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Review

A Review on Mine Fire Prevention Technology and Theory Based on Bibliometric Analysis

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Abstract: Of all mine disasters, fires are very threatening to mine safety and often lead to the most serious consequences. Research on mine fire prevention technology and theory has experienced significant growth and is attracting escalating academic interest and attention. However, dedicated literature reviews on this topic are scarce. For the purpose of uncovering the research characteristics and trends on mine fire prevention technology and theory, this paper employs bibliometric analysis using the Web of Science Core Collection database. This study presents a detailed analysis of relevant articles published between 2010 and 2022. An assessment of the influences of journals, countries, institutions, and authors was conducted through a citation analysis. Furthermore, this paper describes co-authorship networks among different countries, institutions, and authors. Lastly, a review of the mine fire prevention techniques and theories researched during this period was carried out through a keyword clustering analysis. Four main research topics in mine fire prevention research were identified: "mine fire control technology", "mine fire occurrence mechanism", "mine fire prediction technology", and "mine fire monitoring technology". Additionally, the theory study of spontaneous combustion and its underlying mechanisms may represent a potential focus for future research. These findings contribute to providing a solid foundation for future research endeavors in this field of fire prevention.

Keywords: mine safety; fire; prevention technology; prediction; control; bibliometric analysis

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1. Introduction

Coal has been acknowledged as a significant global energy source for over two centuries. It is widely utilized in various fields, such as power generation, steel production, and chemical manufacturing. Nonetheless, mine disasters pose an urgent and vexing issue in the exploitation of this resource [1]. The rapid expansion of the mining industry has led to increased prominence of various mine hazards. Underground coal mining means more deadly hazards due to confined spaces, toxic and harmful gases, mine water, machinery, surrounding rock, and other dangerous sources [2]. These hazards lead to significant casualties, environmental degradation, and coal resource depletion. Of these mine hazards, fire is very threatening to mine safety and often leads to the most serious consequences [3]. In order to predict and prevent the occurrence of mine fire accidents, many scholars have carried out a series of research works on mine fire prevention technology and theory.

The current research in mine fire accident prevention technology and theory typically focuses on the following areas: assessing the propensity for spontaneous combustion, determining the natural ignition period, as well as forecasting and monitoring natural ignition events. The determination of the propensity for spontaneous ignition in coal is primarily based on oxidation kinetics, which is considered the mainstream approach [4,5]. Nonlinear methods, such as the maximum Lyapunov index method, can also be employed to evaluate the propensity for spontaneous ignition in sulfide ores [6–8]. To determine the natural ignition period of coal, modeling methods and experimental methods are commonly employed. Gao YL et al. developed an effective model for calculating the minimum time to spontaneous ignition [9]. Zhang D et al. demonstrated the effectiveness of calculating the spontaneous ignition period of coal in an oxygen-deprived environment using an experimental method based on pure oxygen adiabatic [10]. The most frequently employed indicator gas in the early prediction of natural ignition is CO [11]. Additionally, ratios of gases such as CO/O_2, CO_2/CO, O_2/N_2, and C_2H_4/C_2H_6 can serve as predictive indicators [12–14]. Wireless and sensor network technology has been used in natural coal ignition monitoring [15,16]. Remote sensing technology aids in the identification and dynamic monitoring of spontaneous combustion in expansive coal mining regions [17]. The method that utilizes satellite thermal infrared (TIR) remote sensing to determine the thermal anomalies of underground coal fires has been widely adopted [18]. Moreover, fiber-optic temperature measurement technology has been utilized for temperature monitoring in mining areas [19].

Filling and plugging materials are currently well received and actively developed due to their broad applicability, significant performance, affordability, and other advantages [20]. Fire outbreaks can be effectively managed through advanced fire suppression techniques, such as inert gas or liquid nitrogen injection, pressure balancing, ventilation reversal in underground mines, nitrogen foam application, air-mining zone insertion, and water mist utilization [21]. The utilization of chemical flame retardants to suppress the occurrence of smoldering combustion is a crucial method to prevent or delay mine fires [22]. Three-phase foams, composed of solid, liquid, and gas phases, are recognized as effective fire protection measures in underground mines [23,24]. Cheng WM et al. developed a smart gel to prevent spontaneous coal combustion. It exhibits superior fire-suppression properties compared to other gels, making it an ideal material for fire control [25].

Bibliometric analysis has emerged as an essential tool for measuring scientific progress in diverse disciplines [26]. In contrast to narrative reviews, this study employs bibliometric analysis to enhance rigor and minimize bias through a structured and replicable process [27]. It is commonly utilized to systematically evaluate the progress of specific scientific domains, analyzing the distribution patterns of authors, journals, institutions, keywords, and hotspots. Additionally, bibliometric analysis assists in informing future research by searching for authors, titles, keywords, and cited references in online literature databases [28]. This study contributes to four key areas: (1) addressing the gap in bibliometric analysis within the field of mine fire prevention; (2) assessing the influences of highly cited articles and journals, while visualizing the collaborative network among countries, institutions, and authors, to offer researchers a comprehensive perspective; (3) identifying significant research themes in mine fire prevention through keyword clustering and hotspot analysis, which helps illustrate the evolving research frontiers and allows researchers to stay updated on advanced topics; and (4) comprehending the progress and limitations of the current research based on the analysis results and providing suggestions for future research planning and implementation.

In Figure 1, the research route of this paper is presented. This paper is structured into five sections. Section 2 encompasses the data retrieval and processing procedures, as well as the research methodology. Section 3 presents the results of the bibliometric analysis. Section 4 discusses the findings, and Section 5 concludes the paper and suggests future research directions.

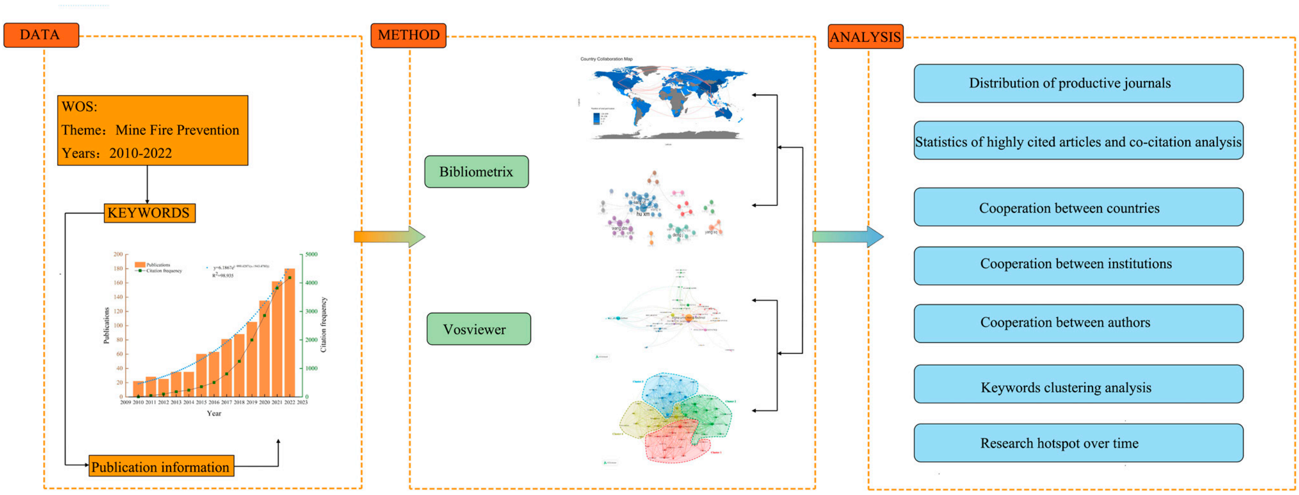

Figure 1. A schematic diagram of the research idea.

2. Data and Methods

2.1. Data

The data were comprehensively retrieved from the Web of Science Core Collection due to its comprehensive bibliometric research information. This study focused on investigating articles relevant to mine fire prevention and control that were published between 2010 and 2022. The deadline for data acquisition was set as 31 December 2022. To fulfill the research objectives, relevant topics on mine fire prevention and control were selected for the article search. Using the advanced search function of the Web of Science website, relevant topics were selected for searching, and articles unrelated to the study were subsequently filtered out. A total of 1082 articles were included from 2010 to 2022, covering 3273 authors, 361 journals, 53 countries, and 70 institutions.

2.2. Methods

Many software programs have been designed for bibliometric analysis, such as Vosviewer, R language, and Citespace [29–31]. Vosviewer and R language were chosen for this study due to their excellent network diagram generation capabilities. The Vosviewer software is a robust bibliometric analysis tool that efficiently assesses relationships among publications, institutions, and authors. The software can generate visual networks like co-citation, literature coupling, and co-occurrence networks [30]. The bibliometric package in R language can efficiently analyze gathered datasets, acquiring detailed data on countries, authors, institutions, journals, and keywords, among others [31].

3. Results

3.1. Articles Issued over the Years

In Figure 2, the information about articles published in the years from 2010 to 2022 is presented. The orange bar represents the total number of papers per year, the green solid line represents the number of citations per year, and the blue dashed line represents the publication trend [32]. By applying the polynomial fitting function in the Origin software, we found the best-fitted curve that corresponded to the actual data and publication trend for the total number of articles and citations per year. The fitted curve was determined to be a compound exponential function:

$$y = 6.1867e^{-999.4287/(x-1943.4780)}, \quad (1)$$

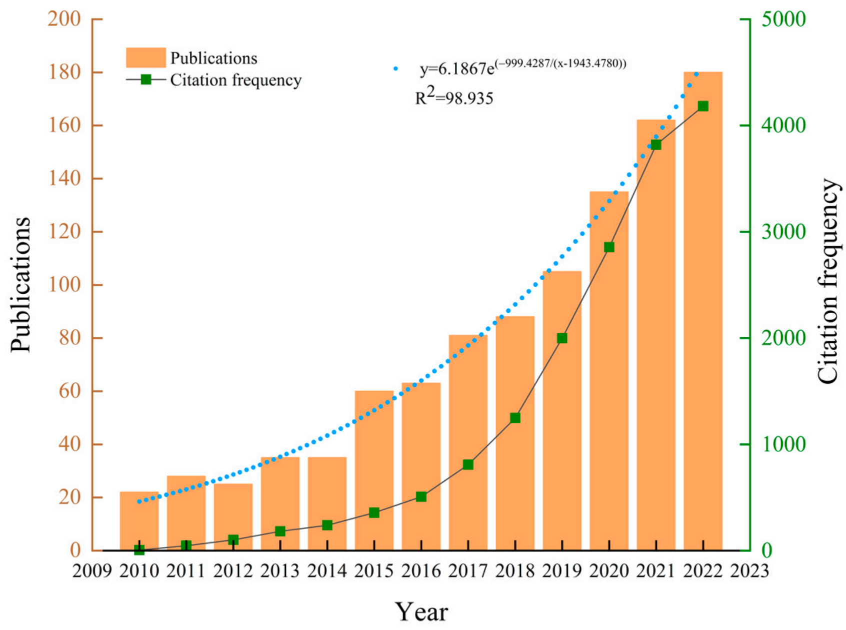

Figure 2. Articles published in the years from 2010 to 2022.

The growth rate of articles related to mine fire prevention and control remained relatively steady between 2010 and 2014, with a sharp increase of 71% in 2015. This upward trend accelerated between 2015 and 2022, when nearly 87% of all articles within this field were published, demonstrating exponential growth dynamics. Similarly, the number of citations per year increased steeply, with 239 citations in 2014 and 4183 in 2022, representing an approximately 17-fold increase from 2014. This acceleration indicates both the rapid development of research in the mine fire prevention and control field since 2015 and the escalating interest of researchers. Based on these observed trends and the publication trend line, it can be presumed that research in mine fire prevention and control will continue to undergo rapid development.

3.2. General Statistics and Co-Citation Analysis

3.2.1. Distribution of Productive Journals

In Figure 3, the annual article counts of the top five journals in mine fire prevention and control from 2010 to 2022 are presented. The article counts of these journals follow a general trend. The counts were relatively low from 2010 to 2015. However, from 2015 to 2022, the number of publications consistently increased, albeit with a lower growth rate after 2022. In Figure 4, the total article count of each journal is displayed. Out of 361 journals, only 13 journals have more than 15 articles, whereas 297 journals have 3 or fewer articles. Table 1 presents the top 10 most active journals in mine fire prevention and control based on their article counts. *Combustion Science and Technology* ranked first with 60 published articles, followed by *Fuel* (52 articles) and *Process Safety and Environmental Protection* (49 articles). *Fuel* has the highest total citation count among these journals, with 1888 citations, and its H-index is also the highest, reaching 26. *Process Safety and Environmental* and *Journal of Loss Prevention in the Process* are also journals with high citations and H-index counts. *Process Safety and Environmental* has a total citation count of 1309 and an H-index value of 22; the *Journal of Loss Prevention in the Process* has a total citation count of 746 and an H-index value of 15. The H-index is a composite metric used to evaluate the quantity and quality of the academic output of journals in a given field. The total citation frequency (TC) refers to the number of times an article is cited within a global dataset. A higher H-Index or higher total citation frequency implies that the journal's articles are more relevant to the research field [33]. Journals with higher impact factors have more citations in the field of mine fire prevention and control, including *Fuel* (8.035, 36.31), *Process Safety and Environmental* (7.926, 26.71), *International Journal of Mining Science and Technology* (7.67, 25.87), *Environmental Science and Pollution Research* (5.19, 23.4), and the *International Journal of Coal Geology* (6.3, 27.1). Interestingly, the impact factor of the *Journal of Loss Prevention in the Process Industries* is relatively low, at only 3.916, but it has the highest average number of citations in the field of mine fire prevention and control, with a value of 37.3.

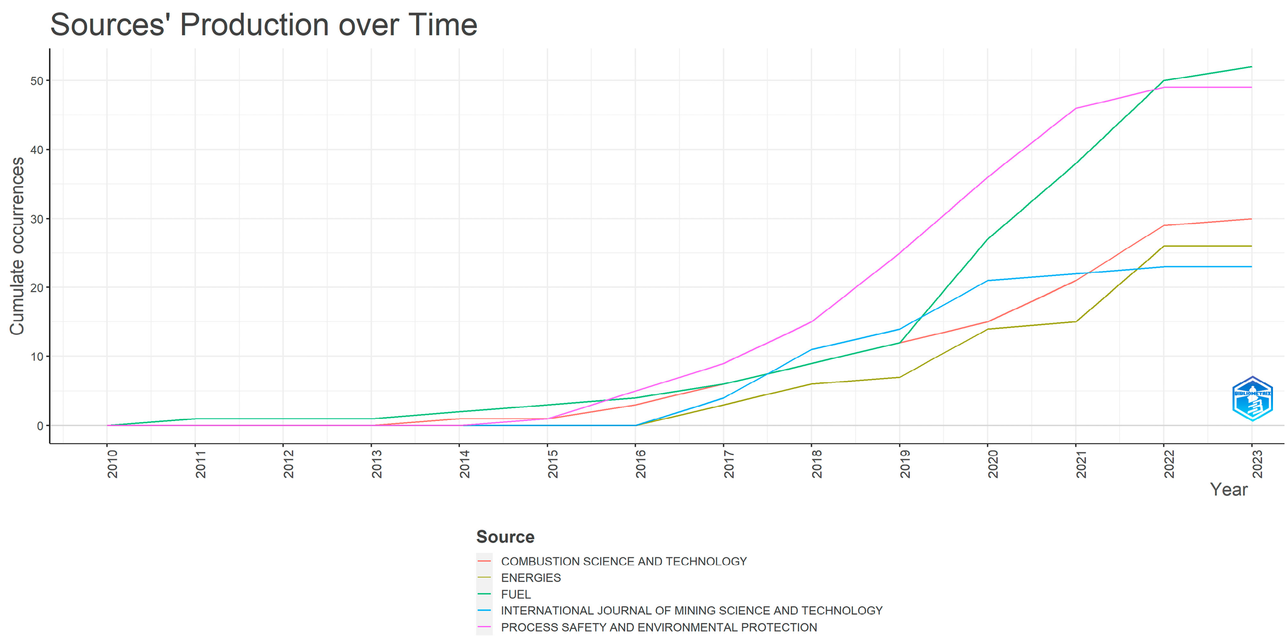

Figure 3. Annual article volume chart of the journals.

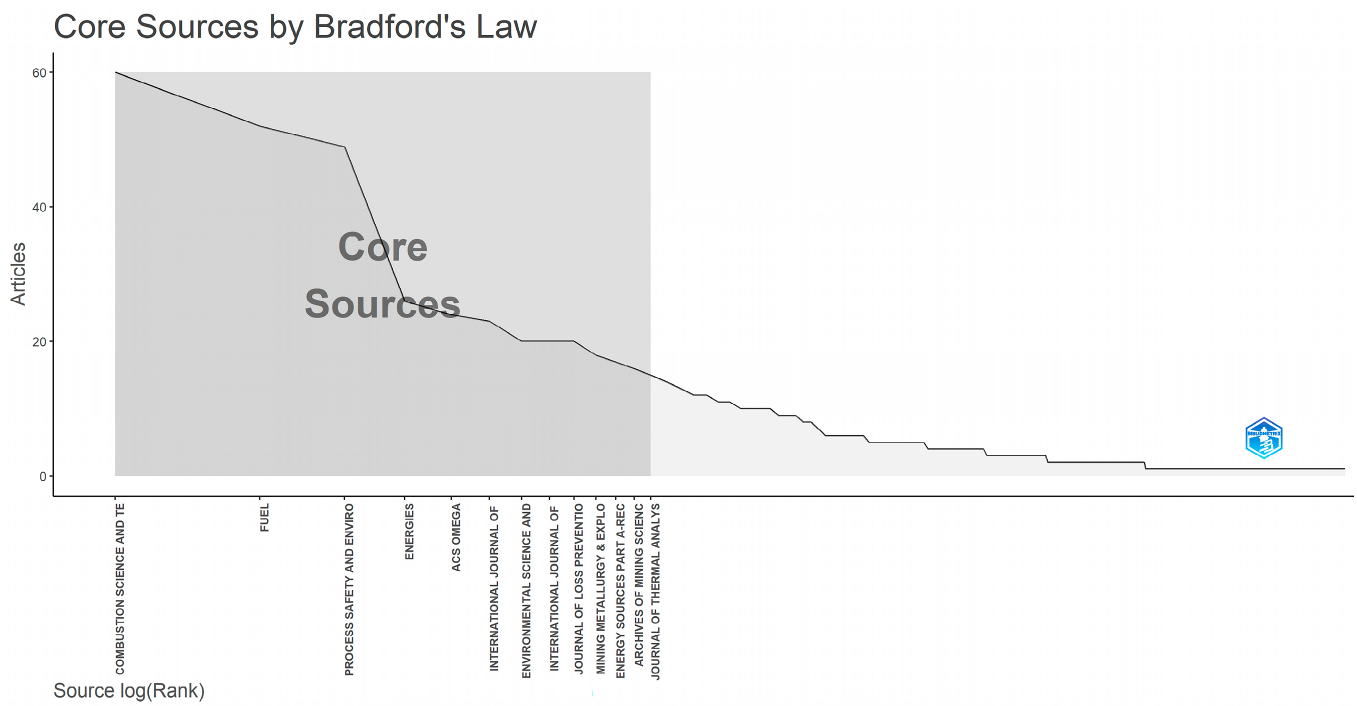

Figure 4. Distribution chart of journal articles.

Table 1. Top 10 journals with high publication numbers.

No.	Journal Title	Articles	H-Index	[1]TC	[2]IF (2022)	Average Article Citations
1	*Combustion Science and Technology*	60	10	322	2.133	5.37
2	*Fuel*	52	26	1888	8.035	36.31
3	*Process Safety and Environmental Protection*	49	22	1309	7.926	26.71
4	*Energies*	26	7	168	3.252	6.46
5	*ACS Omega*	24	6	82	4.132	3.42
6	*International Journal of Mining Science and Technology*	23	15	595	7.67	25.87
7	*Environmental Science and Pollution Research*	20	10	468	5.190	23.4
8	*International Journal of Coal Geology*	20	13	542	6.300	27.1
9	*Journal of Loss Prevention in the Process Industries*	20	15	746	3.916	37.3
10	*Mining Metallurgy & Exploration*	18	4	50	1.695	2.78

[1]TC = times cited; [2]IF = impact factor.

3.2.2. Statistics of Highly Cited Articles and Co-Citation Analysis

In Table 2, the information about the top 10 articles based on local citations is displayed. The TC per year is used to measure the impacts of recently published papers. Local citations refer to the number of articles referenced by other articles within the local dataset, whereas global citations refer to the number of articles referenced by other works in the literature in the global Web of Science database [34]. The discrepancy between local and global citations indicates that the topic of mine fire prevention and control is also gaining attention from other fields [35]. Table 2 reveals that articles based on local citation rankings do not necessarily have more global citations. For example, in Table 2, "Shao ZL, 2015" ranked third in local citations, and "Ren XF, 2019" ranked eighth in local citations, but it ranked more in global citations than "Shao ZL, 2015". This implies that these articles are likely to attract attention beyond the field of mine fire prevention and control. In Figure 5, the citation network of the literature is displayed. The size of the nodes represents the number of citations, and the distance between nodes indicates the correlation between the citations. Nodes of the same color indicate closely connected citation clusters. Three citation clusters in red, green, and blue are formed, among which "Cheng WM, 2017" and "Shao ZL, 2015" belong to the green cluster, and "Deng J, 2015" and "Xia TQ, 2016" belong to the red one. Notably, these four articles ("Cheng WM, 2017", "Shao ZL, 2015", "Deng J, 2015", and "Xia TQ, 2016") are all of the top ten most cited articles based on local citations. This indicates that there is a certain correlation between the research content of these highly cited articles.

Based on the research topics, the top ten articles with the highest numbers of local citations are classified into the following three groups. As is shown in Figure 5, the first group, "Development and improvement of mine fire extinguishing materials", corresponds to green cluster 1; the second group, "Study on spontaneous combustion process and oxidation mechanism of coal mines", corresponds to red cluster 2; and the third group, "Coal mine spontaneous combustion index monitoring and fire prediction", corresponds to blue cluster 3.

Development and improvement of mine fire extinguishing materials (cluster 1): The article titled "An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties" proposed an intelligent gel (IG) to prevent spontaneous coal combustion [25]. The authors of the article titled "Controlling coal fires using the three-phase foam and water mist techniques in the Anjialing Open Pit Mine, China" improved the three-phase foam coal fire extinguishing system and developed a water mist coal fire extinguishing system [36]. The authors of the article titled "Aqueous three-phase foam supported by fly ash for coal spontaneous combustion prevention and control" studied the preparation and characterization of nitrogen-containing three-phase foam loaded with fly ash (FA) [23]. The article titled "Novel sodium silicate/polymer composite gels for the prevention of spontaneous combustion of coal" proposed a new gel material for coal mine fire prevention and extinguishing [37], and the article titled "A New Approach to Control a Serious Mine Fire with Using Liquid Nitrogen as Extinguishing Media" proposed an instant liquid nitrogen perfusion fire extinguishing application [21].

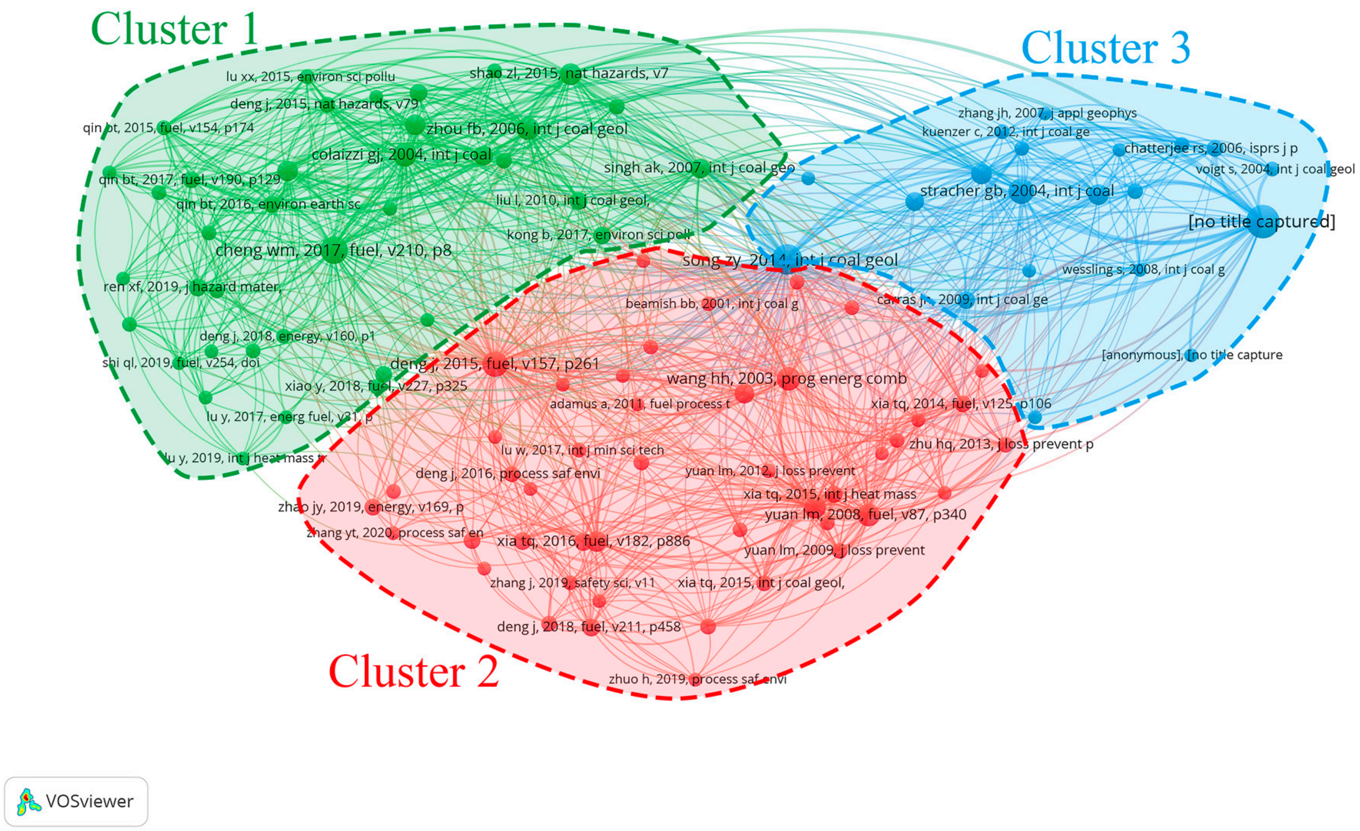

Figure 5. Articles' co-citation network diagram.

Study on spontaneous combustion process and oxidation mechanism of coal mines (cluster 2): The authors of the article titled "Experimental studies of spontaneous combustion and anaerobic cooling of coal" constructed a 15-ton experimental furnace to conduct large-scale experiments on the spontaneous combustion and anaerobic cooling of coal, aiming to study the spontaneous combustion process and oxidation mechanism of coal [38]. The article titled "Effect of longwall face advance rate on spontaneous heating process in the gob area-CFD modeling" investigated the oxidation of coal in goaf with a numerical simulation using the Fluent software [39]. The article titled "Controlling factors of symbiotic disaster between coal gas and spontaneous combustion in longwall mining gobs" extended the fully coupled coal–oxygen heating model of spontaneous combustion to a symbiotic model of coal gas flow and spontaneous combustion by introducing a cumulative gas release function in the set of coupled control equations [40].

Coal mine spontaneous combustion index monitoring and fire prediction (cluster 3): The authors of the article titled "Forecasting spontaneous combustion of coal in underground coal mines by index gases: A review" reviewed the mechanism and practical knowledge of using indicator gas technology to predict spontaneous combustion [41]. The authors of the article titled "Determination and prediction on 'three zones' of coal spontaneous combustion in a gob of fully mechanized caving face" developed a PSO-SVR model for predicting the spontaneous combustion temperature of cinder [42].

Table 2. Top 10 papers with local citations.

No.	Title	First Author	Year	Local Citations	Global Citations	Times Cited Per Year
1	"An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties" [25]	Cheng WM	2017	91	299	42.71
2	"Experimental studies of spontaneous combustion and anaerobic cooling of coal" [38]	Deng J	2015	83	237	26.33
3	"Controlling coal fires using the three-phase foam and water mist techniques in the Anjialing Open Pit Mine, China" [36]	Shao ZL	2015	54	83	9.22
4	"Effect of longwall face advance rate on spontaneous heating process in the gob area—CFD modelling" [39]	Tarabab	2011	53	100	7.69
5	"Controlling factors of symbiotic disaster between coal gas and spontaneous combustion in longwall mining gobs" [40]	Xia TQ	2016	51	105	13.13
6	"A New Approach to Control a Serious Mine Fire with Using Liquid Nitrogen as Extinguishing Media" [21]	Zhou FB	2015	50	75	8.33
7	"Aqueous three-phase foam supported by fly ash for coal spontaneous combustion prevention and control" [23]	Qin BT	2014	38	76	7.60
8	"Determination and prediction on "three zones" of coal spontaneous combustion in a gob of fully mechanized caving face" [42]	Deng J	2018	37	82	13.67
9	"Novel sodium silicate/polymer composite gels for the prevention of spontaneous combustion of coal" [37]	Ren XF	2019	36	112	22.4
10	"Forecasting spontaneous combustion of coal in underground coal mines by index gases: A review" [41]	Liang YT	2019	36	89	17.80

3.3. Analysis of the Cooperative Relationship

3.3.1. Cooperation between Countries

In Figure 6, the national spatial distribution of research on mine fire prevention and control between 2010 and 2022 is displayed. The number of network curve links represents the number of cooperative relationships between countries; the depth of color blocks representing different countries is positively correlated with the number of published articles from each country. Based on the spatial distribution of publications, cooperation is mainly concentrated in three regions: Asia, Oceania, and North America. China is a closely related and leading country in the field of mine fire prevention and control. It is also more active than other countries, with 60% of articles on this topic being written by Chinese authors. Australia and the United States are major players in the cooperation network. Table 3 presents the research article output across countries. China had the greatest number of publications among all countries, followed by the United States, Australia, and India. Interestingly, the average citation frequency is higher in Australia, Canada, and South Africa compared to China and the United States.

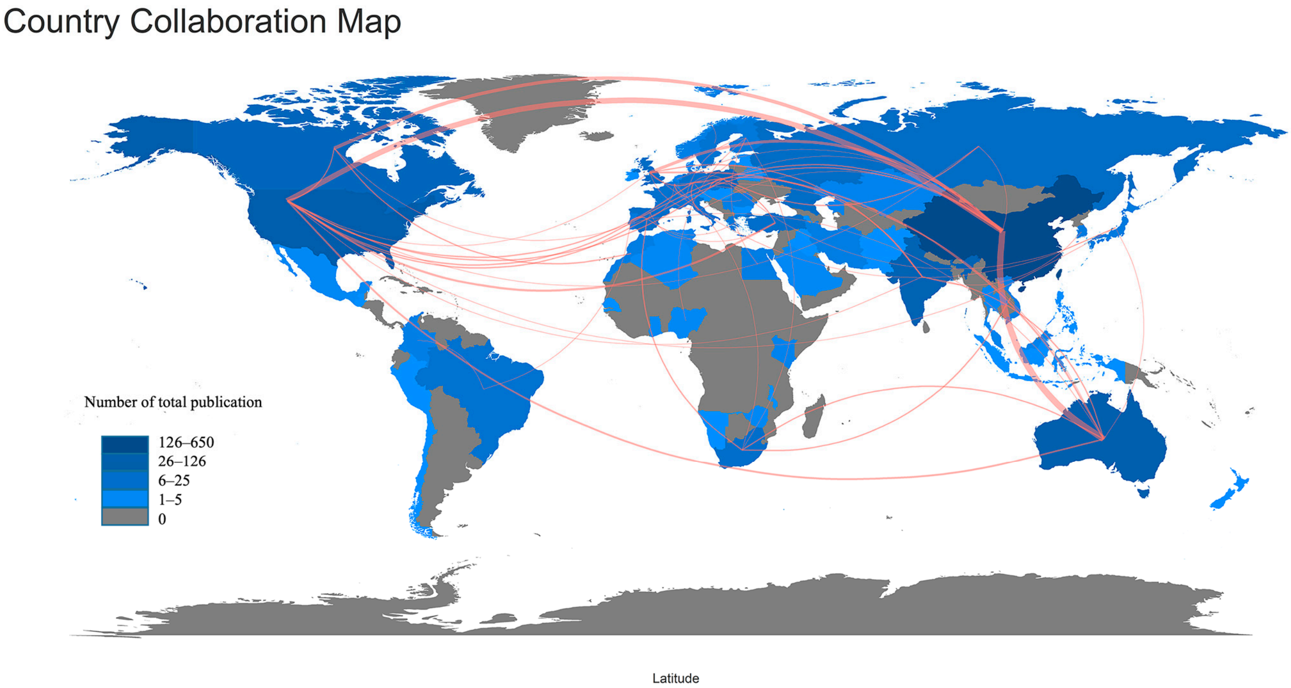

Figure 6. Cooperation diagram between countries.

Table 3. The top 11 countries with high article numbers.

No.	Countries	Articles	Times Cited	Citation Frequency	Average Article Citations	H-Index
1	China	650	4565	9606	14.78	48
2	USA	114	2130	2234	19.6	26
3	Australia	96	1740	2039	21.24	26
4	India	65	823	963	14.82	17
5	Canada	43	968	1001	23.28	19
6	Poland	43	370	402	9.35	11
7	Russia	24	296	309	12.88	7
8	Britain	22	413	413	18.77	8
9	Spain	21	328	339	16.14	10
10	South Africa	20	348	421	21.05	9
11	Turkey	20	159	159	7.95	8

3.3.2. Cooperation between Institutions

In Figure 7, the institutional cooperation network of research-related articles is displayed. The size of each node represents the number of articles, and the connection between nodes indicates the degree of cooperation. The figure indicates that the China University of Mining and Technology is the most cooperative institution in the field of mine fire prevention and control. In Table 4, the information of the top fifteen institutions that publish articles is displayed. The top ten institutions, all from China, correspond with the highest number of published papers by Chinese authors in Table 3. Interestingly, despite having the second highest number of papers, the United States has no institutions in the top fifteen. One possible explanation is that authors in the field of mine fire prevention and control from the United States are relatively dispersed.

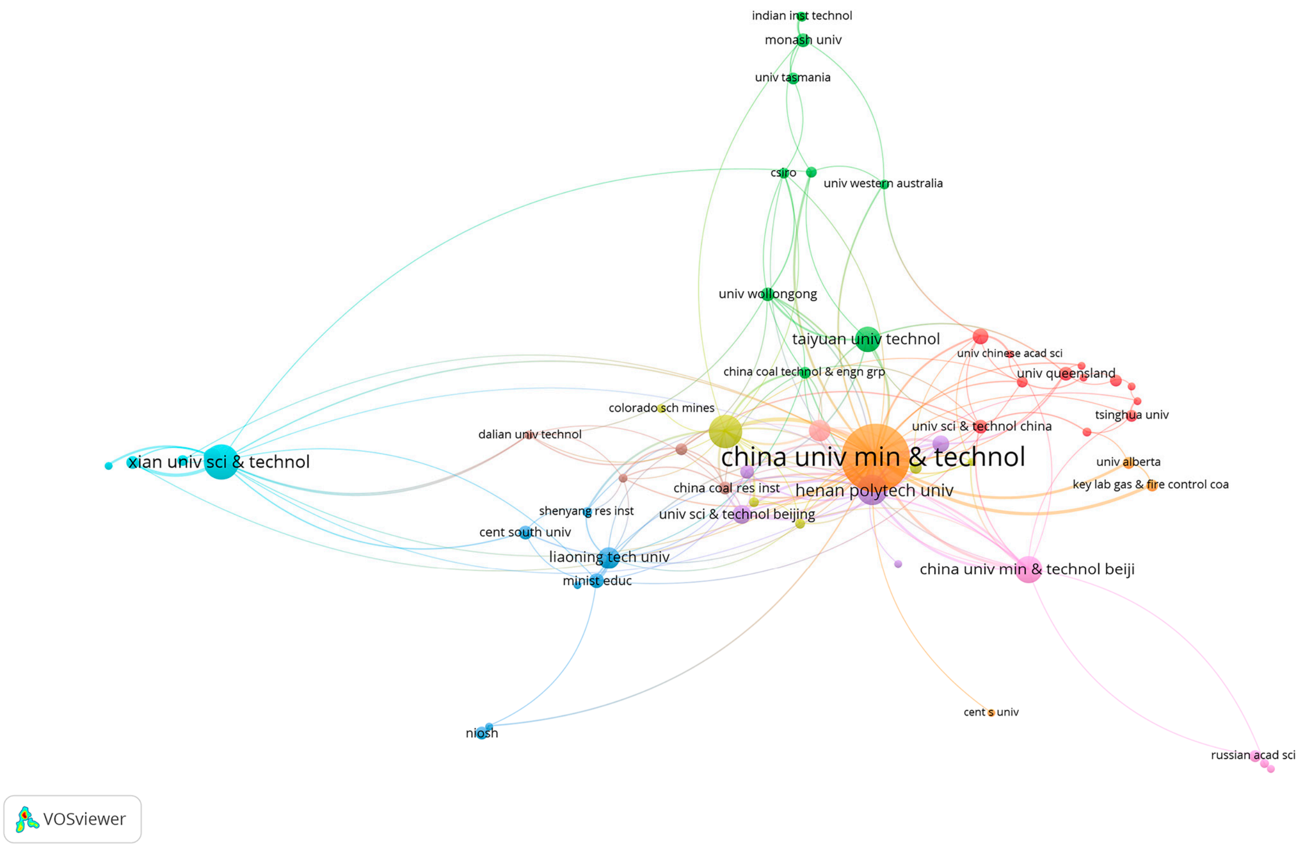

Figure 7. Institutional cooperation network.

Table 4. The top fifteen institutions that publish articles.

Rank	Institutions	Country	Articles
1	China University of Mining and Technology	China	368
2	Shandong University of Science and Technology	China	126
3	Xian University of Science and Technology	China	97
4	Henan Polytech University	China	75
5	China University of Mining and Technology, Beijing	China	48
6	Taiyuan University of Technology	China	47
7	Liaoning Technical University	China	36
8	Anhui University of Science and Technology	China	33
9	Hunan University of Science and Technology	China	26
10	University of Science and Technology Beijing	China	25
11	Central Mining Institute	Poland	23
12	Indian School of Mines	India	21
13	National Yunlin University of Science and Technology	Taiwan, China	18
14	Shenyang Institute of Engineering	China	16
15	University of Tasmania	Australia	16

3.3.3. Cooperation between Authors

This study analyzes the number of authors' articles and the number of citations. There are 3273 authors involved in the field of mine fire prevention and control. In Figure 8, the association between the number of authors and their publications is displayed. The dashed line represents the theoretical curve according to *Lotka*'s law and the solid line represents the actual curve. Lotka's law describes the quantitative relationship between the frequency of authorship of scientific papers and the number of papers written. According to the generalized *Lotka's* law based on bibliometrics [43],

$$F(X) = C/x,^{n} \quad (2)$$

F(X): the proportion of scientists who write *x* papers out of all scientists;
n: frequency;
C: subject characteristic constant.

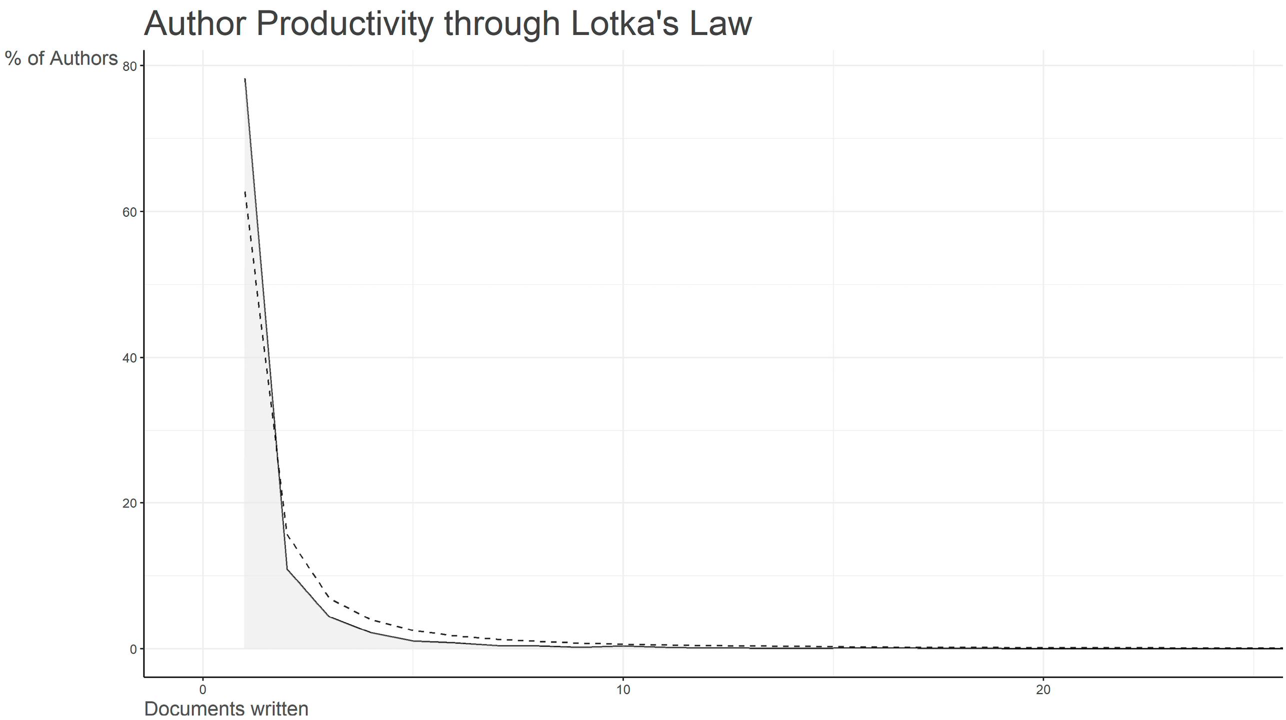

Figure 8. Distribution of the author's volume.

From Equation (2), it can be seen that the number of authors who published n articles is about $1/2^{n}$ of the number of authors who published one article. Between 2010 and 2022, 1023 articles were published in the field of mine fire prevention and control, which were written by 3159 authors. Out of the 3159 authors, 2500 authors published only one paper. According to Lotka's law, the number of authors who published two, three, four, and five papers should be 625, 278, 156, and 100, respectively. However, a statistical analysis suggests that the number of authors who published two, three, four, and five articles are 339, 134, 65, and 32, respectively. These findings suggest that the actual number of authors is much lower than the theoretical number of authors predicted by Lotka's law. In Figure 9, the productivity of the top ten authors from 2010 to 2022 is displayed. The size of the circle corresponds to the number of articles, and the color intensity is positively correlated with the total number of citations each year. In Table 5, the articles of the top ten most cited authors are displayed. Hu XM is the most frequently cited author with a total of 738 citations, while Deng J is the most prolific author, who wrote 27 articles. Wang DM is the earliest author in the field of mine fire prevention and control. In 2011, he proposed a coverage optimization strategy for cyber-physical systems for detecting coal mine fires in the paper titled "Coverage Optimizing of Cyber-Physical System for Coal Mine Fire Detection", which is based on the probabilistic measurement and thermal detection range models [44]. The period of 2014–2016 is the most frequent period in which Wang DM published papers.

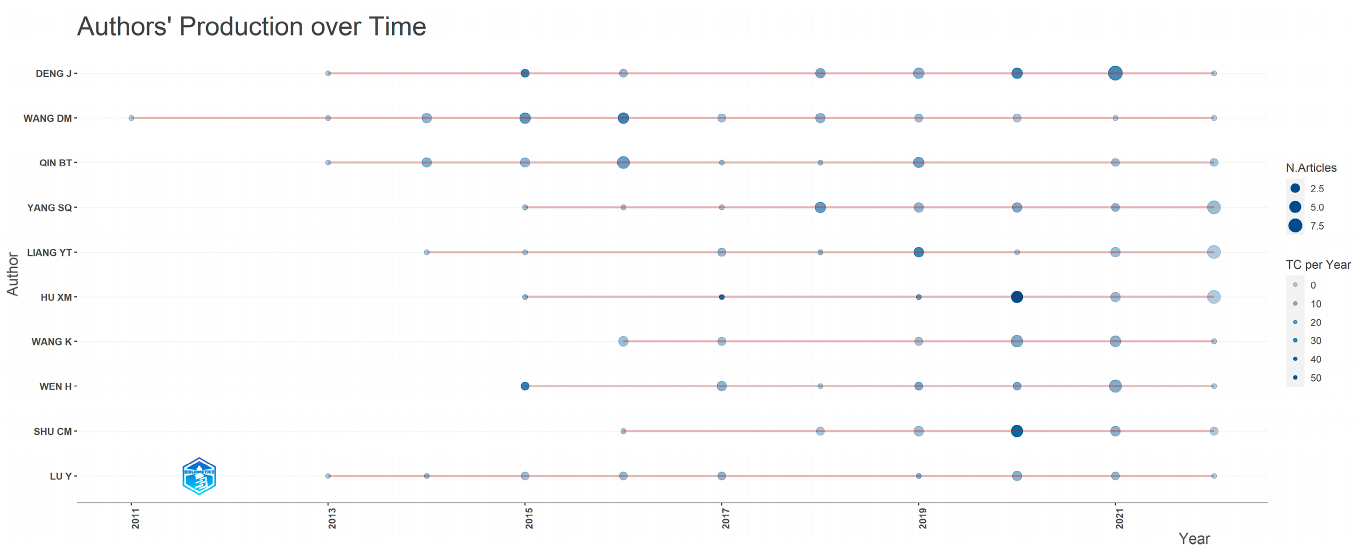

Figure 9. Authors' production over time.

Table 5. Top 10 authors for total citations.

No.	Authors	TC	Articles	H-index	Average Article Citations
1	Hu XM	738	22	9	33.55
2	Deng J	725	27	12	26.85
3	Cheng WM	710	10	8	71.00
4	Wang DM	709	24	13	29.54
5	Zhao YY	639	9	7	71.00
6	Zhou FB	573	14	13	40.93
7	Wen H	561	17	9	33.00
8	Qin BT	516	24	13	21.50
9	Li ZH	495	9	8	55.00
10	Qi GS	492	14	8	35.14

TC = times cited.

In Figure 10, the co-author clustering relationships in the field of mine fire prevention and control are displayed. The various color-coded nodes in the figure correspond to different author groups [45]. In total, 48 author groups have contributed to this publication. By limiting the minimum frequency of occurrence, smaller clusters of authors are hidden in Figure 10. The largest cluster (dark blue segment) in the figure is formed by Hu XM from the Shandong University of Science and Technology, Liang YT from the State Key Laboratory of Coal Safety Mine Technology, and Wang W from the China Coal Research Institute. The second largest one is formed by Wang DM and Qin BT from the China University of Mining. The third largest one is formed by Technology (purple segment) and Deng J from the Xian University of Science and Technology and Shu Cm from the National Yunlin University of Science and Technology (light blue segment).

We analyzed the largest cluster of researchers in Figure 10. The cluster has published 150 articles in the field of mine fire prevention and control. Hu XM is the author with the most papers in the cluster. From 2010 to 2022, Hu XM published 22 papers, which were cited 264 times locally. In 2017, Hu XM [25,37,46] proposed a new type of mining fire extinguishing material to prevent spontaneous coal combustion. In 2019, he proposed a new gel material for fire prevention and extinguishing fires in coal mines. In 2022, he proposed a new type of inorganic solidified foam (NICF) to prevent spontaneous coal combustion. This is followed by Liang YT [41,47], who participated in the publication of 21 papers, with a total of 112 citations. In 2014, he proposed using Fourier transform infrared spectrometer (FTIRS) to analyze the coal index gas in real time to monitor spontaneous combustion. In 2019, he analyzed the use of gas indicators to predict the spontaneous combustion of coal in underground coal mines. The cluster mainly focuses on studying fire prevention and extinguishing materials, as well as spontaneous coal combustion monitoring and prediction technology.

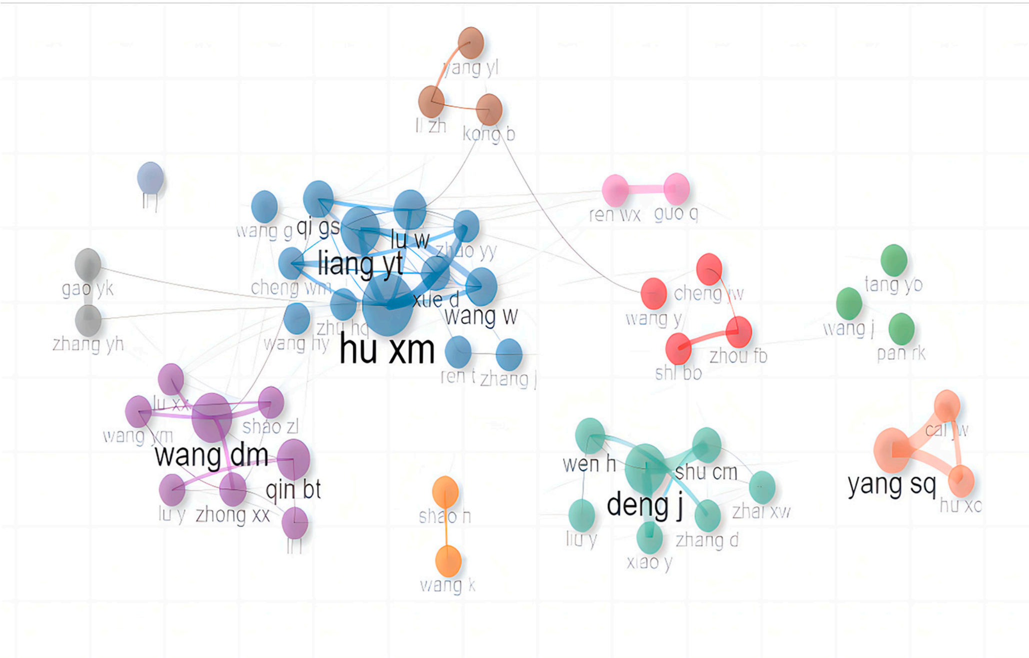

Figure 10. Author collaborative cluster diagram.

The second largest cluster published a total of 78 articles, as shown in the purple section of Figure 10. Wang DM and Qin BT were the largest contributors to the cluster, and both participated in the publication of 24 articles. Qin BT [23,48] studied the preparation and characterization of N2-containing three-phase water foam supported by fly ash (FA). In 2015, Wang DM [4,36] improved the three-phase foam coal fire extinguishing system and developed a water mist coal fire extinguishing system for coal fires. In 2016, he proposed a ring-chain reaction mechanism to describe spontaneous coal combustion using quantum chemical calculations. In 2019, Qin BT proposed the formation conditions for methane explosions caused by spontaneous coal combustion. Furthermore, the distribution of oxygen and methane concentration was studied in areas affected by spontaneous coal combustion using a reduced mine experimental device. The main focus of the cluster is on the study of the fire extinguishing system for coal fires and the mechanism of spontaneous coal combustion.

The third largest cluster has published a total of 81 articles, as shown in the light blue section of Figure 10, with Deng J contributing to 28 of them, making him the author with the highest contribution to the cluster. To investigate the spontaneous combustion and anaerobic cooling of coal, Deng J [38,49] established a 15-ton experimental furnace and conducted a large-scale spontaneous combustion experiment. In 2018, he proposed a three-dimensional distribution map and contour map of gas and temperature in the goaf based on field test data (O_2, CO, carbon dioxide, methane, and temperature) and changes in gas and temperature using grid data interpolation. In 2021, Hu Wen [50] established a calculation model for the development stage of a mine fire using the CFD numerical simulation method and ANSYS Fluent software. The cluster mainly studies the mechanism of spontaneous combustion and mine fires through experiments and simulations. Additionally, the theory study of spontaneous combustion and its underlying mechanisms may represent a potential focus for future research.

3.4. Research Themes and Hotspots Analysis

3.4.1. Keywords Clustering Analysis

In Figure 11, the keyword co-occurrence network clustering under the research topic of mine fire prevention and control is displayed. The same node color represents a cluster with the same research topic. The sizes of nodes and keywords in the graph are proportional to the frequency of keywords, and the distance between two keywords is inversely proportional to the strength of the relationship between them [51]. A total of 5326 keywords were obtained from these 1082 articles, and 64 were obtained after the minimum frequency of occurrence was set to 16 and duplicate keywords were combined. The 64 keywords were grouped into four clusters, namely Cluster 1 for mine fire prevention technology and management; Cluster 2 for mine fire mechanism and process; Cluster 3 for mine fire prediction and simulation; and Cluster 4 for mine fire monitoring and detection.

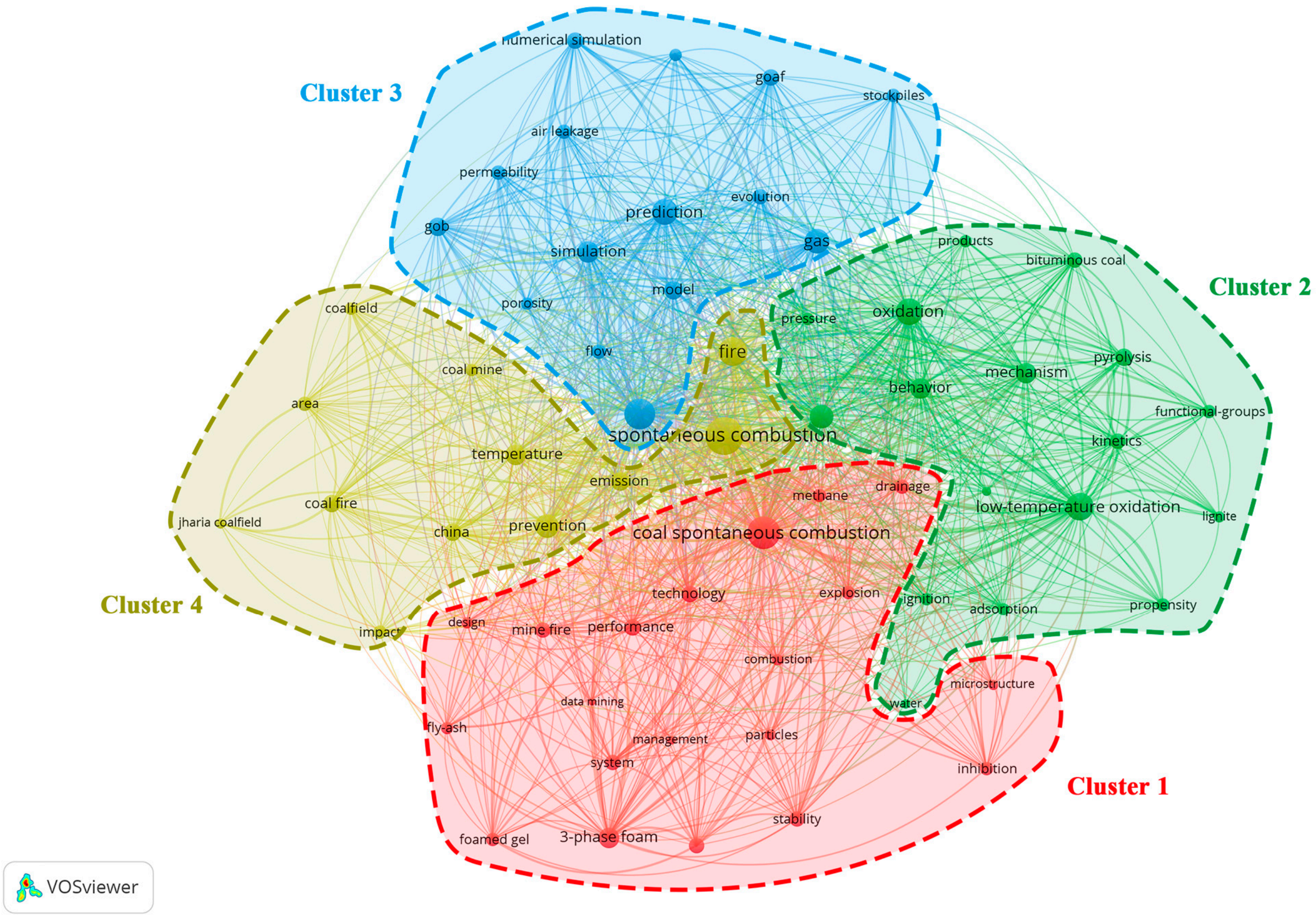

Figure 11. Keyword clustering network.

Cluster 1: "Mine fire control technology", including the following keywords: "coal spontaneous combustion", "technology", "3-phase foam", "fire-prevention", "caustic gel", "management", etc. Currently, many traditional mine fire prevention technologies, such as water injection grouting, the injection of inert gas, and the use of inhibitors, gel, two-phase or three-phase foam, and polymer materials, have been developed and frequently utilized [52]. Nevertheless, traditional mine fire prevention techniques possess certain limitations. Early water injection grouting technology is susceptible to slurry running and breaking under the influence of terrain, causing significant environmental impacts. Inert gas can easily diffuse and escape from the injection area, requiring high sealing requirements. Chemical inhibitors are expensive and difficult to apply. The poor fluidity of the gel leads to a small application area. The poor stability of the two-phase foam and the three-phase foam leads to a short action time, and the polymer material reaction will produce toxic gas and a large amount of heat [20]. Many researchers have improved these traditional mine fire prevention and extinguishing technologies, or developed new technologies based on the advantages and disadvantages of different technologies. Cheng WM proposed a new IG for mine fire prevention that exhibits enhanced thermal stability due to its incorporation of expandable graphite, as opposed to conventional temperature-sensitive and polyacrylamide gels [25]. Tests show that a 10% IG sample can inhibit the oxidation of hydroxyl groups during heating. Lu Y developed a new technology called paste foam [53]. Paste foam not only has the characteristics of paste, but also has the characteristics of foam. At the same time, the paste foam can also overcome the shortcomings of both, thereby significantly improving the efficiency of controlling the spontaneous combustion of coal piles. Ren XF proposed a new gel material called HPAM-Al^{3+}/WG hydrogel for fire prevention and extinguishing in coal mines. Combining the advantages of silica and polymer gels, this material displays excellent permeability, water retention capacity, compressive strength, and inhibition characteristics, which can significantly improve fire suppression and reduce material costs [37]. Di X introduced a method called gel-stabilized foam (GSF) that was successfully employed in the Yuncheng coal mine [54]. This foam displays excellent flame suppression capabilities, foam stability, and a cooling effect due to the use of suitable foaming agents, foam stabilizers, and gelation systems. Considering that the materials used for gel foam mainly come from chemical products, which will endanger the human body and cause environmental pollution, a new type of biomass sodium alginate gel foam (SC-GF) was prepared. This new type of gel foam has excellent fire prevention and extinguishing performance but also has the characteristics of environmental protection [55].

Cluster 2: “Mine fire occurrence mechanism”, containing the following keywords: “coal”, “oxidation”, and “low-temperature”. The pyrite induction theory is the earliest theory used to explain the mechanism of mine fire, including terms such as “mechanism”, “kinetics”, and “pyrolysis”. Other theories that have emerged since then include the bacteriology theory, the phenolic action theory, and the coal oxygen compound theory. Spontaneous combustion in coal mines typically requires several conditions: a predisposition of the coal seam to spontaneous combustion, sufficient oxygen supply conditions, and sufficient storage time for oxidation heat. Low-temperature oxidation is the primary cause of spontaneous coal combustion. If there is enough oxygen to support the low-temperature reaction between coal and oxygen, the heat generated by coal oxidation cannot dissipate fully via conduction or convection, resulting in an increase in the net temperature of the coal. If the heat generated by coal oxidation is not fully dissipated to the surrounding environment through conduction, convection, and radiation, the exothermic processes of microbial metabolism, coal-water interaction, and pyrite oxidation will promote the self-heating of coal [56]. The theory of coal oxygen compounds has gradually been accepted by most scholars, and many scholars have adopted new experimental techniques and methods to carry out further research. Quantum chemical methods were used to conduct a series of calculations based on the reactions of the primary active sites involved in spontaneous coal combustion. This led to the establishment of a cyclic chain reaction mechanism of spontaneous coal combustion and the description of the primary reaction pathway of the heating process in the coal oxidation process for the first time [4]. Shi XQ proposed a method for calculating the key parameters of coal oxidation reactions based on temperature-programmed experiments. Additionally, a one-step global numerical model of coal oxidation was established, which took into account the influence of multi-component materials [57].

Cluster 3: “Mine fire prediction technology”, involving keywords such as “prediction”, “mine”, “simulation”, “model”, “gas”, and so on. The prediction technology of mine fires is based on the exothermic characteristics of coal oxidation and the actual mining conditions. It estimates the spontaneous combustion tendency, spontaneous combustion period, or maximum spontaneous combustion area of loose coal at the low-temperature oxidation stage of coal. Currently, several prediction methods exist, including differential scanning calorimetry (DSC), thermogravimetric analysis, Russian U index, differential thermal analysis, cross-point temperature, X-Ray Diffractometer, the Olpinski index method, and the Adiabatic calorimetric method [58]. Many researchers have developed prediction models or techniques, such as mathematical models, TNO models, cloud models, adiabatic calorimeters, remote sensing, and GIS technologies, among others [56,59,60]. The detection and trend analysis of several special gas products released during coal oxidation is the most basic prediction technology of mine fires in practice. The production of carbon oxide, hydrogen, methylene and other hydrocarbon gases can be used to predict the early heating of coal. Mine fires' tendency to start due to the heating of coal can be determined using various experimental techniques that are well known in applications. However, no standard test method exists to prove the reliability of every technique. The Wits-Ehac test is applicable to all oil shales (single paper covered), and to some extent, most coal samples. Therefore, further analytical work may be necessary to standardize and support its use in mine fire risk assessment applications.

Cluster 4: "Mine fire monitoring technology", including the following keywords: "spontaneous combustion", "emission", "prevention", "temperature", "coal fire", "impact", etc. Mine fire monitoring and detection is of great value to coal mine safety. The common methods of mine fire monitoring and detection include remote sensing satellite image technology, airborne thermal infrared technology, and others [61]. Mine fires caused by spontaneous coal combustion produce a mixture of combustion products, including methane, carbon monoxide, and other greenhouse gases. Monitoring the emissions of these gases and changes in temperature helps to increase the understanding of the evolution trend of mine fires. Ribeiro J et al. proposed an optical fiber sensing system that is capable of conducting a real-time evaluation of the status of coal gangue piles [62]. The system includes gas emission monitoring, point temperature measurement, and distributed temperature measurement. Shao ZL et al. conducted magnetic and spontaneous potential detection on 46 coal fire points in Xinjiang, China and found that while the magnetic method is very sensitive to fire zones that have cooled from high temperatures, it is not sensitive to the combustion front. In addition, while the natural potential is abnormal in fires with shallow burial depths, it cannot accurately reflect deep coal fires [63]. Combining the F magnetic method and natural potential data can more accurately delineate the range of coal fires.

3.4.2. Research Hotspot over Time

A timeline graph represents the evolution of knowledge over time [45]. In Figure 12, the changes in the top 10 keywords related to mine fire prevention and control from 2010 to 2022 are displayed. These keywords include "behavior", "fires", "gas", "low-temperature oxidation", "mine", "model", "oxidation", "prediction", "prevention", and "spontaneous combustion". These keywords saw an increase in growth after 2014, and the growth rate slowed in 2022, "spontaneous combustion" had the fastest growth rate. In Figure 13, the yearly prevalent topics in the field of mine fire prevention and control are displayed, where the diameter of the circle denotes the frequency of the topic. The topics are selected based on a maximum limit of five themes per year, and a minimum frequency of 10 is set for each theme. Apart from the term "fires" that we searched for, the keywords "area", "model", "temperature", and "China" had the highest occurrence rates, with "area" and "model" appearing for 6 years, and "temperature" and "China" appearing for 5 years. It is noteworthy that in 2020, "spontaneous combustion", "mine", "low-temperature oxidation", "prediction", and "gas" had the most occurrences. The keyword "functional-groups" emerged in 2021 and increased in 2022.

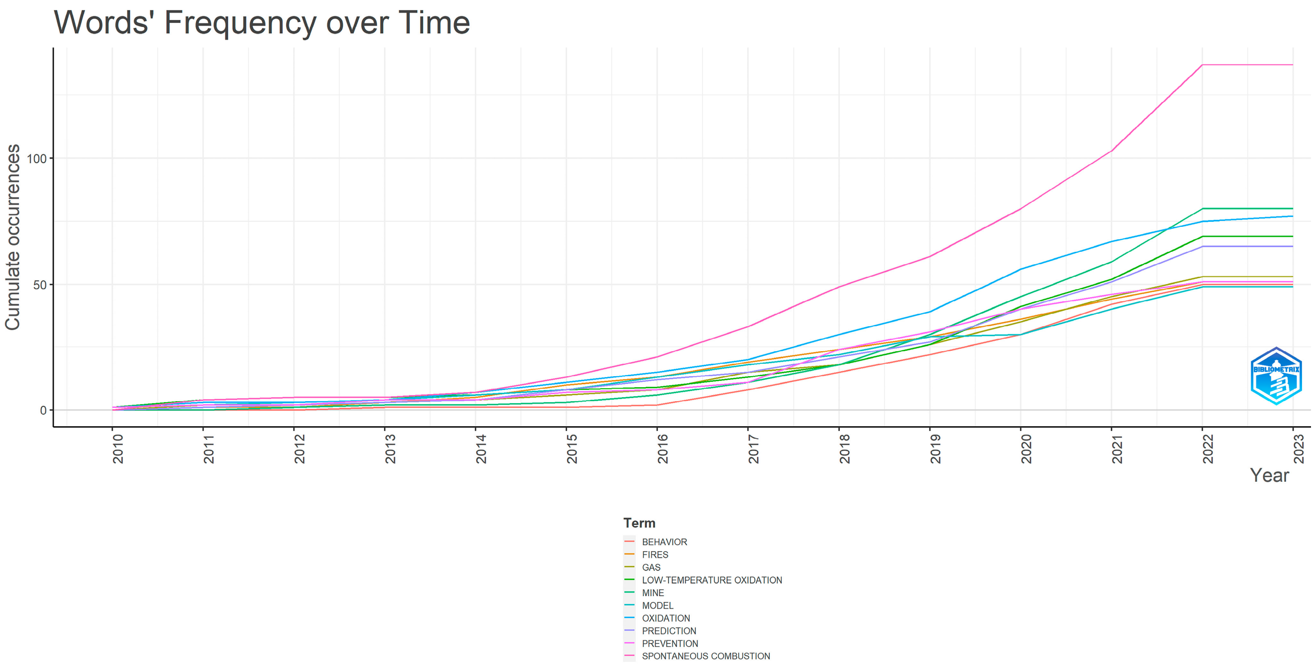

Figure 12. Keyword frequency over the years.

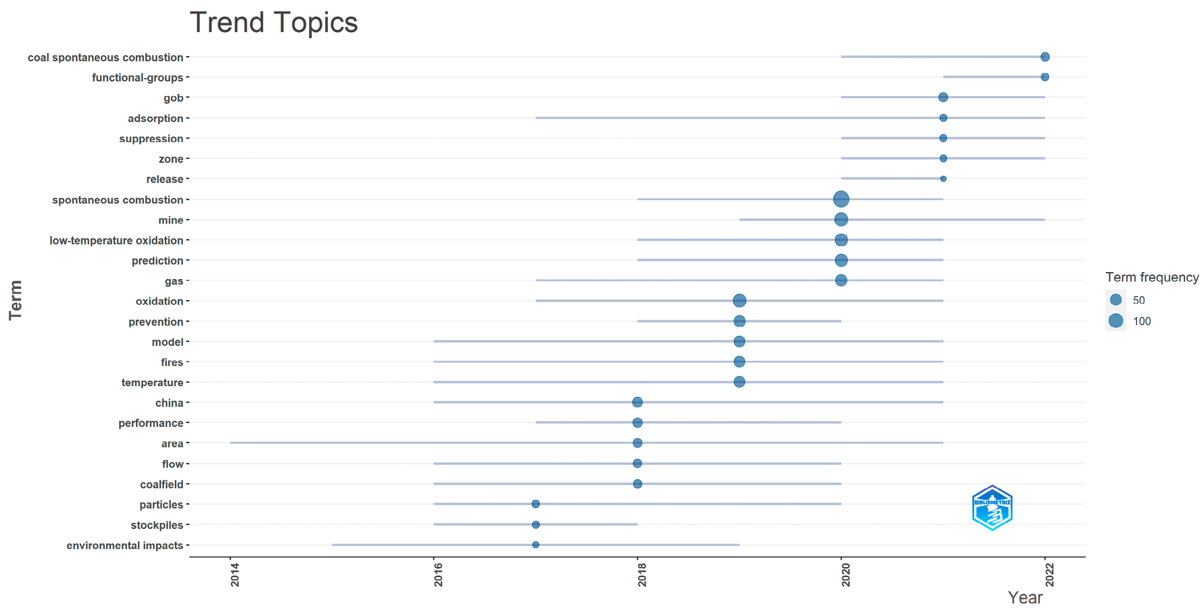

Figure 13. Trend of the topics.

4. Discussion

The field of mine fire prevention and control has garnered the attention of numerous scholars. However, there is a scarcity of review studies that comprehensively analyze the field in a quantitative manner. The objective of this study is to systematically and quantitatively evaluate the articles in the field of mine fire prevention and control, using the Web of Science core database as the basis. This study unveils data from numerous scholars and institutions that have contributed to the scientific advancement in the field of mine fire prevention and control from 2010 to 2022.

Firstly, we analyzed the count of articles issued over the years and observed a relatively stable growth rate in the number of articles related to mine fire prevention and control during the first five years (2010–2014). The growth rate significantly increased in 2015 with a remarkable 71% surge. Approximately 87% of the articles were published between 2015 and 2022, implying that research in the field of mine fire prevention and control has garnered significant attention since 2015.

Secondly, we evaluated the influence of journals and highly cited articles. The total number of articles published in journals within the field of mine fire prevention and control is limited, with over 80% of the journals publishing three or fewer articles. Among these, the journal titled *Combustion Science and Technology* has the highest number of articles in the field, counting 60 articles, but its influence is not significant. On the contrary, *Fuel* is the most influential journal in the field of mine fire prevention and control, receiving 1888 citations and possessing an H-index of 26. And the finding that articles with high local citation coefficients may not possess a greater number of global citations suggests that mine fire prevention and control is also of interest to other disciplines. Moreover, we categorized the highly cited papers into three main research directions: the development and enhancement of mine fire prevention and extinguishing material, the study of mine fire processes and mechanisms, and the assessment and prediction of mine fires.

Thirdly, we conducted an analysis of the collaboration between various countries, institutions, and authors in the field of mine fire prevention and control. China dominates the field of mine fire prevention and control, contributing to 60% of the total publications. The top 10 institutions with the highest number of published papers are all located in China. Moreover, China leads in national collaborations, which is followed by Australia and the United States. These findings emphasize China's prominent role and active involvement in the field of mine fire prevention and control. A total of 3159 authors have published articles in the field of mine fire prevention and control, with 2500 authors contributing to only a single paper. Hu XM, the most cited author in the field of mine fire prevention and control, is affiliated with the largest research cluster in this field. The research cluster primarily explores fire prevention and extinguishing materials, as well as monitoring and prediction techniques for spontaneous coal combustion. Wang DM, the earliest published author in the field, has the second largest research cluster. Additionally, Deng J, the most published author in the field of mine fire prevention and control, has the third largest research cluster.

Finally, we analyzed research themes and hotspots. The present research themes can be categorized into four main areas through keyword clustering: "mine fire prevention and control technologies", "mine fire occurrence mechanisms", "prediction and simulation of mine fires", and "mine fire monitoring and detection". Throughout a span of 12 years (2010–2022), 25 prominent themes have altered, demonstrating the evolving research frontiers within this field. The current stage of research in the field of mine fire prevention and control has achieved significant advancement, and the mechanism of mine fire has been basically determined. While mine fire prediction technology is moving towards standardization, the specific standards have not yet been clearly defined. The magnetic and natural potential methods have been applied in mine fire prediction technology, but the research on the corresponding mine fire monitoring and detection technology is limited due to the large differences in the geographical environment of different mines. Additionally, the theory study of spontaneous combustion and its underlying mechanisms may represent a potential focus for future research.

5. Conclusions

With the increasing attention on the field of mine fire prevention and control in recent years, a systematic and comprehensive analysis of the field, using a bibliometric analysis, can yield valuable insights for future research. This research provides a new cognitive perspective on the progress of technical and theoretical work on mine fire prevention. This paper aims to provide a comprehensive and in-depth understanding of the research on mine fire prevention and control, employing a bibliometric approach and analyzing 1082 papers obtained from the Web of Science Core Collection. This paper identifies and discusses publication trends, analyzes key characteristics of publications and authors using bibliometric methods, and examines the research on mine fire prevention and control from the perspectives of countries, institutions, and authors. Additionally, this paper presents co-authorship networks of countries, co-citation networks of authors and journals, along with a detailed analysis. Furthermore, this study identifies four major topic clusters and further analyzes the research framework by examining keyword trends in the field of mine fire prevention and control. The evolution of research frontiers is also illustrated through the changes in keywords and themes over time. Despite the interesting findings obtained from this study, it is essential to acknowledge its limitations. Firstly, the bibliometric maps generated by the keyword network analysis provide only limited information on the data; the titles and abstracts should also be fully explored. Secondly, the absence of a standardized evaluation framework for a bibliometric analysis introduces potential subjectivity when using diverse analysis methods.

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