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Article

Spatiotemporal Evolution and Frontier Focus Analysis Based on Coal Fire Control Body of Knowledge

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Abstract: Mine fire accidents frequently constitute a major threat to mining safety, and their potential consequences are extremely severe, which highlights the urgency of fire prevention and control research. In this study, the CiteSpace software was used to conduct a metrological analysis of 717 relevant studies in the field of mine fire prevention and control (MFPC), aiming to reveal the research trends and trends in this field. This analysis found that the annual number of MFPC articles showed a significant upward trend, indicating that it is in rapid development during the active period. China, the United States, and Australia are the main contributors in this field, and the institutional contribution of China University of Mining and Technology is particularly outstanding, reflecting the regional concentration of research activities. The analysis of cooperation networks reveals the close cross-regional collaboration among European countries. The inhibition effect and evaluation criteria and the inhibition technology under different coal characteristics have become the focus of research. Activation energy, release, and quantum chemistry have become recent hot spots, reflecting the research on the mechanism of forward physicochemical synergistic inhibition and the in-depth exploration of the molecular level. It indicates that future research will focus on the development of temperature-responsive retardant materials, the application of quantum chemistry theory, and the exploration of the microscopic mechanism of coal spontaneous combustion through molecular simulation technology to further optimize the fire prevention strategy. In summary, the findings of this study not only provide a comprehensive picture of current research activities in the MFPC field but also indicate potential directions for future research and have important guiding significance for promoting the development of this field.

Keywords: knowledge graph; visualization; mine fire prevention and control; CiteSpace

Citation: Han, D.; Niu, G.; Liu, B.; Wang, F.; Ren, Y.; Su, C.; Yao, Y.; Zhao, Z. Spatiotemporal Evolution and Frontier Focus Analysis Based on Coal Fire Control Body of Knowledge. *Fire* **2024**, *7*, 187. https://doi.org/10.3390/fire7060187

Academic Editor: Thomas H. Fletcher

Received: 28 April 2024
Revised: 23 May 2024
Accepted: 28 May 2024
Published: 30 May 2024

1. Introduction

China's energy system is notably characterized by an abundance of coal resources and a relative scarcity of petroleum resources. Coal occupies a vital position as the cornerstone of national energy [1–4]. Due to the complex and changeable geological conditions of coal seams in our country, the safety production of coal mines is faced with severe challenges, so various disasters occur frequently. Among them, the spontaneous combustion of coal (SCC) is particularly concerning because of the seriousness of its potential hazards, the difficulty of prevention and control, and the far-reaching impact on resources and the environment [5,6]. Figure 1 shows the trend of the incidence and death toll of coal mine fire accidents in China from 2008 to 2023. Although, in recent years, China's supervision and management of coal mine safety production has been continuously strengthened, which has led to a significant decrease in the incidence rate and death rate of coal mine accidents.

However, due to the huge coal production, wide distribution of mines, complex mining conditions, and differences in various levels, mine fire prevention and control (MFPC) work is still facing a severe situation [7].

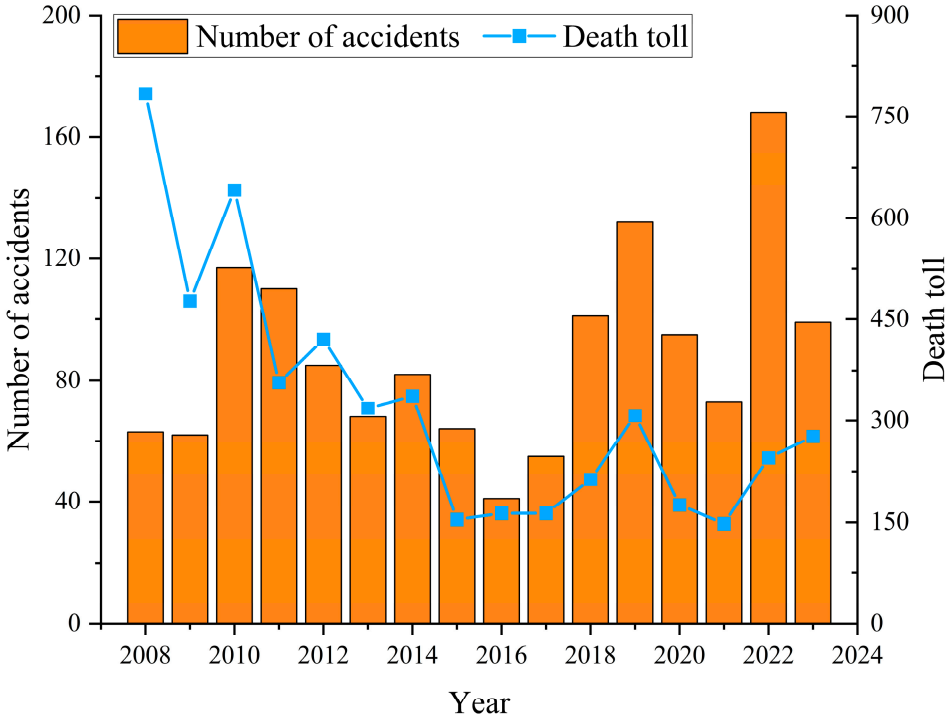

Figure 1. Number of coal mine accidents and death toll in the past 15 years.

Scholars from various countries have developed and researched a wide range of fire suppression materials for use in dealing with spontaneous coal combustion. These include slurries, foams, inert gases, colloids, and retardants [8–16]. Inhibition technology can be divided into the following three basic categories according to their principle of action: physical inhibition, chemical inhibition, and physicochemical synergistic inhibition with both characteristics [17–28]. The physical inhibition method is mainly to slow down the occurrence of coal oxygen reaction by endothermic cooling, isolating oxygen, and covering the surface active center of coal. The chemical inhibition method is to add appropriate inhibitors according to the reaction mechanism of coal and oxygen and slow down the oxidation rate of coal samples by reducing the reactivity of groups on the surface of coal, reducing the content of free radicals in the system, and changing the reaction path. These fire-fighting materials with different characteristics and concerns, in their respective research and evolution processes, have not only greatly enriched and improved the knowledge system in the MFPC field but also accumulated rich scientific research results and effectively promoted technological innovation and development in the field.

To date, many scholars and experts have invested extensive and in-depth research work in the direction of MFPC, but there is less organization of existing results [29–32]. The current literature review has significant limitations in revealing the network relationships among knowledge communities and their evolution and fails to clearly present the dynamic development of scholars' understanding of knowledge, the intrinsic connections among research themes, key documents and journals that have made a difference in the course of research, and clues that indicate the future research trends of scholars. In order to clearly and accurately explore these issues, it is necessary to use bibliometric tools and textual analysis techniques, with a view to extracting scholars from the voluminous literature and realizing in-depth insights and a scientific analysis of relevant research fields. Currently, the main tools commonly used in academia for visualization and analysis are CiteSpace, SPSS, Ucinet, and Vosviewer [33–37]. In order to explore the research status and development

trend of coal porosity, Shao et al. [38] analyzed two visual analysis software (Vosviewer and CiteSpace) and found and summarized the main knowledge framework of coal porosity research. The results show that there has been a significant paradigm shift in the study of coal pores, that is, from the traditional macroscopic description and analysis to the more detailed microscopic level. In addition, several current hot trends in coal pore research are pointed out in the analysis as follows: molecular simulation technology, pore structure, methane storage, and methane adsorption behavior. Hu et al. [39] conducted a detailed analysis of the literature on coal fire detection technology in the past decade using CiteSpace and Vosviewer software, revealing that although a solid basic theoretical system and research framework has been established in this field, prospective research is still insufficient. The focus of coal fire detection research is to continuously improve the level of refinement of data processing and the accuracy of detection devices, which is exactly the focus of current research frontiers in this field. Duan et al. [40] drew a knowledge domain map using Vosviewer and CiteSpace to study the development and trend of coal-related free radicals. The research results show that the main research in this direction includes the spontaneous combustion of coal, pyrolysis, control, coal and biomass, environmental hazards, and coal geochemistry. The depth and breadth of research in this field have been significantly expanded. The overall background and influencing factors of the coal free radical phenomenon have been discussed not only at the macro level but also at the micro level. The research by Wang et al. [41] reveals that in recent years, the research on functional groups in coal has been significantly deepened to the microscopic level, marking the maturity and perfection of the basic theoretical system and research means in this field. The core framework of the current research revolves around the following key pillars: gas adsorption in coal, functional group evolution analysis during heat treatment, and functional group classification and spatial distribution analysis. In the future, the research of functional groups in coal will focus on the application of quantum chemistry theory and molecular simulation experiments. In order to study the research status of underground coal mine fire scene, Wang et al. [42] found that the research on "underground coal mine fire detection technology" is a research hotspot through visual analysis. The advantages of detection methods currently used in this field are analyzed. Zhao et al. [43] systematically combed and analyzed the academic literature on the application of acoustic emission technology in coal published worldwide from 2010 to 2020 in-depth using the visual analysis software CiteSpace. The results show that the time domain parameters of AE, such as cycle count, energy, waveform, and signal intensity, have reached a mature level. However, further improvement of acoustic emission positioning technology will be an important focus of future research. At present, the fractal dimension of signal strength, acoustic emission count, and B-value are generally regarded as the mainstream means to identify the fracture phenomenon. It is worth paying attention to the obvious inadequacies in dealing with the complex challenges encountered in practical engineering projects regarding the activity laws of steep-dip coal seam and its surrounding rocks during deformation. Yang et al. [44] used CiteSpace to analyze the correlation among countries, authors, and keywords in the research field of SCC. The research shows that the low-temperature oxidation process, kinetic principle, internal mechanism construction and model development constitute the core issues of SCC research. Recently, the research focus is mainly on the research and development of three-phase foam technology, fire extinguishing strategy, and foam preparations.

Based on the above, in order to accurately grasp the research achievements and research directions in MFPC field, the Web of Science (WOS) core database is used as the data source, the CiteSpace analysis method is used to analyze the literature distribution and hot research achievements, and the hot issues in the MFPC field are summarized. It provides a reference for the research frontier, the determination of scientific problems, and the choice of research direction and provides a scientific basis for reducing the risk of coal mine fires.

2. Data and Methods

2.1. Data Sources

WOS is an influential professional and comprehensive scientific information service platform in the research community, which has been accepted by many scholars and personnel [45], contains more than 12,000 world-authoritative and high-impact scholarly journals in a variety of research fields, such as natural sciences, engineering, and technology, and is considered to be the most suitable database for bibliometric analysis. Therefore, this paper uses the core data set of WOS as the source data. The subject of the search is "mine fire prevention and control" or "prevention of spontaneous combustion of coal", which means that the title, abstract, and keywords of the journal are not required to be included in the search. This means that as long as there are terms related to mine fire prevention and control or prevention of spontaneous combustion of coal in the title, abstract, or keywords, we can find these documents. The search node time is December 2023. A total of 717 documents were obtained by manually removing irrelevant documents one by one. A total of 717 references were obtained by lifting and filtering in CiteSpace.

2.2. Methodology

This paper mainly uses the bibliometric analysis method to study the knowledge structure and evolution process in this field. Bibliometrics is a statistical method used to evaluate and quantify the emergence and development trend of a specific research topic [46]. CiteSpace is a multi-view information visualization software. Professor CM Chen developed the CiteSpace knowledge graph analysis software and introduced it to China. Its main function is to display evolution trends and knowledge associations of the scientific frontier through visual analysis, including keyword co-occurrence analysis, keyword clustering, institution distribution disclosure, author cooperation exploration, literature integration, and other visual means. Its unique feature is that the method can accurately translate the massive data contained in the WOS database into various knowledge graphs and reveal the deep architectural features and associated connotations of the scientific research field through visual methods. The data processing and analysis work adopted in this paper is accomplished with the help of CiteSpace version 6.3.R1, an advanced visual bibliometric tool.

3. Results and Discussion

3.1. Year-to-Year Trends in the Number of Articles Issued

As a quantitative index, the number of studies can reveal the degree of academic activity and its development in a certain subject field to some extent. It directly reflects the accumulation of research results of related disciplines and the active situation of knowledge innovation. Figure 2 shows the number of publications in the direction of MFPC from 2000 to 2023. According to the change trend of MFPC's annual publication volume, it can be divided into the following three stages: the initial period and the exploration period (2000–2008), and the average number of MFPC papers in this stage is only four per year. This may be due to the fact that the field was still in its infancy during this period, and researchers were exploring new methods and technologies to prevent and control mine fires [47–50]. In addition, technologies such as the Internet and social media were not yet widespread during this period, so the dissemination of articles was limited. The period of steady growth (2009–2019) was an important phase in the global MFPC research journey, which lasted for a decade, and the annual publication volume in the field showed a continuous and steady increase, with an average of about 25 academic articles published each year [51–55]. During the explosive growth period (2020 to 2023), the average number of papers published in the direction of MFPC in this stage is 107 per year, and the number of papers has surged [56–63]. The main reason is that the research in MFPC field continues to deepen, resulting in an increasing number of fruitful results accumulated by researchers, which not only build a solid foundation for subsequent research but also indicate the direction of research. The increasing number of publications each year clearly indicates

that MFPC is receiving unprecedented attention, indicating that the field is about to enter a new stage of development.

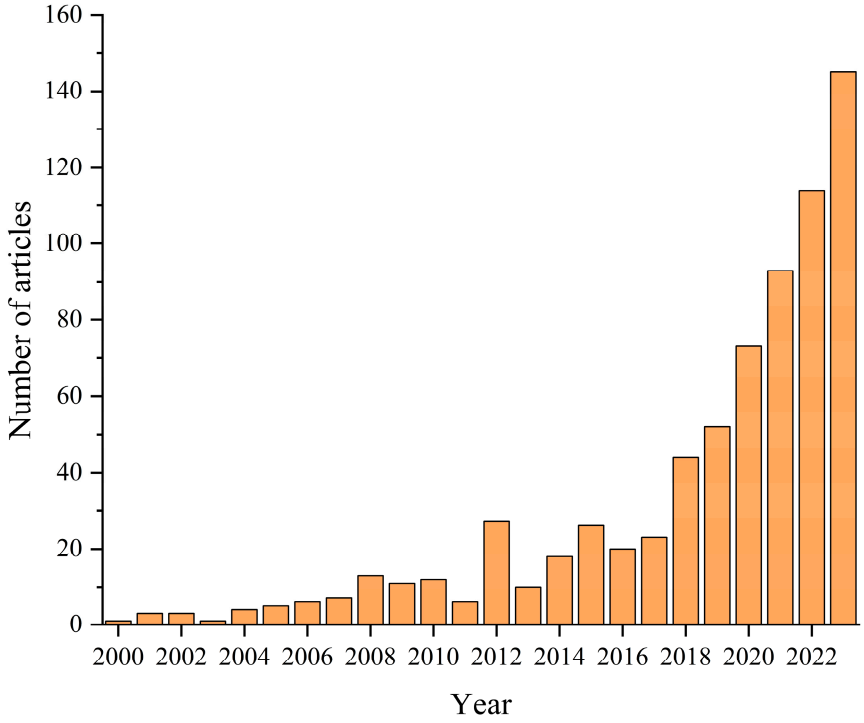

Figure 2. Annual production of articles in the field of mine fire control.

3.2. Analysis of National Publications and Cooperation

We used CiteSpace to create a knowledge map for country/region cooperation analysis to identify the major countries in the MFPC space and their partnerships, as shown in Figure 3. It was observed that as many as 36 countries participated in the MFPC study. The top three countries were China, with a total of 642 publications (89.54%), the United States, with 27 publications (3.77%), and Australia, with 21 publications (2.93%). Each node in Figure 3 represents a different country, and the number of articles for each country is represented by the size of the node. The colors of the nodes and the thicknesses of the lines carry specific meanings. The darker the center color of the node, the earlier the research in this field was carried out. The lighter the external color of the node, the more active the MFPC research has been in the country/region in recent years. These nodes are connected to each other by wires, which graphically show the cooperative links between different geographical areas. The thickness of the connection can directly reflect the closeness of cooperation and interaction between countries and regions. The thicker the line between the two nodes, the closer the connection between the two countries. On the other hand, the smaller the connection, the weaker the cooperation between the two countries. When a node is surrounded by a pink circle, it means that the node has a large centrality and plays an important role in the network. It is clear that European countries cooperate more closely with each other than in any other part of the world. China has close cooperation with Australia, Canada, and the United States. Among these, China, the United States, England, and other countries have an important role in the research of MFPC field in the whole national network. In order to further promote this field to a higher stage of development, China, Canada, and the United States, which are rich in global scientific research output, need to strengthen the deep cooperation and collaborative innovation among the three countries. The United States, China, and some European countries started MFPC research earlier, and in recent years, China, the United States, and Canada mainly have been committed to MFPC research.

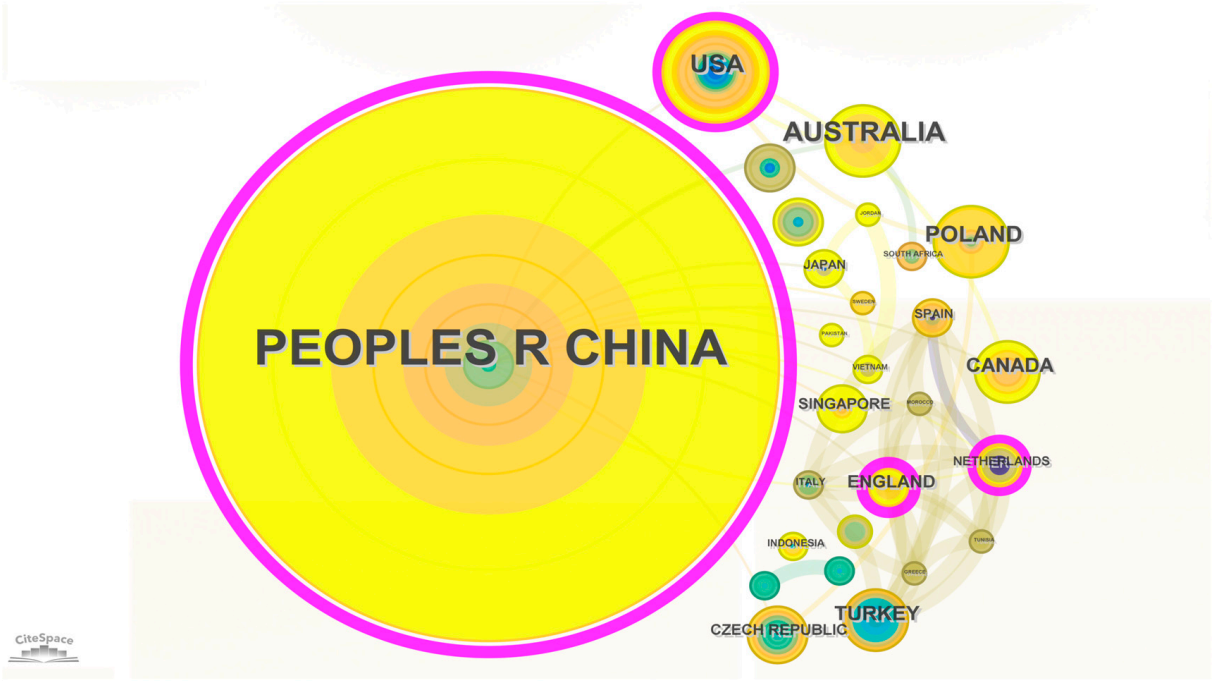

Figure 3. Knowledge map of cooperating countries.

3.3. Analysis of Research Institutions and Cooperation

In order to identify the most productive institutions in the MFPC field and the collaborations between them, an analysis of research institutions and inter-institutional collaborations is provided [38]. CiteSpace-related parameters are determined to generate a research institution collaboration graph with 247 nodes and 318 connectivity lines, as shown in Figure 4. The level of research output of the institutions is visually displayed by the node size, and the connections between the nodes depict the closeness of cooperation between the research institutions. As can be seen in Figure 4, in the MFPC field, six universities, including the China University of Mining and Technology (CUMT), Xi'an University of Science and Technology (XUST), Shandong University of Science and Technology (SDUST), Henan Polytechnic University (HPU), Anhui University of Science and Technology (AUST), and University of Science and Technology of Beijing (USTB), by virtue of their remarkable achievements in related scientific research output, are firmly in the forefront of all research institutions, which is specifically reflected in the number of papers ranked in the top six. CUMT, XUST, and SDUST play an important role in the whole network of research institutions. Among these, CUMT has established close cooperation with more than 20 research institutions. Examples include SDUST, USTB, HPU, the Chinese Academy of Sciences, Hunan University of Science and Technology, Pennsylvania State University-University Park, Curtin University, West Virginia University, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Pennsylvania Commonwealth System of Higher Education (PCSHE), and the Czech Academy of Sciences. This research reveals that the cooperation between academic institutions presents obvious regional characteristics, that is, the cooperation behavior mostly occurs between institutions in similar geographical locations or in the same region, forming a relatively dense regional collaboration network. In contrast, cross-border or even intercontinental cooperation is rare. This phenomenon shows that despite the increasing attention paid to international scientific research cooperation under the trend of globalization, in practice, academic institutions still tend to give priority to geographical proximity and convenience of resource sharing within a region when choosing partners, resulting in transnational and trans-continental cooperation being less frequent than intra-regional cooperation. Of course, this does not mean that research cooperation between countries or continents cannot be achieved, but in the existing re-

search cooperation models, it has not yet become the mainstream and needs to be further promoted and developed.

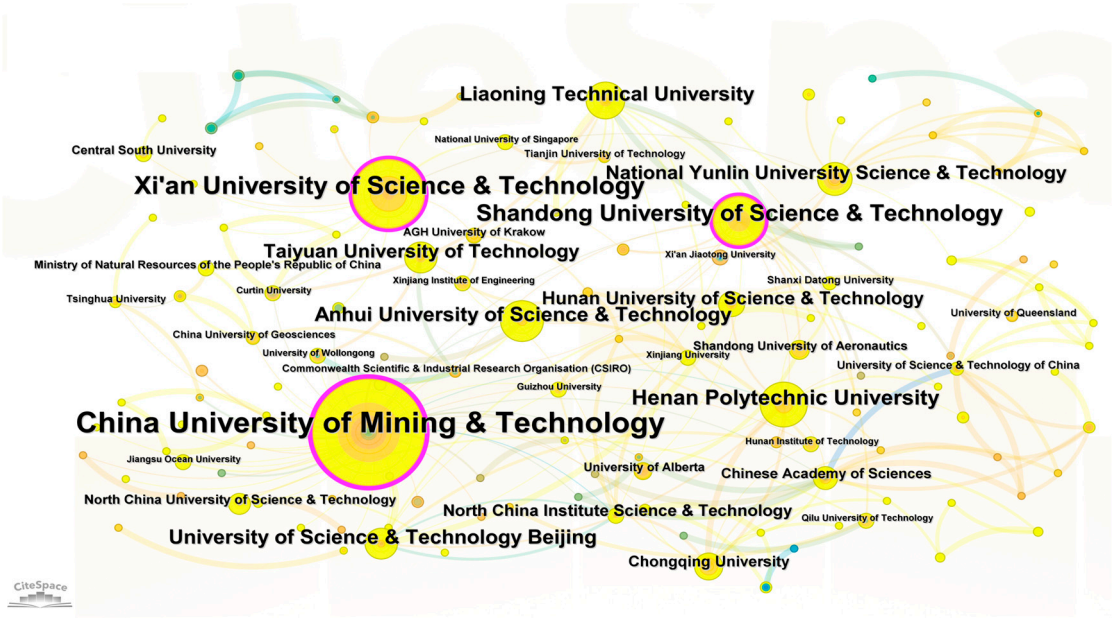

Figure 4. Analysis of research institution collaboration.

3.4. Author Analysis

3.4.1. Analysis of the Volume of Publications and Cooperation

Price's Law, which was developed by British physicist and historian of science Derek J. de Solla Price, is an important theory to describe the growth of scientific literature [64]. The specific formula is as follows:

$$M = 0.794 \times \sqrt{N_{max}} \quad (1)$$

M represents the minimum number of highly active, influential, and significant contributors in a certain research direction. N_{max} represents the maximum number of papers published by a single author in their field of expertise within a particular research direction. Through systematic statistics and in-depth mining of the literature information data, we can comprehensively obtain a series of key information about relevant authors, including, but not limited to, scientific research output, the average citation of a single paper, the influence distribution of journal-published papers, the coverage and depth of research topics, the composition and stability of cooperation networks, and other multidimensional indicators. These detailed data not only help us objectively evaluate the efficiency and influence of the author's academic output but are also crucial to identifying the author's status and role in the academic world. In the in-depth analysis of author groups, the high-yield authors and the core authors have undoubtedly become the focus of in-depth analysis of researchers because of their unique status and significant contributions. Table 1 lists the top 10 authors and their related information. In Table 1, the N_{max} is 39, that is, the M is 4.96, so core authors in the MFPC field need to publish at least five articles.

Table 1 details the list of the top ten authors in the number of published papers, as well as their respective countries, academic institutions, specific paper output, and corresponding output ratio. Among them, Deng Jun of XUST published 34 papers and is ranked first, accounting for 4.7 percent. Shu Chimin of the National Yunlin University of Science and Technology published 27 articles (3.8%), ranking second. Hu Xiangming from SDUST (22 articles) and Xiao Yang from XUST (22 articles) tied for third place, accounting for 3.1% each.

Table 1. Institutions to which the main authors belong, the number of publications, and their percentage share of the total number of publications.

Rank	Author	Organization	Volume of Publication	Proportions	Rank	Author	Organization	Volume of Publication	Proportions
1	Deng Jun	Xi'an University of Science and Technology	34	4.7%	6	Wen Hu	Xi'an University of Science and Technology	19	2.6%
2	Shu Chimin	National Yunlin University of Science and Technology	27	3.8%	7	Wang Wei	Tsinghua University	18	2.5%
3	Hu Xiangming	Shandong University of Science and Technology	22	3.1%	8	Lu Wei	Shandong University of Science and Technology	16	2.2%
4	Xiao Yang	Xi'an University of Science and Technology	22	3.1%	9	Liang Yuntao	Shandong University of Science and Technology	15	2.1%
5	Yang Shengqiang	China University of Mining and Technology	20	2.8%	10	Qin Botao	China University of Mining and Technology	15	2.1%

The WOS data set was imported into the CiteSpace platform for analysis. The research period was set to 2000 to 2023, and the interval was set to be every two years. When performing the "node type" analysis, the focus was placed on the "author" category. The "Pathfinder" path algorithm is used, supplemented by "Pruning networks" and "pruning the merge network" pruning network technologies to conduct an in-depth analysis of the occurrence frequency of keywords and thus generate a graph showing the author cooperation mode.

As can be seen in Figure 5, in the lower left is a cooperative network composed of Deng Jun, Shu Chimin, and Bai Zujin [65–69]. One of them, Deng Jun, is also closely associated with Yang Shengqiang of CUMT. In the middle section is a collaborative network consisting of Hu Xiangming, Lu Wei, Huang Zhian, Xue Di, and Liang Yuntao [70–77]. In the bottom right is a collaborative network consisting of Wang Deming, Qin Botao, Shi Quanlin, and Wang Wei [78–82]. Among them, Wang Deming first proposed a new type of prevention and control technology, three-phase foam, in 2004. In the top left, is a collaborative network consisting of Yang Shengqiang and Zhou Buzhuang, among others [83–87]. In the upper right center, is a collaborative network consisting of Tan Bo, Wang Haiyan, Niu Huiyong, and Shao Zhuangzhuang [88–96]. On the right is a collaborative network consisting of Li Zenghua and Kong Biao et al. [97–99]. According to the author cooperation map, most of the MFPC researchers are from CUMT, XUST, HPU, SDUST, and the China University of Mining and Technology (Beijing). In addition, the author's institutions show significant geographical proximity and particularly close cooperation with each other, which indirectly confirms the large number of scholars in the MFPC field, but the research activities show obvious fragmentation characteristics, lacking large-scale and organized collaborative research and knowledge exchange. In the development of the MFPC field, in-depth academic exchanges and cooperation among leading scholars have played a decisive role in promoting the progress of the entire discipline. In view of this, it is urgent to take measures to strengthen the cooperation and communication among researchers in the MFPC field to promote resource integration and knowledge sharing.

3.4.2. Author Co-Citation Analysis

In-depth author co-citation analysis of the academic literature is a key research method to reveal and understand the law of scientific knowledge dissemination and disciplinary interaction. Its core lies in the detailed tracking and analysis of a specific phenomenon, that is, when two or more authors' independent works become the common objects of other researchers' papers at the same time, which is called the "co-citation phenomenon". Co-citation is not only an intuitive manifestation of academic influence but also an important indicator to measure the potential connection and cooperation tendency between authors and even among their subject fields.

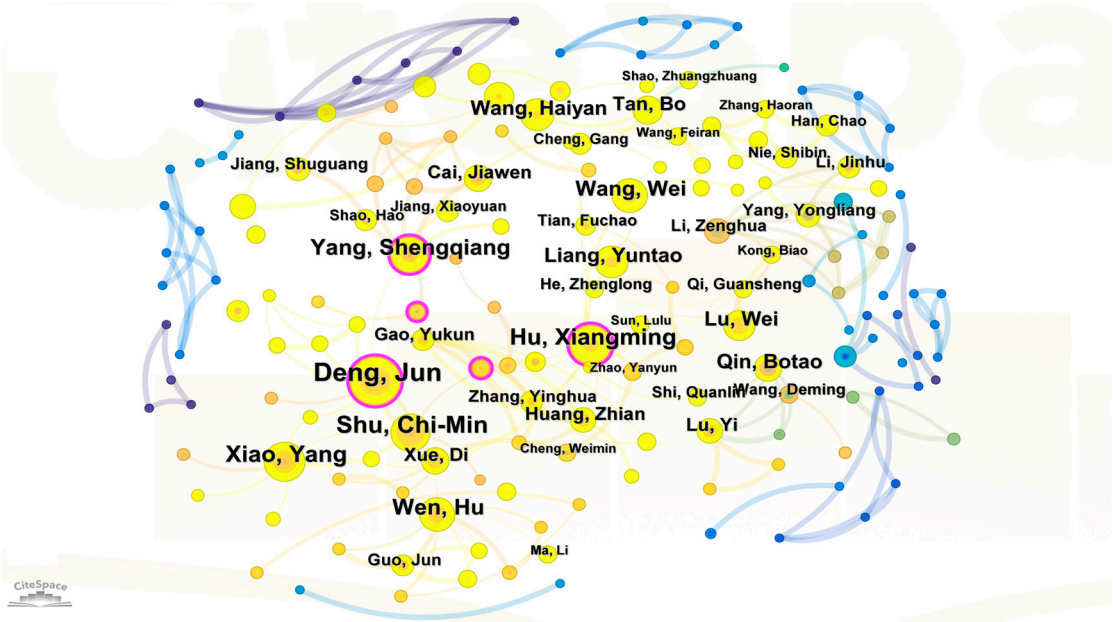

Figure 5. Author collaboration analysis.

The highly cited authors, such as Deng Jun, Qin Botao, Cheng Weimin, Song Zeyang, and Wang Deming, revealed in Figure 6, represent active and influential academic forces in this research field. Among them, Professor Deng Jun not only performs well in academic output but also has had these achievements widely recognized and highly cited in academic circles. Professor Qin Botao and Professor Wang Deming have made remarkable achievements in applying three-phase foam to SCC. Carras JN from CSIRO has done a remarkable job studying SCC phenomena and the use of carbon dioxide injection to prevent coal seam fires. On the other hand, Song Zeyang from XUST focuses on in-depth research in areas such as energy conversion and coal field fires.

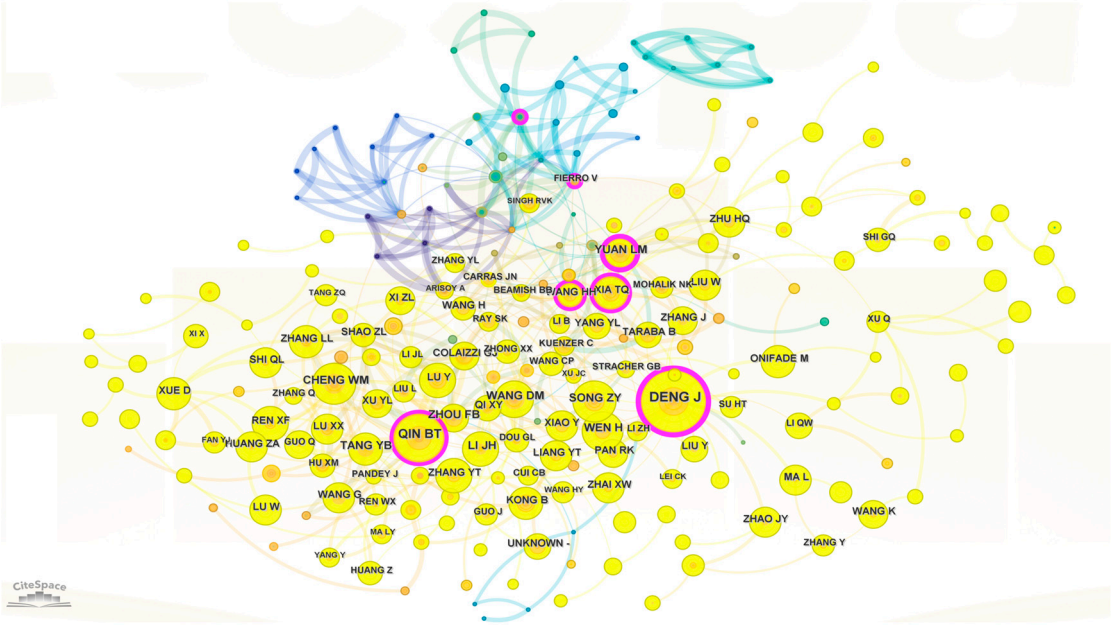

Figure 6. Mapping of co-cited authors.

3.5. Journal Analysis

3.5.1. Analysis of Major Journals

Academic journals play a central and irreplaceable role in the exchange and diffusion of scientific research [35]. Based on the detailed data provided by the WOS database, we conducted an in-depth review of MFPC papers published in the field and selected the top journals from them; the specific information is shown in Table 2. Among them, *Fuel* magazine, with its 90 published papers, topped the list, accounting for 12.55%; *Combustion Science and Technology*, with 72 papers (10.04%), and *Energy*, with 33 papers (4.60%), followed. *Process Safety and Environmental Protection* ranked first, with an average citation of 35.8, and *Fuel* ranked second, with an average citation of 30.9888. *Fuel* and *Process Safety and Environmental Protection* are at the top of the list in terms of the number of publications (first and fourth), impact factor (7.4 and 7.8), and average citations (second and first). The top ten journals focus on energy science, chemical engineering, and geochemistry, which together constitute a key platform for knowledge production and interaction in related research fields.

Table 2. Top ten journals in terms of number of publications.

Rank	Journal	Volume of Publications	Proportions	Impact Factor	Total Citations	Average Citation	Citation Index
1	Fuel	90	12.55%	7.4	2789	30.9888	SCI
2	Combustion Science and Technology	72	10.04%	1.9	522	7.2500	SCI
3	Energy	33	4.60%	9.0	658	19.9394	SCI
4	Process Safety and Environmental Protection	30	4.18%	7.8	1074	35.8000	SCI
5	ACS Omega	29	4.05%	4.1	202	6.9655	SCI
6	Journal of Thermal Analysis and Calorimetry	19	2.65%	4.4	229	12.0526	SCI
7	Environmental Science and Pollution Research	18	2.51%	5.8	379	21.0556	SCI
8	Energies	17	2.37%	3.2	113	6.6471	SCI
9	Energy Sources Part A-Recovery Utilization and Environmental Effects	17	2.37%	2.9	116	6.8235	SCI
10	Journal of Loss Prevention in the Process Industries	15	2.09%	3.5	155	10.3333	SCI

3.5.2. Journal Co-Citation Analysis

Select the node type as "Cited Journal" and the path algorithm as "Pathfinder" to obtain the co-citation graph of journals, as shown in Figure 7. Table 3 provides details of the top 10 journals with high citations.

Table 3. Top ten highly cited journals.

Rank	Journal	Co-Citation	Rank	Journal	Co-Citation
1	Fuel	519	6	Energy and Fuels	248
2	International Journal of Coal Geology	358	7	International Journal of Mining Science and Technology	240
3	Process Safety and Environmental Protection	349	8	Journal of China Coal Society	234
4	Journal of Loss Prevention in the Process Industries	279	9	Combustion Science and Technology	230
5	Fuel Processing Technology	271	10	Energy	228

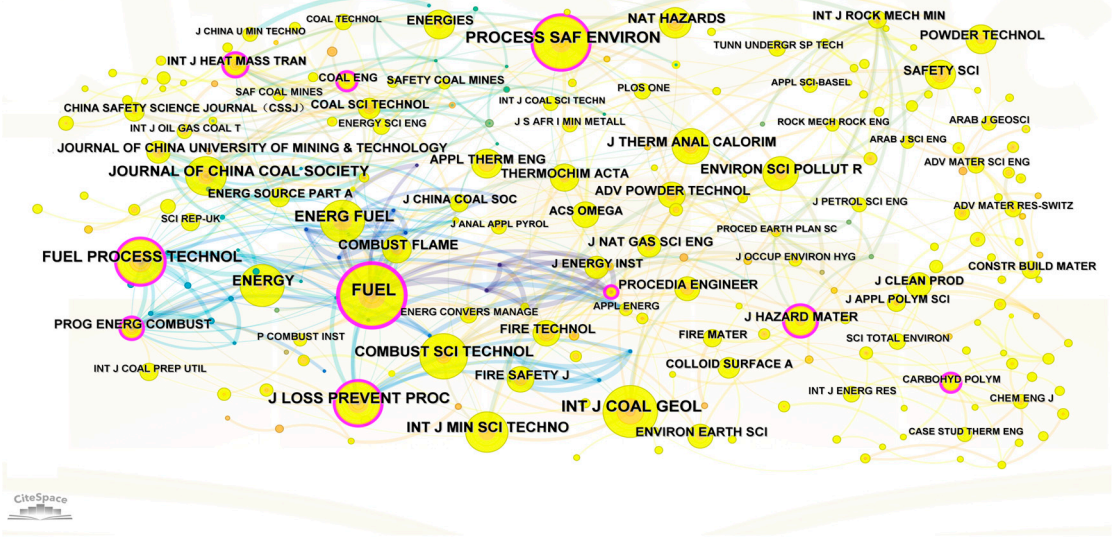

Figure 7. Journal co-citation knowledge map.

Among journal co-citations, *Fuel*, the *International Journal of Coal Geology*, *Process Safety and Environmental Protection*, the *Journal of Loss Prevention in the Process Industries*, and *Fuel Processing Technology* are frequently cited. In terms of co-citation, *Fuel* ranked first, with 519, the *International Journal of Coal Geology* ranked second, with 358, and *Process Safety and Environmental Protection* ranked third, with 349. Among these, *Fuel* and *Process Safety and Environmental Protection* play a key role in both average citation and co-citation. In general, the ten journals listed in the table are all prestigious academic publishing platforms around the world, and they have high profiles and influence in the MFPC research field. These include *Fuel*, *Energy*, *Process Safety and Environmental Protection*, and *Combustion Science and Technology*. These journals play a key role in mine fire control research.

3.6. Core Literature Citation Analysis

For an in-depth analysis of the most influential literature in the MFPC field, we selected the ten most frequently cited studies as research objects, including one review article and nine monographs. As shown in Table 4, the publication time distribution of these highly cited studies is as follows: one of them was published before 2008, which constituted the early representative achievement; six papers were published between 2009 and 2019, showing the active research trend in this field during the decade; and the remaining three papers, published after 2020, reflect the latest research in the field in recent years. Of these ten papers, four are related to colloid control technology (#1, #2, #6, #8), two are related to foam control technology (#3, #7), two are related to injection inerting control technology (#9, #10), one is related to mine fire suppressant retardant (#5), and one paper summarizes the existing technology in the MFPC field (#4). Cheng et al. [100] published an article entitled "An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties" in *Fuel* in 2017, which was cited 354 times; Ren et al. [101] published an article entitled "Novel sodium silicate/polymer composite gels for the prevention of spontaneous combustion of coal" in the *Journal of Hazardous Materials* in 2019, which was cited 154 times. The two most cited articles are research articles. The reason is that the MFPC field entered a period of stable development around 2009, during which the number of published studies is relatively limited, and it is not enough to support a comprehensive and systematic review or summational research. Since 2019, the MFPC field has entered a stage of rapid development, especially in foam fire prevention technology and colloidal fire prevention technology, showing significant innovative vitality and technological progress.

In terms of colloidal fire prevention technology, researchers have actively absorbed the mature experience and advanced technology of medical, food, and other related industries and achieved a substantial jump in technology and innovation. After two years of rapid development, the MFPC field finally gave birth to the first comprehensive and systematic review and analysis of various current fire prevention technologies, marking the integration of theoretical research and practical experience in this field to a new height.

Table 4. Top ten highly cited studies.

Rank	Title	Types	Journal	Author	Year	Citation
#1	An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties	Article	Fuel	Cheng et al. [100]	2017	354
#2	Novel sodium silicate/polymer composite gels for the prevention of spontaneous combustion of coal	Article	Journal of Hazardous Materials	Ren et al. [101]	2019	154
#3	Prevention, control and/or extinguishment of coal seam fires using cellular grout	Article	International Journal of Coal Geology	Colaizzi, GJ [102]	2004	131
#4	Overview of commonly used materials for coal spontaneous combustion prevention	Review	Fuel	Li et al. [103]	2020	112
#5	Inhibiting effects of three commercial inhibitors in spontaneous coal combustion	Article	Energy	Deng et al. [104]	2018	104
#6	Synthesis and characteristics of fire extinguishing gel with high water absorption for coal mines	Article	Process Safety and Environmental Protection	Li et al. [105]	2019	102
#7	Aqueous three-phase foam supported by fly ash for coal spontaneous combustion prevention and control	Article	Advanced Powder Technology	Qin et al. [106]	2014	98
#8	Fire prevention and control using gel-stabilization foam to inhibit spontaneous combustion of coal: Characteristics and engineering applications	Article	Fuel	Xue et al. [107]	2020	96
#9	Coal spontaneous combustion and N2 suppression in triple goafs: A numerical simulation and experimental study	Article	Fuel	Liu et al. [108]	2020	91
#10	A New Approach to Control a Serious Mine Fire with Using Liquid Nitrogen as Extinguishing Media	Article	Fire Technology	Zhou et al. [109]	2015	84

3.7. Hot Spots and Frontiers of Mine Fire Prevention and Control Research

3.7.1. Keyword Co-Occurrence Analysis

Keywords play an irreplaceable role in the structure of academic papers. In essence, they are highly condensed and precise refinements of the thesis theme, aiming to convey the core issues and ideological essence of the article in the most concise form. They are like "labels" for the content of the article, conveying the core issues and research directions in a concise and clear manner. Therefore, keyword analysis is actually a process of systematic testing and in-depth interpretation of the key points of the paper [34]. The WOS data were formatted and converted using CiteSpace, the time was 2000–2023, the time slice was 2 years, and the "keyword" was set to "Node type" to analyze the content. The keyword co-occurrence network that was generated according to the above settings has been visually displayed in Figure 8. The meaning of each element in the figure is provided by keywords that appear in the form of nodes. The line reveals the association law of keywords as follows: if a pair of keywords appear in the same study, there must be a line between them. In the network diagram, there is a direct proportional relationship between the size design

of nodes and the actual occurrence times of the keywords they represent in the literature data set. Specifically, the size of the node area becomes an intuitive scale to measure the actual use of the keyword in the research literature, following the principle of "the larger the area, the more mentions". This means that when a node presents a larger area in the graph, it actually reveals that the corresponding keyword has been frequently used and emphasized in the literature collection.

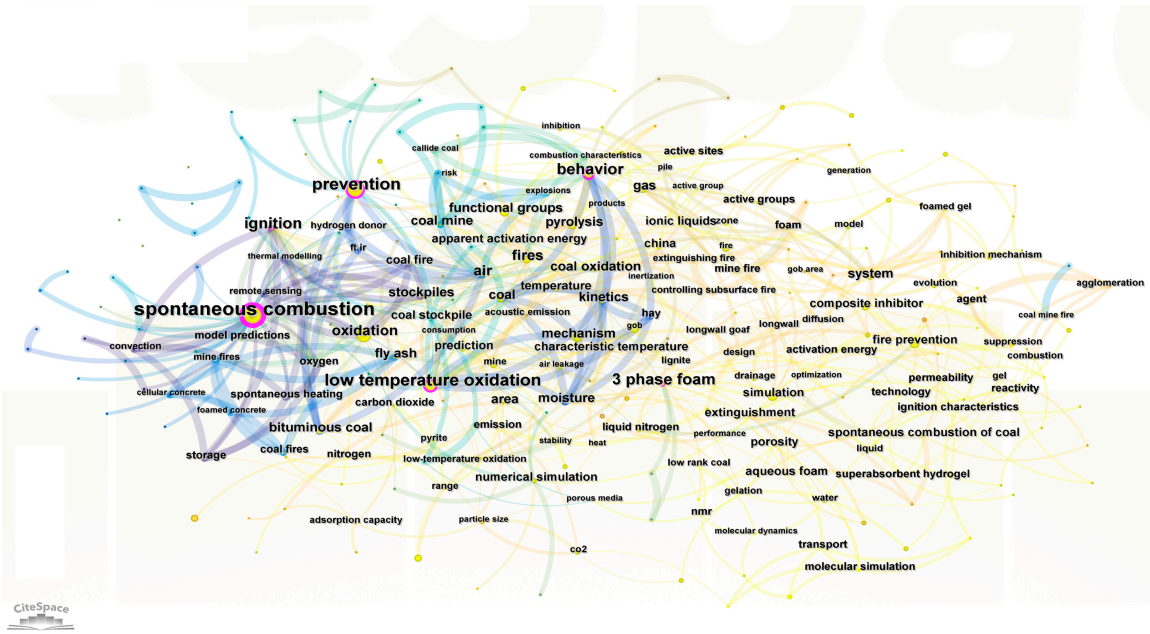

Figure 8. Keyword co-occurrence mapping.

As can be seen in the figure, spontaneous combustion and low-temperature oxidation are the core keywords; their significant network center status and extensive connectivity highlight their critical role in the field of mine fire research. This not only reflects the deep concern of the scientific research community for SCC processes, especially oxidation reactions occurring at low temperatures, but also reveals the seriousness of these processes as potential causes of mine fire accidents, so it has become the focus of research by researchers. At the same time, the high frequency of the keywords prevention and behavior and their close correlation with many other keywords further reveal the focus of the research. The strong correlation of prevention with words such as fire agent, inhibition mechanism, and design indicates how to effectively prevent the development of fire sources through scientific design and the selection of appropriate fire extinguishing agents and inhibition mechanisms in MFPC research. It became the key technology strategy of MFPC. This highlights the central role of preventive measures in reducing mine fire risk. On the other hand, the close connection between the keywords behavior and oxidation, temperature, and model predictions reveals researchers' great concern for the characteristics of mine fire behavior and how to use models to predict their dynamic changes. This indicates that researchers are committed to studying the interaction between the physical and chemical behavior of fire and environmental variables in order to more accurately predict the development trend of fire, and then formulate more targeted prevention and control strategies. In addition, the keywords 3 phase foam, gas, ionic liquid, and gel in the map are closely related to the above important concepts, reflecting the cutting-edge trend of MFPC field in technical applications. These advanced technologies not only play an important role in physical, chemical, or physicochemical inhibition strategies but they are directly related to the solution of core problems such as spontaneous combustion, low-temperature oxidation, prevention, oxidation, and behavior. This shows the deep integration of theory and practice. In summary, this analysis not only reveals the focus of mine fire prevention and control

research, such as spontaneous combustion and low-temperature oxidation mechanism, but also emphasizes the necessity of prevention measures and fire behavior research and shows the development of key technologies in the MFPC field, providing clear directional guidance and potential innovation points for subsequent research.

3.7.2. Keyword Clustering

Thirty-three clusters were obtained from the 290 keyword extractions, and the clusters with less than ten clusters were filtered by CiteSpace's built-in filtering function. Figure 9 shows the main clusters in this paper, according to # 0, # 1. . . . .# 7 sort. In the MFPC field, the CiteSpace analysis map reveals the research on the inhibition effect of different control technologies on various types of coal under different storage methods, states, and external environments. According to the unique properties of different coal, especially the characteristic temperature and the formation of signature gas during spontaneous combustion, the effects of various inhibition techniques are evaluated. In recent years, blocking mechanism and gel foam have become hot topics and have widely drawn the attention of academia and industry, and many scholars have focused their research on the blocking mechanism of anti-fire gels [110–114]. The rapid development of computer technology and software technology is promoting the progress of scientific research with unprecedented efforts, especially in the field of MFPC; the numerical simulation of various inhibition technologies has gradually emerged and become the focus of academic and industrial attention [115–122]. This kind of research mainly discusses how various materials affect the active site of SCC at the molecular level. In short, the research in the MFPC field is deepening, and new prevention and control technologies and evaluation systems are gradually taking shape, which will further promote scientific and technological progress and development in this field.

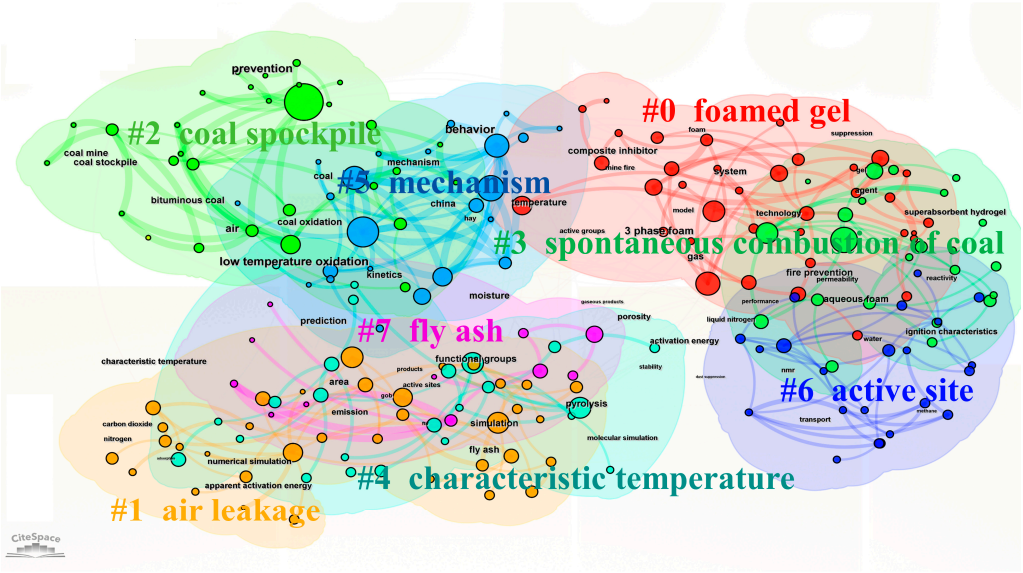

Figure 9. Knowledge map for keyword clustering.

3.7.3. Keyword Bursting

CiteSpace, a scientific knowledge graph analysis tool, is used to dig deeply into the literature data in MFPC field in order to reveal its frontier fields and future development trends, and the mutation word analysis function built into the software is adopted. The purpose of this function is to identify keywords with significant changes in frequency over a period of time, that is, abrupt changes through a specific algorithm. These keywords are often closely related to emerging trends and hot issues in the research field and are important clues to reveal the development context and future direction of the discipline. A specific value ($\gamma = 0.6$) was assigned to the key parameter γ in the mutation word analysis,

and 33 keywords meeting the mutation word criteria were successfully identified from the literature data in the MFPC field. In order to focus more on the most representative and influential mutation words, the top 25 keywords were further selected from the 33 keywords. These keywords were more prominent in the degree of mutation, and their Burst value ranked first among all mutation words. These keywords are sorted by Burst value size, and the sorting results are visually shown in Figure 10. Year indicates the year in which the keyword first appears; begin and end indicate the start and end year in which the keyword is used as the frontier; and strength indicates the emergence strength. The red line represents the specific period in which the keyword has become a hot topic of academic research, light blue represents that the node has not yet appeared, and dark blue indicates that the node has begun to appear.

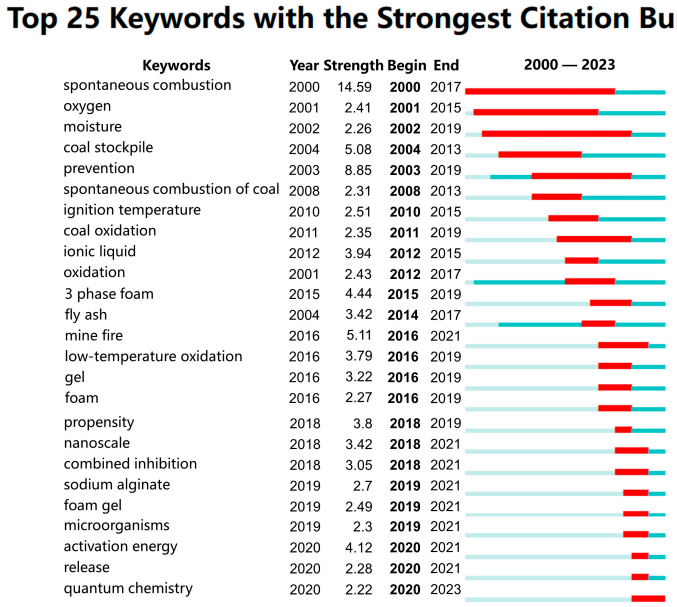

Figure 10. Sorting the top 25 emergent keywords.

As can be seen in the figure, spontaneous combustion ranks first, with a significant outburst intensity value of 14.59, which indicates the deep concern about the spontaneous combustion mechanism of coal and its prevention and control strategies in this field. Prevention followed, with a strength of 8.85, underscoring the centrality of prevention measures in mine fire prevention and the emphasis placed on highly effective inhibitors and suppression mechanisms. The intensity values of mine fire and coal stockpile are 5.11 and 5.08, respectively, which suggests that researchers should consider fire risk control in specific application scenarios, especially the safety management of open coal stockpile, a fire-prone area. The high breakout strength of three-phase foam and release (4.44 and 4.12, respectively) reflects the rise of innovative retarding technologies, particularly those that can release retarding ingredients in a timely manner to enhance flame retardancy. It is worth noting that the discovery of activation energy and quantum chemistry marks a change in research perspective, that is, from the traditional macroscopic analysis to the in-depth exploration of the microscopic mechanism of coal spontaneous combustion. This is closely related to the popularity of molecular simulation software, which enables researchers to explore in more detail how different inhibitors affect the oxidation reaction path and activation site of coal at the molecular level, thus promoting the development of physicochemical synergistic inhibition methods. The decline of moisture and ignition temperature means that the research on the basic physical properties of coal has become mature, and the rise of new keywords, such as release and quantum chemistry, indicates that MFPC research is entering a new stage of development. It focuses on deeper theoretical understanding and technological innovation. In summary, the emergence and change in

these keywords not only reveal the shift of research hotspots in the MFPC field but also provide clues for future research directions, namely, strengthening the exploration of the inhibition mechanism at the microscopic level, developing intelligent responsive inhibition materials, and optimizing the design and application of inhibitors using advanced computational techniques. This map provides valuable visual evidence for understanding the evolution of knowledge structures in the MFPC field, facilitating cross-disciplinary exchanges and collaboration, and providing new ideas for addressing complex scientific challenges.

4. Conclusions

In this study, the CiteSpace software is used to conduct an in-depth metrological analysis of the MFPC literature, which provides a strong basis for the research trend and future development direction of this field. The analysis results show the following:

(1) The annual volume of articles in the MFPC research field has grown significantly, especially between 2020 and 2023, indicating that the field is experiencing an unprecedented period of active development. China's research contributions in the MFPC field are the most prominent, followed by the United States and Australia, showing the dominance of these countries in international research. CUMT ranks among the best research institutions. *Fuel* and *Process Safety and Environmental Protection* play a key role in both average citation and co-citation. The top 10 cited articles are one review and nine papers. One of these is entitled "An intelligent gel designed to control the spontaneous combustion of coal". The research paper "Fire prevention and extinguishing properties" topped the list for citations;

(2) The high occurrence rate of prevention and behavior keywords emphasizes the importance of prevention measures and coal spontaneous combustion behavior research. In terms of technology, the reference to retarding technologies, such as three-phase foams, gels, and ionic liquids, highlights the key role of materials and technological advances in the MFPC field. A keyword cluster analysis reveals the in-depth discussion of MFPC research in the evaluation of inhibition effect, adaptability of different coal characteristics, influence of external environmental factors, etc., and further confirms the status of inhibition mechanism as a current research hotspot;

(3) The emergence of activation energy, release, quantum chemistry, and other recent hot words indicates that the research focus is shifting to the mechanism of physicochemical synergistic inhibition, energy release control, and the application of quantum chemistry theory in the study of coal spontaneous combustion. It indicates that the field is developing in the direction of more micro and theoretical depth;

(4) The CiteSpace analysis reveals the dynamic changes in MFPC research, including the diversification of research topics, the iterative updating of technologies and the frontier transformation of research hotspots. Future research should continue to focus on the in-depth exploration of the coal spontaneous combustion mechanism, strengthen the development of physicochemical synergistic inhibition materials, and apply advanced computational methods, such as quantum chemical simulation, to improve the theoretical guidance and practical application level of MFPC. Exploring new chemical inhibitors, simplifying the preparation and application process of materials, improving the thermal stability of materials, extending the action time, and improving the environmental safety of materials are the main problems facing the development of fireproof materials. These findings not only provide a comprehensive overview of the current MFPC research but also point the way for future research direction and have important scientific value for reducing mine fire risk and ensuring mining safety.

Author Contributions: Conceptualization, D.H. and G.N.; data curation, B.L.; investigation, Y.R., C.S., Y.Y. and Z.Z.; methodology, D.H. and F.W.; writing—original draft, D.H. and G.N.; writing—review

and editing, G.N., B.L., F.W. and Y.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially sponsored by the China University of Mining and Technology (Beijing) College Student Innovation Training Program (202412032) and supported by the Fundamental Research Funds for the Central Universities.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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

Nomenclature

MFPC	mine fire prevention and control
SCC	spontaneous combustion of coal
WOS	Web of Science
CUMT	China University of Mining and Technology
XUST	Xi'an University of Science and Technology
SDUST	Shandong University of Science and Technology
HPU	Henan Polytechnic University
AUST	Anhui University of Science and Technology
USTB	University of Science and Technology of Beijing
CSIRO	Commonwealth Scientific and Industrial Research Organisation
PCSHE	Pennsylvania Commonwealth System of Higher Education

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