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Analysis of the Current Status and Hot Technologies of Coal Spontaneous Combustion Warning

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Abstract: Coal spontaneous combustion disasters are one of the most serious types of mine disasters in China at present, posing a huge threat to underground personal safety and coal production operations. In order to prevent and control coal spontaneous combustion hazards and construct an efficient early warning system, this paper presents a review of coal spontaneous combustion early warning based on the Web of Science database search of 583 papers related to coal spontaneous combustion early warning collected from 2002 to 2021, using VOSviewer visualization software. The number of publications and partnerships at the author, institution and country levels are obtained, and the research hotspots in the field of coal spontaneous combustion warning are obtained based on keyword co-occurrence and clustering. The results show that the research results of scholars with a high publication volume have significant influence in the field of coal spontaneous combustion warning and prevention and control, and a more mature camp has been formed among the research authors; a more stable core group of institutions has been formed in the field of coal spontaneous combustion warning; most of the national publications are concentrated in mineral resource-mining countries; the analysis of hot keywords shows that "sign gas warning" and "warning models and technologies" are the key contents of this field. The analysis of hot keywords shows that "sign gas early warning" and "early warning model and technology" are the key contents of this field. The research content of this paper is helpful for researchers to find the latest information on the current research and trends in the field of spontaneous combustion prevention and coal seam monitoring.

Keywords: coal spontaneous combustion warning; marker gas; warning model; VOSviewer

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Citation: Wang, F.; Ji, Z.; Wang, H.; Chen, Y.; Wang, T.; Tao, R.; Su, C.; Niu, G. Analysis of the Current Status and Hot Technologies of Coal Spontaneous Combustion Warning. *Processes* **2023**, *11*, 2480. https://doi.org/10.3390/pr11082480

Academic Editors: Feng Du, Aitao Zhou and Bo Li

Received: 29 July 2023
Revised: 12 August 2023
Accepted: 16 August 2023
Published: 18 August 2023

1. Introduction

1.1. Coal Spontaneous Combustion Hazards and the Need for Early Warning

Energy is an important part of the national economy, which is related to the development of the national economy. China is rich in coal resource reserves and ranks first in the world in coal resource reserves; behind the high reserves, China is also a country with a high incidence of major coal mine accidents. In recent years, with the development of scientific and technological progress and disaster warning systems, the number and severity of coal mine disasters have been decreasing, but coal spontaneous combustion is still a serious threat to the safe mining of coal. The spontaneous combustion of coal is one of the five major disasters in mines. The spontaneous combustion of coal not only generates toxic and harmful gases and easily causes gas, coal dust and other explosive accidents, but also seriously threatens the safe mining of mines, causing serious casualties and significant economic losses. According to statistics, there are 4108 coal mines in China, with a production capacity of 4303×10^9 Mg, of which 852 coal mines are mining coal seams prone to spontaneous combustion, with a production capacity of 1631 $\times$ 10^9 Mg; and 1540 coal mines are mining spontaneous combustion seams, with a production capacity of 1542 $\times$ 10^9 Mg. The proportion of coal mines mining easy spontaneous combustion and spontaneous combustion seams is 58.2% and the production capacity is 73.7% [1], which shows that the problem of spontaneous combustion of coal seriously affects the safety of coal mining. In recent years, coal spontaneous combustion accidents have occurred frequently. On 7 December 2018, the spontaneous combustion pyrolysis gas explosion of coal left in the mining area of Tang Yang coal mine of Shandong Yulong Mining Group killed three people and injured three others [2]; on 16 December 2015, the spontaneous combustion of coal in the coal mine of Xiangyang District, Hegang City, HeiLongjiang province caused a gas explosion that killed 19 people [3]. This series of catastrophic events shows that the situation of coal spontaneous combustion disaster prevention and control is still serious. And in recent years, as China's shallow coal resources tend to be mined out, coal mining is gradually developing in the direction of deep mining, thus leading to the increasing complexity of coal spontaneous combustion disaster management; therefore, the construction of an efficient coal spontaneous combustion warning system has been the key to preventing and controlling coal spontaneous combustion in mines.

Experts and scholars have made great contributions to the study of the coal spontaneous combustion early warning system and provided abundant guiding theories for the establishment of the system. Guo et al. [4] combined experimental data and numerical simulation to reconstruct the data curve and established an early warning model for coal spontaneous combustion. Yue et al. [5] used the self-designed coal spontaneous combustion experimental platform to simulate the self-heating and oxidation heating of processed raw coal, and finally established a six-level warning system of "gray, blue, yellow, orange, red, and black" to quantitatively classify the risk of coal spontaneous combustion and effectively prevent and control underground coal fire disasters. Shu et al. [6] established a coal spontaneous combustion grading warning prediction prevention and control system, which realized the dynamic grading identification of coal fire disaster. Xie et al. [7] established a mine fire accident early warning prediction system based on the comprehensive consideration of various functions such as monitoring, alarm, feedback, and linkage. Lei [8] made targeted improvements to the shortcomings of the currently adopted early warning system and proposed a new fire warning scheme, which realized accurate and timely monitoring of underground fires and provided a guarantee for rapid elimination of fire hazards. Tan [9] et al. obtained the relationship between temperature and maker gas during coal warming based on the programmed warming method, and used it as an early warning reference for coal spontaneous combustion fires. Zhong [10] et al. reviewed the principle of coal spontaneous combustion monitoring and early warning technology and the current status of research and application from two aspects of coal spontaneous combustion precursor information monitoring technology and prediction forecasting methods. Ren et al. [11] established a novel early warning indicator for the marker gas produced during coal spontaneous combustion. Wen H. et al. [12] used the gas index to judge the development trend and initial characteristic temperature point of coal spontaneous combustion, and put forward a multi-index comprehensive early warning method based on the comprehensive index of Graham (G), carbon monoxide/carbon dioxide and 100$\times$ (ethylene/carbon monoxide). Graham (G) is mostly calculated by the increase in carbon monoxide concentration and the decrease in oxygen concentration in the process of coal oxidation. Under normal circumstances, its value is less than 0.5%. If the value continues to rise and exceeds 0.5%, it indicates that self-heating occurs in the mine, and active measures should be taken to prevent disasters. When it exceeds 1%, it indicates that the spontaneous combustion of coal has occurred in the coal mine, and measures should be taken to prevent the expansion of disasters. Wang K. et al. [13] divided the coal oxidation process into a slow oxidation stage, rapid oxidation stage, and accelerated oxidation stage by critical temperature and dry cracking temperature. A three-level early warning index for quantitative prediction of coal spontaneous combustion is proposed. Zhou et al. [14] obtained the change curve of the volume fraction of the index gas of low, medium and high metamorphic degree through the temperature programmed control experiment, and then used the Logistic function to fit the volume fraction of the index gas with the temperature to obtain the mathematical model of the index gas and temperature of different metamorphic degree, determined the inflection point temperature, and finally combined with the initial temperature of the index gas to divide the risk level of coal spontaneous combustion. According to the experimental data of low-temperature oxidation, Guo et al. [15] established a mathematical model between coal temperature and carbon monoxide concentration. Taking oxygen, carbon dioxide and ethanol as independent variables, the carbon monoxide concentration was calculated by the GA-SVR model, and a set of prediction model of coal body temperature was established. Wu et al. [16] established a mathematical prediction model of carbon monoxide concentration in a return air corner of a working face under normal operating conditions. Then, based on the carbon monoxide formation rate of coal oxidation at room temperature and critical temperature, the carbon monoxide safety prediction and spontaneous combustion warning concentration were calculated, and a new index of coal spontaneous combustion warning was established.

1.2. Knowledge Graph Development

At present, coal spontaneous combustion early warning has become a popular research topic; the research content of coal spontaneous combustion early warning is extensive and diverse, and the research hotspots are in continuous evolution; the research network of domestic and foreign scholars in the direction of coal spontaneous combustion early warning is concentrated, and there are few frontier branches; the research results lack systematic correlation and integration; the coal spontaneous combustion early warning methods still need to be improved; and there is a lack of comprehensive research on the application of coal spontaneous combustion early warning. The rise of knowledge graph visualization technology provides a new direction to better understand the research hotspots and research frontiers in the field of coal spontaneous combustion early warning. Shao et al. [17] used CiteSpace and VOSviewer for coal hole visualization. Hong et al. [18] demonstrated the origin and knowledge base and basic and frontier disciplines of international coal safety management research through knowledge mapping visualization. Hong et al. [19] used CiteSpace to demonstrate the current status of research in the field of coal and gas protrusion and predicted the future development trend. Liu et al. [20] reviewed and analyzed the research progress of spontaneous combustion hazard using CiteSpace and VOSviewer. Wang et al. [21] conducted a research hotspot of mine fires based on CiteSpace and development trends were analyzed and studied. Jamroz D [22] applied visualization technology to identify coal types and determine the possibility of significant differences among different coal types. Yang et al. [23] used Citespace to conduct a bibliometric analysis of coal spontaneous combustion scientific publications worldwide, showing the characteristics and research trends of coal spontaneous combustion databases.

Through the above analysis, a large number of scholars have conducted theoretical analysis, numerical simulations and field experimental research on coal spontaneous combustion early warning. However, due to the diversity of research contents, the research results and research directions in this field still cannot be accurately controlled. In this paper, we use the Web of Science core database as the data source to conduct statistical analysis and data mining of coal spontaneous combustion early warning research literature from 2002 to 2021; track the distribution characteristics of the literature volume, research subjects and hot fronts; and draw a knowledge map to reveal the trajectory, characteristics and laws of coal spontaneous combustion early warning research in order to provide reference and information on the knowledge framework, dynamic changes and development trends in the field of coal spontaneous combustion early warning.

2. Data Sources and Research Methods

2.1. Data Sources

In this paper, Web of Science (core collection) is selected as the data source, which has been accepted by many scholars as the world's largest comprehensive digital literature resource database covering the largest number of disciplines [24] and contains more than 12,000 authoritative and high-impact academic journals in various research fields such as natural sciences, engineering and technology [25,26], and is considered the most suitable database for bibliometric analysis. In this paper, we use the search engine of WoS with the search formula TS = (coal spontaneous combustion warning) OR TS = (coal spontaneous combustion prediction) OR TS = (coal spontaneous combustion iconic gas) OR TS = (coal spontaneous combustion index) AND PY = (2002–2021). A total of 583 papers were searched.

2.2. Research Methodology

VOSviewer is a mainstream visual analytics tool for knowledge graphs, a visual analytics software developed by Dr. NeesJan van Eck and Prof. Ludo Waltman at the Center for Science and Technology (CWTS) of Leiden University [27,28], which uses a probabilistic approach to data normalization to provide easy and graphically beautiful production of web knowledge graphs. In this paper, 583 valid documents in the field of coal spontaneous combustion early warning research were retrieved and exported in tab-delimited file format (the records contain full records and references), and VOSviewer (version 1.16) was used to analyze the distribution characteristics of the literature carriers and research subjects as well as hot fronts through cooperative network topology and keyword co-occurrence analysis, and present them in a visual form. It is intended to help researchers accurately grasp the main lines of research, recognize the knowledge structure and distribution characteristics, and gain insight into research hotspots.

3. Analysis of Collaboration Characteristics

3.1. Author Co-Authorship Analysis

An analysis of the literature authors in the field of coal spontaneous combustion warning reveals the representative scholars and core authors in the field. According to Price, a leading American scientometrician [29], half of the papers on the same research topic are authored by a group of highly productive authors who are numerically equal to the square root of the total number of authors (Equation (1)).

$$\sum_{m+1}^{I} n(x) = \sqrt{N} \tag{1}$$

where $n(x)$ denotes the number of authors who have authored a paper, $I = n_{max}$ denotes the number of papers by the most productive authors in the field, and N is the total number of authors.

The VOSviewer statistics show that $n_{max} = 32$, $N = 1802$. The minimum number of core author publications m in the field of coal spontaneous combustion warning is represented by Equation (2).

$$\mathrm{m} = 0.749 \times \sqrt{n_{max}} = 0.749 \times \sqrt{32} = 4.24 \tag{2}$$

Therefore, the authors with more than 5 publications (including 5) were positioned as the core authors in this field, and the core authors were counted as 53, with a total of 421 publications, accounting for 72.2% of the total publications, which exceeded the threshold of 50% proposed by price, and therefore, the core author group in the field of coal spontaneous combustion early warning research was considered to have emerged.

The core group of authors in the field of coal spontaneous combustion early warning is shown in Figure 1. As shown in Figure 1, the size of the node represents the amount of the author's posting, the color of the node represents different cooperative groups, and the thickness of the connection between the nodes represents the strength of the cooperative relationship. Throughout the cooperation group, there was a red camp represented by Liang Y.T., Liu H.W., Ren T., Wang J.F., Wu J.M., Zhang J. and Zhang Y.L.; a green camp represented by Guo J., Wang K., Wang W.F., Wen H., Zhai X.W. and Zhang D.; a blue camp represented by Deng J., Li B., Ma L., Shu Chi-Min, Wang C.P. and Xiao Y.; a red camp represented by Cai J.W., Hu X.C., Song W.X., Xu Q., Yang S.Q., Cai J.W., Hu X.C., Song W.X., Yu Q. and Zhang Y.L.; and a yellow camp represented by Xu Q., Yang S.Q. and Zhou B.Z. On the whole, international collaborative relationships in the field of coal spontaneous combustion warning are fragmented, the connectivity of the collaborative network is not high and the characteristics of small-scale collaboration among authors are more obvious. Specifically, the collaboration among emerging and highly productive authors is obvious and closer, concentrated among Deng J., Wen H. and Zhang Y., with a high degree of collaboration and close cooperative relationships. In contrast, several other subnetworks have smaller authors and limited mutual collaborative relationships among authors. In addition, the subnetworks are less connected and more independent from each other.

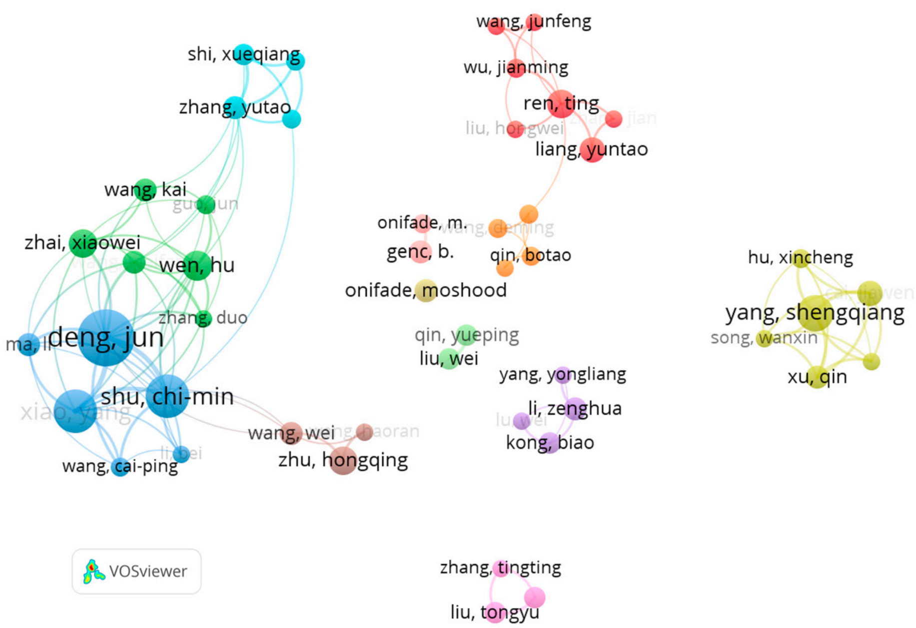

Figure 1. Collaborative group of core authors in the field of coal spontaneous combustion warning.

The top 10 most prolific authors with more than 5 publications in this field are shown in Table 1. Analyzed in terms of publication volume, the top three authors are Deng J., Xiao Y. and Xu Q.M. (Taiwanese name: Shu Chi-Min), with publication volumes of 32, 21 and 21, respectively. Deng J. and Xiao Y. work at Xian Univ. Sci. & Technol., and Xu Q.M. works at Yunlin Univ. Sci. & Technol. in Taiwan, and the three scholars have had several collaborative experiences. From the analysis of their published papers, the three scholars are more concerned with the research and application of coal fire disaster prevention and control theories and technologies, such as the analysis of coal gangue spontaneous combustion characteristics by thermogravimetric-Fourier infrared spectroscopy, the study of oxidation thermodynamic parameters of poor coal, and the discussion of the mechanism of coal spontaneous combustion resistance and its application technology [30–32]. At the same time, from the level of authors, the Citations index of these three authors is basically consistent with the ranking of the number of articles. It can be seen that both the number and the level of academic output are in the forefront. They were followed by Prof. Yang S.Q. from China Univ. Min. & Technol. and Wen H. from Xian Univ. Sci. & Technol. with 16 and 12 publications, respectively. These two scholars have paid more attention to the disaster-causing mechanism of coal spontaneous combustion and prediction and prevention and control technology, such as exploring the disaster-causing mechanism of gas and spontaneous combustion composite in high gas-prone coal seams [33], the graded warning method of coal natural fire and studying the preferred index for early prediction of spontaneous combustion in high gas coal seams [34–36]. All of the above scholars have been cited more than 13 times/article, indicating that the research results of these scholars have significant influence in the field of coal spontaneous combustion warning and prevention and control.

Table 1. Information statistics of the top 10 most prolific authors.

Rank	Author	Documents	Citations	Avg. Citations	Total Link Strength
1	J. Deng	32	527	16.47	72
2	Chi-Min Shu	21	347	16.52	50
3	Y. Xiao	21	417	19.86	53
4	S.Q. Yang	16	280	17.50	33
5	H. Wen	12	167	13.92	27
6	T. Ren	11	220	20.00	18
7	X.W. Zhai	11	92	8.36	21
8	H.Q. Zhu	11	137	12.45	9
9	J.W. Cai	9	139	15.44	28
10	Y.T. Lian	9	245	27.22	8

3.2. Analysis of Institutional Cooperation

The analysis of the collaborating organizations in coal spontaneous combustion early warning research makes it possible to clarify information about the most productive organizations in the field and how they cooperate with each other. Globally, there are 464 institutions involved in coal spontaneous combustion early warning research and published papers, among which, there are 36 institutions with more than five publications, and the top 10 research institutions with the greatest number of papers published in this field shown in Table 2. In Table 2, 90% of the organizations are from China, which is mainly due to the fact that China is one of the world's leading countries in mining mineral resources. In order to meet the national requirements of building intelligent fire monitoring systems for coal mines and to guarantee the safe mining of coal mines and the effective implementation of coal spontaneous combustion prevention, the organizations are conducting more in-depth research on coal spontaneous combustion warning. Three institutions, China Univ. Min. & Technol., Xian Univ. Sci. & Technol. and China Univ. Min. & Technol. Beijing, ranked as the top three in terms of number of publications, with 128, 71 and 29, respectively. In terms of average citations per article, China Univ. Min. & Technol. topped the list with 19.05 citations per article, while Natl. Yunlin Univ. Sci. & Technol., Univ. Witwatersrand and Shaanxi Key Lab Prevent & Control Coal Fire ranked 2nd to 4th with 18.52 citations per article, 18.39 citations per article and 18.25 citations per article, respectively. Natl. Yunlin Univ. Sci. & Technol., Univ. Witwatersrand and Shaanxi Key Lab Prevent & Control Coal Fire were ranked 2nd to 4th with 18.52, 18.39 and 18.25 times/article, respectively. China Univ. Min. & Technol., Xian Univ. Sci. & Technol., China Univ. Min. & Technol. (Beijing) are both domestic public comprehensive universities. Natl Yunlin Univ. Sci. & Technol. is a national university of science and technology established by the Taiwan government. Univ. Witwatersrand is a comprehensive public university, formerly known as the South African Mining School, which was founded in 1896 and is a famous century-old school in South Africa. It ranks fourth in the domestic university rankings in South Africa and is also a world-class top university. It is a world-class university enjoying an international reputation, with advanced teaching facilities, high-level teachers and high-tech scientific research results. Shaanxi Provincial Key Laboratory of Coal Fire Disaster Prevention and Control was approved by Shaanxi Provincial Science and Technology Department in October 2016. Facing the major needs of fire prevention and control in coal resources and their exploitation and utilization process, the key laboratory mainly carries out research work in the following three directions, with the goal of solving the formation mechanism of coal fire and its induced disasters, identification and early warning, prevention and control, and other key issues: (1) the dynamic basis of coal fire disaster formation; (2) identification and early warning of coal fire hazards; (3) coal fire disaster prevention and control theory and technology.

Table 2. Information statistics of the top 10 high-productivity institutions.

Rank	Organization	Country	Documents	Citations	Total Link Strength
1	China Univ. Min. & Technol.	China	128	2439	66
2	Xian Univ. Sci. & Technol.	China	71	929	49
3	China Univ. Min. & Technol. Beijing	China	29	244	15
4	Shandong Univ. Sci. & Technol.	China	27	409	17
5	Liaoning Tech. Univ.	China	26	215	10
6	Natl. Yunlin Univ. Sci. & Technol.	China	21	389	30
7	Henan Polytech. Univ.	China	20	316	24
8	Taiyuan Univ. Technol.	China	18	183	10
9	Univ. Witwatersrand	South Africa	18	331	11
10	Shaanxi Key Lab Prevent & Control Coal Fire	China	16	292	26

Cooperation among countries is shown in Figure 2. In terms of linkage, China Univ. Min. & Technol. and Chinese Acad. Sci., Key Lab Gas & Fire Control coal mines, State Key Lab Coal Resources and Tsinghua Univ., Univ. Alberta form the yellow camp; China Coal Res. Inst., Chongqing Univ., Henan Polytech Univ., Hunan Univ. Sci. & Technol., North China Inst. Sci. & Technol., Univ. Queensland and Univ. Sci. & Technol. Beijing are in the blue camp; Ccteg Shenyang Res. Inst., Dalian Univ. Technol., Taiyuan Univ. Technol., Univ. Sci. & Technol. China, Univ. Wollongong and Xian Univ. Sci. & Technol. Xust form the red camp. In general, a more stable and mature core group of institutions has been formed in the field of coal spontaneous combustion warning, and the limited cooperation is often due to various factors such as research area, research direction, working mode and geographical location.

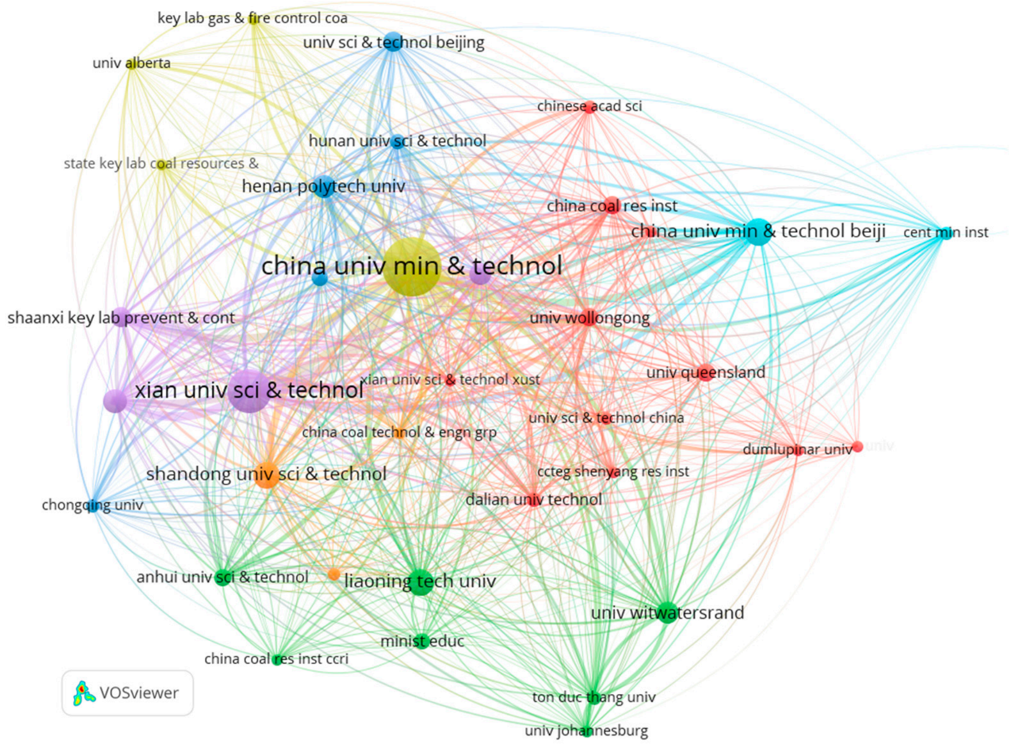

Figure 2. Collaborative clusters of core institutions in the field of coal spontaneous combustion warning.

3.3. Country Cooperation Analysis

Close cooperation between countries is an important factor driving the development of coal spontaneous combustion early warning research, using VOSviewer to map the knowledge of cooperation between cooperating countries. As shown in Figure 3, the size of the node represents the number of documents issued by the country, the color of the node represents different clusters and the thickness of the connection between the nodes indicates the strength of the cooperative relationship between the countries. As many as 45 countries in the world are engaged in coal spontaneous combustion early warning research, and the top 20 high-productivity countries are collated in Figure 4. Overall, studies on coal spontaneous combustion warning are mainly concentrated in mineral resource-producing countries such as China, Australia and India, with China topping the list with 425 articles. These mineral resources mining countries are the core force of the current international research in the field of coal spontaneous combustion warning, to ensure that the safe and stable supply of coal plays a vital role in the economic development of these countries; this is because of the huge demand of coal for the development of the country, and thus promotes the development of the field of coal spontaneous combustion warning. Specifically, three distinct regional cooperation camps have formed from the geographical span: the green camp, with China as the core, such as Australia, Canada, Russia, etc.; the yellow camp, represented by South Africa, South Korea and Vietnam; and the red camp, represented by the USA, Poland, Turkey India, Germany and Japan. In terms of coal reserves, it is in line with the distribution of coal reserves in the Asia-Pacific market and the Europe and America Atlantic market: the coal-exporting countries and regions in the Asia-Pacific coal market mainly include Australia, Indonesia, China, Russia, Vietnam, North Korea, etc.; the coal exporting countries and regions in the Europe and America coal market mainly include Australia, South Africa, Russia, Poland, USA, Canada, Colombia, etc.

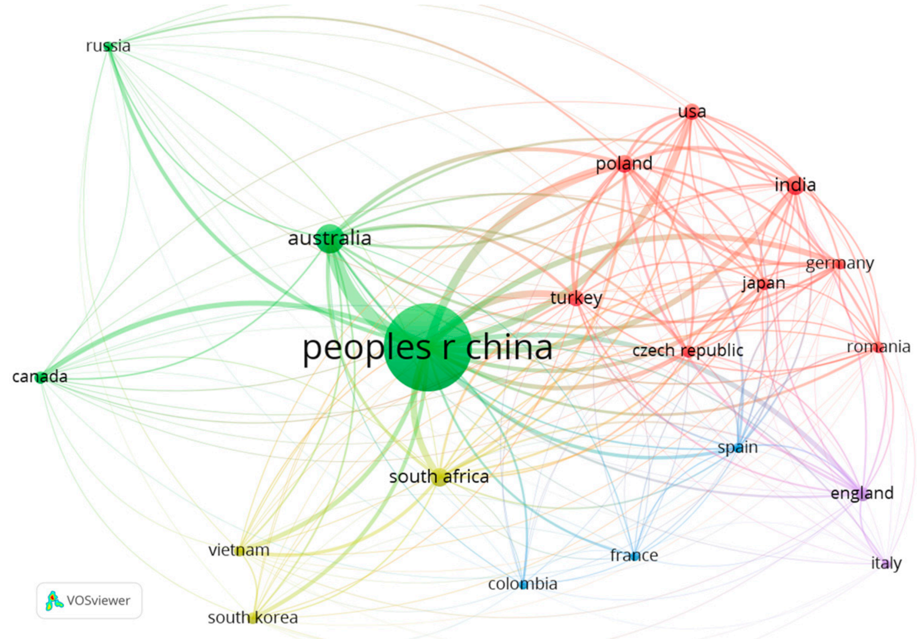

Figure 3. Core national cooperation groups in the field of coal spontaneous combustion early warning. Note: The size of nodes indicates the number of publications, the color of nodes indicates different cooperation groups, and the connecting lines between nodes indicate the cooperation relationship.

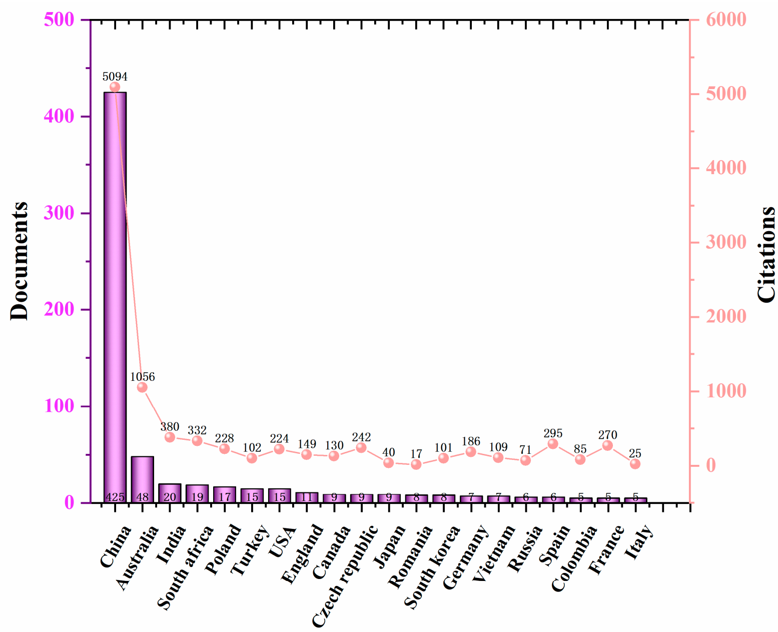

Figure 4. Information on the top 20 high-yielding countries.

4. Analysis of Research Hotspots

The key words in the literature are extracted, and the key words are co-occurred to analyze the hot areas of coal natural warning research. The keywords of the literature reflect the research subject and core of the paper, which is a high summary of the topic of the article, so the keywords can be used to explore the hot topics and cutting-edge trends in the research field. VOSviewer was used to statistically analyze the selected collection of papers, with a total of 2168 keywords, 152 keywords with a co-occurrence frequency greater than 5 and 41 keywords with a co-occurrence frequency greater than 15. Figure 5 shows the co-occurrence network diagram of keywords for coal spontaneous combustion early warning research. It can be seen that the key words "Coal Spontaneous Combustion, Index Gas, Oxygen-Consumption, Goaf, Numerical Simulation" are representative terms in the field of coal spontaneous combustion warning, and they together constitute the cornerstone of the research in the field of coal natural warning. In terms of network layout, these keywords are also key nodes in the field of coal spontaneous combustion warning research, and the nodes around them together form high-impact research themes and hot research directions in the field of coal spontaneous combustion warning. The keyword information of the research in the field of coal spontaneous combustion warning was ranked and analyzed according to the co-occurrence frequency (those with more than five co-occurrence frequencies), and 30 high-frequency important keywords were obtained, as shown in Table 3. The top 10 keywords are coal spontaneous combustion, index gas, oxygen-consumption, goaf, numerical simulation, coal oxidation, ftir, self-ignition characteristics, 3-phasefoam, model predictions. The whole process of coal spontaneous combustion and oxidation is accompanied by the consumption and generation of gas. In recent years, with the development of technology, the detection threshold of sensors has been gradually reduced and the sensitivity of detection has been gradually improved, which provides strong technical support towards determining the signs and status of coal spontaneous combustion by detecting the gas released by partial coal spontaneous combustion. According to Figure 5, "sign gas early warning" and "early warning model and technology" can be summarized as the core hot topics in this field.

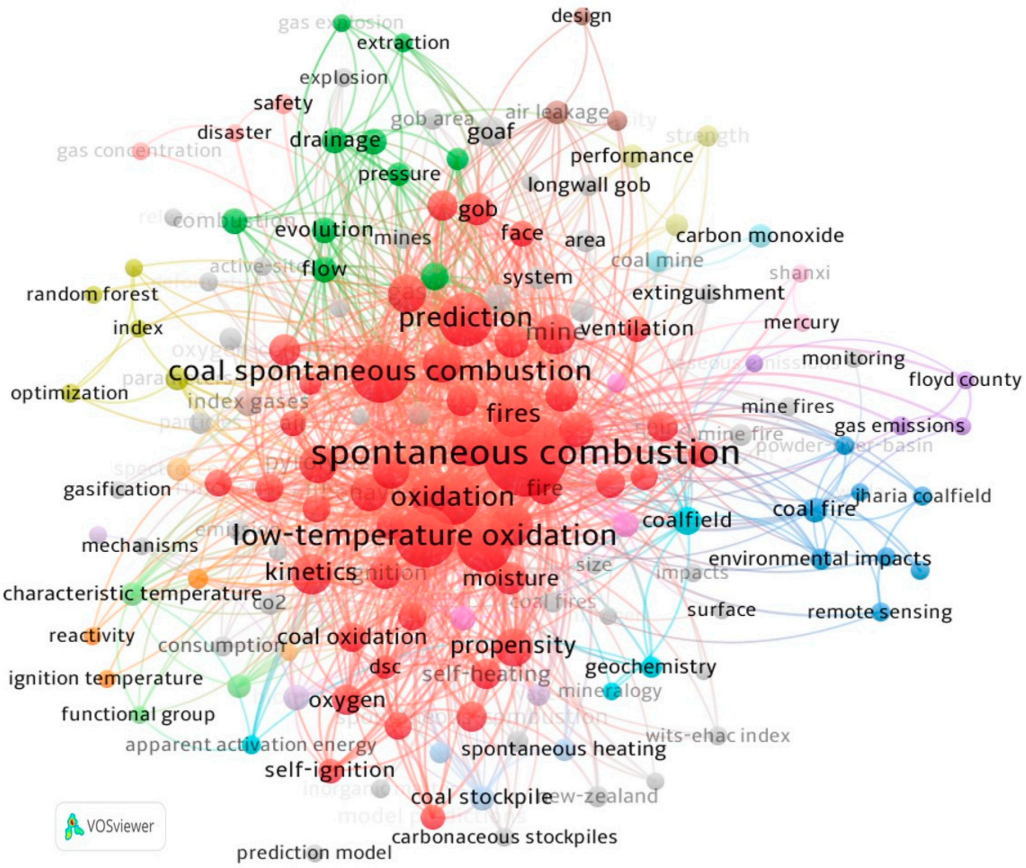

Figure 5. Keyword colinear mapping.

Table 3. Statistics of the first 30 keywords' information.

Serial Number	Keyword	Occurrences	Total Link Strength	Serial Number	Keyword	Occurrences	Total Link Strength
1	Coal spontaneous Combustion	95	411	16	Spectroscopy	10	61
2	Index gas	20	109	17	Porosity	7	42
3	Oxygen-consumption	20	113	18	Apparent activation energy	6	39
4	Goaf	19	66	19	Carbonaceous stockpiles	6	30
5	Numerical simulation	19	88	20	Gas emissions	6	35
6	Coal oxidation	17	88	21	Sorption	6	28
7	Ftir	14	81	22	Critical temperature	5	35
8	Self-ignition characteristics	14	109	23	Crossing point temperature	5	21
9	3-phasefoam	12	91	24	Functional group	5	31
10	Model predictions	11	67	25	Gas concentration	5	27
11	Pore structure	11	63	26	Ignition temperature	5	21
12	Activation energy	10	51	27	Prediction model	5	14
13	Carbon monoxide	10	23	28	Random forest	5	38
14	Characteristic temperature	10	60	29	Support vector machine	5	29
15	Oxygen consumption rate	10	52	30	Temperature oxidation	5	38

4.1. Marker Gas Early Warning Study

In the process of coal oxidation, a series of marker gases such as carbon oxides, alkanes, olefins and alkynes are produced along with the consumption of oxygen. With the increase in temperature, the above-mentioned marker gases will show regular changes consistent with the change in temperature. Therefore, to a certain extent, the use of marker gases can reflect the spontaneous combustion of coal and the state of ignition. Some of these gases, such as CO, are always present throughout the process of self-heating and the heating of coal, and the lowest temperature that can be monitored is only 50 °C with high concentration; organic gases such as olefins and alkynes will only appear at higher coal temperatures, so they are usually used as a sign that the coal has entered the high-temperature stage of spontaneous combustion. In actual production, some gases that are selected as indicators to monitor coal spontaneous combustion can reliably determine the signs and status of natural ignition. Scholars at home and abroad have explored various aspects of the generation patterns and characteristics of the marker gases.

Chen et al. [37] simulated the simulation experiment of self-heating oxidation and the heating of coal samples using a self-developed experimental platform, and provided a basis for the establishment of an early indicator system for spontaneous combustion warning in the goaf. Wen et al. [38] used the traditional programmed warming test method to study the whole process of spontaneous combustion of coal at five kinds of oxygen concentrations: 21%, 17%, 9%, 5% and 3%. Experimental results show that the variation in the marked gas precipitation of the spontaneous combustion process of coal under the concentration of lean oxygen is very complicated. Therefore, in the field application, the impact of the dynamic change of the lean oxygen concentration on the spontaneous combustion process of coal can be combined into the production conditions, which will greatly help fire prevention. Coal spontaneous combustion disasters mainly occur in the oxygen-poor environment under coal mines. The formation law of hydrocarbon gases can accurately reflect the degree of spontaneous combustion of coal. Guo et al. [39] studied the influence of the degree of hypoxia on the formation of hydrocarbon gases by heating experiments of coal spontaneous combustion program under different anoxic environments. Studying the characterization temperature is of great significance for predicting and preventing spontaneous combustion of coal. Deng et al. [40] on the basis of the programmed heating experimental system and the analysis of the original marked gas, established the gas growth rate analysis, and tested the characteristic temperature of the marked gases such as CO and C_2H_4, CO/CO_2 and alkane ratios, in order to determine the characteristic temperature of coal with different degrees of metamorphism and compare it with the gas index analysis. The results show that the temperature corresponding to the extreme value of the heating rate is the characteristic temperature point of spontaneous combustion of coal, and different metamorphic coal has different extreme values. What's more, the growth rate analysis is more concise, effectively identifying key temperature points and reducing uncertainty.

The coal spontaneous combustion process of coal with different metamorphic degrees is quite different, and there is a possible relationship between the parameters of coal spontaneous combustion characteristics and metamorphic degrees. Therefore, the degree of metamorphism during low-temperature oxidation becomes a factor that cannot be ignored. Deng et al. [41] studied the influence of coal metamorphism on gas precipitation and characteristic temperature point variation in the low-temperature oxidation stage by using thermogravimetric programmed temperature system. The results show that the release amount and heat release intensity of CO and CO_2 released from coal by self-thermal oxidation at low temperature increase with the increase in temperature, and the oxygen consumption rate accelerates and increases exponentially. With the deepening of the metamorphic degree of coal samples, the difference among all the above parameters is small and does not change much. Wang et al. [42] studied the characteristic gas release law in the low-temperature oxidation process of long-flame coal for a specific coal seam. The experimental results show that the precipitation amount of CO, C_2H_4 and C_2H_6 gas produced by self-thermal oxidation of coal in specific coal seam increases with the increase in temperature. The trend is exponential growth first. Particle size, as an important factor on the amount of gas precipitation, has an important role. The production rate is negatively correlated with the particle size, and the yield is positively correlated with the temperature. CO and C_2H_4 can be used as important index gases for the prediction of coal spontaneous combustion. The critical temperature of coal spontaneous combustion is judged by the initial appearance temperature of various index gases and the correlation change rate between index gases and oxygen consumption of coal samples. The critical temperature is determined to be 60~80 °C. Deng et al. [43] used a self-built large-scale experimental platform for the large-scale simulation of coal spontaneous combustion. In the experiment, the changes in temperature, gas ratio, oxygen consumption and thermal strength in the whole process of coal rising from room temperature to 452.7 °C and then falling to room temperature were simulated. The ratios of CO_2/CO, CH_4/C_2H_6, C_2H_4/C_2H_6 and C_3H_8/C_2H_6 were analyzed. The results showed that the spontaneous combustion temperature of coal below 70 °C increased slowly with time, and the oxygen consumption and thermal strength increased slowly with temperature and accelerated when the temperature exceeded 100 °C. In anaerobic cooling, the cooling rate decreases with decreasing temperature. The temperature characteristics of coal spontaneous combustion can be better reflected by using a variety of gas ratios. Liang et al. [44] used the commonly used beam tube system, gas chromatography, infrared spectroscopy and other gas detection methods to monitor most of the gas compounds in the process of coal spontaneous combustion, and analyzed the generation order of these gas products. The results show that carbon oxides, hydrogen, methylene and other hydrocarbon gases are produced in the initial self-heating stage of coal spontaneous combustion. Based on the above conclusions, it is a more accurate method to determine the process of coal spontaneous combustion by using different gas ratios.

Among the various characteristic gases of spontaneous combustion of coal, the production of hydrocarbon gases is an important marker, and the production mechanism of hydrocarbons is not the same, but its production and consumption are mostly related to the types of microscopic functional groups. Since the production of hydrocarbons mostly occurs in the high-temperature stage, the monitoring of hydrocarbon marks that the risk of spontaneous combustion of coal has entered a serious harm stage. For example, the production of aromatic hydrocarbons shows a tendency to increase and then decrease [45,46] and release a variety of polycyclic aromatic hydrocarbons at high temperatures. The polycyclic aromatic hydrocarbons produced in raw coal are highly toxic, so monitoring them can reduce personnel hazards. Methane is another common hydrocarbon in the spontaneous combustion of coal, and it is very easy to cause spontaneous combustion. The presence of methane causes significant changes in the spontaneous combustion process of coal, which are often reflected in the content of functional groups. Cai [47] and Zhao [48] analyzed the changes in functional groups in coal under methane action using Fourier transform infrared spectroscopy (FTIR), thereby analyzing the formation of methane and the process changes of spontaneous combustion of coal under a methane atmosphere. Yang et al. [49] studied the role of ethylene and propylene in gas products, and found that small particles of coal can delay the time of coal adsorption to reach the saturation state in the process of adsorption by using two gases, and ethylene exhibits stronger activity in the adsorption process, so the detection of the content of hydrocarbons in the air can effectively warn the early stage of the coal spontaneous combustion process.

4.2. Research on Early Warning Model and Technology

In order to achieve the fine classification of the coal spontaneous combustion process and the accurate early warning of the hidden dangers of spontaneous combustion and to ensure the effective development of the prevention and control of spontaneous combustion of underground coal and the safe mining of coal resources, Guo et al. [4] reconstructed the data curve by combining experimental data and numerical simulations, and established an early warning model of spontaneous combustion of coal. Yue et al. [5] treated the fresh raw coal mined from the working surface and conducted a large-scale experiment of kilogram size in the laboratory, and used the self-designed coal spontaneous combustion experimental platform to simulate the self-heating oxidation and heating up. In the experiment, the gas and temperature indicators are collected and the curve fits of the stages of spontaneous combustion of coal are divided, and the characteristics of each stage are analyzed. After screening, CO, O_2, C_2H_4 and C_2H_6 are selected as the main application indicators, supplemented by φ (CO)/φ (O_2) and φ (C_2H_4)/φ (C_2H_6) as auxiliary analysis standards. According to the size of each index, the spontaneous combustion of coal is predicted, and a six-level early warning system of "gray, blue, yellow, orange, red and black" is established to quantitatively divide the risk of spontaneous combustion of coal, and effectively prevent and control underground coal fire disasters. Shu et al. [6] monitored the characteristics of the spontaneous combustion stage of coal through laboratory coal spontaneous combustion and ignition tests for coal samples from the western region. The characteristic gas reference standards with CO, O_2, Δφ (CO)/Δφ (O_2), C_2H_4 and C_2H_6 as the indicators were determined, and a coal spontaneous combustion grading early warning prediction and prevention and control system was established. Among the five indicators, CO, O_2 and Δφ(CO)/Δφ(O_2) have a good effect on the prediction of coal spontaneous combustion hazards, thus realizing the dynamic classification identification of coal fire disasters.

In addition, many scholars have established a series of fire hazard assessment methods based on the temperature characteristics and gas characteristics of the coal spontaneous combustion process, mainly including the fire coefficient R-2 [50], electromagnetic radiation (EMR) [51], PSO-SVR model [52], RF model [53], R/S analysis [54], and carbon monoxide generation rate (SCOGR) [55]. These methods were analyzed for a large number of data in the process of spontaneous combustion and heating of coal, extracted the temperature change law, used big data calculation methods or fitted the heating curve, or captured the physical parameters with landmark changes, and finally obtained an accurate, reliable and stable coal spontaneous combustion risk assessment method.

In addition, scholars [56–59] analyzed the movement law of gas in the goaf, predicted the spontaneous combustion of coal combined with the change of underground gas flow, and established a related model. The prediction of coal spontaneous combustion from the perspective of gas release mainly relies on the change in the stress of the underground coal seam, leading to the change in the pore structure, leading to an increase in air leakage; the channel of coal–oxygen binding is expanded, and oxygen is more likely to enter the depth of the coal body through these gaps, so the coal–oxygen composite reaction occurs internally. So far, a variety of means to predict the spontaneous combustion of underground coal have made great development and progress in both the theoretical stage and the application stage. Generally, in the field application, the characteristic gas early warning is the mainstay, and the temperature change of the coal body is assisted by other monitoring signals for real-time monitoring, which greatly reduces the disaster hazard of spontaneous combustion of coal, improves the safety and quality of underground operators and greatly reduces the economic losses in the mining process.

In the field of coal seam monitoring, Martirosyan, A.V. [60], in response to the high implementation cost of coal mine monitoring systems, proposed to consider the prototype of a real-time monitoring system for toxic and combustible gas concentrations that has been developed, triggering a response mechanism when concentrations exceed prescribed limits. Kazanin O. I. [61] analyzed the methane emission process of long wall panels through numerical simulation and proposed to adjust the degassing parameters and change the distance between ventilation crosscuts to improve the methane control of long wall panels. Sidorenko A.A. [62] made a proposal to achieve the highest possible level of coal production.

5. Conclusions

In this paper, 583 valid documents collected by Web of Science (core collection) are selected, and VOSviewer (version 1.16) is used to analyze the distribution characteristics of literature carriers, research subjects and hot spot frontiers through cooperative network topology and keyword co-occurrence analysis, and systematically and comprehensively analyze the evolution process of coal spontaneous combustion early warning research, and draw the following conclusions:

(1) The research authors have formed a fixed research cluster, and the degree of cooperation between the clusters is high and the relationship is close, but the connection and cooperation between the clusters is not high, and the international cooperation is relatively lacking. Research institutions have formed the main research force of scientific research institutions such as China Univ. Min. & Technol., Xian Univ. Sci. & Technol., and China Univ. Min. & Technol. Beijing, and have formed a relatively mature core community in the field of coal spontaneous combustion early warning. The number of research results in the field of spontaneous combustion of coal between countries is consistent with the distribution trend of geographical reserves of coal resources, and articles in this field are mostly found in large coal resource-producing countries, and the number of articles published has obvious geographical distribution characteristics.

(2) The research on spontaneous combustion of coal is of great significance to the safe mining of underground mines, and the hot topics of research in this field can be summarized as "flag gas early warning" and "early warning model and technology". In the research field of marker gases, it is often used to detect landmark gases such as carbon monoxide produced during the spontaneous combustion of coal as the judgment criteria for the signs and status of spontaneous combustion of coal, and this method has achieved remarkable results in practical application. Early warning model and technology research is guaranteed research that serves the safe production of underground coal mines, and this research field focuses on the precise early warning of the fine classification and spontaneous combustion hazards of the spontaneous combustion process of coal. The future development of early warning model and technology research will be based on big data, supported by intelligence and informatization, to achieve real-time monitoring of coal body status, early perception of dangerous situations, and timely early warning to ensure production safety. In the future, in the field of coal spontaneous combustion early warning, we should also strengthen information exchange and data exchange between authors, institutions and countries, rely on big data, artificial intelligence, digital twins and other technologies to achieve interdisciplinary integration and development in multiple fields, and further promote the research in the field of coal spontaneous combustion to be precise and intelligent.

(3) The paper provides valuable information to experts involved in the prevention of spontaneous combustion of coal. On the one hand, it helps researchers to reduce the time spent in developing research questions for empirical articles, conducting bibliometric analysis or conducting content analysis for systematic literature reviews. On the other hand, it helps them to seek the latest information on the existing research and trends in the field of coal spontaneous combustion prevention, such as internal coal fire, coal chemical composition, coal pollution scale and type, coal crushing degree, moisture and ash content and coal seam monitoring.

Author Contributions: F.W.: formal analysis, writing—original draft, visualization. Z.J.: methodology, conceptualization, writing—review and editing. H.W.: methodology, conceptualization, writing—review and editing. Y.C.: writing—original draft, visualization. T.W.: formal analysis, visualization. R.T.: investigation. C.S.: investigation. G.N.: investigation. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially sponsored by the National Natural Science Foundation of China (52074156).

Data Availability Statement: The data are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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