work centers on rock burst monitoring and early warning and mine pressure disaster control, with notable advances in microseismic monitoring, dynamic disaster prediction, and multi-parameter integrated early warning. Zhang Qinghua focuses on coal mine safety management and early warning model development, emphasizing the integration of theory with engineering practice. Other leading scholars, including Zou Yunlong, Ning Xiaoliang, He Xueqiu, and Qu Xiaocheng, have contributed systematic studies on risk identification, gas disaster prediction, and data-mining-based early warning, forming the backbone of the field and supporting diversified theoretical development.

The collaboration map shows a relatively tight and efficient network around Jiang Fuxing, Zhang Qinghua, and related teams, who occupy central positions and connect key resources and expertise. Most prolific authors became active after 2010, aligning with the maturation of China's coal mine safety technology system and the wider adoption of risk early warning concepts. Research themes have evolved from early hazard identification and accident prevention, to system construction and model research, and more recently to the integration of big data, artificial intelligence, and the Internet of Things to enable intelligent safety management.

Structurally, the core network exhibits a "core-driven-peripheral collaboration" pattern: core teams lead methodological innovation, while peripheral participants contribute to application-oriented studies via projects. Although several stable teams have formed across risk identification, monitoring and early warning, system modeling, and intelligent sensing, collaboration remains overall limited and lacks nationwide, cross-institutional platforms. Strengthening cross-institutional and interdisciplinary cooperation through national key laboratories, academic alliances, and multi-source data-sharing mechanisms could accelerate a shift from fragmented research to clustered innovation and further enhance international competitiveness and influence.

2.4.2 Analysis of Publishing Institutions

Institutional analysis helps to gain an in-depth understanding of the distribution of research forces and collaborative relationships among institutions within a specific research field, while also identifying institutions with high academic influence, thereby facilitating academic exchange and cooperation and promoting the overall development of the field. The software calculation results show that the network contains 300 nodes, 293 links, and a density of 0.0065. These data indicate that the sample literature involves 300 institutions, among which 293 cooperative relationships exist, and that the overall network density is relatively low at only 0.0065. This suggests that institutions involved in coal mine risk early warning research in China are relatively dispersed and lack sufficient communication and collaboration. Fig. 3 presents the institutional knowledge map of publications in the field of coal mine risk early warning, in which node size represents the number of publications by each institution, and links between nodes indicate collaborative relationships.

In terms of institutional types, the map includes national key laboratories, research institutes and enterprises such as the Chongqing Research Institute of China Coal Technology & Engineering Group, and is not limited to universities. Based on publication output, institutions such as China University of Mining and Technology, the Chongqing Research Institute of China Coal Technology & Engineering Group, national key laboratories, Xi'an University of Science and Technology, and University of Science and Technology Beijing have published a relatively large number of studies in the field of coal mine risk early warning. These institutions demonstrate active research performance and maintain close connections and cooperation with other research organizations.

In terms of frequency, the six most high-frequency keywords are early warning, rock burst, monitoring and early warning, early warning system, coal mine, and coal spontaneous combustion, with occurrence frequencies of 77, 62, 40, 37, 33, and 28, respectively. Their corresponding betweenness centrality values are 0.48, 0.29, 0.30, 0.20, 0.18, and 0.11, respectively. Betweenness centrality represents the importance of a node within the network, and an increase in centrality corresponds to a greater level of influence. Therefore, in this knowledge map, keywords with relatively high centrality values greater than 0.1 constitute the focal points of coal mine risk early warning research, such as rock burst, monitoring and early warning, and coal spontaneous combustion.

3.2 Analysis of the Developmental Trajectory of Research Themes

Keyword clustering is widely used in scientific research to identify hotspots and track academic trends. Using the keyword co-occurrence module in CiteSpace, this study constructed a keyword-clustering knowledge map for coal mine risk early warning (Fig. 5) and evaluated its quality using modularity (Q) and mean silhouette. In general, $Q > 0.3$ indicates significant clustering, while a silhouette value > 0.7 suggests high efficiency and strong reliability. The results show $Q = 0.5625$ and silhouette = 0.8483, demonstrating that the clustering map is robust and convincing. Based on the top eight clusters, several key hotspot topics were identified.

The first hotspot is early-warning systems, represented by keywords such as “early warning models,” “sensors,” and “coal mine safety.” Prior studies have explored model development and system construction using methods such as self-organizing neural networks, extension theory, fuzzy mathematics, and layered system architectures (perception–transmission–application), providing methodological support for practical deployment.

The second hotspot is gas early-warning technology, which emphasizes indicator selection and model building based on monitoring data. Representative approaches include correlation and grey relational analysis, support vector machines combined with immune genetic BP algorithms, spatiotemporal sequence modeling for gas concentration prediction, multi-source geological information fusion, and data-mining-based prediction of gas explosion risk and warning levels.

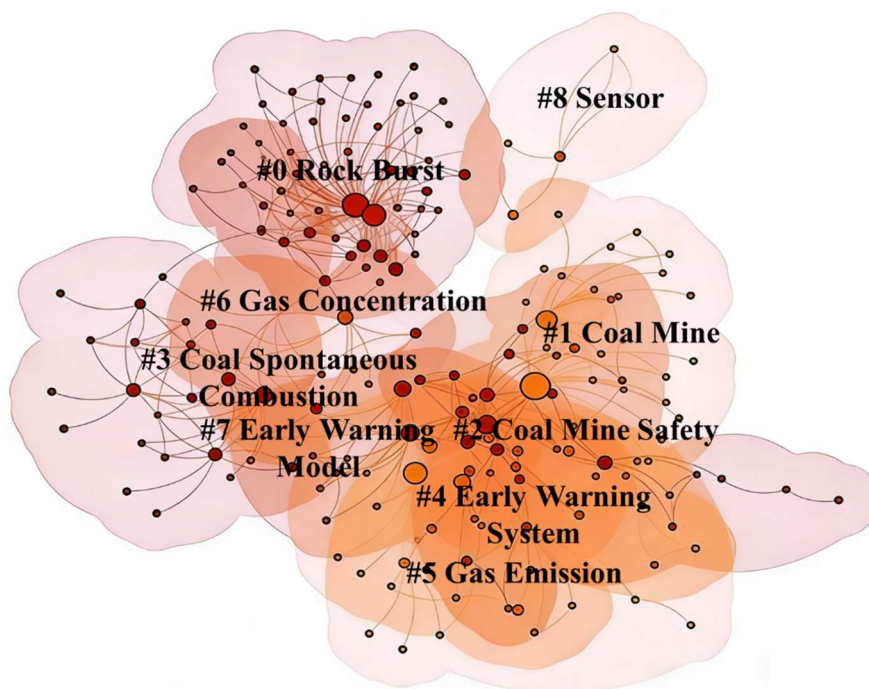


Fig. 5 Keyword clustering map in the field of coal mine risk early warning

The third hotspot is rock burst early warning, focusing on multi-parameter integrated monitoring and forecasting. Typical studies investigate classification and warning methods based on microseismic monitoring, as well as comprehensive schemes combining electromagnetic radiation, microseismic signals, and stress-related parameters to identify precursors and support prediction and pre-relief strategies.

The fourth hotspot is coal spontaneous combustion early warning, which has expanded from temperature-based monitoring to indicator-gas analysis, multi-source information fusion, and graded warning frameworks. Related work includes determining critical temperatures, developing information-fusion early warning methods, proposing prevention measures across mining stages, using large-scale experimental furnaces to analyze heating and oxygen-consumption behavior, applying sensor-network monitoring, defining stage temperature ranges and corresponding indicators, and constructing graded warning models using machine-learning methods such as random forests.

3.3 Analysis of Development Trends in Research Themes

Unlike traditional approaches that focus on statistically high-frequency keywords, burst keyword analysis emphasizes the sudden increase in keyword frequency within specific time windows, thereby more effectively revealing the evolutionary trajectories of research hotspots across different stages. Burst strength reflects the degree of widespread academic attention a topic receives during a certain period, while the starting and ending years indicate the temporal process of emergence, persistence, and decline of that research focus.

The burst keyword results obtained using CiteSpace (Table 3) show that coal mine risk early warning research exhibits clear stage-based characteristics. Early burst keywords such as “coal mine,” “early warning,” “gas concentration,” and “outburst early warning” appeared earlier and persisted for longer durations, reflecting a long-term research focus on overall coal mine safety, the introduction of disaster prevention and mitigation concepts, and the monitoring and control of typical hazards such as gas accidents. During this stage, research primarily concentrated on macro-level risk identification, extraction of monitoring indicators, and the preliminary construction of early warning systems, exhibiting a research pattern centered on specific disaster types. In contrast, keywords with later burst onsets, such as “coal spontaneous combustion,” “indicator gases,” and “graded early warning,” show higher burst strengths, indicating that recent research has gradually shifted toward more refined and intelligent directions. In particular, “coal spontaneous combustion” has the highest burst strength, suggesting that under complex geological conditions and deep mining scenarios, the concealed nature and complex evolution of coal spontaneous combustion hazards have made them a new research frontier. The burst of “indicator gases” reflects a transition from traditional temperature-based monitoring to multi-source information fusion, whereby changes in gas concentrations such as CO and C₂H₄ are used to identify stages of coal spontaneous combustion, promoting the evolution of early warning mechanisms from single-indicator judgments. Meanwhile, the burst of “graded early warning” indicates that research has moved beyond determining whether to issue a warning toward exploring how to scientifically classify warning levels and guide management decision-making, reflecting the practical demand for a shift in coal mine safety management from extensive to refined and operational approaches.

Overall, the evolution of burst keywords clearly illustrates the transition of coal mine risk early warning research from macro-level hazard identification to fine-grained indicator extraction and intelligent early warning. This process demonstrates the continuous deepening of research priorities from traditional experience-based management toward data-driven, model-oriented, and graded control approaches, while also revealing that future studies may further focus on multi-source information fusion, intelligent early warning model construction, and the quantitative linkage between warning outcomes and response mechanisms.

Table 3. Distribution of Keyword Burst Terms

Keyword	Burst Strength	Start Year	End Year	2001 - 2025
Coal mine	5.41	2001	2015	
Early warning	3.92	2007	2015	
Outburst early warning	3.96	2012	2019	
Gas concentration	3.22	2011	2018	
Coal spontaneous combustion	6.15	2019	2025	
Indicator gases	3.73	2019	2025	
Graded early warning	3.57	2019	2025	

4. Conclusion

From the perspectives of temporal evolution as well as author and institutional distributions, coal mine risk early warning research in China has undergone a long-term development process characterized by an “initial stage–rapid growth stage–fluctuation stage,” with a continuously expanding research scale but an overall low-density collaboration network. A group of prolific authors has gradually emerged, and core institutions are mainly concentrated in research-intensive organizations such as China University of Mining and Technology, the Chongqing Research Institute of China Coal Technology & Engineering Group, and national key laboratories. In contrast, the participation of enterprises and government agencies remains relatively limited, and cross-institutional and interdisciplinary collaborative innovation still needs to be further strengthened.

From the perspective of research hotspot analysis, coal mine risk early warning studies have formed four core directions: early warning systems, gas early warning, rock burst early warning, and coal spontaneous combustion early warning. Research on early warning systems emphasizes model construction and system integration. Gas early warning research focuses on multi-parameter monitoring and intelligent prediction. Rock burst research concentrates on comprehensive early warning based on multiple parameters such as microseismic activity, electromagnetic signals, and stress. Coal spontaneous combustion research has expanded from traditional temperature-based monitoring to indicator gas analysis, multi-source information fusion, and the construction of graded early warning frameworks.

The evolution of burst keywords indicates that research themes have shifted from macro-level disaster-type studies toward intelligent and refined early warning technologies. In particular, coal spontaneous combustion, indicator gases, and graded early warning have emerged as key frontiers in recent years, reflecting the deep integration of data-driven, model-driven, and decision-driven approaches in coal mine risk early warning research.

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