A visual knowledge map analysis of mine fire research based on CiteSpace

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Abstract

Mine fire has always been a serious disaster in coal industry; many academic achievements have poured out in the past two decades for solving this problem. In this study, visual analysis was conducted to grasp the hotspots and development trend of mine fire research. Papers that published in 1999–2020 were retrieved as the data basis from Web of Science, and CiteSpace was used to carry out knowledge map analysis. The results shown that number of papers has increased steadily since 2005 and achieved explosive growth since 2014. Deng J is the first published author among many scholars. China, the USA, and Australia are active areas in mine fire research and China University of Mining and Technology ranks first in this field. The highest co-occurrence frequency keyword is “spontaneous combustion.” International Journal of Coal Geology and Fuel provide guidance for mine fire research. Fire prevention technology, low carbon, ecology, and sustainable development are the hot research in recent years. The prevention and control of mine fire from combustion mechanism should be further strengthened.

Keywords Coal fire · CiteSpace · Coal spontaneous combustion · Visual analysis

Introduction

Nearly 90% coal mines in China adopt the well exploitation. The mining depth increase and the complex hydrogeological conditions of coal mines lead to a great threat for the coal mine. Mine fire produces a large number of toxic gases and smoke, which diffuses to the whole mine by air flow through the ventilation network. It is easy to reach the location far from the fire source and to cause wind reversal aggravating the miner’s risk. With the injuries and death increase, mine fire shows a threat to the safety produce. The main methods of fire prevention and control include technical measures for exploitation (Shao et al., 2022) and prevent air leakage, pressure balance for fire extinguishing, preventive grouting, inhibitor injection, inert gas, gel fire prevention, and three-phase foam (Tan et al., 2020a; Duan et al., 2020). The coal fire extinguish is mainly through water, grouting, loess covering, and stripping although the water is loss seriously along the fracture when filling water or grouting (Kong et al., 2017).

So far, a large number of scholars and experts have done a lot of research on mine fire (Ádám et al., 2021; Alipour et al., 2021; Yao et al., 2021; Szkułdarek and Janas, 2021). The research content is wide and diverse; however, the sorting out of present achievements is few. Most of the traditional visualization methods involve explore and interpret the existing data by analysts. It uses people’s vision and knowledge reserve to seek information, which has limitations and omissions inevitably. In the information explosion age, people are no longer satisfied with the traditional visualization method, which only reflects the surface information of data. The present visual analysis method helps us seeking data in high efficiency and evaluating the current research object progress, which discovers the following research direction and new rules.

Knowledge map has widely use in fires. Li. (2016) studies the characteristics and evolution of the structure of safety science by taking the scientific and technological texts accumulate for a long time as the research object. Based on CiteSpace, the
application of FDS software in the field of fire simulation is analyzed. Lin (2020), Fu et al. (2020), and other researchers (He et al., 2019; Cui et al., 2019; Wang et al., 2016) conduct visual analysis on FDS fire simulation, gas explosion, fire numerical simulation, forest fire, and other fields based on CiteSpace software. Jin et al. (2019) uses VOSviewer to catch visual research on building safety. CiteSpace shows the evolution of a knowledge field on a network map and is one of the most popular drawing tools of knowledge map Chen et al. (2015). Therefore, in order to analyze the dynamic, polymorphic, and multi-source data in the field of mine fire, this paper uses CiteSpace software to draw knowledge map from the perspectives of publication distribution, authors, institutions, countries, and keywords, in order to provide valuable information for the academic research and development in this field. The main purpose of this paper is to provide researchers with a clear direction to promote the outstanding problem discovery and solution in the coal mine fire field. Finally, through greater collaboration between institutions and researchers in different countries and regions, resources can be pooled to advance the industry as a whole.

Research method

CiteSpace summarize

CiteSpace is a multi-view information visualization software. The main function is to show the evolution trend and knowledge association of the science frontier through the visualization analysis. CiteSpace transforms the data exported from the WOS database to draw various knowledge maps and display the research field details by node size, network connectivity, and other factors (Liu 2020). This paper uses the visual bibliometric analysis tool CiteSpace 5.8.R3 to process and analyze the data.

Using and debugging

The Time Slicing is to segment the time zone of the data to be analyzed. The analysis time in this paper is set as 1999–2020, and the Time Slicing is 1 year. The Text Processing is used to select the Term extraction location and supplementary selection of common word analysis types. Network configuration area includes Node Types, Links, and Selection Criteria, and the Network types depend on the analysis object. Different nodes generate different types and functions networks. Author, Institution, and Country generate cooperation map. Term and Keyword produce the corresponding network. Cited Reference, Cited Author, and Cited Journal are a co-cited network analysis of guiding papers, authors, and source journals, respectively. Threshold selection includes four algorithms, and they are Top N per slice, Top N% per slice, Threshold Interpolation, and Select Citers.

Pruning parameters and functional areas work for the network Pruning, including PFNET (path finding network) and MST (minimum spanning tree) algorithms. They are used to cut the connections in the network for the improvement of network density and readability. Finally, Visualization is adopted to set up Visualization results, including Cluster View, TimeZone View, and Timeline View.

Database

Based on the research object and characteristics, all the data and information are from the Web of Science core database of ISI, which has the most authoritative data source in the world at present. It has more than 5500 kinds of scientific journals in this database. With the Web of Science Core Collection and the topic of “Mine Fire or Coal Spontaneous Combustion,” 5181 papers are conducted from 1999 to 2020. Three thousand forty-eight papers are obtained by further refining the retrieval results. The data are imported into CiteSpace; then, 1334 papers are visualized through the de-merging and screening functions of the tool.

Data analysis

Number of articles in different periods

The paper quantity is an important parameter to measure the quality in a certain field, which reflects the research results and active degree in a certain subject. By analyzing the papers quantitative characteristic, it judges the social and academic attention degree to this field. This reveals the academic research and development trend (Xue et al., 2020). Figure 1 shows the amount of mine fire published in WOS from 1999 to 2020, presenting an obvious upward trend on the whole. In the initial period (1999–2005), the number of papers published in 1999 is Fig. 1. The possible reason is that due to the poor communication technology at that time, all papers cannot be uploaded. After that, with the rapid development of economy and the popularization of the Internet, the article number published begins to rise slowly. In stable transition period (2005–2014), the annual average number of papers published is about 28. With the increase of coal demand and the coal mining increase, the coal mine accidents are also increasing. The coal safety problem demand prompt solution. So, there is a huge increase in the paper number in this period. The number of published papers increases from 68 in 2014 to 267 in 2020, which lies in booming growth period (2014–2020) (Tan et al., 2019, 2020a, b, c; Zhu et al., 2021e). During this period, the academic community’s understanding of mine fire rises to a new height, and the study of mine fire is still developing vigorously.
Author analysis

Author publication statistics

When analyzing the number of papers published by 682 authors, prolific authors are the analysis focus. Prolific authors are those who publish more papers in a certain field. According to Price’s law, the specific formula is as follows:

\[ M = 0.794 \times \sqrt{N_{\text{max}}} \]  

where \( M \) represents the minimum number of core authors in a certain field and \( N_{\text{max}} \) represents the maximum number of core authors in a certain field. According to Price’ law, the author who has a high number of papers includes Deng J, Shu CM, Qin BT, Wang DM, and Zhu HQ. Deng J has published a large number of papers from 2015 to 2020, making great contributions to the research on mine fire. Deng J mainly engages in the theory and technology research of coal fire disaster prevention and control. In recent years, he has made a series of achievements in scientific issues such as nature of coal spontaneous combustion, characteristic information identification of coal spontaneous combustion, and coal fire disaster prevention, which has published a lot of highly cited papers (Deng et al., 2015, 2016, 2018; Xiao et al., 2018; Deng et al., 2017a, b). Shu CM, from National Yunlin University of Science & Technology, mainly studies the whole process of primary and secondary spontaneous combustion of coal and publishes some valuable papers from 2017 to 2020 (Zhao et al., 2019; Wang et al., 2016; Deng et al., 2017a, b; Liu et al., 2015).

Author cooperation relationship

WOS paper data is imported into CiteSpace, setting the time span to 1999–2020 and time slice to 1 year. “Author” is chosen as “Node Types” analysis content after format transformation.

![Fig. 1 Chronological distribution of mine fire dispatch](image1)

![Fig. 2 Author cooperation relationship map](image2)
Path algorithm conducts keyword frequency analysis for “Pathfinder, Pruning networks, pruning the merged network.” Thus, an author collaboration map of “Nodes = 682,” “Links = 797,” and “Density = 0.0031” is obtained.

In Fig. 2, the author cooperation map of mine fire presents a relatively close distribution on the whole. On the left is a large cluster formed by four groups, Wang DM, Qi GS, Pan RK, and Yan SQ, and on the right, it is a small cluster.

Table 1 Statistics of high-yield institutions’ publications

| Number | Counts | Centrality | Institutions                                      |
|--------|--------|------------|---------------------------------------------------|
| 1      | 283    | 0.09       | China Univ Min & Technol                          |
| 2      | 91     | 0.03       | Xian Univ Sci & Technol                           |
| 3      | 87     | 0.04       | China Univ Min & Technol Beijing                  |
| 4      | 46     | 0.04       | Natl Yunlin Univ Sci & Technol                    |
| 5      | 42     | 0.12       | Henan Polytech Univ                               |
| 6      | 42     | 0.07       | Shandong Univ Sci & Technol                       |
| 7      | 37     | 0.25       | Taiyuan Univ Technol                              |
| 8      | 30     | 0.08       | Liaoning Tech Univ                                |
| 9      | 26     | 0.00       | Shaanxi Key Lab Prevent & Control Coal Fire      |
| 10     | 23     | 0.01       | Univ Queensland                                   |
| 11     | 21     | 0.01       | Hunan Univ Sci & Technol                          |
| 12     | 18     | 0.04       | Monash Univ                                       |
| 13     | 17     | 0.07       | Univ Witwatersrand                                |
| 14     | 17     | 0.00       | Cent Min Inst                                     |
| 15     | 15     | 0.00       | Selcuk Univ                                       |
| 16     | 15     | 0.12       | Anhui Univ Sci & Technol                          |
| 17     | 14     | 0.00       | Indian Sch Mines                                  |
| 18     | 14     | 0.02       | Univ Sci & Technol Beijing                        |
| 19     | 14     | 0.01       | Chinese Acad Sci                                  |
| 20     | 13     | 0.01       | Chongqing Univ                                    |
| 21     | 13     | 0.00       | North China Inst Sci & Technol                    |
| 22     | 13     | 0.05       | Minist Educ                                       |
represented by Shu CM (Lu et al., 2019, 2021; Luo et al., 2022; Pan et al., 2020). Wang DM and Qin BT, Dou GL, Li XB, Lu XX, Dong SJ, Shi GQ, Wang YM, Wang Y, Hu C, and Ma LY (Qin et al., 2018; Ma et al., 2017; Zhang et al., 2021, 2019; Yuan et al., 2018; Wen et al., 2020; Sun et al., 2019; Li et al., 2020; Shao et al., 2018; Lee et al., 2020; Yan et al., 2019; Du et al., 2018) are a small team of 10 people. Most of them are from China University of Mining and Technology, Henan Polytechnic University, China University of Mining and Technology (Beijing), Xi’an University of Science and Technology, etc. Represented by China University of Mining and Technology, the internal cooperation among institutions indicates that the mine fire academic research have gradually become mature. Meanwhile, the academic exchanges between authoritative authors play a key role in the research of this field.

In addition, QI GS cooperates with Liang YT, Li JL, and Qi XY frequently. Pan RK is closely associated with Hu DM, Wu MY, Ma JW, and Wang J. Yang SQ has a cooperative relationship with Tang ZQ, Cai JW, and Song WX (Cai et al., 2019; Xu et al., 2019; Song et al., 2019). Shu CM is closely related to four authors, Wang CP, Deng J, Zhao JY, and Zhang YN. This means that there are many scholars studying mine fire in the world, but most of their researches are scattered, and there

Table 2 Statistics of high-yielding country publications

| Number | Counts | Centrality | Country               |
|--------|--------|------------|-----------------------|
| 1      | 678    | 0.25       | People’s Republic of CHINA |
| 2      | 140    | 0.58       | USA                   |
| 3      | 103    | 0.31       | Australia             |
| 4      | 58     | 0.18       | India                 |
| 5      | 46     | 0          | Poland                |
| 6      | 27     | 0.03       | South Korea           |
| 7      | 27     | 0.06       | Canada                |
| 8      | 25     | 0.3        | Spain                 |
| 9      | 24     | 0.17       | South Africa          |
| 10     | 21     | 0.5        | Germany               |
is no large-scale cooperation and exchange behavior. Most of them are organized in the form of small groups of three or four people. Therefore, the large-scale cooperation among authors in the mine fire field research needs to be strengthened. At present, the cooperation between authors is affected by regional, economic, linguistic, and cultural factors or other aspects.

### Authors’ co-citation

Authors’ co-citation analysis refers to the situation where two or more authors are simultaneously cited by other authors’ papers, which obtains the distribution of highly cited authors and understands the research topics in the field. On the micro level, it reveals the interweaving and dependence between some disciplines. On the macro level, it reflects the discipline composition and structural characteristics of the scientific system to a certain extent (Zuo et al., 2021).

“Cited Author” is used as “Node Types,” and path algorithm is set as “Pathfinder” for Author analysis. Thus, an author co-cited network map of “Nodes = 880,” “Links = 3090,” and “Density (Density) = 0.0051” is obtained, as shown in Fig. 3. It can be seen from the map that some co-cited authors cooperate closely. Deng J, Wang HH, Stracher GB, Carras JN, and Song ZY are highly cited authors. In this paper, it is found that Deng J is not only a prolific author, but also a highly cited author. His paper is abundant in quantity and is of good quality as well. Wang HH, from University of Newcastle, mainly studies low temperature oxidation of coal Stracher Glenn B. of the University System of Georgia, who studies coal fires. Carras JN, from Commonwealth Scientific & Industrial Research Organisation (CSIRO), has made outstanding contributions in coal spontaneous combustion and CO₂ injection into coal seam fire prevention and control. Song ZY is from Xi’an University of Science and Technology, and his research focuses on coal field fire, energy, and fuel.

Combine with the analysis of prolific authors, it is found that the number of Chinese authors with high citation frequency on the list is significantly reduced. It indicates that Chinese authors have more paper in the mine fire, but their citation frequency is not proportional. The citation frequency of an author’s paper reflects the author’s status and influence in a certain research field. Therefore, Chinese authors need to make efforts in this regard to maintain a high number paper, ensuring the quality of papers and improving their influence in their research.

![Fig. 5 Comparison of the paper number between China and the USA](image)

![Fig. 6 A network of country cooperation relationship](image)
Research institution analysis

Institution publication statistics

The high-yield institutions with more than 22 publications are selected from 535 research institutions as the main research objects in Table. 1. China University of Mining and Technology from China ranks the first with 283 papers, with 26, 37, 57, 43, and 45 paper distributed in the past 5 years. Wang DM, Kong B, Xin HH, XIA TQ, and others from this institution make significant contributions to the study of mine fire related to three-phase foam, coal spontaneous combustion, gas extraction, and so on. Meanwhile, 9 of the top 22 institutions in the number of publications are from China, they are China Univ Min & Technol, Xian Univ Sci & Technol, China Univ Min & Technol Beijing, Natl Yunlin Univ Sci & Technol, Henan Polytech Univ, Shandong Univ Sci & Technol, Taiyuan Univ Technol, Liaoning Tech Univ, and Shaanxi Key Lab Prevent & Control Coal Fire. It is

| Counts | Centrality | Cited journal                |
|--------|------------|-------------------------------|
| 535    | 0.07       | Int J Coal Geol               |
| 512    | 0.05       | Fuel                          |
| 339    | 0.02       | Sci Total Environ             |
| 286    | 0.05       | Environ Sci Technol           |
| 269    | 0.04       | Science                       |
| 240    | 0.04       | Nature                        |
| 240    | 0.07       | Fuel Process Technol          |
| 223    | 0.03       | J Hazard Mater                |
| 221    | 0.01       | Atmos Environ                 |
| 213    | 0.01       | J Loss Prevent Proc           |
found that Chinese research institutions have conducted extensive research on mine fire, which indicates that Chinese institutions have become effective forces in the mine fire research.

**Institution cooperation relationship**

CiteSpace is used to determine relevant parameters after several debugging and generates a cooperation map of research institutions with 535 nodes and 544 links, as shown in Fig. 4. Each node and its size represent an institution and cooperation frequency; meanwhile, the links between nodes represent the cooperation relationship (Liu et al., 2020a, b). China Univ Min & Technol establishes the largest node and close cooperation with 15 institutions, for example, China Univ Min & Technol Beijing, Henan Polytech Univ, Univ Sci & Technol Beijing, and other institutions. This presents a cooperative network radiating outward from the center of China Univ Min & Technol. In Australia, Univ Queensland, Monash Univ, Curtin Univ, CSIRO Energy CSIRO, and Univ Wollongong work closely. Univ Kentucky, NIOSH, Penn State Univ, Morehead State Univ, and West Virginia Univ have frequent contact in the United States. It is found that the cooperation between institutions is regional, and the cooperation between countries or continents is rare. Figure 4 roughly divides the cooperative relationship into three parts. They are the American cooperative network centered on Univ Kentucky, the Chinese cooperative network centered on China Univ Min & Technol, and the Australian cooperative network centered on Univ Queensland.

### Country analysis

**Country publication statistics**

According to the statistical analysis of the 94 countries publications, price’s law calculation demonstrates that the minimum publication among 11 high-yielding countries is 21, as shown in Table 2 and Fig. 5. China ranks the top with 678 papers, accounting for

### Table 4  Detailed information of highly cited journals

| Abbreviation | Publishing country | Primary classification | Secondary classification | Average IF (2019 – 2021) | Citation frequency (2020-2021) |
|--------------|--------------------|------------------------|--------------------------|--------------------------|-------------------------------|
| *Int J Coal Geol* | the Netherlands | Engineering technology Q2 | Energy and fuels Q2 Geoscience Q1 | 5.051 | 27,351 |
| *Fuel* | the Netherlands | Engineering technology Q2 | Energy and fuels Q2 Engineering: Chemical engineering Q2 | 5.205 | 137,125 |
| *Sci Total Environ* | the Netherlands | Environmental science and ecology Q2 | Environmental science Q2 | 5.584 | 232,429 |
| *Environ Sci Technol* | USA | Environmental science and ecology Q1 | Engineering: Environment Q2 Environmental science Q1 | 7.222 | 361,186 |
| *Science* | USA | Comprehensive Q1 | Comprehensive Q1 | 41.322 | 1,380,869 |
| *Nature* | England | Comprehensive Q1 | Comprehensive Q1 | 42.475 | 1,512,938 |
| *Fuel Process Technol* | the Netherlands | Engineering technology Q2 | Applied chemistry Q2 Energy and fuels Q3 Engineering: Chemical engineering Q2 | 4.482 | 40,911 |
| *J Hazard Mater* | the Netherlands | Environmental science and ecology Q1 | Engineering: environment Q2 Environmental science Q1 | 7.707 | 206,544 |
| *Atmos Environ* | England | Environmental science and ecology Q2 | Environmental science Q3 Meteorology and atmospheric science Q2 | 3.92 | 115,151 |
| *J Loss Prevent Proc* | the Netherlands | Engineering technology Q3 | Engineering: Chemical engineering Q4 | 2.282 | 11,964 |

### Table 5  Listing of high frequency keywords

| Number | Counts | Centrality | Keywords |
|--------|--------|------------|----------|
| 1      | 299    | 0.05       | spontaneous combustion |
| 2      | 191    | 0.05       | coal |
| 3      | 190    | 0.07       | low temperature oxidation |
| 4      | 148    | 0.18       | fire |
| 5      | 136    | 0.07       | oxidation |
| 6      | 93     | 0.01       | mechanism |
| 7      | 83     | 0.01       | temperature |
| 8      | 76     | 0.09       | mine |
| 9      | 76     | 0.03       | kinetics |
| 10     | 69     | 0.10       | model |
| 11     | 68     | 0.05       | pyrolysis |
| 12     | 67     | 0.08       | behavior |
| 13     | 66     | 0.04       | bituminous coal |
| 14     | 63     | 0.19       | prevention |
| 15     | 59     | 0.03       | gas |
| 16     | 56     | 0.07       | emission |
| 17     | 54     | 0.08       | propensity |
50.82%, and the USA ranks second with 140 papers, accounting for 10.49%. From 2 papers in 2008 to 164 papers in 2020, China shows a rapid progress and becomes one of the high-yielding countries in the world. China’s research achievements in the mine fire field and the degree of concern far exceed other countries, which has become the backbone of all countries in this field. The USA has been publishing papers on mine fires since 1999, which is a pioneer in the field. The number of papers, published in 2018, is 15 at most. Other high-yielding countries include Australia, India, Poland, South Korea, Turkey, Canada, and Spain. It is concluded that all high-yielding countries in mine fire are also recognized as big coal producers in the world.

Country cooperation relationship

By using CiteSpace and adjusting parameters, the map of national research cooperation with 94 nodes and 116 links is obtained, as shown in Fig. 6. Nodes and its size represent countries and the cooperation frequency, meanwhile the line between nodes represents cooperation relationship (Xu et al., 2021). The USA has cooperative relations with 10 countries, such as People’s Republic of China, the Netherlands, Peru, Mexico, Canada, and Pakistan. Peoples Republic of China has close cooperation with the USA, North Ireland, and South Korea. Australia has close contact with Pakistan, United Arab Emirates, Germany, and Sweden. As two high-yielding countries, China and Australia carry out independent research, and their cooperation intensity with other countries is much lower than that of the USA. The countries active in mine coal make great contributes to mine coal development, such as the USA, Australia, and India. There are some studies of paste in the USA, Vietnam, and other countries for coal fire prevention, mainly lime, gypsum, and other fire extinguishing slurry (Valiulin et al., 2020).

Journal co-citation analysis

Taking “Cited Journal” as the analysis content and path algorithm as “Pathfinder” for author analysis, a Journal co-citation map of “Nodes = 814,” “Links = 2937,” and “Density = 0.0089” is obtained, shown in Fig. 7. In addition,
“Generate a Narrative” in “Export” is used to obtain an arrangement list of cited journals. The top 10 journals are listed, as shown in Table 3 and Table 4.

In journal co-citation, *Int J Coal Geol*, *Fuel*, *Science of Total Environment*, *Environ Sci Technol.*, *Science*, and *Nature* are frequently cited. *Int J Coal Geol*, *Fuel*, *Fuel Process Technol*, and *J Loss Prevent Proc* belong to engineering journals. *Sci Total Environ*, *Environ Sci Technol*, *J Hazard Mater*, and *Atmos Environ* belong to the environmental science and ecology journals, while *Science* and *Nature* belong to the general journals. Moreover, the ESPR is co-cited in environmental protection, energy conservation, and emission reduction, which is closely related to mine fire research. Its specialty makes it a high co-citation. On the whole, these journals are internationally famous and widely cited, which reflects that these journals are important knowledge supply in mine fire research and also show the importance of these journals in this field.

**Research hotspots analysis**

**Keyword co-occurrence**

Keywords, representing the core and essence life-quintessence of the article, are a high-level summing-up to the article theme, so the keyword analysis examines the research focus of the papers (Zhu et al., 2021a). High frequency keywords are used to ensure the research hot pot in a certain field, and 17 high frequency keywords are obtained through order statistics in mine fire research, which is listed in Table. 5. The top 10

![Keyword cluster analysis map](image)
keywords includes “spontaneous combustion,” “coal,” “low temperature oxidation,” “fire,” “oxidation,” “mechanism,” “temperature,” “mine,” and “kinetics,” “model” (Zhu et al., 2021a, 2021b, 2021c, 2021d).

The WOS data is imported into CiteSpace and formatted transformation, the time span from 1998 to 2020, time slice is 1 year. “Keywords” is set as “Node Types” analysis content, and path algorithm is set as “Pathfinder” for author analysis. Thus, a keyword co-occurrence network map of “Nodes= 528” and “Links = 1853” is obtained, as shown in Fig. 8.

Nodes represent keywords, and the number of nodes represents the keyword number in the paper. The line reflects the relationship between keywords, and the node size represents the keyword frequency. Centrality is one of the criteria to describe the nodes importance, indicating the possibility that a node becomes the “intermediary” of other nodes. The CiteSpace visual interface specializes the high intermediate centrality nodes. When the intermediate centrality is greater than 0.1, a purple circle appears on the outside of the node’s annual ring (Liu et al., 2020a, b).

According to the node radius in the map and the order in the table, the five keywords of “Spontaneous combustion,” “coal,” “low temperature oxidation,” “fire,” and “oxidation” are cited more than 100 times, followed by “mechanism,” “Temperature,” “mine,” “kinetics,” and “Model” are all cited more than 50 times (Wen et al., 2017; Du et al., 2015; Yang et al., 2015; Kim et al., 2016; Wu et al., 2017). According to the analysis results, it is not difficult to see that the high-frequency keywords represent the main problems existing in the research, and generally these problems are also common or difficult to solve in practice. So the research should focus on addressing these major questions.

**Keyword cluster**

Thirty-nine clusters are obtained from 528 keywords extraction, and the main clusters are displayed in Fig. 9. According to #0, #1…… #20 sort, the map covers 21 clusters from #0 to #20, #0 India, #1 model, #2 restoration, #3 thermoplastic powder, #4 moisture, #5 coal, #6 composite inhibitor, #7 vegetable oils, #8 gas, #9 fine particulate matter, #10 product, #11 coal stockpile, #12 mechanical thermal expression, #13 carbon nanotubes, #14 discrimination, #15 coalfield, #16 emergency rescue, #17 forest burned areas, #18 emission, #19 threatened species, #20 foam stability (Jolanta et al., 2017; Qin et al., 2017, 2016; Jo et al., 2015; Lu et al., 2017).

Modularity $Q$ and mean silhouette $S$ are two indicators reflecting the definition of cluster boundary and cluster size. In the map, Modularity $Q=0.8057$ ($Q>0.3$) indicates clear boundaries between research topics and significant field differentiation. Mean silhouette $S=0.91$ ($S>0.7$) with good clustering effect. The labels and related descriptions of each cluster are shown in Table 6 and Table 7.

| Cluster | Keywords                        | Size | Silhouette | Mean year |
|---------|---------------------------------|------|------------|-----------|
| #0      | india                           | 48   | 0.905      | 2010      |
| #1      | model                           | 41   | 0.806      | 2010      |
| #2      | restoration                     | 40   | 0.941      | 2005      |
| #3      | thermoplastic powder            | 30   | 0.975      | 2015      |
| #4      | moisture                        | 29   | 0.929      | 2006      |
| #5      | coal                            | 28   | 0.855      | 2013      |
| #6      | composite inhibitor             | 27   | 0.836      | 2016      |
| #7      | vegetable oils                  | 27   | 0.994      | 2009      |
| #8      | gas                             | 26   | 0.894      | 2011      |
| #9      | fine particulate matter         | 25   | 0.886      | 2016      |
| #10     | product                         | 24   | 0.876      | 2010      |
| #11     | coal stockpile                  | 23   | 0.817      | 2011      |
| #12     | mechanical thermal expression   | 21   | 1.000      | 2009      |
| #13     | carbon nanotubes                | 20   | 0.877      | 2016      |
| #14     | discrimination                  | 20   | 0.965      | 2012      |
| #15     | coalfield                       | 17   | 0.94       | 2006      |
| #16     | emergency rescue                | 14   | 0.989      | 2012      |
| #17     | forest burned areas             | 14   | 0.913      | 2012      |
| #18     | emission                        | 10   | 0.996      | 2013      |
| #19     | threatened species              | 8    | 1.000      | 2010      |
| #20     | foam stability                  | 6    | 0.983      | 2015      |
### Table 7: Keyword cluster information table

| Cluster | Top terms |
|---------|-----------|
| #0      | spontaneous combustion; plugging property; temperature; mine fire; india; temperature; impact; mine fire; india; area; india; coal fire; jharia coalfield; wuda; aster |
| #1      | spontaneous combustion; activation energy; thermal analysis; analytical solution; ignition behavior; low temperature; self-heating; safety engineering; proactive inertisation; mine safety; model; low temperature oxidation; aliphatic hydrocarbon; unsaturated hydrocarbons; proactive inertisation |
| #2      | spontaneous combustion; situ fourier; surface characteristics; infrared spectroscopy; grey correlation analysis; low-temperature oxidation; functional group; inhibiting effect; thermal release intensity; thermogravimetric analysis; product; initial exothermic temperature; element occurrence; methane migration; surface characteristics |
| #3      | spontaneous combustion; free radical reaction; porosity changes; porous media; gangue hill; coal stockpile; temperature profile; coal oxidation; theroplastic powder; extinguishing fire; coal stockpile; prevention; goaf; statistical model |
| #4      | spontaneous combustion; mechanical thermal expression; particle size; mineral matters; pore structure; forest fire; historical mining; environmental pollution; prescribed fire; water pollution; mechanical thermal expression; forest fire; lignite; prescribed fire; ash |
| #5      | spontaneous combustion; emission regularity; co-generation mechanism; advanced characterization; iron nanoparticles; carbon nanotubes; rare earth elements; colombian coals; spontaneous coal; analytical approach; carbon nanotubes; potential hazardous elements; nano-minerals; human exposure; advanced characterization |
| #6      | spontaneous combustion; inhibition characteristic; particle size; crystal structure; foaming agent; discrimination; crystal structure; quarry; anisotropy; mining explosion; discrimination; explosion; quarry blast; earthquake; daxing mine |
| #7      | spontaneous combustion; bi-point source; reverse dispersion modelling; emission factor; fire extinguishment; coalfield; coal fire; natural example; in situ gasification; depth; coalfield; depth; east basuria colliery; coal fire; back-calibration |
| #8      | numerical simulation; emergency rescue; smoke plume control; porous media; critical velocity; porous media; coal stockpile; natural convection; convection visualization; cooling area; emergency rescue; fds; cfd; porous media; numerical simulation |
| #9      | table mountain; pinus pungens; appalachian mountains; fire history; satellite data; forest fire; metal contamination; post-mining environment; water quality; mining disturbance; forest burned areas; gas chromatography-mass spectrometry (gc–ms); africa; serpentine barren; pinus virginiana |
| #10     | spontaneous combustion; underground coal mine; ambient temperature; toxicity; gangue hill; emission; toxicity; sampler; partition coefficient; deposition; emission (14.45, 0.001); pah; fluorine release; microbial remediation |
| #11     | bauxite mining; vegetation structure; tropical savannas; new caledonia; ultramafic substrates; new caledonia; ultramafic substrates; tropical savannas; bauxite mining; vegetation structure; threatened species; conifers; tropical savannas; ultramafic substrates; new caledonia |
| #12     | spontaneous combustion; mercury emission; gangue hill; coal oxidation; gaseous products; fire; rehabilitation; savanna; fuel; minesite; restoration; fire; mining; lampropholis; reptile |
| #13     | spontaneous combustion; carbon dioxide; temperature-sensitive retardant microcapsule; fire-retardant mechanism; coal mine fires; tendency; mathematical origin; coal spontaneous combustion; sulfide mineral; powder; foam stability; kinetic based simulation method; three-phase foams; mathematical origin; powder |
| #14     | spontaneous combustion; clay suspensions; alginate fluid gels; ash content; coal mining; theroplastic powder; extinguishing fire; oxygen consumption; polymorphic foam clay; coal self-oxidation; theroplastic powder; inert gas; flame retardant; convection; synergistic effect |
| #15     | spontaneous combustion; apparent activation energy; differential scanning calorimetry; mechanism function; particle size; low-temperature oxidation; functional group; cyclic reaction; oxidation; moisture; moisture; inversion temperature; crossing-point temperature; self-ignition; drying |
| #16     | spontaneous combustion; discrete particle swarm optimization; mine ventilation network; gob flow field; mineral matter; low-temperature oxidation; solid biofuels; co emissions; heavy metals; thermokinetic parameter; coal; gasification; basin; greenhouse gas; energy |
| #17     | spontaneous combustion; free radical reaction; porous material; ultra-wideband spectrum; densified coal; low-temperature oxidation; functional group; cyclic reaction; porous material; ultra-wideband spectrum; composite inhibitor; coal spontaneous combustion; prediction; inorganic matter; inhibition mechanism |
| #18     | spontaneous combustion; foam evolution; pickering foams; coal residues; microstructure; coal wastes; vegetable oils; oil agglomeration; coal residues; microstructure; vegetable oils; sewage sludge; coal wastes; adsorption; sorption |
| #19     | spontaneous combustion; free radical reaction; dangerous area division; pollinator; apioidea; active site; oxidation; pyrolysis; bituminous coal; functional group; gas; active site; pyrolysis; pore structure; programmed heating |
| #20     | spontaneous combustion; systems-theoretic accident model; comprehensive evaluation; indicator; wetting time; low-temperature oxidation; coalification degree; pore development; coal-rock dynamic disaster; nuclear magnetic resonance; fine particulate matter; smoke exposure; time series; coal mine fire; risk |
emerged to reduce energy consumption and carbon dioxide emissions, so as to resist climate change. The time of “coal” surge and stabilization keeps pace with the hot spot time of international coal policy. This indicates that the burst term intensity is influenced by the political and economic environment at that time and is closely related to relevant policies.

### Conclusion

According to the published papers number, the research on mine fire can be divided into three stages: initial period (1999–2005), stable transition period (2005–2014), and vigorous growth period (2014–2020), with an overall upward trend.

In terms of research subjects, Deng J from Xi’an University of Science and Technology in China ranks the top in the 67 prolific authors. In addition, Chinese authors occupy an increasing proportion in this field. There are many scholars studying mine fire in the world, but most of their researches are scattered, and there is no large-scale cooperation and communication.

From the research space, China Univ Min & Technol ranks first among high-yield institutions, and the cooperation between institutions is mainly in neighboring regions. There is also a strong regional distribution in the cooperation

### Top 25 Keywords with the Strongest Citation Bursts

| Keywords              | Year | Strength | Begin | End   | 1999 - 2020 |
|-----------------------|------|----------|-------|-------|-------------|
| coal                  | 1999 | 10.83    | 2000  | 2015  |             |
| jharia coalfield fire | 1999 | 3.31     | 2001  | 2006  |             |
| area                  | 1999 | 3.45     | 2007  | 2013  |             |
| stockpile             | 1999 | 3.6      | 2008  | 2017  |             |
| western lignite       | 1999 | 3.33     | 2008  | 2009  |             |
| corporation           |      |          |       |       |             |
| temperature           | 1999 | 3.21     | 2008  | 2013  |             |
| prevention            | 1999 | 2.83     | 2008  | 2010  |             |
| powder river basin    | 1999 | 3.52     | 2009  | 2018  |             |
| wuda                  | 1999 | 4.08     | 2012  | 2016  |             |
| eastern kentucky      | 1999 | 3.31     | 2012  | 2015  |             |
| world                 | 1999 | 3.31     | 2012  | 2015  |             |
| model prediction      | 1999 | 3.03     | 2012  | 2014  |             |
| environmental impact  | 1999 | 2.86     | 2012  | 2015  |             |
| oxygen                | 1999 | 6.55     | 2013  | 2015  |             |
| rank                  | 1999 | 2.93     | 2014  | 2017  |             |
| 3 phase foam          | 1999 | 3.42     | 2015  | 2017  |             |
| dsc                   | 1999 | 2.89     | 2015  | 2017  |             |
| china                 | 1999 | 6.74     | 2016  | 2018  |             |
| model                 | 1999 | 3.45     | 2016  | 2017  |             |
| truman shepherd       | 1999 | 3.39     | 2016  | 2018  |             |
| particle              | 1999 | 3.2      | 2016  | 2018  |             |
| temperature oxidation | 1999 | 3.13     | 2016  | 2017  |             |
| floyd county          | 1999 | 3.13     | 2016  | 2017  |             |
| fly ash               | 1999 | 2.97     | 2016  | 2017  |             |
among countries, with China, the USA, and Australia as the center of the cooperation network. The countries where the high-yield institutions are located have made significant contributions to the research on mine fire.

Based on the research knowledge, *Int J Coal Geol* and *Fuel* are the most influential journals in *Coal*, and the paper published in the two journals has strong influence and recognition. “An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties.” is the highest cited paper. After 2015, the content of paper is more convincing, accounting for 90% of highly cited paper.

With the research hotspots, mine fire mainly involves basic research fields such as coal spontaneous combustion, goaf fire, and low temperature oxidation. Affected by the economic and political environment at that time, the research hotspot lasts for at least 2 years, accompanied by the emergence and sharp decline of burst term. It is speculated that the research will focus on fire prevention, low carbon, ecology, and sustainable development in this field.

Coal spontaneous combustion and low temperature oxidation are still the focus of current research so the challenge remains in the mine fire prevention and control at low temperature oxidation. In the future, the coal spontaneous combustion problem should be solved from the micromechanism perspective, and the reaction kinetics characteristics in combustion process should be analyzed combined with simulation modeling.

**Author contribution** Feiran Wang: Formal analysis; writing, original draft; visualization. Bo Tan: Methodology, conceptualization, writing—review and editing. Yue Chen: Writing, original draft; visualization. Xiyang Fang: Formal analysis, visualization. Guowei Jia: Investigation. Haiyan Wang: Methodology, conceptualization, writing—review and editing. Gang Cheng: Investigation. Zhuangzhuang Shao: Investigation.

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**Data availability** The data and materials used to support the findings of this study are available from the corresponding author upon request.

**Declarations**

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