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Bibliometric Analysis of Research Progress and Perspectives of Deep Underground Rockburst Using Knowledge Mapping Method

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Abstract: In order to ensure the successful construction and stable operation of deep engineering projects, significant progress has been made in researching deep underground rockburst issues from various perspectives. However, there have been few systematic analyses of the overall research status of deep rockburst to date. In this study, a bibliometric approach using CiteSpace software (version 6.2.R3) was employed to visualize and analyze knowledge maps of 353 research articles on deep rockburst collected from the Web of Science core database from 1996 to 2022. The results show that the number of publications experienced exponential growth after an initial stage of budding and peaked in 2016. In terms of collaboration, China plays an absolute central role. The top three highly cited journals were the *International Journal of Rock Mechanics and Mining Sciences*, *Rock Mechanics and Rock Engineering*, and *Tunneling and Underground Space Technology*. In the keyword co-occurrence analysis, the keyword "prediction" had the highest frequency of occurrence in the past two decades, indicating it as the major research focus in deep rockburst studies. The keyword co-occurrence clustering analysis revealed eight clusters, including conventional criteria, acoustic emission, geology, seismic velocity tomography, dynamic disturbance, and others, representing the primary research topics. This study provides a comprehensive analysis of the current research progress and development trends of deep underground rockburst, helping to understand the key areas of focus in this field and providing potential prospects for future investigations for researchers and practitioners.

Keywords: deep underground; rockburst; bibliometrics; knowledge mapping; CiteSpace

Citation: Wang, L.; Zhu, Z.; Wu, J.; Zhao, X. Bibliometric Analysis of Research Progress and Perspectives of Deep Underground Rockburst Using Knowledge Mapping Method. *Sustainability* **2023**, *15*, 13578. https://doi.org/10.3390/su151813578

Academic Editors: Gong Jian, Minxi Chen, Xinyu Ye and Dejian Li

Received: 20 July 2023
Revised: 11 August 2023
Accepted: 7 September 2023
Published: 11 September 2023

1. Introduction

During the construction of underground engineering projects involving deep burial and hard brittle surrounding rock, a special rock mechanics phenomenon known as rockburst can occur, caused by the sudden release of stored energy in hard brittle rock formations [1–3]. These bursts can result in severe casualties, structural damage, and economic losses, making them common dynamic geological hazards in deep underground construction projects [4,5]. South Africa, in particular, experiences a high incidence of rockburst accidents, primarily occurring in its gold mines. In 1975 alone, South Africa experienced 680 rockburst accidents in 31 gold mines, resulting in 73 fatalities and significant losses for 4800 work shifts. Virtually all gold mines in South Africa are affected by rockburst. Consequently, South Africa stands as one of the earliest countries to systematically study rockburst, and has been conducting research in this field for an extended period [6].

A comprehensive understanding of the mechanisms and prediction methods of rockburst is vital for effective prevention strategies. As the exploration of underground spaces and mines continues, countries including China, Chile, the United States, Canada, Western Australia, and many others have progressively recognized and conducted in-depth research on rockburst issues [7–10]. With the increasing demand for the utilization and development of deep-seated resources and underground spaces, it has become increasingly important to fully understand and study rockburst problems encountered in deep rock mass engineering construction. As excavation depths increase, rockbursts are becoming more prevalent. Deep rock masses, defined as rock masses with depths exceeding 3000 m, present more complex geological origins and occur in unique environments characterized by high geo-tress, high temperature, high pore pressure, and strong mining disturbances. These factors contribute to the frequent and intense occurrence of rockburst in deep rock mass engineering projects, highlighting the critical importance of understanding the factors that contribute to rockbursts for the safety of future deep underground construction projects [11–18]. Such incidents pose threats to personnel, property, and engineering stability.

Currently, the research on deep rockburst mainly revolves around four aspects: theoretical analysis, experimental studies, numerical simulations, and engineering case data analysis. The main research areas include the causal mechanisms of rockburst, prediction of rockburst tendencies, and prevention and mitigation measures for rockburst [19–28]. The study of the predisposition of rock materials to rockburst is one of the fundamental aspects of rockburst prediction. Due to the complexity of rockburst phenomena, accurate prediction of rockbursts is challenging. Researchers have employed various theories, including energy theory, strength theory, and fracture damage theory. For instance, Hoek and Brown [29] established stress–strength parameters for rockburst in practical rock engineering to assess their potential, which is a vital component of rockburst mechanism research [30]. Zhang et al. [31] combined engineering case data and proposed a new rockburst tendency grading parameter based on five engineering factors. Gong et al. [32,33] introduced the peak strain energy storage index and the peak strength energy impact index based on precise peak elastic strain energy, establishing rockburst parameters from an energy perspective for rockburst assessment and prediction. Despite the application of diverse methods, there is currently no universally accepted method for predicting rockburst occurrence times [34–39].

It is evident that research on deep rockbursts has attracted widespread attention from scholars. Considering the significant progress made in various aspects of deep rockburst research, it is necessary to provide a comprehensive overview of the field, which will facilitate an understanding of the existing knowledge domain and explore potential research directions. Bibliometric analysis serves as a vital method for revealing the evolution of specific research topics, enabling a better understanding of research trends and emerging interests [40–42]. By applying statistical techniques, bibliometric analysis provides a macroscopic analysis of the published literature. To the best of our knowledge, some review papers have provided an overview of rockburst prediction in mines or metal mines, as well as rockburst criteria [30,43–45]. However, these reviews only focus on a small number of papers in specific research areas and have not reported on comprehensive bibliometric analyses of deep rockburst research from the perspective of deep engineering. Bibliometric analysis will provide a comprehensive analysis, revealing the most important aspects and directions for future research on this topic. What is more, the bibliometric method reduces distortion and bias caused by subjective information filtering by comprehensively mining the research foundation literature.

This paper utilized bibliometric analysis to statistically analyze the literature, constructed a knowledge map, and quantitatively examined the global research progress on deep underground rockburst from 1996 to 2022. Various criteria were applied to analyze the literature, and a data-driven bibliometric study was conducted based on the literature review to explore indicators for further research on this topic. The remaining sections of this paper are structured as follows: Section 2 introduces the literature data retrieved for this study, as well as the bibliometric methods and software used. Section 3 analyzes the results processed using bibliometric methods and presents the results in terms of publication quantity and trends, collaboration networks, research hotspots, and keyword analysis, with the aid of a knowledge map. Sections 4 and 5 discuss the current research hotspots and future research directions for deep underground rockbursts, and present the conclusions of this study. The scheme of the document collection and bibliometric analysis is shown in Figure 1.

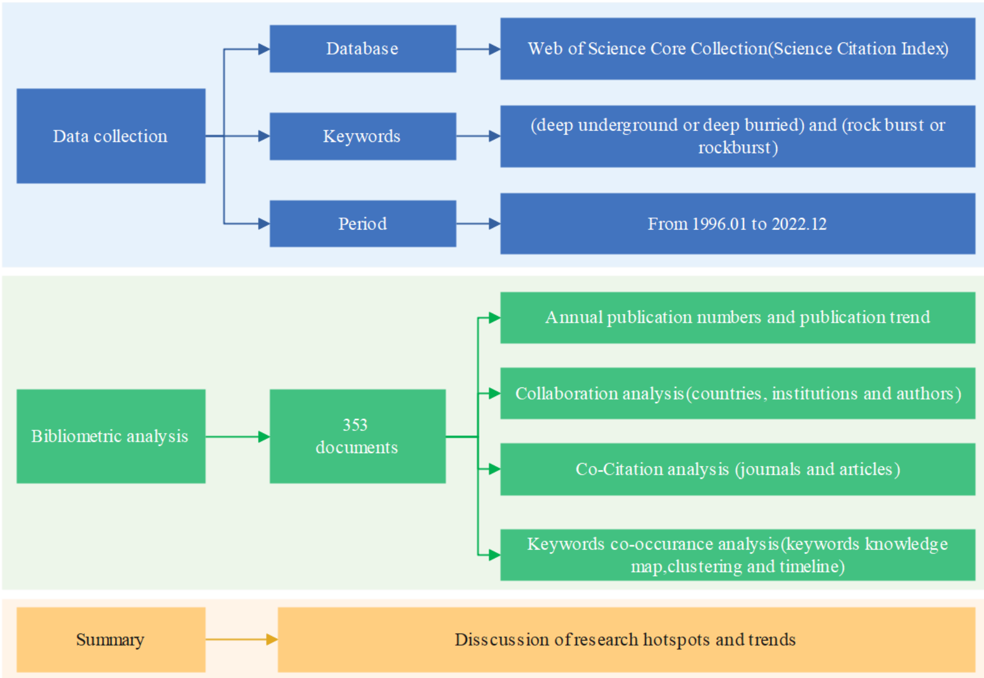

Figure 1. Scheme of document collection and bibliometric analysis.

2. Data and Methods for Bibliometric Analysis

2.1. Literature Dataset Acquisition and Compilation

The first and pivotal step in conducting bibliometric analysis is to utilize appropriate databases and predefined search criteria. The Web of Science databases, including the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (A&HCI), are authoritative platforms widely used in academic research [46]. These databases are comprehensive and multidisciplinary and encompass core journals, making them highly valuable for literature reviews and bibliometric analysis across various fields. In this study, literature retrieval was performed using the Web of Science database, specifically the Science Citation Index (SCI), which holds significant international influence in the field of science and engineering research. This database offers a straightforward and comprehensive search interface, allowing logical operators, such as "AND", "OR", and "NOT", to refine the search. For this study, a topic-based search was conducted using the following search formula: TS = ("deep underground" OR "deep buried") AND TS = ("rockburst" OR "rock burst"). Only research articles were selected and saved as the document type. Considering that the first paper was published in 1996 and the year 2023 is not yet over, the search time frame was set from 1 January 1996 to 31 December 2022. Following the retrieval process, a manual review of the titles and abstracts of the retrieved articles was conducted to filter out irrelevant and duplicate documents. Ultimately, a total of 353 relevant articles were obtained. To facilitate knowledge mapping analysis, the "All Records and References" and "Full Record" information of the 353 article documents were exported from the database in both plain text and Excel formats. The compiled dataset, consisting of 353 articles, served as the sample for knowledge mapping analysis.

2.2. Method for Bibliometric Analysis

Bibliometric research is a research technique that provides a quantitative overview of a field of research, and methods include citation analysis, co-citation analysis, bibliography coupling, coauthor analysis, and co-word analysis [47]. In this study, the bibliometric analysis was conducted using CiteSpace, software developed by Dr. Meichao Chen from Drake University in the United States, based on Java programming language (version 6.2.R3) [48–50]. CiteSpace utilizes co-citation analysis to visualize and analyze the imported literature dataset. It offers visualization functions, such as collaboration networks, literature coupling, and clustering of research hotspots. Additionally, it conceptualizes and visualizes research hotspots by calculating the strength of the relationships between nodes related to a specific scientific question. To begin with, the literature dataset compiled from the authoritative Web of Science (WOS) database was imported into the CiteSpace software. By adjusting the visualization parameters, the desired objectives of scientific measurement analysis were achieved through the creation of knowledge maps. This study conducted bibliometric analysis from four perspectives: analysis of publication output characteristics, collaboration analysis, co-occurrence analysis of keywords, and clustering analysis. These analyses ultimately led to the creation of a comprehensive knowledge map.

It is worth noting that when CiteSpace generates certain knowledge maps during the analysis process, betweenness centrality is a commonly used and valuable index to quantitatively determine the importance of nodes in these maps. The betweenness centrality of a node refers to the number of times the node acts as a bridge between other nodes in the network, and it is considered an indicator of node importance. Nodes with high betweenness centrality values (greater than 0.1) signify that they play a central role in the visualized network, which is referred to as a pivotal point [51–53]. The betweenness centrality, proposed by Freeman et al. [54] in CiteSpace software, is calculated using the following formula:

$$BC_i = \sum \frac{n^i_{jk}}{g_{jk}} \tag{1}$$

where g_{jk} represents the number of shortest paths from node j to node k, and n^i_{jk} represents the number of shortest paths passing through node i. Betweenness centrality is a crucial parameter in network analysis. Nodes with a centrality value greater than 0.1 are considered significant and play a vital role in the network. Higher centrality values indicate greater influence and importance of the nodes in the field.

3. Results

3.1. Annual Publication Numbers and Publication Trend

The variation in the number of publications in the field of deep underground rockburst is an important indicator of the progress in this research area. By plotting the distribution of publication numbers over the years, researchers can gain an overall understanding of the developmental stages in this field and make predictions about future trends [55]. Figure 2 presents the annual publication numbers and cumulative publication numbers based on the retrieval dataset.

As shown in Figure 2, the first research article on deep underground rockburst was published in 1996. The annual number of publications has shown a continuous growth trend, indicating the increasing research focus in this field. Based on the publication trend in the field of deep underground rockburst, the research progress can be divided into three stages:

Sprouting Stage (1997–2011): During this stage, a total of 40 articles were published, accounting for only 11.3% of the total publications. This indicates that the study of deep underground rockburst was still in its nascent phase and received limited attention from scholars. However, there was a slight increase in the number of articles from 1 in 1996 to 7 in 2010, indicating a slow growth of interest in this field during this stage.

Stable Development Stage (2012–2016): In this stage, the number of articles significantly increased compared to the previous stage, maintaining an average annual publication number of around 15. This period marked a stable academic focus on rockburst issues during the construction and operation stages of deep engineering projects.

Rapid Development Stage (2017–2022): The number of articles published in 2018 (32 articles) doubled compared to that in 2016 (16 articles), showing a sharp growth trend and reaching its peak in 2022 (58 articles). A total of 244 articles were published during this stage, accounting for 69.2% of the total. It can be inferred that the field of deep underground rockburst has gained widespread attention from the academic community and has entered a period of rapid development. It is worth noting that in 2016, China's "Thirteenth Five-Year Plan" explicitly emphasized the strategic deployment in four areas: deep sea, deep earth, deep space, and deep blue. In response to this strategic call, China has undertaken numerous deep-earth engineering designs and constructions, such as shale gas extraction, carbon dioxide and nuclear waste storage, and geothermal resource extraction. This has brought great opportunities and challenges to the in-depth study of deep underground rockburst problems [56–60]. In analyzing the publication counts of scholars from different countries in the literature from 2016 to 2022, it was found that 94.85% of the research in the field of deep underground rockburst was contributed by Chinese scholars, which is a significant factor contributing to the substantial increase in publications since 2016.

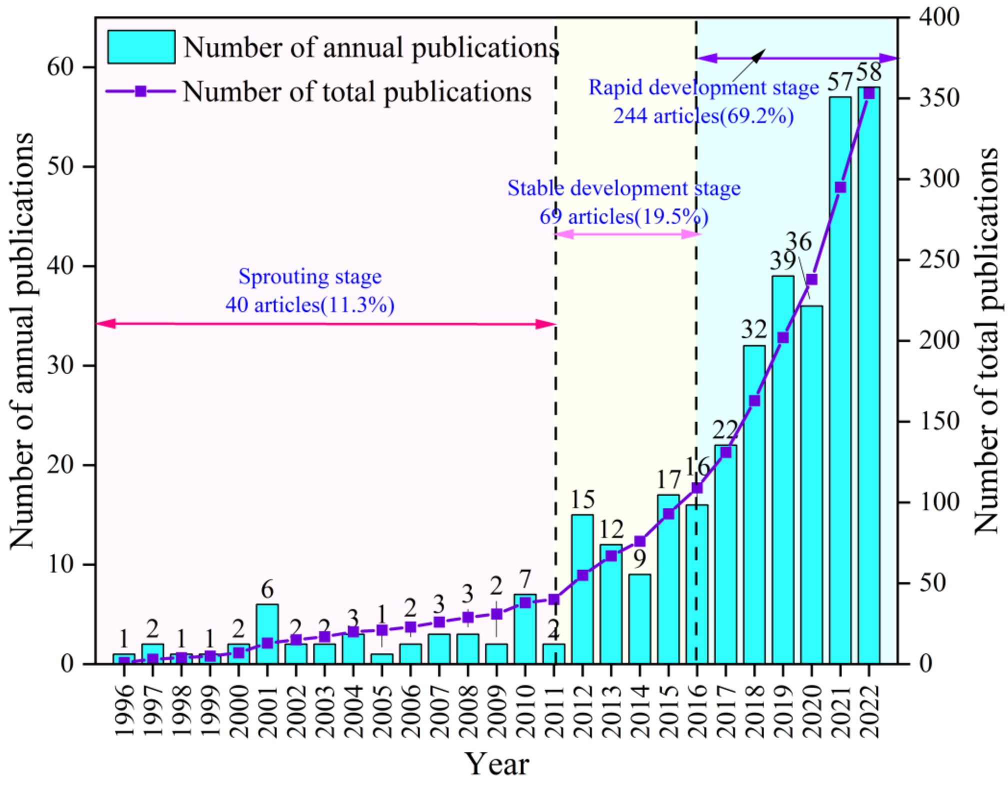

Figure 2. Numbers of annual publications and total publications from 1996 to 2022.

3.2. *Scientific Collaborative Networks Analysis*

With the development of globalization, academic exchanges and collaborations have become increasingly widespread. Identifying collaborative relationships helps in understanding the current research landscape. National collaboration networks, institutional collaboration networks, and author collaboration networks provide insights into collaborative relationships on the macro-, meso-, and micro-scales, respectively.

3.2.1. International Collaboration Networks

Using CiteSpace software, the co-occurrence network knowledge map of international collaboration relationships in the field of deep rockburst was analyzed and visualized, as shown in Figure 3. Each node in the figure represents a country, and the size of the node indicates the number of publications from that country. The colored rings represent different years, with the thickness of the rings representing the number of publications in that year. The connections between nodes represent co-authorship relationships between countries, and the thickness and darkness of the lines indicate the strength of the collaboration relationships [61,62]. Table 1 presents the top 10 contributing countries in this research field, along with their year of first publication and their betweenness centrality.

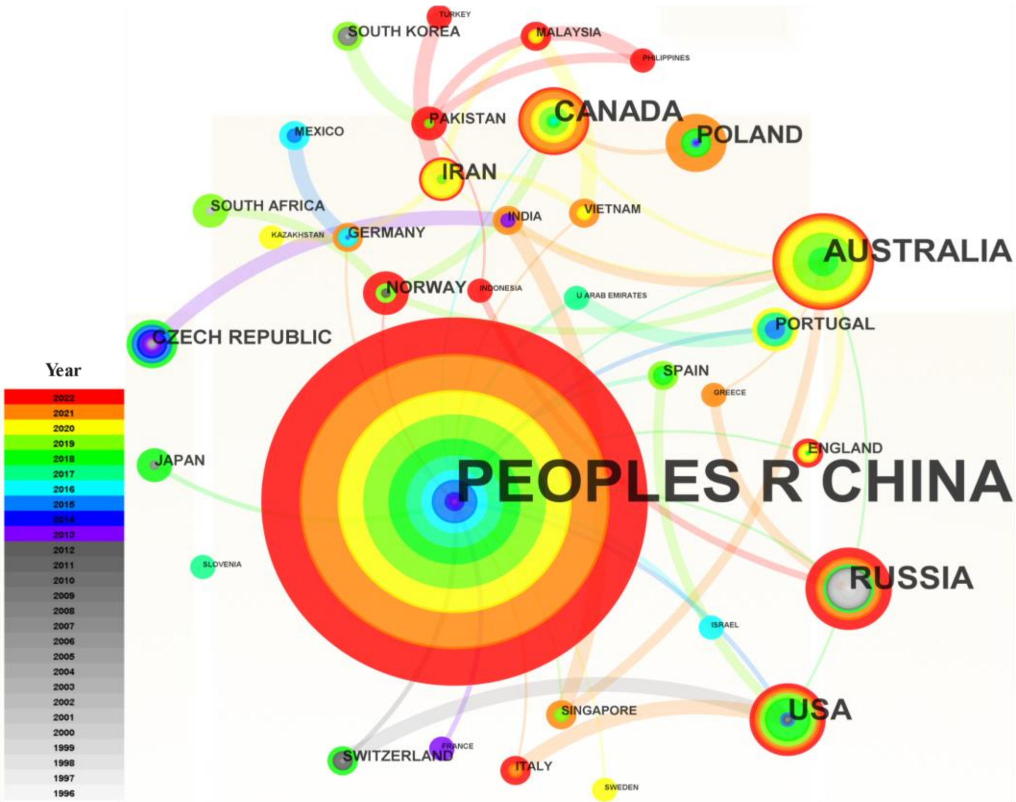

Figure 3. International collaboration network knowledge map of deep underground rockburst from 1996 to 2022.

Table 1. Top 10 countries with most publications on deep underground rockburst.

No.	Country	Publication	Centrality	Year of the First Publication
1	China	293	1.18	2001
2	Australian	20	0.51	2000
3	Russia	17	0.18	1996
4	USA	14	0.03	2002
5	Canada	13	0.12	2007
6	Poland	9	0	2008
7	Iran	7	0.34	2017
8	Czech Republic	5	0	2004
9	Portugal	4	0.01	2015
10	Norway	4	0.12	2012

A total of 34 countries/regions have conducted research in the field of deep underground rockburst. The top 10 countries in terms of total publications are China, Australia, Russia, the United States, Canada, Poland, Iran, the Czech Republic, Portugal, and Norway. Six countries have high betweenness centrality (>0.1), namely China, Australia, Iran, Russia, Canada, and Norway, in descending order. China, with the highest publications, has contributed 293 articles from 1996 to 2022, accounting for 83.01% of the global total.

This is 14.65 times and 17.24 times more than the second-ranked Australia and the third-ranked Russia, respectively. China has a betweenness centrality of 1.18, indicating its absolute core position in the global research field of deep rockburst. However, analyzing the network knowledge map reveals that although China occupies a central position, its connections with other countries are relatively thin, indicating a lower level of international collaboration activity.

Through the analysis of international collaboration networks, we gain insights into the distribution of research output and collaborative relationships among countries in the field of deep rockburst. This knowledge provides a foundation for further understanding the dynamics of international collaboration and exploring opportunities for future research cooperation in this domain.

3.2.2. Collaboration Networks of Research Institutions

The knowledge map of institutional collaboration networks in the field of deep underground rockburst is depicted in Figure 4. The publication contributions, year of first publication, and betweenness centrality of the top 10 research institutions are summarized in Table 2.

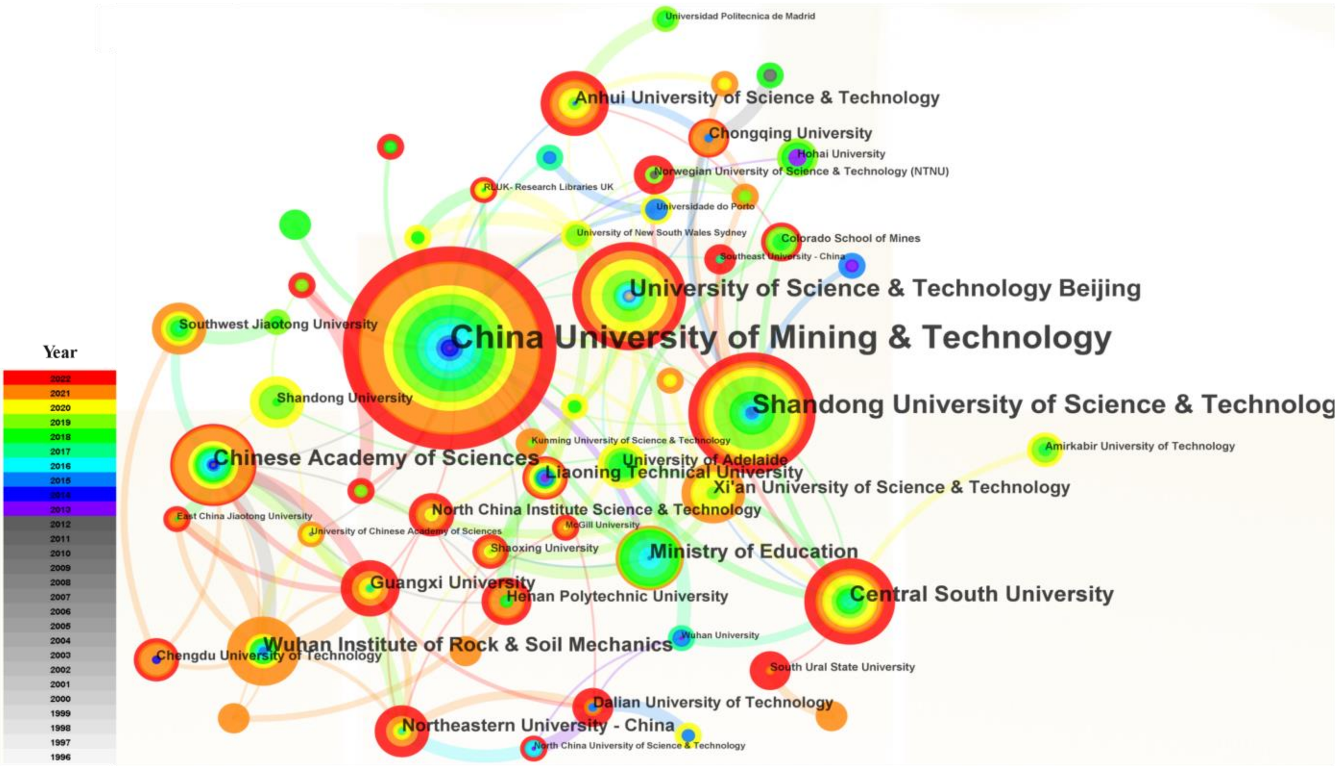

Figure 4. Institutional collaboration network knowledge map of deep underground rockburst from 1996 to 2022.

It can be observed that over 200 research institutions are engaged in this topic, with the majority of them located in China. The primary research institutions include the China University of Mining and Technology (115 articles), Shandong University of Science and Technology (44 articles), University of Science and Technology Beijing (25 articles), Central South University (20 articles), Chinese Academy of Sciences (19 articles), Shandong University (15 articles), Wuhan Institute of Rock and Soil Mechanics (14 articles), Anhui University of Science and Technology (12 articles), Xi'an University of Science and Technology (10 articles), and Guangxi University (9 articles), all of which are based in China. The institution with the highest publication output is the China University of Mining and Technology, which has 2.61 times more than the second-ranked Shandong University of Science and

Technology and accounts for 32.57% of the total publications. Its betweenness centrality is 0.45, indicating that the China University of Mining and Technology holds a core position in the research field of deep rockburst. The China University of Mining and Technology is a nationally key university in the field of mining and engineering, with two national key laboratories, one national engineering research center, and several key laboratories of the Ministry of Education. It has made significant contributions to the research in the field of deep rockburst. In terms of betweenness centrality, in addition to the China University of Mining and Technology, other institutions playing core roles (with values greater than 0.1) in the visualization network are Central South University (0.16), Shandong University of Science and Technology (0.14), and the Chinese Academy of Sciences (0.11). From this, it can be concluded that each institution has made substantial contributions to the prevention and control of deep rockburst.

Table 2. Top 10 research institutions with most publications on deep underground rockburst.

No.	Institution	Publication	Centrality	Year of the First Publication
1	China University of Mining and Technology	115	0.45	2001
2	Shandong University of Science and Technology	44	0.14	2006
3	University of Science and Technology Beijing	25	0.09	2001
4	Central South University	20	0.16	2005
5	Chinese Academy of Sciences	19	0.11	2008
6	Shandong University	15	0.01	2013
7	Wuhan Institute of Rock and Soil Mechanics	14	0.01	2008
8	Anhui University of Science and Technology	12	0.06	2015
9	Xi'an University of Science and Technology	10	0.05	2015
10	Guangxi University	9	0.02	2010

3.2.3. Author Collaboration Networks

The knowledge map of author collaboration networks in the field of deep rockburst is illustrated in Figure 5. The publication contributions, year of first publication, and betweenness centrality of the top 10 authors are summarized in Table 3.

Figure 5. Author collaboration network knowledge map of deep underground rockburst from 1996 to 2022.

Table 3. Top 10 authors with most publications on deep underground rockburst.

No.	Author	Publication	Centrality	Year of the First Publication
1	Wu Cai	11	0.02	2014
2	Linming Dou	10	0.01	2014
3	Manchao He	9	0.02	2013
4	Jianqiang Chen	7	0.01	2019
5	Enyuan Wang	6	0	2016
6	Dazhao Song	5	0	2012
7	Wenlong Zhang	5	0	2021
8	Xueqiu He	5	0.01	2019
9	Siyuan Gong	5	0	2014
10	Anye Cao	5	0	2017

The knowledge map effectively reveals the knowledge network is highly effective in identifying author collaboration relationships and distinguishing influential authors. By examining the size of the nodes in the network, it became evident that the top five authors with the highest publication output are Wu Cai (11 articles), Linming Dou (10 articles), Manchao He (9 articles), Jianqiang Chen (7 articles), and Enyuan Wang (6 articles). They serve as central authors within five large collaborative networks, demonstrating their higher degree of collaboration compared to others. However, the overall pattern of the author group exhibits a dispersed and small clustered characteristic. The betweenness centrality values for all authors are below 0.1, signifying that while there is close communication and collaboration within research teams, the collaboration among different teams is relatively scattered. Therefore, there is a pressing need to further strengthen the collaborative exchanges between teams.

3.3. Co-Citation Analysis of the Literature

When two papers are cited by a third paper, they establish a co-citation relationship [63–65]. The same concept can be applied to co-citation analysis within journal associations. The analysis of citations can be divided into two parts: co-citation analysis of the literature and co-occurrence analysis of journal citations. In the visible representation, the lines indicate the presence of a connection between two papers when they are cited together, indicating a co-citation relationship. In the co-citation network figure, the nodes represent the time of citation, and the size of the nodes corresponds to the frequency of citations [66,67].

3.3.1. Co-Cited Research Journals

The knowledge map of co-cited journal networks in the field of deep underground rockburst is illustrated in Figure 6. The host country, cited time in the field of deep burst, and influencing factors (2022) of the top 10 journals are summarized in Table 4.

In the figure and table, it can be observed that the size of each node represents the frequency of citation in the field for a journal. Generally, journals with higher citation frequencies have greater authority and influence in the field [68,69]. The *International Journal of Rock Mechanics and Mining Sciences*, *Rock Mechanics and Rock Engineering*, and *Tunneling and Underground Space Technology* are positioned at the core of the knowledge graph, indicating their close relationships with other journals. These three journals have high impact factors in 2022, with values of 6.849, 6.518, and 6.407, respectively. They are top-tier journals in the field of geotechnical engineering and have been cited 283, 218, and 200 times in the context of deep rockburst research. In addition to these three journals, the top ten cited journals include *Engineering Geology*, *International Journal of Mining Science and Technology*, *Journal of Rock Mechanics and Geotechnical Engineering*, *Bulletin of Engineering Geology and the Environment*, *Safety Science*, *Journal of Central South University*, and *Journal of the Southern African Institute of Mining and Metallurgy*. These journals have all been cited more than 80 times, indicating their significant contributions to the field of deep rockburst. In terms of publication number, the top 3 journals have published no less than 40 articles, underscoring their recognition among scholars in the field. It is noteworthy that the three most frequently cited journals also rank among the top three in terms of publication number. Thus, these three journals have made significant contributions to deep underground rockburst research.

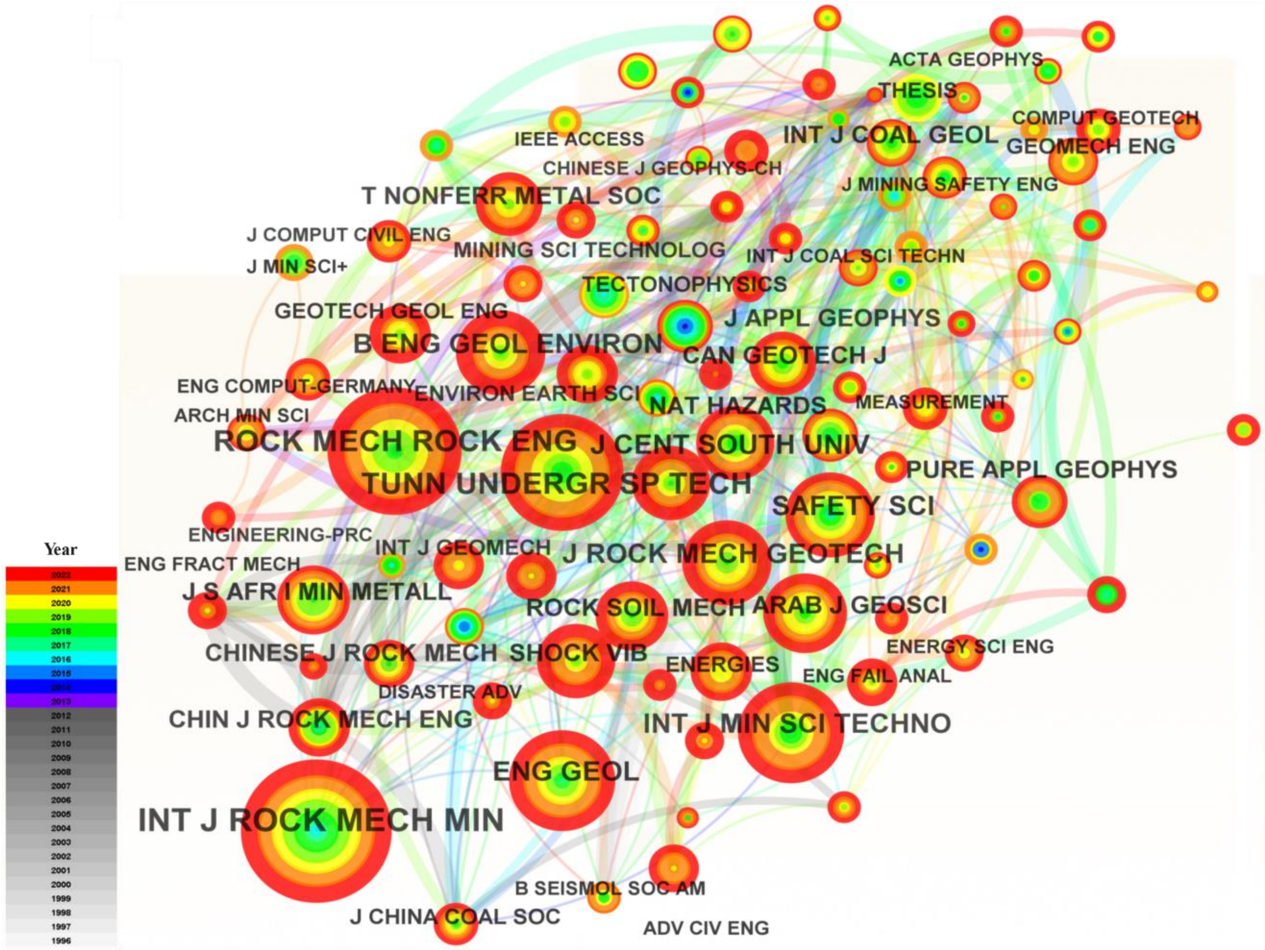

Figure 6. Journal co-citation network knowledge map of deep underground rockburst from 1996 to 2022.

Table 4. Top 10 cited journals on deep underground rockburst.

No.	Journal Name	Host Country	Cited Times	Influencing Factors (2022)
1	*International Journal of Rock Mechanics and Mining Sciences*	England	283	6.849
2	*Rock Mechanics and Rock Engineering*	Austria	218	6.518
3	*Tunneling and Underground Space Technology*	England	200	6.407
4	*Engineering Geology*	Holland	138	6.902
5	*International Journal of Mining Science and Technology*	China	129	7.670
6	*Journal of Rock Mechanics and Geotechnical Engineering*	China	113	5.915
7	*Bulletin of Engineering Geology and the Environment*	Germany	107	4.130
8	*Safety Science*	Netherlands	176	6.392
9	*Journal of Central South University*	China	92	2.392
10	*Journal of the Southern African Institute of Mining and Metallurgy*	Southern African	88	0.640

3.3.2. Co-Cited Articles on Deep Underground Rockburst

By analyzing the citations of the literature, influential articles in the field of deep rockburst can be identified, and the citation rate of an article is considered an important indicator of its research value [70,71]. The knowledge map of co-cited article networks in the field of deep underground rockburst is illustrated in Figure 7, where each node represents an article identified by the first author's name and publication year, and the size of the node represents the total number of citations. Large nodes indicate articles that have been cited multiple times and are widely recognized by scholars, thus indicating their significance in the field. Table 5 provides detailed information on the top 10 cited articles. It is important to note that the citation frequency was obtained from CiteSpace based on a selected set of 430 articles, and therefore, differs from the total citation frequency in Web of Science.

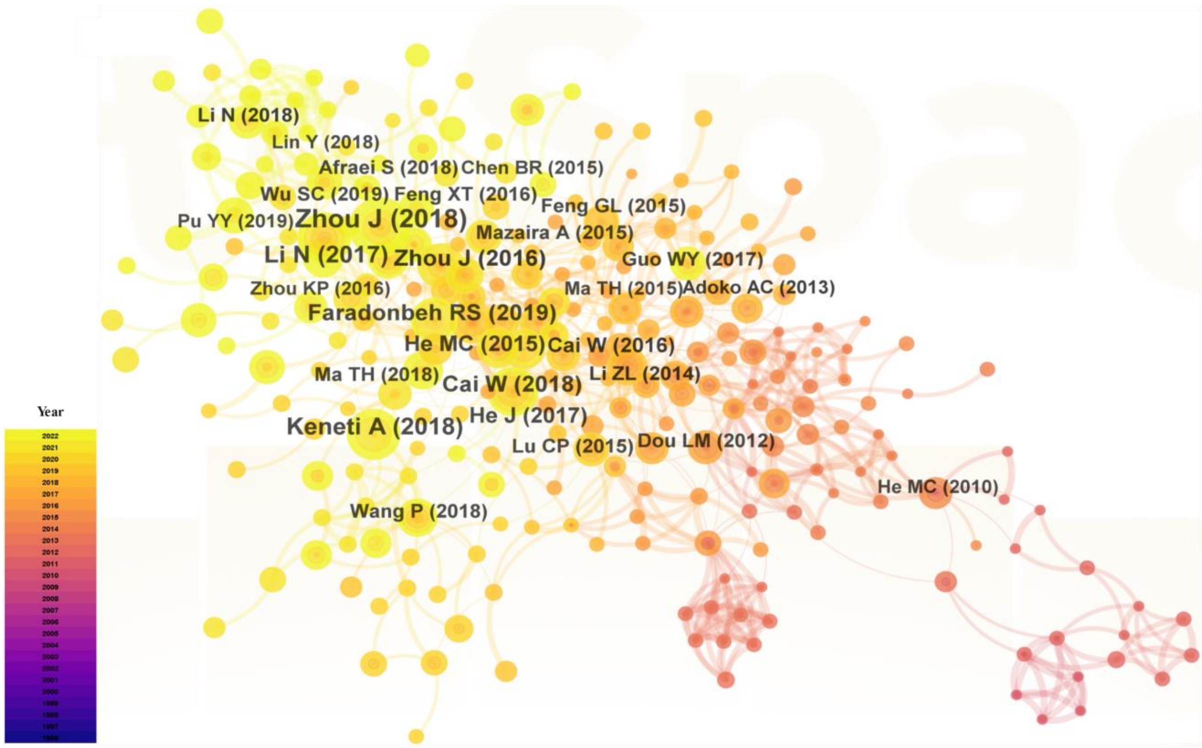

Figure 7. Article co-citation network knowledge map of deep underground rockburst from 1996 to 2022.

Table 5. Top 10 cited articles on deep underground rockburst.

No.	Title	Author	Cited Times	Year
1	*Predicting Rock Burst Hazard with Incomplete Data Using Bayesian Networks* [72]	Ning, Li et al.	24	2017
2	*A Fuzzy Comprehensive Evaluation Methodology for Rock Burst Forecasting Using Microseismic Monitoring* [11]	Wu, Cai et al.	23	2018
3	*Long-term Prediction of Rockburst Hazard in Deep Underground Openings Using Three Robust Data Mining Techniques* [16]	Faradonbeh, Roohollah Shirani et al.	21	2019
4	*Classification of Rockburst in Underground Projects: Comparison of Ten Supervised Learning Methods* [73]	Jian, Zhou et al.	20	2016
5	*Rockburst Laboratory Tests Database—Application of Data Mining techniques* [26]	Manchao, He et al.	18	2015
6	*A Principal Component Analysis/Fuzzy Comprehensive Evaluation Model for Coal Burst Liability Assessment* [74]	Wu, Cai et al.	16	2016
7	*Intense Rockburst Impacts in Deep Underground Construction and Their Prevention* [75]	Mazaira, A. et al.	15	2015
8	*Rockburst Mechanism and Prediction Based on Microseismic Monitoring* [76]	Tian-Hui, Ma et al.	14	2018
9	*Statistical Assessment of Rock Burst Potential and Contributions of Considered Predictor Variables in the Task* [77]	Afraei, Sajjad et al.	14	2018
10	*Fractal Behaviour of the Microseismic Energy Associated with Immediate Rockbursts in Deep, Hard Rock Tunnels* [78]	Xiating, Feng	13	2016

Li et al. [72] utilized five parameters, namely tunnel depth, uniaxial tensile strength of the rock, uniaxial compressive strength of the rock, and elastic energy index, to construct a Bayesian network (BN) using a tree-augmented naive Bayes classifier structure. The expectation–maximization algorithm was employed to learn from a historical dataset of 135 rockburst cases, and belief updating was performed using the junction tree algorithm. The model was validated through an 8-fold cross-validation and a separate set of new incomplete case histories that were not used during BN training. The results demonstrated the lowest error rate for this method among traditional standards that handle incomplete data. Sensitivity analysis indicated that the maximum tangential stress of the surrounding rock was the most influential parameter, providing valuable guidance for future rockburst predictions. Wu, Cai et al. [11] developed a rockburst prediction method involving the use of a fuzzy comprehensive evaluation model, which allows for a more quantitative assessment of the likelihood of rockburst events. In the fuzzy model, Gaussian-shaped membership functions were established using the exponential distribution function from the reliability theory. The weights for each indicator were determined using the performance measure F-score in the confusion matrix. By combining the maximum membership degree principle (MMDP) with variable fuzzy pattern recognition (VFPR), a comprehensive prediction result was obtained. This method has been applied to forecast rockburst incidents in a coal mine in China. To select the spectral indicators for predicting rockburst using the fuzzy evaluation model, coal samples collected from the mining area underwent indoor acoustic emission measurements. The model parameters were first calibrated using four months of historical spectral data, during which six rockburst events were observed. The calibrated model was able to predict subsequent rockburst events in the mine. Faradonbeh, Roohollah Shirani et al. [16] investigated the applicability of three novel data mining techniques, namely emotional neural network (ENN), gene expression programming (GEP), and the decision tree-based C4.5 algorithm, in predicting rockburst occurrences under binary conditions. For this purpose, they collected 134 rockburst events from various case studies and established models based on input parameters, such as maximum tangential stress, uniaxial tensile strength, uniaxial compressive strength, and elastic energy index, using training datasets. The strength of the constructed models was evaluated by measuring the root mean square error (RMSE) and the prediction success rate (PSP) when testing the data. The results showed that all three new models exhibited high accuracy and applicability, with the GA-ENN and GEP methods outperforming the C4.5 method. Additionally, the elastic energy index (EEI) criterion provided more accurate results compared to other conventional criteria, resembling the outcomes of the C4.5 model and being more practical for real-world applications. Finally, sensitivity analysis identified the maximum tangential stress as the most influential parameter, offering guidance for rockburst prediction.

The above three articles employed case studies combined with mathematical methods to establish rockburst prediction methods and approaches. By combining them with knowledge mapping analysis, it can be observed that these articles play a central role in the knowledge map, representing the research hotspots and development progress of deep rockburst studies in the past five years. The research methods for deep rockburst often involve field analysis of case studies, laboratory experiments, and numerical simulations. The main focus of the research is centered around the prevention and control of deep rockburst, prediction methods for rockburst, and the underlying mechanisms of rockburst occurrences.

3.4. Keywords Co-Occurrence Analysis

Keyword co-occurrence is based on the research content and focuses on the key topics in the field, providing a deeper understanding of the existing research issues [79]. This is achieved through three methods: keyword co-occurrence network, keyword temporal network, and keyword clustering. In the first two methods, nodes represent keywords, and the size of the node corresponds to the frequency of the keyword. Larger nodes indicate a higher frequency of occurrence, and they are proportional. The color of the node represents the publication year. When keywords appear in the same document, a connecting line is drawn between them. The color of the line corresponds to the year, and its thickness represents the co-occurrence strength, while the color also indicates the time after the occurrence of the keyword.

3.4.1. Analysis of Keywords Co-Occurrence and Citation Burst

The keyword co-occurrence network knowledge map in the deep rockburst research is shown in Figure 8.

In this network, the size of the keywords is proportional to their frequency of occurrence. Keywords with a frequency exceeding 20 include “prediction” (frequency = 54), “failure” (frequency = 48), “stress” (frequency = 36), “energy” (frequency = 34), “mechanism” (frequency = 33), “numerical simulation” (frequency = 29), “tunnels” (frequency = 29), “classification” (frequency = 26), “coal” (frequency = 22), and “mine” (frequency = 22). It is important to note that the keywords “rockburst” and “rock burst” have been excluded as they do not describe the current research trends. Additionally, the keywords “prediction” and “rockburst prediction” have been merged as they represent the same entity. By combining the knowledge maps, it can be observed that there are interconnected relationships among the keywords, with some keywords having higher frequencies of research. However, the overall research trend appears to be diverse. Clearly, the keyword “prediction” has had the highest frequency of occurrence in the past two decades. Reasonable prediction of rockburst is a necessary prerequisite for ensuring engineering safety and helps in taking effective measures in advance. Researchers have proposed various methods for rockburst prediction, which can be classified into four categories: empirical methods, simulation techniques, mathematical algorithms, and monitoring techniques. Furthermore, keywords related to “failure, classification, and energy” frequently appear, indicating that the study of rockburst mechanisms is a hot topic. Understanding the mechanisms of rockburst is the basis for developing prediction and prevention methods. Many researchers have analyzed rockburst mechanisms through laboratory experiments and case studies. Currently, the prevailing mechanisms for deep rockburst formation include the energy theory strength theory, and two-body interaction theory, which explain the mechanisms of rockburst from different perspectives [80–88].

Keyword co-occurrence analysis can provide detailed information on the hot topics in a given field, but the results cannot be used to analyze development trends, especially the latest trends in the field [66,68,89]. Keyword citation burst refers to a sharp increase in the usage of certain keywords during a specific period, which can partially reflect the dynamics and potential research issues in a particular field [90]. Table 6 presents the top 10 keyword burst citations in the past 10 years.

Through Table 6, it can be observed that these bursting keywords cover the objects, content, purposes, methods, and research scales related to rockburst in deep rock masses. Within the entire field of deep rockburst research, scholars’ main work revolves around these keywords for discussion and investigation. The earliest appearance of these high-frequency keywords was in 1996, with a concentrated burst period from 2013 to the present. The bursting keyword years, sorted from earliest to latest, are: energy release, tunnels, mine, classification, deep, stability, tomography, coal, support, and evolution. This indicates that in the field of deep rockburst, engineering projects that involve rockburst and risks of rockburst tend to be concentrated in tunnels, mines, and coal-related contexts. Measures taken in engineering projects often focus on energy release and development perspectives. They involve classifying rock masses and implementing corresponding support measures using tomography to ensure stability and reduce the risks and hazards associated with rockburst. Furthermore, as human activities and engineering constructions penetrate deeper into the subsurface, research on deep rockburst has gained increasing attention since 2016. Although rockburst issues are more prevalent in deep rock masses, research often starts with surface rockburst. Starting from 2016, as deep engineering projects advance, the study of deep rockburst considering high geo-stress, high pore pressure, high geothermal gradient, and mining-induced disturbances has received widespread attention and investigation. Understanding the mechanisms, predicting tendencies, and implementing protective measures for rockburst in deep rock masses will become a frontier and hot topic for further advancements into deep rock in the future.

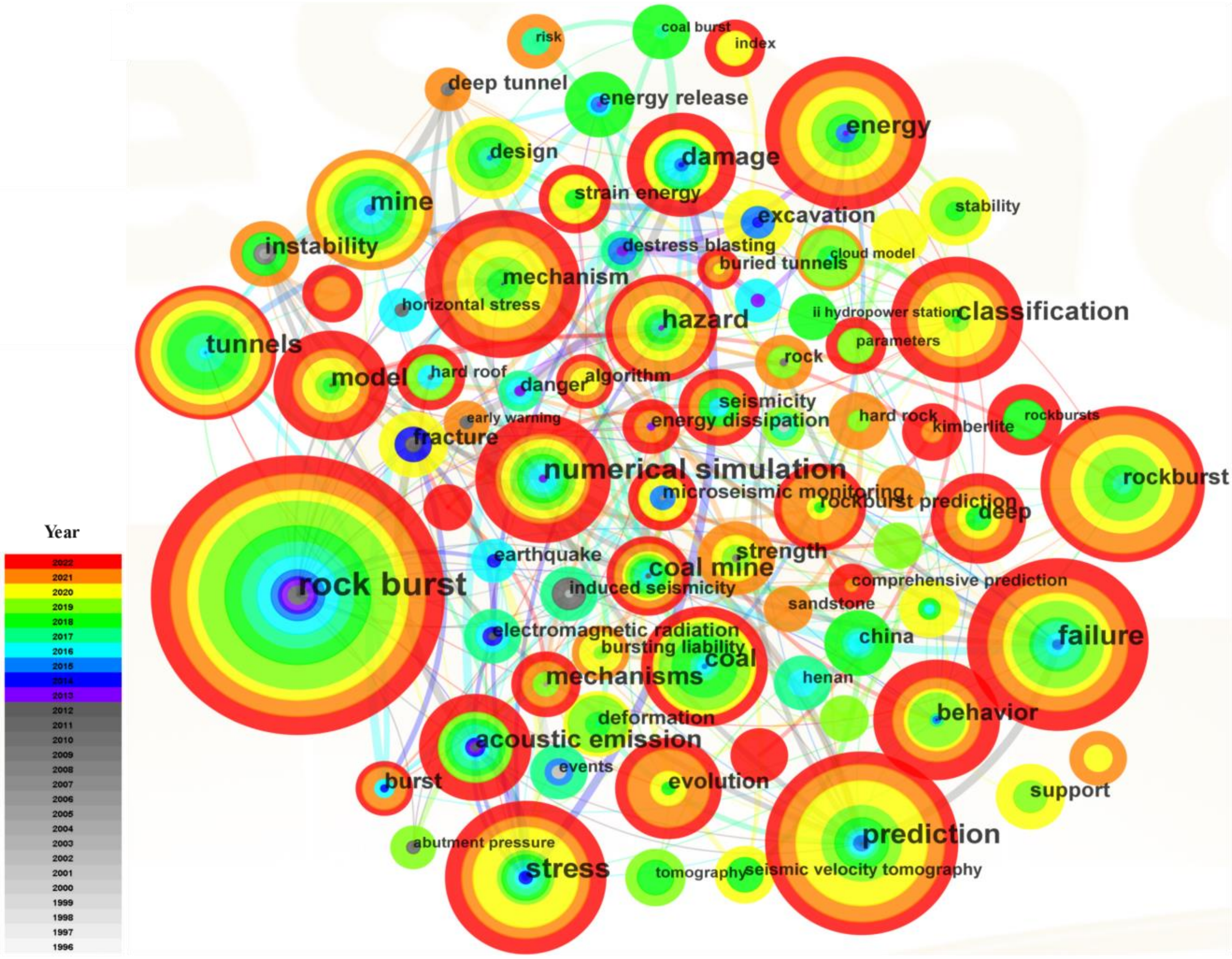

Figure 8. Keyword co-occurrence network knowledge map in the deep rockburst research.

Table 6. Top 10 keywords with the strongest citation bursts during 2010–2022.

Keywords	Year	Strength	Begin	End	2010–2022
Energy release	2013	2.58	2013	2018	------**------------**--------
Tunnels	2015	4.11	2015	2018	----------**--------**--------
Mine	2015	3.25	2015	2017	----------**------**----------
Classification	2016	2.79	2016	2018	------------**------**--------
Deep	2016	2.26	2016	2017	------------**----**----------
Stability	2018	2.51	2018	2020	----------------**------**----
Tomography	2018	2.39	2018	2019	----------------**----**------
Coal	2013	2.22	2018	2019	----------------**----**------
Support	2019	2.75	2019	2020	------------------**----**----
Evolution	2018	2.85	2020	2022	--------------------**------**

Hyphens represent years from 2010 to 2022. The red hyphens represent burst years, and black hyphens mean the keyword was not a hot spot in the specific year.

3.4.2. Keyword Clustering Analysis

Clustering analysis is an important data mining technique used to detect semantic themes hidden in textual data. CiteSpace can provide clustering for users based on nouns or keywords found in the literature. Clustering labels can be created using latent semantic indexing (LSI), log-likelihood ratio (LLR), or mutual information (MI) algorithms [91]. Research data can then be classified into different units and identify potential research topics and their relationships [52,63,89,92]. In this study, keyword clustering was performed using the LLR algorithm, grouping keywords into the same topic and dividing the research data into different unit slices, as shown in Figure 9. Each cluster is named based on the highest value obtained from the algorithm, and clusters are ranked in descending order based on the number of keywords they contain. The size of each unit slice represents a number of articles, and the clustering module Q value is 0.6702, indicating a significant clustering structure (Q > 0.3) [93]. The average silhouette value S is 0.7516, which is considered reasonable for clustering (S > 0.5) and convincing for clustering (S > 0.7) [94]. Therefore, the generated clustering knowledge map can be used for research hotspot analysis. Since the text data were retrieved based on rockburst, the cluster related to rockburst was set as #0.

In analyzing Figure 9, the network was divided into nine modules: Cluster #1—conventional criteria, Cluster #2—acoustic emission, Cluster #3—geology, Cluster #4—seismic velocity tomography, Cluster #5—dynamic disturbance, Cluster #6—rockburst prediction, Cluster #7—bursting liability, Cluster #8—chip evacuation forces, and Cluster #9—phosphorylation. These nine clusters encompass the majority of the literature and can be regarded as the main clusters representing research topics. There are certain links and overlaps between these clusters, suggesting some associations among them. It is evident that the formulation and research of conventional criteria (#1) for addressing rockburst issues in deep engineering is currently the most popular topic. These criteria directly influence the progress and stability of relevant engineering constructions. Currently, experimental techniques for rockburst analysis focus on acoustic emission (#2) combined with seismic velocity tomography (#3) to analyze rockburst mechanisms and predict rockbursts (#6) and bursting liability (#7) from the perspective of energy evolution. This promotes the establishment of rockburst prediction criteria, engineering preventive measures, and protective remedies. In summary, the research on deep rockburst issues can be categorized into three main aspects: the prevention and control of deep rock mass burst, prediction methods for rockburst, and the causative mechanisms behind rockbursts.

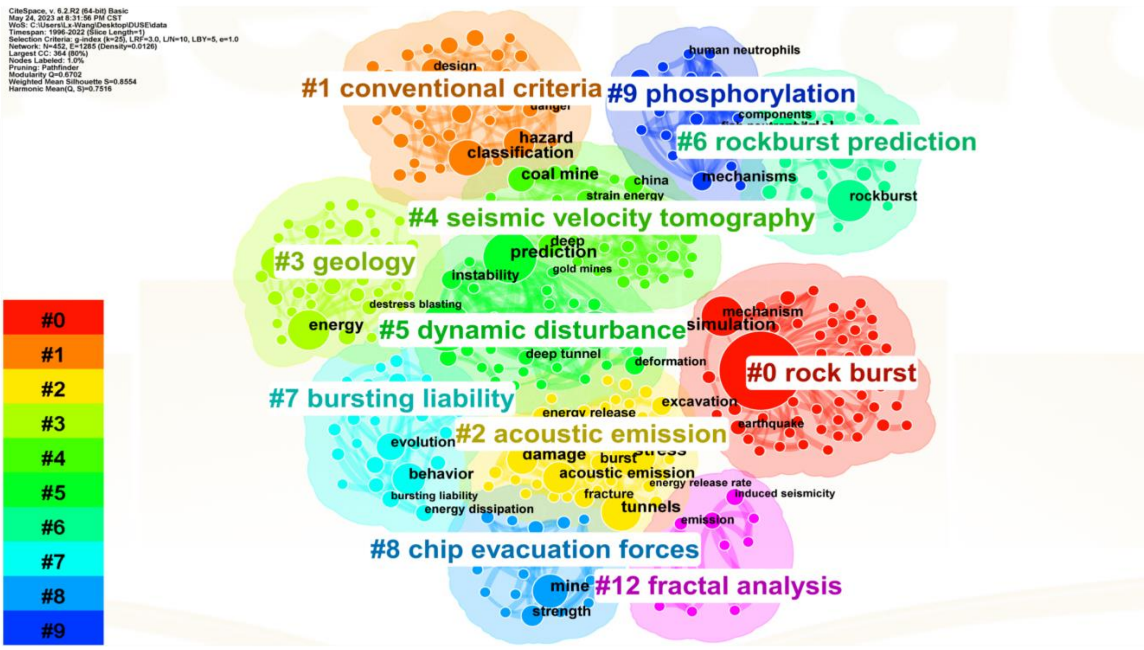

Figure 9. Main clusters in the field of deep underground rockburst.

3.4.3. Keywords Timeline of Clusters

The timeline of the keywords involved in the nine main clusters is shown in Figure 10.

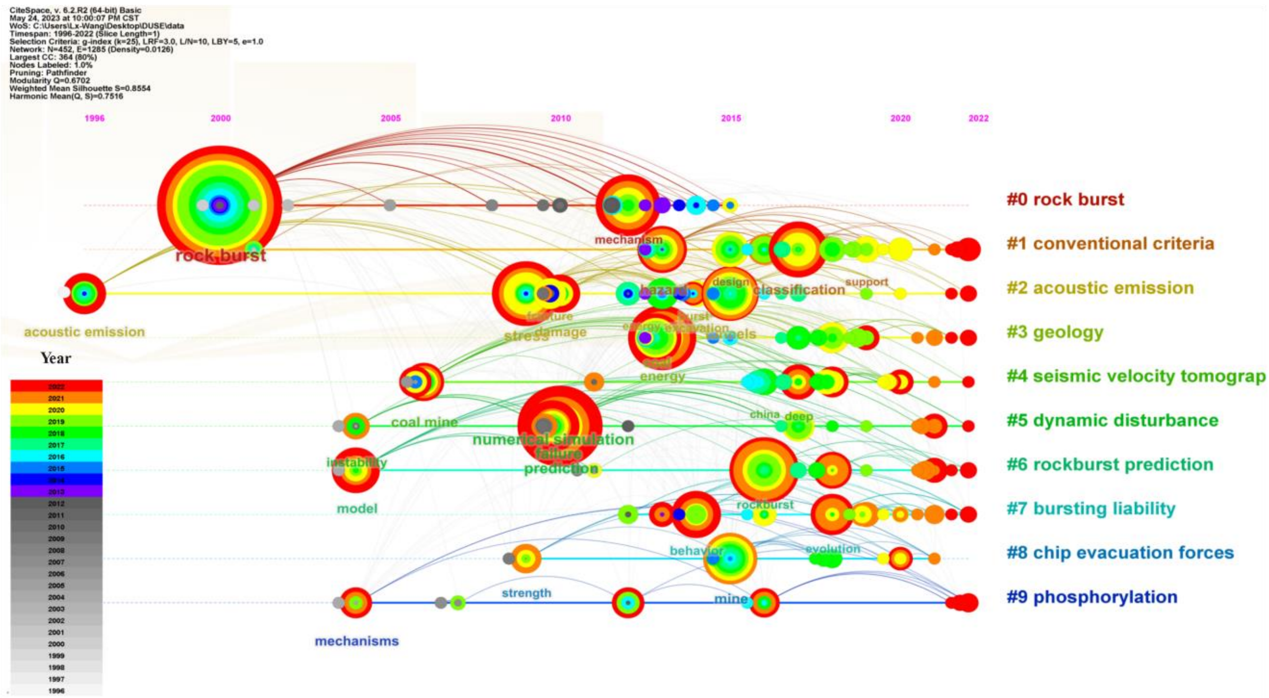

Figure 10. Timeline view of keywords of top 9 clusters.

Among them, acoustic emission has the longest duration, spanning the entire research period from 1996 to the present in the study of deep rock mass bursts. Acoustic emission is an important experimental and monitoring technique initially used to explore underground deep spaces. With the increasing maturity of acoustic emission technology, it has become an important research method for studying the mechanisms and predicting tendencies of rock mass bursts in underground deep rock formations. From Figure 10, it can be observed that numerical simulation is also an important approach in studying deep rockburst issues and has made significant contributions to understanding the mechanisms and tendencies of rock mass bursts under dynamic disturbances.

Since 2016, China has conducted the most research on deep rockburst issues. In its national "Thirteenth Five-Year Plan", China has explicitly emphasized the strategic deployment in the four domains of deep sea, deep earth, deep space, and deep blue. Under this strategic deployment, China has undertaken numerous engineering designs and constructions related to deep rock masses, such as shale gas extraction in deep earth, carbon dioxide and nuclear waste storage, and geothermal resource extraction. This has brought significant opportunities and challenges to the in-depth study of deep rockburst. It can be observed that since 2016, more new keywords have emerged and become hot topics, indicating that there is increased attention and research on deep rockburst issues. This signifies that more research content, research methods, research objects, and research approaches have been adopted for studying deep rockburst issues, demonstrating the growing interest in and importance of studying deep rockburst.

4. Discussion

4.1. Current Research Hotspots

Through the analysis and research of major countries, research institutions, and collaborative networks, it can be observed that Chinese research institutions and scholars have made significant contributions to the study of deep rockburst. Since Chinese President Xi Jinping pointed out at the National Conference on Science and Technology Innovation that exploring the deep earth is a strategic scientific and technological problem that we must address, there have been increasing incidents of deep rock mass burst in China due to the continuous advancement of deep engineering projects [1,43,76,95]. This has injected new vitality and research hotspots into the study of deep rockburst. Therefore, rockburst hazards have become a key hotspot issue, attracting attention and research from various countries. Through co-occurrence analysis and clustering analysis based on keywords, it is evident that the research methods adopted for studying deep rockburst issues mainly include laboratory research, case analysis, microseismic monitoring, and numerical simulation research. In terms of research content, deep rockburst issues mainly focus on three aspects: (1) the causes and mechanisms of deep rockburst, (2) the tendencies and predictions of deep rockburst, and (3) the prevention and control measures of rockburst in deep engineering. In combining the emergence of keywords and the research trends in deep rockburst issues, it can be observed that the current hotspot issue in deep rockburst is the tendency and prediction of deep rockburst. This is also the most important aspect of deep rock mass engineering, directly influencing the development and stable operation of deep rock mass engineering.

4.2. Future Research Perspectives

By analyzing the keywords and clustering terms in the field of deep rockburst and combining the reading of the highly cited literature on deep rock mass engineering, the future research hotspots and recommendations of this research work in this field can be summarized as follows:

(1) Deep rock masses, compared to shallow rock masses, have more complex geological origins and exist in unique environments with high stress, high temperature, high pore pressure, and intense mining disturbances. However, the current research on deep rockburst issues often only considers the high-stress environment in deep rocks, paying less attention to the high-temperature and high-pore-pressure mechanical environments. Therefore, future research on deep rock mass burst should approach studies from the perspective of multi-field coupling of stress–flow–temperature and thoroughly investigate the mechanisms and predictions of rockburst in deep engineering.

(2) Most prediction methods for rockburst involve the use of analytical algorithms, combining multiple quantitative criteria for prediction, and then validating them with existing engineering measurements. Although these methods have a certain degree of rationality, they still have issues, such as an incomplete selection of indicators, neglecting major factors that influence rockburst occurrences, inconsistent classification criteria, and low applicability of methods. Prediction methods based on field monitoring, which enable real-time monitoring of excavation conditions, show promising applications. However, further research is needed on the arrangement of monitoring devices and the determination and applicability of intensity classification methods. Currently, finding a method that accurately predicts rockburst in the majority of engineering scenarios remains challenging. Therefore, establishing prediction methods for rockburst with broader applicability and studying their feasibility and effectiveness will be the focus and difficulty of rockburst disaster research.

(3) In the existing research on deep rock mass burst, little consideration has been given to special jointed rock masses, such as columnar joints, and geological structures, such as faults. There is a lack of consideration for the anisotropic mechanical properties of rocks and the external complex and uncertain environments. This is also a significant reason for the relatively low accuracy of deep rockburst prediction and prevention methods. Therefore, in future research, in-depth studies should be conducted on complex rock conditions and geological structures in deep areas to improve the accuracy of rock mass burst predictions under various conditions.

5. Conclusions

In this study, a bibliometric analysis of the data from 353 studies using CiteSpace software was conducted to review the research on deep rockbursts from 1996 to 2022.

The publication quantity and trends, national and institutional collaboration networks, co-cited references, journal co-occurrences, and keyword co-occurrences and clustering were analyzed. Knowledge maps were generated accordingly, leading to the following main conclusions:

(1) In the collaboration network analysis, it is evident that China holds an absolute core position in the field of deep rockburst research globally and has connections with other countries. The proportion of publications authored by Chinese scholars is as high as 83.01%. Among them, 115 articles were led by the China University of Mining and Technology, which is the largest research institution in deep rockburst studies. The overall authorship network exhibits an overall dispersed and small-scale aggregation pattern, indicating relatively close communication and collaboration within research teams but scattered collaboration between teams.

(2) In the citation analysis, the *International Journal of Rock Mechanics and Mining Sciences*, *Rock Mechanics and Rock Engineering*, and *Tunneling and Underground Space Technology* are the highest cited journals, demonstrating close co-citation relationships with other journals. The most highly cited article is *Predicting Rock Burst Hazard with Incomplete Data using Bayesian Networks* by Ning, Li et al. [71], which has been cited 24 times in the field of deep rockburst. This article establishes rockburst prediction criteria based on five parameters: tunnel depth, maximum tangential stress of surrounding rock, uniaxial compressive strength of surrounding rock, uniaxial tensile strength, and elastic energy index, providing strong guidance for subsequent rockburst predictions.

(3) Based on the keyword co-occurrence analysis, the keyword "prediction" has had the highest frequency of appearance in the past two decades. Rational prediction of rockburst is a necessary prerequisite for ensuring engineering safety and taking effective measures in advance. Therefore, rockburst prediction is a hot topic in deep rockburst research. Through keyword citation burst analysis, it can be observed that since 2016, with the continuous advancement of deep engineering, the issue of deep rockburst has gained widespread attention and research. Understanding the rockburst mechanism, tendency prediction, and protective measures for deep rock mass engineering will also become frontier hot topics for further human exploration into deep rock masses.

(4) In the clustering analysis, the main clusters identified are: #1—conventional criteria, #2—acoustic emission, #3—geology, #4—seismic velocity tomography, #5—dynamic disturbance, #6—rockburst prediction, #7—bursting liability, #8—chip evacuation forces, and #9—phosphorylation. These nine major clusters represent the current research topics.

(5) In terms of future research prospects, future studies on deep rock mass burst should approach the topic from the perspective of multi-field coupling of stress–flow–temperature, considering special jointed rock masses, such as columnar joints, and geological structures, such as faults. Moreover, studies should incorporate the anisotropic mechanical properties of rocks and the complex and uncertain external environments. The focus should be on understanding the mechanisms of rockbursts, establishing prediction methods with broader applicability, and studying their feasibility and effectiveness.

Overall, this study provides a comprehensive overview of the research on deep rock mass burst and identifies the key research topics and future directions for further exploration in deep rock masses.

Author Contributions: L.W. and Z.Z. contributed to the study conception and design of the bibliometric method. X.Z. and J.W. performed the CiteSpace analysis. L.W. and Z.Z. made a comprehensive analysis and discussion on the results of bibliometrics. The first draft of the manuscript was written by Z.Z. and L.W. All authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the National Natural Science Foundation of China (Grant Nos. 41831278 and 51878249).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon reasonable request from the corresponding author, L.W.

Acknowledgments: Thanks to the Foundation for Research Support of the National Natural Science Foundation of China (Grant Nos. 41831278 and 51878249).

Conflicts of Interest: The authors declare no conflict of interest.

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