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Review article

Bibliometric analysis and review of mine ventilation literature published between 2010 and 2023

Yan Xue, Jinmiao Wang *, Jun Xiao

School of Environment and Resources, Xiangtan University, Xiangtan, 411105, China

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ABSTRACT

To provide scholars with a quick understanding of the current status, research hotspots, and future trends in the field of mine ventilation, this paper conducted a visualized bibliometric analysis and a comprehensive review of mine ventilation-related literature from 2010 to 2023 using CiteSpace. A thorough analysis of the publication time, co-authorship, co-citation, keywords, and research topics of the literature was carried out. Based on this, through systematic literature reading and summarization, research topics in the field of mine ventilation were organized, analyzed, and classified. The results indicate that mine ventilation research from 2010 to 2023 went through three stages: stable development, slow growth, and rapid ascent. Nie Wen and China Univ Min & Technol were the most prolific authors and institutions in the field of mine ventilation. China had the highest number of publications during 2010–2023, while Canada and Poland exhibited the highest centrality, signifying their key roles in the mine ventilation domain. Deep mine ventilation and intelligent mine ventilation emerged as research hotspots and mainstream trends in the future. The analysis of multiple hazard coupling studies represents a research direction that mine ventilation needs to develop. Numerical simulation techniques should not be limited to static analysis, as dynamic simulation is a focal area of interest.

1. Introduction

Mineral resources serve as a crucial material foundation for the development of modern society, and their exploitation holds significant importance in economic development [1,2,3]. As shallow resources gradually deplete, resource development is transitioning towards deeper levels, making underground mining the primary method of resource extraction. Underground mining environments, such as coal mines and metal mines, are characterized by complex conditions involving toxic and harmful gases like gas, dust, CO, and NO_X, as well as high temperatures and humidity, which pose severe threats to the health and safety of underground workers [4,5]. "Mine ventilation" serves as an important means to address these safety hazards[6].

Mine ventilation entails supplying fresh air from the surface to the underground environment, ensuring a sufficient oxygen supply for both workers and oxygen-dependent equipment. Concurrently, it dilutes and removes toxic and harmful gases and dust from the underground environment, creating a safe, comfortable, and occupationally healthy working environment underground[7]. Research related to mine ventilation can be traced back to ancient Greece when mining engineers recognized the need for at least two ventilation routes for each mining point. In 1912, Agricola systematically discussed mine ventilation in his work "On Metallurgy". The application of computer technology to solve mine ventilation issues began in 1952. By the 1980s, computer-based mine ventilation design had

* Corresponding author.
E-mail address: csuwjm@163.com (J. Wang).

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become the mainstream trend. To date, ongoing exploration continues in research areas such as mine ventilation systems, ventilation networks, ventilation optimization, and dust control to reduce and prevent mine disasters and ensure the life safety and physical health of underground workers.

Bibliometric analysis is a quantitative analysis method based on mathematical statistics, which focuses on the analysis of research hotspots in a specific discipline. It provides an intuitive and effective explanation of the direction, process, characteristics, and regularities of disciplinary knowledge development, enhancing scholars' understanding of the historical development and regularities of the discipline, and facilitating more targeted research in the field [8]. Currently, numerous scholars have applied it to various disciplines, such as AHP research [9], fuzzy theory research in China [10], its application in energy efficiency DEA research [11], and research on multiple criteria decision making [12], and other industry domains [13–16]. The commonly used tools for bibliometric and visual analysis are CiteSpace and HistCite. Their core functionality lies in utilizing visual maps of knowledge domains to comprehensively and macroscopically reflect and approximate the specific domain's scientific development patterns. With these tools, one can analyze the current status of a research field and forecast its prospects [17].

To provide researchers with a comprehensive understanding of the current status, research hotspots, and future trends in the field of mine ventilation, it is essential to conduct a review of existing research on mine ventilation. While there are already a limited number of literature reviews related to mine ventilation, these reviews primarily focus on specific aspects within the field. Examples include technical aspects and influencing factors of coal mine methane (CMM) [18], the occurrence of explosion accidents in the Polish mining industry [19], various gas sensors, control systems, data transmission systems, and ventilation simulators used for monitoring and control [20], different underground ventilation systems [21], the application of Computational Fluid Dynamics (CFD) in ventilation safety research for underground hard coal mining [22], opportunities and challenges in CFD ventilation over the last 20 years [23], and the application of CFD in mine ventilation since 2011 [24]. However, there is currently no comprehensive review article that covers all aspects of mine ventilation.

Therefore, this paper employs CiteSpace to conduct a visual analysis of literature related to mine ventilation research from 2010 to 2023, as documented in the Web of Science and Scopus databases. By combining the results of this visual analysis with the selection of significant literature through HistCite, the paper categorizes research hotspots and development trends in the field of mine ventilation. Through a quantitative analysis of literature in the mine ventilation field, it is possible to unearth new frontiers in mine ventilation, advance the in-depth development of the discipline, offer insights for science and technology decision-making and management, and provide a valuable resource for academic research and information services to researchers.

The specific structure of this paper is as follows: Section 2 provides detailed information on the data sources and research methods utilized in this study. Section 3 conducts a visual analysis of mine ventilation research literature from various perspectives, including publication time, co-authorship, co-citation, and keywords. Section 4 classifies research themes in the field of mine ventilation based on the visual analysis results from Section 3. Section 5 discusses the current research status, emerging topics, and future development trends in the field of mine ventilation. Finally, Section 6 concludes the paper.

2. Methods

2.1. Data source

The data analyzed in this study are sourced from the Web of Science and Scopus. Web of Science is an authoritative citation literature retrieval tool recognized by the global academic community, It effectively explores the history, development, and application of an innovative idea, concept, or method from its proposal to the present. Web of Science has powerful citation tracking, paper

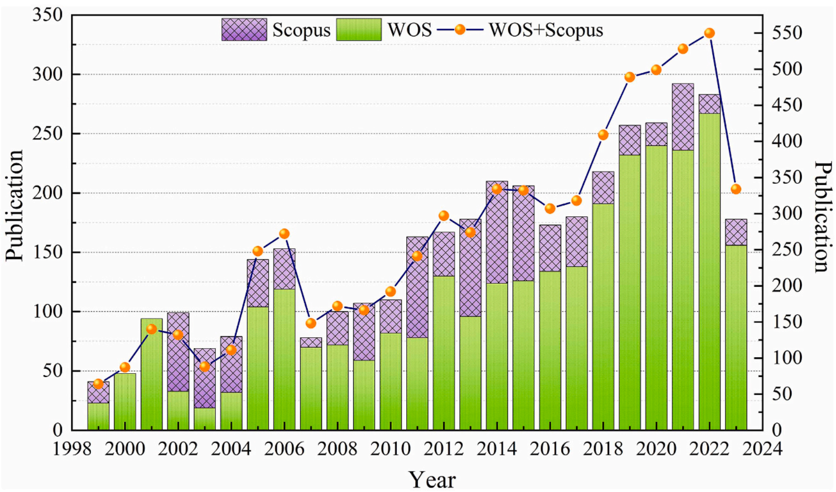

Fig. 1. Summary of mine ventilation publications from 1999 to 2022.

journal evaluation, subject classification, and other functions, and it expands with Endnote, Publons, Kopernio, and other academic tools. Web of Science has also become one of the most commonly used databases for bibliometric analysis because of its powerful functions [25]. Scopus is currently the world's largest abstract and citation database for peer-reviewed academic papers. It offers unique coverage for many disciplines, including engineering， the humanities, and social sciences. Scopus includes profiles for 94,000 institutions compassing universities, research institutions, and businesses. It encompasses data sources for research performance in the QS and THE World University Rankings/Subject Rankings.

This paper used a topic search method for retrieval, with the keyword "mine ventilation" as of October 10, 2023. Between 1999 and 2023, a total of 2,902 bibliographic entries were retrieved from the Web of Science, and 3,829 entries from Scopus [26]. The specific distribution of literature over the years is illustrated in Fig. 1. Before 2010, the overall development of mine ventilation was relatively stable and low, with a generally low publication volume. Both WOS and Scopus averaged 142 publications per year between 1999 and 2010. However, after 2010, mine ventilation development has been robust and on the rise. From 2010 onwards, WOS and Scopus averaged up to 369 publications per year. Based on this, the paper will provide a detailed analysis of the development trends, research focuses, and hot topics in mine ventilation from 2010 to 2023. Scopus and WOS were set in the time range of "2010–2023" resulting in a retrieval of 5,226 bibliographic entries. After removing 1,311 duplicate entries that were simultaneously included in both Scopus and WOS, a final set of 3,915 bibliographic entries was obtained for further analysis and discussion.

2.2. Research method

The method used in this study is bibliometric analysis, which employs mathematical and statistical methods to quantitatively analyze the development, current status, and frontier hotspots of a research field. The commonly used software for bibliometric analysis includes CiteSpace and HistCite. Among them, CiteSpace is a powerful software tool for visualizing and analyzing scientific citations, particularly in the field of citation analysis [27–29]. HistCite, on the other hand, is a simple, intuitive, and clear software for citation analysis, capable of quickly identifying the development trajectory and important literature in a research field [30]. Therefore, in this study, CiteSpace6.1.R6(64-bit) for the bibliometric analysis of the mine ventilation research field. This analysis included author co-authorship analysis, analysis of collaborative institutions and countries, analysis of co-citations, and keyword analysis [31,32]. During the analysis in CiteSpace, a deduplication process was performed on the book records downloaded from Web of Science and Scopus. Following this, parameters are configured with a period set from January 2010 to December 2023, a time slice of 1, the "Cosine" method for calculating node strength, and the "g-index" as the basis for node extraction according to the "Selection criteria". Finally, the entire visualization graph was presented through clustering. Based on this visualization graph, a comprehensive analysis of the research status, hotspots, development patterns, and future trends of mine ventilation from 2010 to 2023 was conducted.

3. Results

3.1. Analysis of publication time

The publication trends in mine ventilation from 2010 to 2023 are illustrated in Fig. 2. Overall, the total number of publications in the field of mine ventilation is relatively low, making it a niche area compared to other research domains. Looking at the percentage of annual publications relative to the total, it's evident that the number of mine ventilation papers has been steadily increasing from 2010 to 2023. Especially after 2015, there has been a significant surge in publications, signifying that mine ventilation has progressively gained prominence and become one of the research hotspots in the field of resource extraction.

From a developmental perspective, the evolution of mine ventilation can be categorized into three distinct phases: steady development, slow growth, and rapid expansion [8]. The steady development phase (2010–2013) saw an average publication output of 122 articles, with the highest number of publications, 151 articles, occurring in 2013. During this phase, the annual publication rate remained relatively modest. In the slow growth period (2014–2017), the average number of publications increased to 228 articles, reaching a peak of 259 articles in 2017. This phase exhibited an annual publication growth rate of 86.91% compared to the steady

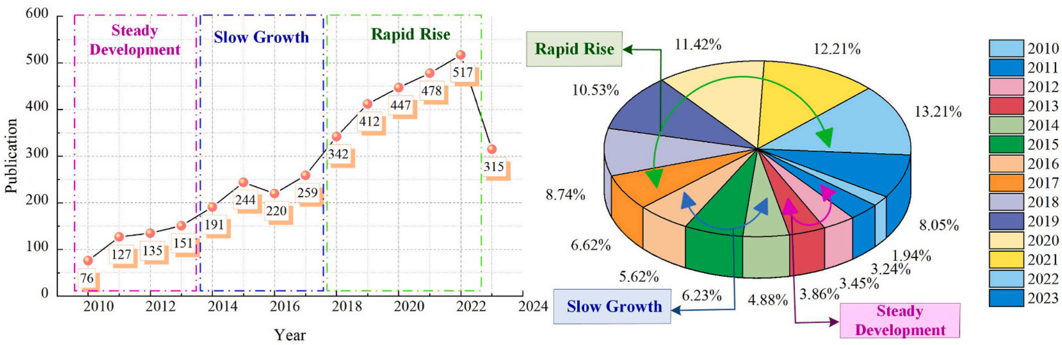

Fig. 2. Publication time analysis for the period 2010–2023.

development period. The rapid expansion phase (2018–2022) experienced an average publication output of 439 articles, with a peak of 517 articles in 2020. In contrast to the steady development and slow growth phases, this period we have demonstrated average annual publication growth rates of 92.21% and 259.26%, respectively.

During 2018–2022, China's publications accounted for 48% of the total publications in the WOS database and 42% in the Scopus database, establishing itself as the leader in the field of mine ventilation during this period. This was attributed to China's issuance of various regulations, including the "Gas Grade Identification Method for Coal Mines", "Safety Regulations for Metal and Non-metal Mines", "Guidelines for Intelligent Construction of Coal Mines" and the revised 2022 version of "Coal Mine Safety Regulations". Under the guidance of government policies and regulations, research in mine ventilation quickly became a focal point in academic studies. Additionally, the introduction of the "Dual Carbon" goals on September 22, 2020, propelled mine ventilation into a new era of research, focusing on energy conservation and emissions reduction.

From the comparative analysis above, it is evident that the field of mine ventilation has garnered increasing attention and recognition from researchers. This trend is particularly noticeable due to the growing demands for occupational safety and health in mining industries worldwide. Moreover, the rise of digitalization and smart technologies in mining operations has further elevated the research interest and significance of mine ventilation. It is anticipated that the research enthusiasm in the field of mine ventilation will continue to escalate and reach new heights in the coming years.

3.2. Co-authorship analysis

Co-authorship analysis aims to analyze the collaboration status, social relationships, and cooperative patterns among authors and institutions/nations in a particular research field. It helps identify the collaboration status in the field, determine leading scholars in research hotspots, and highlight researchers, institutions, or countries worthy of attention. This facilitates a focused analysis of the development trends and research status in the field.

3.2.1. Research institutions and national network analysis

The influence and hierarchical position of research institutions directly or indirectly reflect the breadth and depth of academic

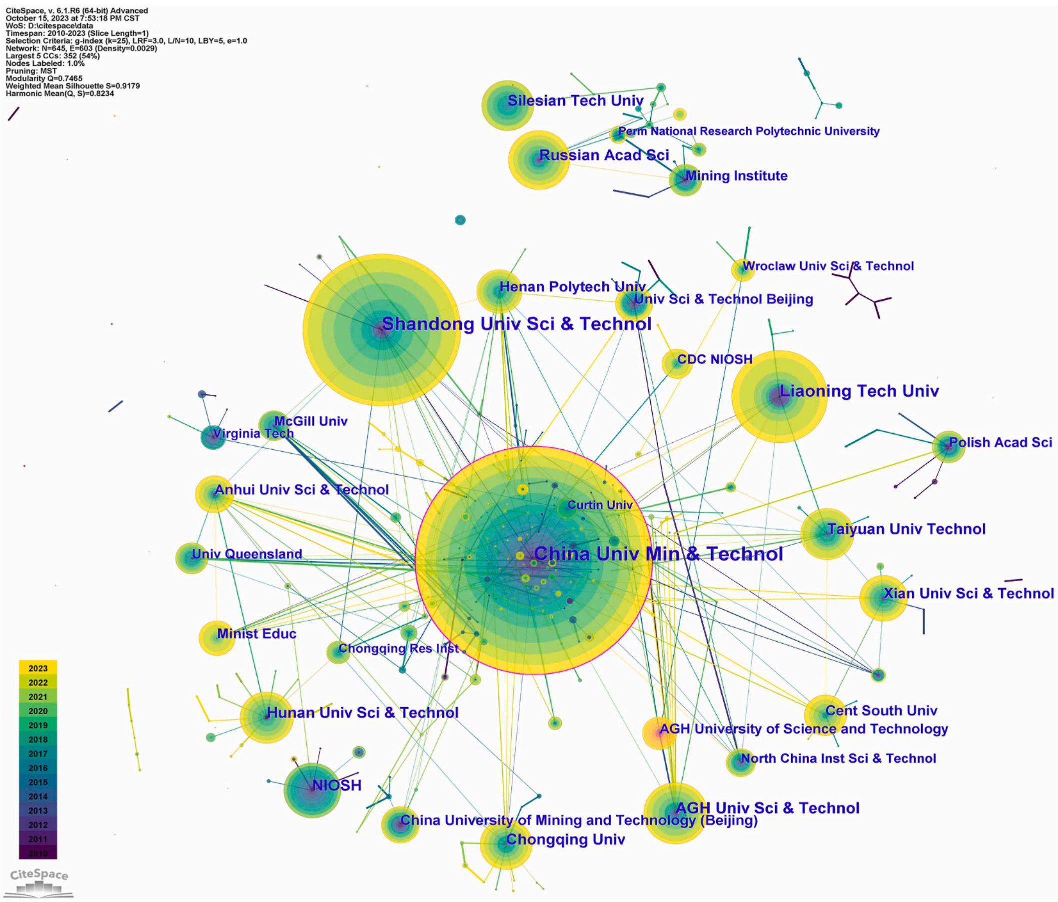

Fig. 3. Institutional collaboration network.

research conducted by their internal scholars. As shown in Fig. 3, the institution co-authorship network consists of 645 nodes connected by 603 links, with a network density of 0.0029. In this representation, the size of each node corresponds to the number of publications from that institution. The centrality of a node, denoted by the thickness of the external purple circle in Fig. 4, measures its importance within the entire network. Nodes with higher centrality are more likely to be key players in the network.

For example, the node representing China Univ Min & Technol is the largest and has the thickest purple circle, indicating that this institution has published significantly more articles in the field of mine ventilation from 2010 to 2023 compared to other institutions. It can be considered a major research institution in the field. Other prominent institutions include Shandong Univ Sci & Technol, China Univ Min & Technol Beijing, and Liaoning Tech Univ, among others. Table 1 provides a list of the top ten institutions by the number of publications, along with the corresponding publication counts and publication years.

The research institutions in the field of mine ventilation exhibit a closely interconnected network with relatively few scattered closed loops. This network structure resembles a radial pattern, where central research institutions are connected to smaller and medium-sized research organizations, which, in turn, are individually interconnected with smaller research structures.

Within Fig. 3, the cooperation between China Univ Min & Technol and other institutions is particularly dense, forming an extensive network of collaborations. Eight of the top ten research institutions, in terms of publications from 2010 to 2023, have close collaborative ties with China Univ Min & Technol. China Univ Min & Technol stands as a vital core institution in the field of mine ventilation, making significant contributions to research in this domain. Russian Acad Sci and Silesian Tech Univ have established independent research communities. These research communities contain fewer research institutions, and the level of collaboration among them is less dense. Nevertheless, this research community holds a prominent position in the field of mine ventilation, second only to the community primarily led by China Univ Min & Technol.

Taken as a whole, the majority of research institutions in the field of mine ventilation originate from China, while research institutions from other countries or regions are relatively scarce. This concentration of research resources in China has resulted in limited resources for smaller institutions, leading to a situation where research techniques and methodologies are somewhat uniform. Enhancing collaborative relationships between major research institutions and smaller research organizations is beneficial for the comprehensive development of the discipline of mine ventilation. It encourages diversification of research directions, and collective brainstorming, and facilitates further expansion of the breadth and depth of academic research in this field [33].

In the context of globalization, academic exchanges between countries play a crucial role in advancing science and technology. Fig. 4 illustrates the contributions and connections of various countries in the field of mine ventilation research. As shown in Fig. 4, from 2010 to 2023, CHINA's node size significantly surpasses that of other countries in terms of publication quantity. However, its betweenness centrality is relatively low, indicating that its scientific research outcomes have limited academic influence on the international stage. It is imperative to deepen cooperation and exchange with foreign scholars and institutions to generate high-impact technological achievements that can lead the field's development [34].

USA, AUSTRALIA, and CANADA exhibit substantial betweenness centrality, signifying close collaborations with other countries.

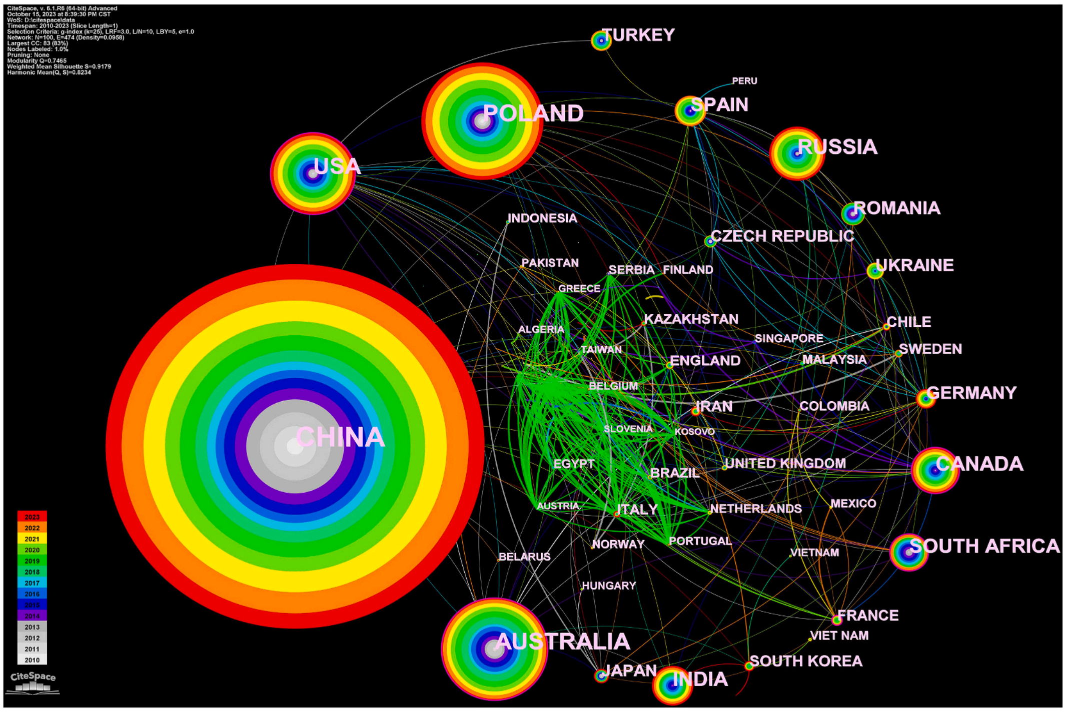

Fig. 4. Network of countries and collaborations.

Table 1
Top ten institutions by number of publications.

	Count	Year	Institutions
1	297	2010	China Univ Min & Technol
2	179	2010	Shandong Univ Sci & Technol
3	163	2011	China Univ Min & Technol Beijing
4	153	2010	Liaoning Tech Univ
5	68	2011	Russian Acad Sci
6	64	2014	Taiyuan Univ Technol
7	62	2010	AGH Univ Sci & Technol
8	62	2015	Silesian Tech Univ
9	57	2010	Chongqing Univ
10	53	2010	Hunan Univ Sci & Technol

They hold core positions within the global network of mine ventilation research and are connected to virtually every other country engaged in mine ventilation research. This demonstrates the significant relationship between research capabilities and a country's strength and background. To further explore the field of mine ventilation, it is essential to receive additional support in terms of economic and scientific cultural contexts.

3.2.2. *Author Co-authorship network analysis*

Co-authors, responsible for paper submission and publication, are generally referred to as authors. Analyzing the collaborative relationships among co-authors allows for the rapid identification of core authors in a research field and reveals their cooperation relationships and strengths. This aids scholars in quickly identifying leading figures in the research area.

Fig. 5 shows the author co-authorship network diagram obtained by clustering the collaboration relationships among authors using CiteSpace. It consists of 793 nodes, 759 connections, and a network density of 0.0024. Due to the extensive distribution of nodes and connections, a Minimum Spanning Tree (MST) provided by CiteSpace was used to simplify the visualization, as depicted in Fig. 5. In Fig. 5, the size of nodes and labels represents the frequency of an author's appearance in the journals. The thickness of connections between nodes indicates the strength of the collaboration between authors. Red nodes in the diagram represent authors with significant impact within their collaborative networks, such as Sasmito AP, who is a key figure in their respective collaboration networks. The color of the connecting lines between authors in Fig. 5 represents the year in which they initiated their collaboration. For instance,

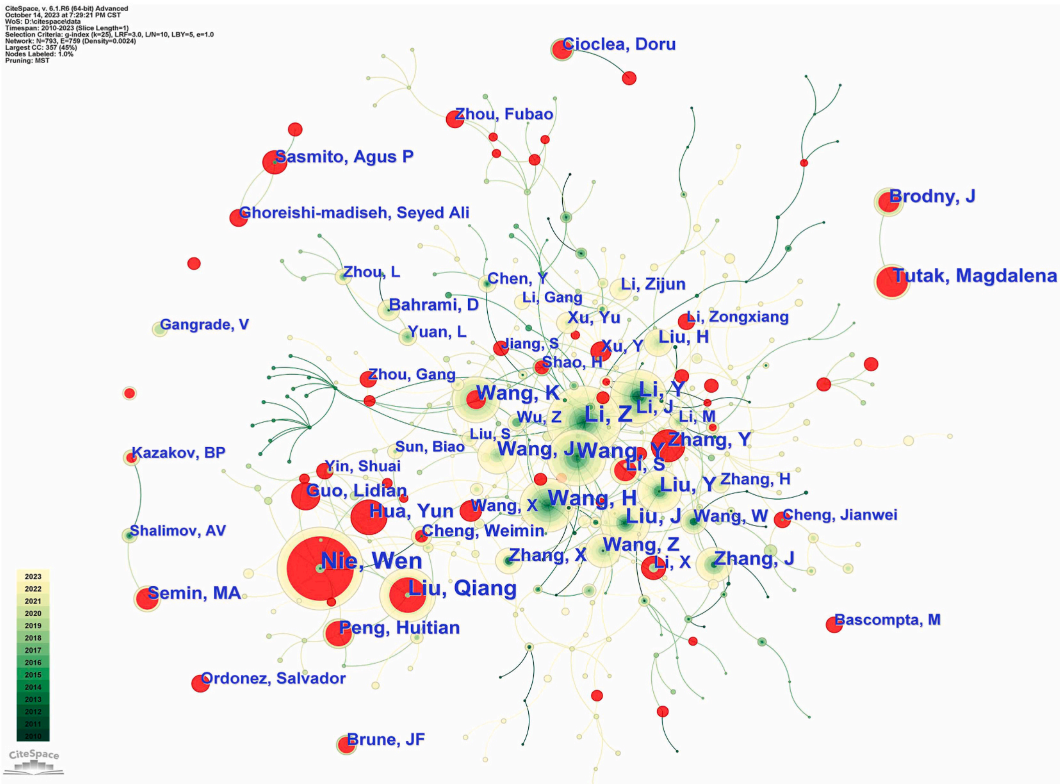

Fig. 5. Author co-authorship network.

Nie Wen and Liu Qiang began their direct collaboration in 2018.

Nie Wen and Li Z have the largest nodes and labels, each with the highest number of publications, amounting to 56 papers each during the period from 2010 to 2023. In this same timeframe, Nie Wen and Li Z each have 10 papers with citation counts exceeding 80. Following them are Wang Y, Li Y, Wang H, and Wang K, each with over 40 publications. Detailed information on the top 10 authors with the highest number of publications during 2010–2023 is provided in Table 2.

The interconnections among authors in Fig. 5 are intricate and complex, indicating that authors in the mine ventilation field have established strong collaborative networks. Among these networks, Wang Y, Li Y, Wang H, and Li Z form the core research community with exceptionally tight connections between each other. These research communities involve a large number of collaborators. In the research community centered around Sasmito AP, there is room for expansion in both the number of authors and their connections. Overall, interactions between Chinese authors and authors from other countries appear to be relatively limited and require strengthening.

These accomplished authors and the research communities they constitute have made significant contributions to the field of mine ventilation research. Therefore, to delve deeper into the study's progress and development trends in the field of mine ventilation, scholars must focus on and pay attention to the core authors and research communities in the mine ventilation domain.

3.3. Co-citation analysis

Co-citation analysis refers to the relationship formed when two articles are cited together by other citing documents. It can be used to explore the relationships between references and uncover the knowledge structure of a research field [35,36]. In this study, CiteSpace was utilized to conduct co-citation analysis in the field of mine ventilation. All references were sorted in descending order based on their citation counts, and the top five highly cited references from each time slice were selected for analysis.

Fig. 6 displays the co-citation network map of mine ventilation literature. The network consists of 989 nodes and 3828 connections, with a network density of 0.0078. The Q clustering coefficient is $0.7465 > 0.3$, indicating a significant clustering effect. The S clustering average silhouette value is $0.9179 > 0.7$, suggesting a convincing clustering result. LSI, LLR, and MZ are the main clustering algorithms in CiteSpace, with LLR being the most accurate and recommended algorithm by Professor Chen Chaomei. Therefore, this study adopts the LLR algorithm for clustering analysis.

Table 3 presents the information on the top 10 clusters in mine ventilation obtained through the LLR algorithm. The "ClusterID" represents the cluster label (cluster name), which is essentially a clustering tag. It refers to selecting the maximum value among closely related keywords clustered together as the cluster label. The "Size" indicates the cluster capacity, i.e., the number of members within the cluster. Clusters with a size smaller than 10 indicate suboptimal clustering results and are excluded from the analyzed. In this study, the average cluster size is greater than 10, which meets the analysis criteria. The cluster name is closely related to the cluster size, where a smaller cluster name implies a larger cluster size and vice versa. The "Silhouette" refers to the silhouette coefficient, which represents the compactness or homogeneity within a cluster. When Silhouette >0.5, the clustering is reasonable, indicating high similarity among members within the cluster and successful clustering. When Silhouette >0.7, the clustering result is convincing, indicating a high level of compactness among members. In this study, the Silhouette coefficient is 0.9179, indicating successful clustering with a high level of confidence in the clustering results. "mean(Year)" represents the average publication year of the cited references within a cluster. "Top Terms" refers to the alternative labels generated by the LLR algorithm for the clusters, arranged in descending order of cluster values.

The cluster information in Table 3 reveals that the current research hotspots are spontaneous combustion, dust dispersion, and control in underground mines. Research methods are primarily focused on case studies and computer simulations. Building upon the previous clustering, the top 10 most frequently cited publications are derived, as shown in Table 4. The top-ranked item by citation counts is Liu et al.[17] in Cluster #3, with a citation count of 88. The second one is Xiu et al. [37] in Cluster #1, with a citation count of 74. The third is Xu et al. [38] in Cluster #3, with citation count of 69. The 4th is Cai et al. [39] in Cluster #3, with a citation count of 69. The 5th is Wang et al.[40] in Cluster #3, with a citation count of 62. The 6th is Yin et al.[41]in Cluster #3, with a citation count of 61. The 7th is Liu et al. [42] in Cluster #3, with a citation count of 59. The 8th is Nie et al. [43] in Cluster #3, with a citation count of 54. The 9th is Chen et al.[44] in Cluster #3, with a citation count of 52. The 10th is Hua et al. [45] in Cluster #3, with a citation count of 52.

Table 2
Top 10 authors by publication count (2010–2023).

	Count	Year	Authors
1	56	2012	Nie, Wen
2	56	2011	Li, Z
3	45	2013	Wang, Y
4	43	2010	Li, Y
5	43	2012	Wang, H
6	41	2016	Wang, K
7	37	2012	Liu, J
8	34	2010	Liu, Y
9	33	2018	Liu, Qiang
10	30	2018	Wang, J

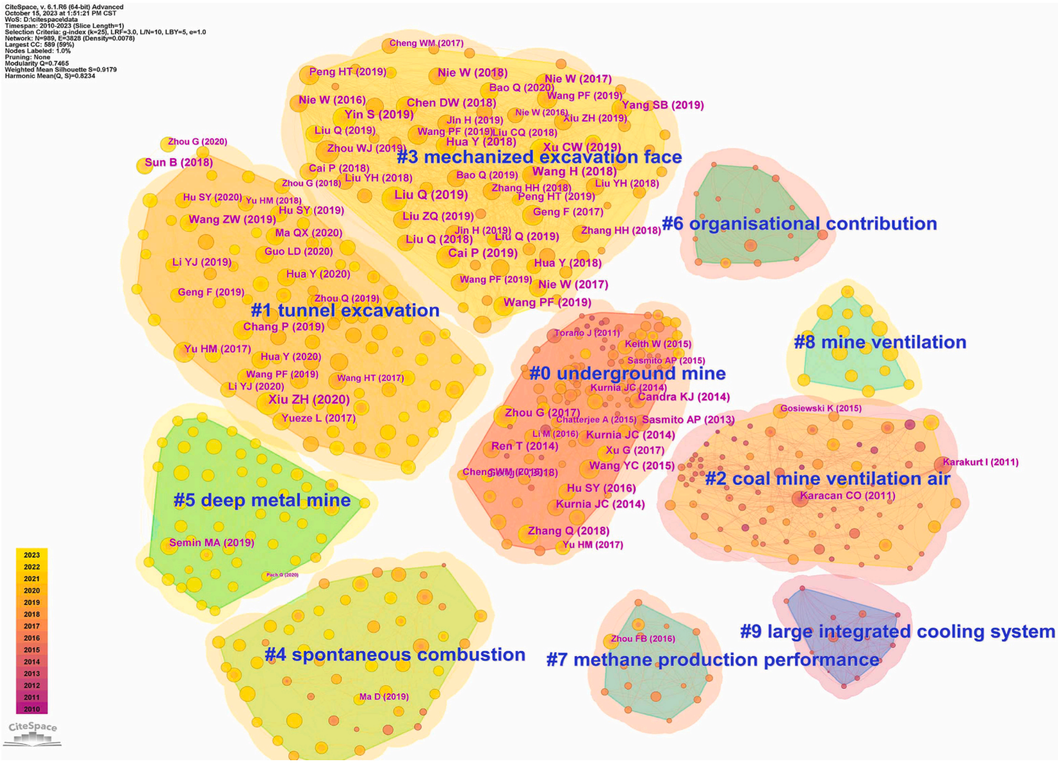

Fig. 6. Co-citation network of authors.

Table 3
Top 10 citation clusters of mine ventilation research literature from 2010 to 2023.

Cluster-ID	Size	Silhouette	mean (Year)	Top Terms
0	118	0.877	2014	underground mine; spontaneous combustion; dust dispersion; case study; computational approach
1	103	0.791	2020	tunnel excavation; return air tunnel; spray dust suppression device; coupling diffusion law; diverging dust control technology
2	87	0.97	2012	coal mine ventilation air; thermal oxidation; ventilation air methane; greenhouse gas emission; coal-packed methane biofilter
3	74	0.907	2018	mechanized excavation face; air-curtain generator position; transient cfd modelling; cleaner production; wind curtain
4	54	0.978	2017	spontaneous combustion; longwall gob; coal mine goaf; spontaneous combustion control; gas management
5	52	0.993	2020	deep metal mine; refrigeration ventilation system; heat transfer characteristics; high temperature tunnel; movable thermal insulation layer
6	17	0.985	2013	organizational contribution; pike river mine disaster; abnormal gas emission; using ventilator control; coalmine ventilation system
7	17	0.996	2014	methane production performance; pressure relief gas extraction; floor heave mechanism; fully-mechanized backfilling mining; gob-side entry
8	15	0.995	2019	mine ventilation; wind resistance measurement; multi-objective intelligent decision; linkage control algorithm; resistance variant
9	15	0.993	2010	large integrated cooling system; versatile energy management system; variable water flow energy efficiency; mine cooling system; saving strategy

Table 5 consists of the top ten documents with the highest co-citation prominence in the co-citation literature analysis. The top-ranked Item by bursts Is Karacan et al. [46] in Cluster #2, with bursts of 21.52. The second one is Sasmito et al. [47] in Cluster #0, with bursts of 18.37. The third is Jundika C. Kurnia et al. [48] in Cluster #0, with bursts of 17.11. The 4th is Jundika C. Kurnia et al. [49] in Cluster #0, with bursts of 16.33. The 5th is Ren et al.[50] in Cluster #0, with bursts of 16.33. The 6th is Karakurt et al. [51] in Cluster #2, with bursts of 15.50. The 7th is Jundika Candra Kurnia et al. [52] in Cluster #0, with bursts of 15.20. The 8th is Toraño et al. [53] in Cluster #0, with bursts of 12.75. The 9th is Y. Wang et al. [54] in Cluster #0, with bursts of 10.62. The 10th is Zhou et al. [55] in Cluster #3, with bursts of 10.53.

Table 6 presents detailed information about the top ten publications ranked by centrality. The top-ranked item by degree is Liu et al. [17] in Cluster #3, with a degree of 67. The second one, Wang et al. [56] in Cluster #3, with the degree of 53. The third, Xu et al. [38]

Table 4
Title and citation frequency of the top 10 cited literature.

Citation Counts	References	DOI	Cluster-ID
88	Liu Q, 2019], BUILD ENVIRON, V147, P444	10.1016/j.buildenv.2018.08.061	3
74	Xiu ZH, 2020, J CLEAN PROD, V248, P0	10.1016/j.jclepro.2019.119197	1
69	Xu CW, 2019, ENERGY, V182, P544	10.1016/j.energy.2019.05.201	3
69	Cai P, 2019, FUEL, V239, P623	10.1016/j.fuel.2018.11.030	3
62	Wang H, 2018, ADV POWDER TECHNOL, V29, P230	10.1016/j.apt.2017.11.007	3
61	Yin S, 2019, J CLEAN PROD, V239, P0	10.1016/j.jclepro.2019.117924	3
59	Liu Q, 2018, POWDER TECHNOL, V329, P371	10.1016/j.powtec.2018.01.064	3
54	Nie W, 2018, ADV POWDER TECHNOL, V29, P835	10.1016/j.apt.2017.12.027	3
52	Chen DW, 2018, J CLEAN PROD, V205, P463	10.1016/j.jclepro.2018.09.009	3
52	Hua Y, 2018, POWDER TECHNOL, V334, P117	10.1016/j.powtec.2018.04.059	3

Table 5
Top 10 literature with the highest burst strength.

Bursts	References	DOI	Cluster-ID
21.52	Karacan CO, 2011, INT J COAL GEOL, V86, *P*121	10.1016/j.coal.2011.02.009	2
18.37	Hua Y, 2018, TUNN UNDERGR SP TECH, V34, P82	10.1016/j.tust.2012.09.006	0
17.11	Hua Y, 2018, APPL MATH MODEL, V38, P3467	10.1016/j.apm.2013.11.067	0
16.33	Hua Y, 2018, TUNN UNDERGR SP TECH, V42, P206	10.1016/j.tust.2014.03.009	0
16.33	Hua Y, 2018, TUNN UNDERGR SP TECH, V41, P241	10.1016/j.tust.2014.01.002	0
15.50	Karakurt I, 2011, RENEW SUST ENERG REV, V15, P1042	10.1016/j.rser.2010.11.030	2
15.20	Candra KJ, 2014, INT J MIN SCI TECHNO, V24, P39	10.1016/j.ijmst.2013.12.007	0
12.75	Torano J, 2011, TUNN UNDERGR SP TECH, V26, P201	10.1016/j.tust.2010.07.005	0
10.62	Wang YC, 2015, J LOSS PREVENT PROC, V36, P146	10.1016/j.jlp.2015.06.003	0
10.53	Wang YC, 2015, INT J MECH SCI, V160, P358	10.1016/j.ijmecsci.2019.06.037	3

in Cluster #3, with the degree of 52. The 4th, Sasmito et al. [57] in Cluster #0, with the degree of 51. The 5th, Liu et al. [58] in Cluster #3, with the degree of 51. The 6th, Cai et al. [59] in Cluster #3, with the degree of 51. The 7th, Liu et al. [60] in Cluster #3, with the degree of 50. The 8th, Yin et al. [41] in Cluster #3, with the degree of 47. The 9th, Guo et al. [61] in Cluster #1, with the degree of 46. The 10th, Nie et al. [43] in Cluster #3, with the degree of 46.

In conclusion, it is evident that Liu et al. [17], Xu et al. [38], Sasmito et al. [57], Yin et al. [41], and Nie et al. [43] are important publications in the field of mine ventilation and hold significant positions in the discipline of mine ventilation.

3.4. *Keyword analysis*

Keywords reflect the core ideas of an article and provide a concise summary of the overall thoughts and content. They reveal the main research directions and focal points of the article, while keyword analysis can reflect the research directions, hot topics, and development trends in a particular field of study[62]. In this paper, the acquired literature information is imported into CiteSpace for co-occurrence and cluster analysis of keywords. Combined with the keyword timeline graph, this analysis helps in examining the research hotspots and evolving trends in the field of mine ventilation.

3.4.1. *Co-occurrence analysis of keywords*

Fig. 7 presents the co-occurrence network of keywords in the field of mine ventilation. The time slice is set to 1 year, clustering labels are based on keywords, and the node type is also keywords. The network consists of 869 nodes and 2259 edges, with a network density of 0.006. In the graph, the size of each node represents its frequency of occurrence, with larger nodes indicating higher occurrence frequencies of the corresponding keywords. The color of the edges between nodes reflects the year of their co-occurrence,

Table 6
The top 10 publications with centrality rankings from 2010 to 2023.

Degree	References	DOI	Cluster-ID
67	Liu Q, 2019, BUILD ENVIRON, V147, P444	10.1016/j.buildenv.2018.08.061	3
53	Wang PF, 2019, TUNN UNDERGR SP TECH, V90, P194	10.1016/j.tust.2019.04.026	3
52	Xu CW, 2019, ENERGY, V182, P544	10.1016/j.energy.2019.05.201	3
51	Wang PF, 2019, TUNN UNDERGR SP TECH, V34, P82	10.1016/j.tust.2012.09.006	0
51	Liu Q, 2019, PROCESS SAF ENVIRON, V132, P367	10.1016/j.psep.2019.10.012	3
51	Cai P, 2018, PROCESS SAF ENVIRON, V118, P93	10.1016/j.psep.2018.06.011	3
50	Liu Q, 2019, ADV POWDER TECHNOL, V30, P2059	10.1016/j.apt.2019.06.019	3
47	Yin S, 2019, J CLEAN PROD, V239, P0	10.1016/j.jclepro.2019.117924	3
46	Guo LD, 2020, BUILD ENVIRON, V178, P0	10.1016/j.buildenv.2020.106846	1
46	Nie W, 2018, ADV POWDER TECHNOL, V29, P835	10.1016/j.apt.2017.12.027	3

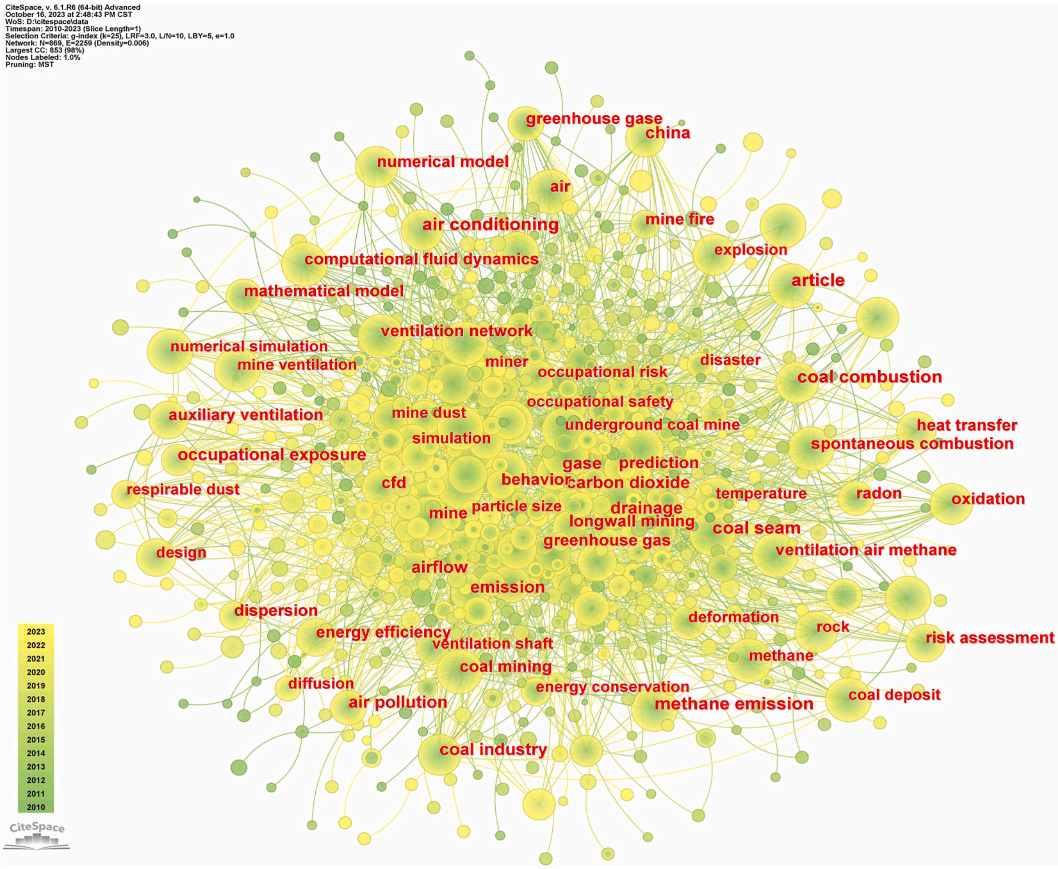

Fig. 7. Keyword Co-occurrence network.

with more edges indicating a higher frequency of co-occurrence. The thickness of the edges represents the strength of their connection, with thicker edges indicating a stronger relationship [27].

From Fig. 7 the top 20 high-frequency keywords are extracted and shown in Table 7. The statistical results indicate that keywords such as "ventilation", "coal mine", "numerical simulation", and "ventilation system" have the highest occurrence frequencies.

Table 8 presents the top ten keywords ranked by centrality for the period 2010–2023. "Year" represents the year when the keyword first appeared, "Begin" and "End" indicate the starting and ending years when the keyword is considered at the forefront, and "Strength" represents the burst strength. Light blue segments indicate articles that are yet to be published, whereas dark blue segments represent the publication timeline of an article. The beginning of a red segment marks the start of a burst period, and the end of a red segment signifies the end of the burst period. The longer the burst duration, the longer the keyword remained in the forefront, indicating a stronger research frontier.

From 2010 to 2014, numerical simulation in mine ventilation became a research hotspot, while "underground mine ventilation" was a focus from 2013 to 2017. In recent years, "external spraying system", "mechanized mining face", "air curtain", and "coal industry" have become key areas of research focus.

Table 7
Top 20 high-frequency keywords in mine ventilation from 2010 to 2023.

	Count	Year	Keywords		Count	Year	Keywords
1	1193	2010	ventilation	11	239	2010	computational fluid dynamics
2	1019	2010	coal mine	12	239	2010	air
3	570	2010	mine ventilation	13	221	2012	simulation
4	541	2010	coal	14	219	2010	coal industry
5	423	2010	ventilation system	15	213	2010	coal deposit
6	402	2010	numerical simulation	16	211	2010	mine ventilation system
7	397	2010	methane	17	204	2010	underground coal mine
8	276	2010	mining	18	201	2010	coal mining
9	265	2010	underground mine	19	183	2010	ventilation network
10	257	2010	mine	20	178	2010	spontaneous combustion

Table 8
2010–2023 Top 10 keywords with the strongest citation bursts.

Keywords	Year	Strength	Begin	End	2010–2023
computer simulation	2010	32.94	**2010**	2014	
mathematical model	2010	23.07	**2010**	2014	
mine ventilation system	2010	12.37	**2010**	2013	
three dimensional	2011	11.64	**2011**	2013	
ventilation system	2010	13.11	**2012**	2013	
underground mine ventilation	2011	12.03	**2013**	2017	
external spraying system	2019	13.89	**2019**	2020	
mechanized mining face	2019	13.44	**2019**	2020	
air curtain	2012	11.74	**2019**	2021	
coal industry	2010	33.31	**2020**	2021	

3.4.2. Keyword cluster analysis

Compared to the co-occurrence analysis, the clustering function in CiteSpace provides a more detailed reflection of research hotspots and trends in the field. Therefore, in this study, CiteSpace was used to perform a clustering analysis on the literature items in the field of mine ventilation. The time slice was set to one year, the LLR algorithm was used for clustering, and the clustering words were derived from the keywords. The pathfinder algorithm was applied for pruning, and the top 14 largest clusters were selected and visualized in Fig. 8. In Fig. 8 a total of 869 nodes and 2259 edges were generated, with a network density of 0.006. The modularity value (Q-value) was 0.5439, indicating significant clustering results. The average silhouette value (S-value) was 0.8133, indicating reasonable clustering and convincing results.

Based on the clustering information from Fig. 8, detailed information for the top 14 keyword clusters in mine ventilation is extracted, as presented in Table 9. Considering both Figs. 8 and 9, it becomes apparent that Cluster #0, Cluster #1, Cluster #2, and Cluster #3 are the most prominent, collectively exceeding a total capacity of 80. This reflects that recent research in the field of mine ventilation has been predominantly concentrated on underground mining operations, with research hotspots revolving around dust dispersion, gas control, and heat management in high-temperature underground environments. It is noteworthy that methane (CH_4)-related topics have been the most studied subjects within the field of mine ventilation. Furthermore, when compared to other simulation software and analysis methods, Computational Fluid Dynamics (CFD) finds the widest application in mine ventilation

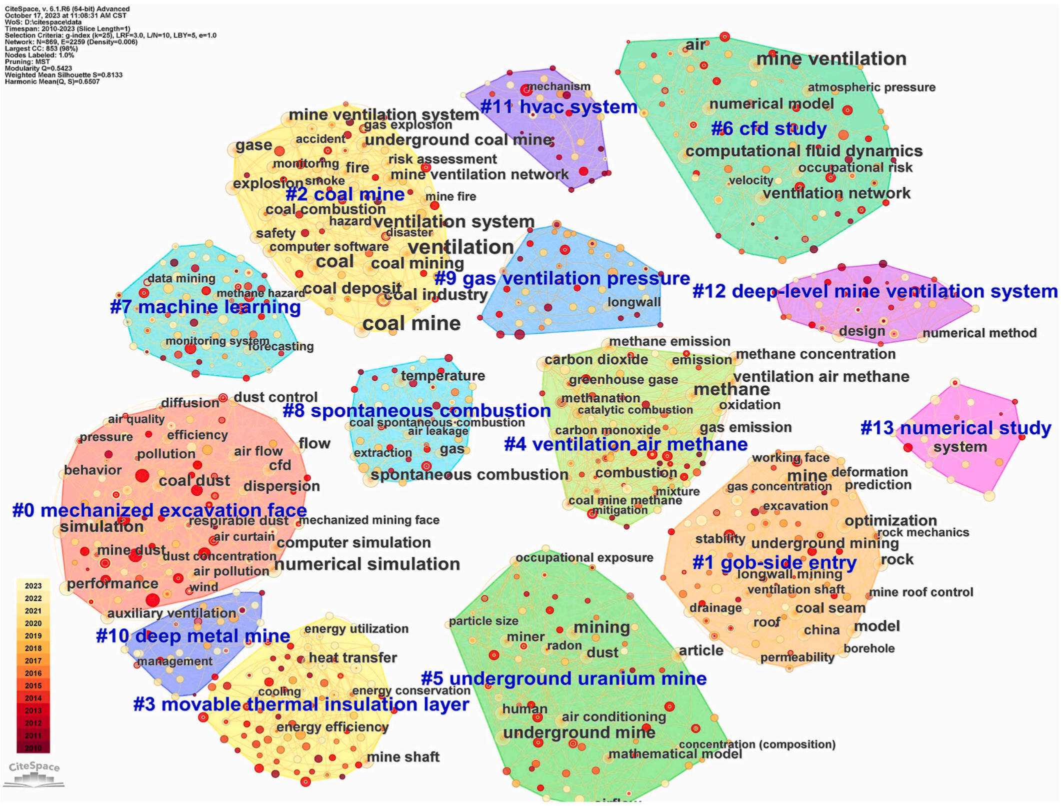

Fig. 8. Keyword clustering map.

Table 9
Information of the top 14 keyword clusters.

ClusterID	Size	Silhouette	mean (Year)	Top Terms(log-likelihood,p-level)
0	92	0.828	2016	mechanized excavation face; tunnel excavation; mechanized mining face; dust diffusion; dust removal
1	88	0.805	2015	gob-side entry; case study; stability analysis; heading face; methane production performance
2	86	0.816	2013	coal mine; gas explosion; underground coal mine; gas outburst; major thermodynamic disaster
3	80	0.803	2015	movable thermal insulation layer; excavation engineering; high temperature tunnel; heat hazard control; geothermal energy
4	78	0.834	2014	ventilation air methane; coal mine ventilation air; heat recovery; gas engine; catalytic combustion
5	76	0.786	2015	underground uranium mine; radon exposure; case report; full atrioventricular block; acute poisoning mercury
6	74	0.761	2014	cfd study; using exhaust curtain ventilation; automatic switchover; low ventilation velocity; smoke sensor
7	67	0.798	2016	machine learning; energy consumption; multi-domain airflow modeling; ventilation characterization; using mobile robot
8	46	0.772	2015	spontaneous combustion; smoke movement; spontaneous coal combustion; shallow-buried gob; hazardous areas determination
9	44	0.838	2015	gas ventilation pressure; airway airflow; underground ventilation; unconventional gas; sheared gas
10	35	0.863	2018	deep metal mine; refrigeration ventilation system; dust variation; underground historic salt mine; using specialized program
12	33	0.83	2014	deep-level mine ventilation system; cylindrical deadlock area; heat transfer prediction; thermal parameter; high temperature mine
11	33	0.874	2014	hvac system; feed coal; co ratio; discharging fuzzy model; event-driven strategy
13	21	0.9	2019	numerical study; temperature distribution; fire behavior; connection roadway fire; driving force

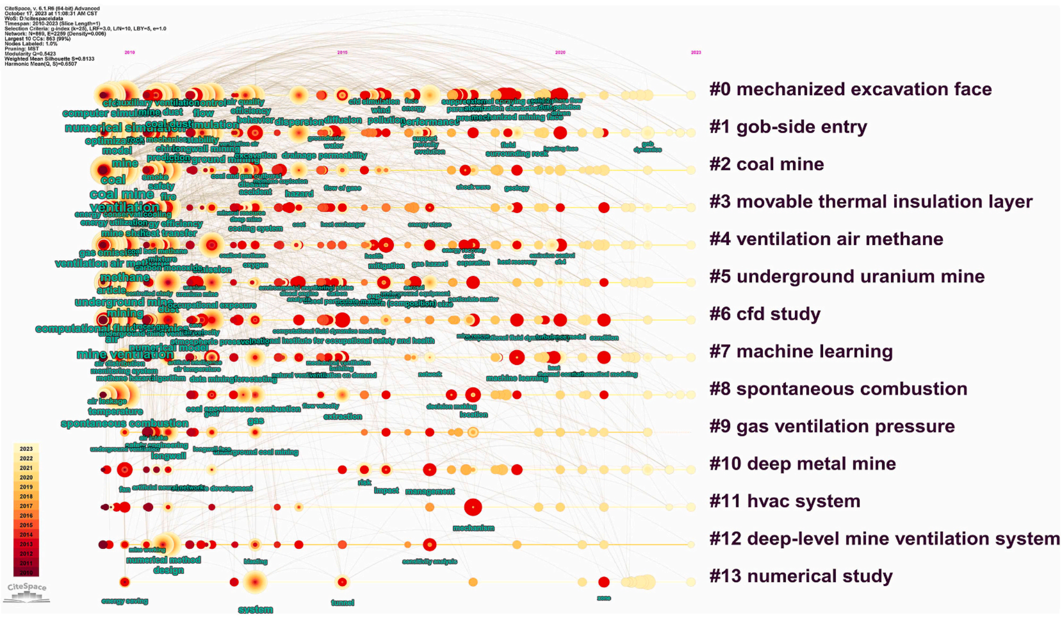

Fig. 9. Mine ventilation topic timeline graph.

research. In terms of the years of research, Cluster #13, "numerical study occupant behavior" although appearing in 2018 and being relatively late, gained substantial cluster capacity. Numerical simulations, due to their cost-effectiveness and the advantages of delivering faster and more precise results, have made "occupant behavior" a recent research hotspot and a new direction in the field of mine ventilation.

3.4.3. Topic evolution study

The timeline graph plays a significant role in understanding the development trends in a research field. Through visual representation, it provides a clear and coherent display of the evolution and trends of topics and keywords over time, enhancing scholars' understanding of the patterns of disciplinary changes. Fig. 9 presents the timeline graph of the top 9 topic clusters in mine ventilation. The clustering labels are derived from titles, abstracts, keywords, and various sources. The labels for clusters 0–13 are "mechanized excavation face", "gob-side entry", "coal mine", "movable thermal insulation layer", "ventilation air methane", "underground uranium mine", "cfd study", "machine learning", "spontaneous combustion", "gas ventilation pressure", "deep metal mine", "hvac system", "deep-level mine ventilation system", and" numerical study ", respectively. Fig. 11 consists of 869 nodes, and 2259 links, with a network density of 0.006. The modularity value (Q value) is 0.5423, and the average silhouette value (S value) is 0.8133, indicating good clustering results that allow for preliminary analysis.

In Fig. 9, the labels of the nodes represent keywords, and the size of the nodes represents the frequency of occurrence. The larger the node, the more frequently the keyword appears, indicating its greater importance in the field. The appearance of nodes within the time interval represents the year of their first occurrence. Using a unique functionality in CiteSpace, the centrality of the nodes is calculated. The outer circles of nodes with higher centrality are colored purple. In Fig. 9, the most frequent occurrences are "mine ventilation" and "coal," suggesting a primary focus on coal mines in mine ventilation research, with limited exploration into other metal and non-metal mines. The research focus appears to be overly narrow, and "face" and "deep mine" have become the primary areas of investigation. Additionally, "computational fluid dynamics" and "data mining forecasting" have emerged as the predominant research methods. Given the inherent hazards in underground working environments, numerical simulations and intelligent forecasting are the primary means for studying underground pollution and its associated risks. "Spontaneous combustion", "methane", "dust", and "hazard" appear with relatively high frequency in the graph. These elements represent the major sources of pollution in underground operations and are pressing issues in the current research landscape of mine ventilation.

The timeline graph provides a detailed and accurate analysis of research trends within the academic field, where the density of nodes reflects the evolving status of respective research areas. In Fig. 9, it can be observed that for Cluster #0, "mechanized excavation face" this research topic has consistently received significant attention, making it one of the focal points in mine ventilation research. Cluster #10, "deep metal mine" emerged as a hotspot in the field of mine ventilation in 2010, but after 2012, it experienced a gradual decline in attention. However, in 2015, it once again became a prominent research focus, with sustained high levels of attention. Consequently, between 2010 and 2023, the research on "deep metal mine" exhibited a trend characterized by peaks, troughs, and sustained peaks. Following this trend, it is likely that this cluster will continue to hold a significant position in mine ventilation beyond 2023. Cluster #9, "gas ventilation pressure" displays a cooling trend in research. As the years progress, the node density gradually decreases, indicating reduced attention and significance from scholars. Conversely, Cluster #13, "numerical study" exhibits a warming trend, suggesting an increasing level of interest and importance among researchers.

The timeline graph for mine ventilation in 2010, as shown in Fig. 10, reveals that keyword collaboration was not very close during that year. It had the lowest keyword collaboration from 2010 to 2023, indicating a period of concentrated and singular research focus. In contrast, 2023 is depicted as the year with the most extensive keyword collaboration in the field of mine ventilation (Fig. 11). The keyword network collaboration in 2023 is notably complex, with almost every node from Fig. 9 having common occurrences. Combined with cluster labels, it is evident that research was conducted across various areas and directions within mine ventilation in 2023, making it the most flourishing year for mine ventilation research.

In summary, from 2010 to 2023, the field of mine ventilation research evolved from initial recognition to becoming a prominent research hotspot within numerous disciplinary domains. An increasing number of scholars have contributed to the field of mine ventilation, resulting in the gradual improvement and maturation of the mine ventilation development system.

3.5. Research topic analysis

To further explore the research status, hot topics, and development trends in the field of mine ventilation, a systematic analysis of

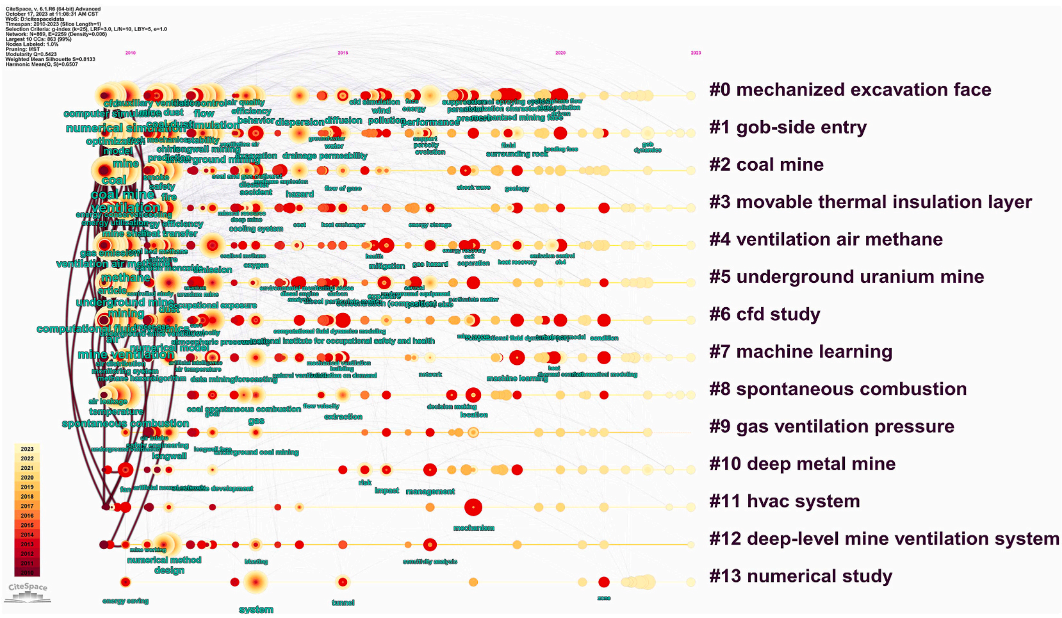

Fig. 10. Mine ventilation timeline graph for the year 2010.

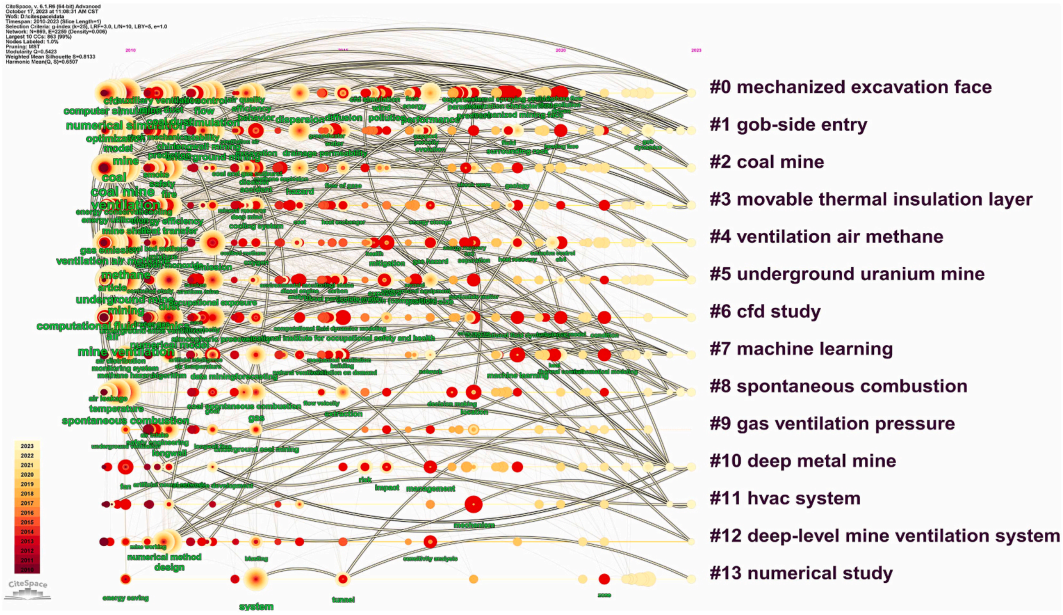

Fig. 11. Mine ventilation timeline graph for the year 2021.

literature metrics was conducted, including analysis of publication time, co-authorship, co-citation, and keyword analysis. Based on these analyses, combined with a systematic literature review and summarization, the research topics in the field of mine ventilation were classified, analyzed, and categorized, considering three aspects: high-frequency keywords, keyword grouping, and clustering results.

1) High-Frequency Keywords

In Section 3.4.1, an analysis was conducted on the most frequently occurring keywords in the field of mine ventilation. These keywords include ventilation, coal, mine, numerical simulation, methane, computational fluid dynamics, air, coal industry, coal deposit, mine ventilation system, ventilation network, spontaneous combustion, computer simulation, mathematical model, three-dimensional, external spraying system, mechanized mining face, air curtain, underground mine, dust, heat transfer, methane emission, machine learning, deep metal mine, deep-level mine ventilation system, data mining, artificial intelligence. Following the logical framework of the discipline, these high-frequency keywords were combined and duplicates were removed, resulting in seven groups of keywords, as shown in Table 10.

2) Keyword Grouping

As presented in Table 10, Word Group 1 revolves around "ventilation system" and "ventilation network", which can be combined to represent the field of "mine ventilation systems and networks". Word Group 2 primarily includes terms such as "mine", "coal", "underground mine", "coal industry", "coal deposit", and "deep metal mine" indicating a focus on "deep mine ventilation". Word Group 3 predominantly involves 3D computer numerical simulations, with the main software being "computational fluid dynamics". Since numerical simulation is a research method and tool rather than a research subject, it is not categorized further. Word Group 4 represents mathematical models, "machine learning", "data mining", and "artificial intelligence" related to data analysis within mines in a big data context. The combination of big data and mathematical methods, along with the application of artificial intelligence in mine ventilation, can be summarized as "intelligent mine ventilation". Word Group 5 can be directly summarized as "remove dust using

Table 10
Group of keywords.

Word Group	Keywords、
1	Ventilation system; ventilation network; ventilation
2	Mine; coal; coal industry; coal deposit; underground mine; deep metal mine; deep-level mine ventilation system
3	Computer simulation; computational fluid dynamics; three-dimensional
4	Mathematical model; machine learning; data mining; artificial intelligence
5	External spraying system; air curtain; dust; air
6	Air; methane; methane emission
7	Spontaneous combustion; heat transfer; longwall ventilation

ventilation". Word Group 6 primarily deals with gas emissions and can be summarized as "gas control through ventilation". The content within Word Group 6 is complex and encompasses various other research areas.

3) Validation of Cluster Results

Based on the aforementioned logical relationships, we have categorized six research themes in the field of mine ventilation: "mine ventilation systems and networks", "deep mine ventilation", "intelligent mine ventilation", "gas control through ventilation", "remove dust using ventilation", and additional topics. During the keyword clustering analysis in section 3.4.2, these six research themes are referenced in Fig. 8, the keyword clustering diagram, and the cluster information presented in Table 9.

Therefore, based on high-frequency keywords, disciplinary logic, clustering results, and a comprehensive literature review, this paper categorizes research topics in the field of mine ventilation into six themes: "mine ventilation systems and networks", "deep mine ventilation", "intelligent mine ventilation", "gas control through ventilation", "remove dust using ventilation", and additional topics.

4. Discussion

In this paper, we conducted a visual analysis using CiteSpace on 5,226 research documents related to mine ventilation spanning from 2010 to 2023. These documents were collected from Web of Science and Scopus databases. These documents include 4,593 articles, 561 proceedings papers, and 66 reviews. The majority of the articles in the field of mine ventilation are scientific research, accounting for 87.9% of the total publications. This is due to the increasing awareness of underground safety and health, making mine ventilation a prominent focus of attention. As a result, an increasing number of scholars have dedicated their efforts to research in mine ventilation, aiming to minimize and even eliminate the occurrence of hazardous incidents.

From the perspective of publication time, mine ventilation research from 2010 to 2023 has experienced three distinct phases: stable development (2010–2013), slow growth (2014–2017), and rapid expansion (2018–2022). Between 2010 and 2013, the number of publications on mine ventilation was relatively low each year, but it maintained a continuous growth trend. The highest number of publications occurred in 2013, with 151 papers. From 2014 to 2017, the number of publications fluctuated, indicating an unstable trend. During this period, researchers didn't seem to pay significant attention to the field of mine ventilation. The highest number of publications in 2017 reached 259 papers.

Starting in 2018, the number of publications in the field of mine ventilation significantly increased compared to the preceding two periods. The development trend became more robust, making it a key research area. In 2018, the 11th World Mine Ventilation Congress was held for the first time in China, and 113 papers were rigorously selected for publication and inclusion in EI. This event marked the internationalization of mine ventilation research. In this context, in 2019, the China National Coal Mine Safety Administration published the "Key Research and Development Catalog for Coal Mine Robots", driving a technological revolution in coal mining and promoting high-quality development in the coal mining industry. This initiative played a pivotal role in advancing and stimulating research in mine ventilation.

Furthermore, under the updated United Nations Framework Convention on Climate Change, starting from June 5, 2020, nations and businesses worldwide initiated the "Race to Zero" campaign, linking energy conservation and emissions reduction with mine ventilation. This development has stimulated progress in the field of mine ventilation [63]. In 2021, during the 23rd China Mining Congress, the International Mining Research Center of the Ministry of Natural Resources, China Geological Survey, released the "Global Mining Development Report (2020–2021)". The report highlighted how climate change is driving the transformation of human production and lifestyle towards low-carbon practices. It also emphasized that global mineral resource supply-demand structures and mining patterns are undergoing significant changes. This shift is influencing research directions and hot topics in mine ventilation, gradually moving towards energy conservation and deep-sea mining, opening up new avenues for development in the field [64]. In 2022, the International Committee for Mineral Reserves Reporting (CRIRSCO) held a special meeting in China, which facilitated the development of mining capital markets and international mining collaborations. This event is expected to usher in a new wave of interest in mine ventilation research in the coming years.

Throughout the entire research process, the co-authorship analysis in CiteSpace revealed that from 2010 to 2023, China has contributed significantly to the field of mine ventilation, with a publication count of 1649, constituting 42% of the total global publications. Seven out of the top ten institutions with the highest publication counts worldwide are based in China, and all of the top ten authors with the highest publication counts are also Chinese. China University of Mining and Technology holds the distinction of being the institution with the highest publication count globally and maintains close collaborations with various other small and mid-sized institutions, forming a complex network structure. This phenomenon is attributed to China's status as the world's largest industrial nation, leading to a continuous rise in demand for mineral resources. Additionally, China's transition from an industrial giant to an industrial powerhouse is expected to drive the growth of strategic emerging mineral resource demands [65].

In the context of the national background and policy environment, China places a heigh emphasis on research and development in the field of mine ventilation. For instance, Nie Wen and Li Z have collectively contributed a significant number of publications, totaling 56 between 2010 and 2023. Among these, Nie Wen's work, "Simulation experiments on the controllability of dust diffusion using multi-radial vortex airflow" stands out with an impressive citation count of 56, establishing itself as a core publication in the field of mine ventilation. Despite Canada's relatively lower total publication count of 159 during the same period (2010–2023), it achieves a remarkable intermediary centrality score of 0.14, securing the top position globally. Canada serves as a critical node in the field of mine ventilation, with the majority of countries engaging in direct or indirect collaborations. This is primarily due to Canada's status as a mining powerhouse. Whether considering the challenging mining environments or deep mining operations, Canada's mining technology is at the forefront on a global scale [66,67].

Therefore, with regard to the enhancement of mining technologies, nations must bolster their collaborative efforts. Furthermore, to promote the comprehensive and rapid development of the academic field of mine ventilation, Canada should strengthen its connections and collaborations with other nations. Together, they can address pertinent technological challenges. Poland, situated at the crossroads of the "Amber Road" and the "Silk Road" and renowned for having one of the richest reservoirs of mineral resources in Central Europe, radiates the influence of its mineral products across the markets of several Central and Western European countries [68]. This is attributed to Poland's unique geographical location and abundant mineral resources. Both Silesian Tech Univ and AGH Univ Sci & Technol in Poland rank among the top ten institutions globally in terms of publication output, underscoring Poland's significant position in mine ventilation research.

As a result, fostering the flourishing development of the mine ventilation field requires encouraging international collaboration among countries and institutions on a global scale. This will facilitate the exchange of ideas, the generation of new concepts, the development of innovative technologies, and collective efforts to surmount the challenges within the field of mine ventilation research.

In the analysis of CiteSpace's co-authorship, keyword, and research topic evolution, this paper categorizes the field of mine ventilation research into six main research themes for analysis: mine ventilation network systems, deep-level mine ventilation, intelligent mine ventilation, gas ventilation management, ventilation and dust control, and additional topics.

(1) Mine Ventilation Systems and Networks

In Section 3.4.1, during the analysis of key terms related to mine ventilation, the research on mine ventilation systems exhibited a strong prominence, ranking third in the overall field of ventilation research. The emergence of this research theme was consistent from 2010 to 2014. The term "ventilation system" appeared a total of 423 times in the literature from 2010 to 2023. Therefore, the study of ventilation systems and networks constitutes a vital component of the mine ventilation field.

Mine ventilation systems transport fresh surface air to underground areas, diluting or removing toxic and harmful gases and dust, thereby providing a relatively safe and comfortable working environment for underground operations [69,70]. The primary focus of investigating ventilation systems involves conducting detailed analyses and hazard assessments of these systems, followed by implementing necessary improvements. For instance, Hu and Li through their analysis of radon control ventilation systems in Chinese uranium mines, compared the strengths and weaknesses of various ventilation systems in radon control and presented existing issues and corresponding improvement measures [71]. Cheng and Yang, using a quantitative approach, introduced a novel comprehensive early warning model for mine ventilation systems to evaluate and enhance their safety [6]. Develo et al utilized Ventsim software to conduct a simulation analysis of the ventilation system in the western mining area of Rosh Pinah zinc mine. They proposed an improvement plan that significantly enhanced the ventilation conditions at the Rosh Pinah zinc mine [72]. When performing comprehensive analyses and assessments of mine ventilation systems, conventional methods, and tools often struggle to deliver rapid results and efficiency in analysis and evaluation. Furthermore, they often lack effective means of visualizing the outcomes. Therefore, Jundika C. Kurnia et al. implemented improvements to the existing mine ventilation system, introducing an innovative intermittent airflow ventilation system [49]. They evaluated Computational Fluid Dynamics (CFD) simulations, resulting in energy savings of over 25%. This paper ranks eighth in terms of burst strength in CiteSpace's citation analysis. The combination of conventional mine ventilation analysis methods with numerical simulations is crucial for mine ventilation system analysis, providing an important reference for scholars in the mine ventilation field to delve deeper into.

The optimization and improvement of ventilation systems and networks serve a dual purpose. Firstly, they aim to enhance the working conditions within the mine, ensuring the safety and stable development of miners and the underground environment. Secondly, these improvements are intended to reduce energy consumption, achieving environmental conservation and energy efficiency goals. In mine ventilation systems, the primary choice for achieving energy savings is the implementation of different ventilation methods based on specific ventilation requirements. In Section 3.4.3, within the analysis of mine ventilation topics, it can be observed that the "energy saving" theme in Cluster #13 had already become a research hotspot in mine ventilation back in 2010. Over time, it gradually integrated with "system" and "tunnel" for in-depth analysis and exploration of mine ventilation issues. As a result, scholars primarily achieve on-demand ventilation by adjusting fan speeds and optimizing ventilation systems. For instance, Nel et al. conducted an evaluation of ventilation energy consumption and greenhouse gas emissions in ten South African mines with constant-speed main fans and variable-speed drives (VSD) [73]. The results indicated that the installation of VSD could save 179,421 MWh of electricity annually and reduce greenhouse gas emissions by 53%. Jia et al. introduced rapid, precise, and on-demand adjustment algorithms, enabling the fast, accurate, and on-demand regulation of intelligent mine ventilation systems [74].

The term "ventilation network" has appeared 183 times in the co-occurrence of keywords in Section 3.4.1 since 2010, indicating its significant relevance and frequency in the discourse. Research on mine ventilation networks represents an abstract study of the overall mine ventilation system. Scholars typically investigate network topology relationships, network models, software, or algorithms for solving network models, as well as aspects like unsteady flow solutions in ventilation networks, airflow distribution, and circulation airflow angles. Therefore, research on mine ventilation networks primarily focuses on simulating and optimizing ventilation networks and developing computational and algorithmic solutions. Jia et al. proposed independent path algorithms and improved adaptive genetic algorithms for modeling, optimizing, dealing with, and hierarchically partitioning ventilation networks [75]. Their work offered an intuitive and quantitative representation of ventilation network characteristics. Dziurzynski used VentGraph software to simulate and solve mine ventilation networks, thereby validating the mathematical models employed within VentGraph [76]. Zhong et al. introduced an improved MICL algorithm, addressing issues such as divergence and slow convergence in complex ventilation networks [77]. Shalimov improved the loop flows algorithm to calculate and simulate airflow distribution in emergencies using a quasi-steady-state approximation [78]. Huaming et al. proposed the use of a depth-first search algorithm to assist ventilation engineers in accurately and rapidly determining the positions of circulating airflow [79].

During the research on mine ventilation systems and networks, the primary methods employed have been algorithmic solutions and numerical simulation and modeling. However, as technology and knowledge continue to advance, there is a growing inclination to use more efficient visualization methods to provide a vivid contrast between the conditions before and after improvements. At present, there are relatively few visualization software options specifically designed for showcasing mine ventilation and network simulations. Scholars in the field of mine ventilation can benefit from combining various visualization software tools with interdisciplinary collaboration and a combination of methods, which can yield unexpected and valuable insights. This approach can significantly contribute to the advancement of research in the field of mine ventilation.

Furthermore, even though research on mine ventilation systems and networks is thriving, the existing body of work typically involves the continuous improvement of existing algorithms. There is a need for more innovative approaches, and developing novel algorithms may lead to better and more efficient solutions for solving mine ventilation networks.

(2) Deep Mine Ventilation

In the co-citation analysis based on titles, the term "deep mine" first appeared in 2020, and it already has a cluster size of 52. It is most closely associated with terms such as "deep metal mine", "refrigeration ventilation system", "heat transfer characteristics", "high-temperature tunnel", and "movable thermal insulation layer". In the co-occurrence of keywords, terms like "coal industry", "coal deposit", "heat transfer", and "temperature" are the most frequent, indicating that the current primary research focuses on deep mine ventilation is on thermal environment regulation.

In the topic analysis, Clusters #3, #10, and #12 all include content related to deep mine ventilation research. Within Clusters #3, #10, and #12, it is evident that research on deep mine ventilation has been a consistent hotspot in the field of mine ventilation, with a specific emphasis on regulating the thermal environment in deep mines. This is because, with the gradual depletion of shallow mineral resources and the continuous improvement in mining technology and equipment, mining activities are moving deeper underground. Deep mining is poised to become a critical form of resource development, and the management of high-temperature thermal issues in deep mines is a significant challenge [80].

Mine ventilation plays a vital role as the primary non-artificial cooling technology[81]. For example, Parra et al. conducted a detailed analysis of the performance of three ventilation systems in deep mine environments using numerical simulation [82]. Xu et al. systematically studied the impact of ventilation duration on the underground thermal environment through numerical simulation [83]. Shuiping et al. analyzed the insulation performance of double-layer air ducts to address the issue of high temperatures at deep mine excavation faces using ANSYS software [84]. Tianyang Wang et al. estimated heat dissipation in deep mine environments based on on-site measurements and numerical simulation, leading to optimized ventilation distribution in deep mines [85].

However, in deep mines, the cooling process through mine ventilation involves high costs and low efficiency. Therefore, in the field of mine ventilation, it is essential to consider how to reduce costs and improve ventilation efficiency while lowering temperatures in deep mines. Additionally, in the practice of managing heat hazards in high-temperature tunneling operations, the removal of toxic and harmful gases and dust after blasting activities must be considered. For instance, Hebda-Sobkowicz et al. proposed a signal segmentation program for long-term monitoring of H_2S concentrations in deep mines [86]. They also performed visual data analysis and found that variations in H_2S data are significantly influenced by the ventilation operating system. Therefore, visualizing and real-time monitoring of the high-temperature heat hazards and high-concentration pollutant areas in deep mines will be a challenge that needs to be addressed in the future development of deep mine ventilation.

(3) Intelligent Mine Ventilation

In the author co-citation analysis, terms like "multi-objective intelligent decision" and "linkage control algorithm" frequently appear in Cluster #8, while "using mobile robot" is identified in Cluster #7 within the keyword co-occurrence analysis. In the topic analysis, "data mining" emerged as a research hot topic as early as 2013. Renowned author Zhou Fubao, a key figure in the author co-authorship network in the field of mine ventilation research, mentioned in the paper "Research progress of mine intelligent ventilation theory and technology" that mine ventilation systems have undergone three stages: from mechanical ventilation to localized intelligent ventilation and finally to global intelligent ventilation [87].

In recent years, with the advancement of automation and intelligence, mining practices have gradually shifted from "traditional mining" to "smart mining". Informatization and intelligence have become an inevitable trend for the healthy development of mines. Ventilation, as a fundamental component of mine safety, is now required to be more accurate, timely, comprehensive, and reliable in the context of automation. Intelligence is the mainstream direction for the future of mine ventilation [88]. Intelligent mine ventilation involves supplying fresh air to mines on-demand, continuously and economically, through intelligent control. This ensures that the air is stable and suitable for respiration, dilutes and removes harmful gases and dust, and enhances the mine's climatic conditions. Additionally, it enables intelligent airflow control during rescue operations. For a long time, ensuring reliable ventilation, effective monitoring, and efficient management has posed a significant challenge in mine ventilation. The fundamental prerequisite for intelligent mine ventilation is the efficient and accurate collection of various underground information.

Therefore, the key focus in the future of mine ventilation research is the high-precision improvement and development of underground sensors. This involves enhancing the sensitivity and applicability of existing sensors, strategically placing sensors, and optimizing their deployment positions. This allows for more precise monitoring of various ventilation parameters in underground settings. For instance, Jha and Tukkaraja employed sensors and GIS to monitor typical ventilation parameters in underground mines, thereby improving the accuracy of underground climatic condition information [89]. Shriwas and Pritchard have also reviewed the challenges and research gaps in mine ventilation monitoring and control systems, providing suggestions and insights for the development of ventilation monitoring [90].

To address these challenges, ZHOU developed a high-precision line segment wind speed sensor using the ultrasonic time-of-flight method, achieving a measurement accuracy of less than 0.1 m/s throughout the process [91]. Liang et al. determined the optimal heating temperature for infrared methane sensors in coal mines and proposed an error optimization analysis method, enabling the precise detection of CO_2, CH_4, and CO concentrations under various environmental conditions in coal mines[92]. G. Chen et al. introduced a chain-based wireless underground sensor network capable of monitoring the environment and locating miners in underground mines [93]. Thirumal and Kumar combined two sensor deployment methods, multilevel and grid, which enhanced the lifespan and energy efficiency of the ventilation network and increased the precision of underground parameter monitoring [94]. Additionally, timely analysis and processing of dynamically collected information underground, making corresponding decisions, promptly regulating airflow, diagnosing abnormal information, and issuing warning signals pose research challenges in the field of intelligent mine ventilation.

Therefore, adjusting airflow based on monitored underground ventilation parameters, integrating with actual underground conditions for more accurate regulation of airflow, optimizing ventilation control methods, improving the utilization of underground airflow, achieving on-demand ventilation, and reducing energy consumption are the future research challenges in intelligent mine ventilation.

FAN conducted modeling and analysis of ventilation system data, achieving ventilation performance assessment and ventilation data prediction, with results presented in a visual format [95]. Zhou et al. developed an industrial Internet of Things (IoT) monitoring and control prototype system [96]. This system can detect the opening of doors in alternative shelter solutions, issue corresponding alarm signals, and dynamically adjust airflow in real time based on underground conditions.

The development of ventilation control software is a focal point in the research on future intelligent ventilation. Ventilation control software effectively addresses technical challenges such as low accuracy in measuring underground ventilation parameters, poor timeliness in network calculations, difficulties in assisting airflow control decisions, and insufficient capabilities of intelligent airflow control equipment. The key focus in the development of ventilation control software lies in accurately monitoring, regulating, deciding, and optimizing underground ventilation systems and various parameters based on the actual conditions of the mine. Currently, ventilation control software like Ventsim and GinVent has been developed and is already in use. Noteworthy researchers K. Wang et al., in the paper titled "Intelligent safety adjustment of branch airflow volume during ventilation-on-demand changes in coal mines," addressed the frequent changes in branch airflow volume during on-demand ventilation [97]. They achieved this by monitoring the airflow in the smallest remaining branches of the ventilation network and developing automatic ventilation system adjustment software.

In the era of big data and information technology, intelligent mine ventilation has become an inevitable trend in the future of mine ventilation. It differs significantly from traditional labor-intensive mine ventilation. Intelligent mine ventilation is poised to make substantial strides in "enhancing safety, reducing human intervention, and improving efficiency". This will involve achieving a ventilation model characterized by "unmanned monitoring and sensing, intelligent analysis and decision-making, and remote control and coordination automation".

(4) Gas Control Through Ventilation

In the analysis of authors' co-citations, "methane production performance" ranks seventh among all clusters. In Section 3.4.1, covering the period from 2010 to 2023, "methane" appeared 397 times, ranking as the seventh most frequent keyword in mine ventilation research. In the keyword theme analysis, Cluster #4, known as "ventilation air methane" has consistently been a focal point of mine ventilation research from 2010 to 2023. Throughout the thematic analysis, terms such as "gas emission", "coalbed methane", "energy recovery", and "emission control" emerge as prominent research keywords in the field of gas ventilation management.

Therefore, gas ventilation control is primarily analyzed and discussed in two aspects: gas emission behavior and control. To prevent the hazards associated with the accumulation of high gas concentrations, scholars in the field of mine ventilation primarily employ a combination of Computational Fluid Dynamics (CFD) and on-site measurements to explore the behavior and distribution of gas in underground mines. This approach aims to control gas behavior at its source and reduce gas concentrations.

For instance, Toraño et al. analyzed gas behavior in underground mines using a combination of CFD numerical simulations and on-site measurements [98]. They identified hazardous areas with high gas concentrations in the mine. Chen et al. used CFD modeling to construct a physical model containing three goaf areas and studied the optimal air volume for safe production[99]. Lu, based on fluid dynamics, analyzed the distribution patterns of gas concentrations in the working face [100]. By altering the ventilation parameters and face conditions, effective control of gas concentrations in mines was achieved. Hasheminasab et al. employed numerical simulations to investigate the ventilation performance of underground mine working areas exposed to methane gas [101]. They found that the use of air-blocking devices and fans effectively reduced gas concentrations in the single-heading development area.

The main measures for gas ventilation control involve first identifying hazardous areas with high gas concentrations. Subsequently, based on the determined tunnel conditions, adjustments and optimizations are made to the existing ventilation parameters to efficiently remove gas.

Consequently, in the future and for an extended period, the emission, diffusion behavior, and governance of gas will be the primary research focus in gas ventilation management. Through a detailed analysis of gas emission and diffusion behavior, precise determination of disaster-prone areas and their severity can be achieved, aiding in the governance and prevention of underground gas incidents. The main research methods for gas ventilation management primarily focus on the optimization and selection of ventilation parameters, ventilation devices, and ventilation systems. Therefore, there is hope that future research will explore new perspectives or aspects of gas control through ventilation.

(5) Remove Dust Using Ventilation

In CiteSpace's co-citation analysis, 9 out of the top 10 most frequently cited papers are related to dust prevention and control. Among the papers with the highest burst strength, 7 are associated with research on dust. In the ranking of centrality, 9 out of the top 10 papers are focused on dust research. Within the important 30 papers in the field of mine ventilation, literature related to dust research constitutes 83%.

With the increasing mechanization of mining processes, a significant portion of the dust generated during mining operations tends to accumulate near the mining face. This not only poses serious health and safety risks to miners but can also lead to dust explosions, posing a severe threat to underground safety. Therefore, the dilution and removal of underground dust have become focal points of research in the field of mine ventilation.

Prominent scholars in the field of mine ventilation, such as Nie Wen and Liu Qiang, have conducted research on the dispersion patterns and control measures of dust at mining faces. For instance, Liu et al. [17] used Computational Fluid Dynamics (CFD) methods to simulate and analyze the impact of an air curtain generator on the dispersion and pollution behavior of underground dust. This research contributed to the enhancing dust control performance of air curtains in tunnels. Nie et al. [43] utilized simulation modeling to analyze the transport of multi-radial vortex airflow and the dispersion patterns of dust, ultimately determining the optimal ventilation parameters that achieve a high dust removal efficiency of up to 90%.

Research on dust control primarily focuses on studying the dispersion behavior of mine dust and controlling dust pollution. The use of an air curtain is a key measure in preventing and controlling excessive dust concentration at mining faces. "Air curtain" first appeared in research in 2012 and has become a focal point in the field of mine ventilation for dust control. Research methods and tools mainly involve Computational Fluid Dynamics (CFD) numerical simulations, as indicated in Table 11.

The thematic analysis reveals that "dust" was initially associated with class Cluster #6, titled "cfd study" in 2012. Over the years from 2010 to 2023, it becomes evident that the primary research direction in dust control has shifted from investigating dust dispersion behavior to controlling the dispersion of dust. Accurate analysis and prediction of the underground dust dispersion and migration patterns enable precise identification of areas with high dust concentrations and pollution levels. This, in turn, enhances the accuracy of underground ventilation and dust control, optimizing airflow utilization and reducing the risk of injuries to underground workers.

In addition to research on air curtains, adjusting ventilation parameters in mine ventilation is another focal point of dust concentration control research. For instance, Wei et al. conducted an in-depth study and analysis of flow patterns and dust transport characteristics under various ventilation parameters, using a combination of similarity experiments and numerical simulations [102]. Xie et al. employed a combination of numerical simulations and field experiments to analyze the impact of the installation position of the push-pull fan on the airflow and dust transport behavior in the roadway [103]. Chang et al. utilized Computational Fluid Dynamics (CFD) to explore the influence of fan length on dust concentration within the roadway and discovered that fans with a length 5 m longer than the actual duct length had superior dust removal performance [104].

Therefore, in the future, the primary means and methods of research on mine ventilation and dust removal will be concentrated for an extended period on the optimization and adjustment of mine ventilation parameters, underground ventilation equipment, and ventilation methods. This is also a key focus and challenge in the study of controlling dust dispersion through ventilation. However, exploring new development areas and trends in the control of high-concentration dust underground through additional perspectives or methods will be a future direction for ventilation and dust removal.

(6) Additional Topics

In mine ventilation research, in addition to the five major categories of ventilation network systems, intelligent mine ventilation, deep mine ventilation, gas ventilation management, ventilation, and dust control, there are also some smaller sub-branches. This

Table 11
Research topics and methods of the top 10 most cited papers.

Author	Research topic	Research methods.
Liu et al.[17]	**dust** air-curtain	CFD
Xiu et al.[37]	**dust** control air flow rates	CFD
Xu et al.[38]	methane	CFD
Cai et al.[39]	**dust** air-curtain	CFD
H. Wang et al. [40]	**dust** air-curtain	CFD
Yin et al.[41]	**dust** air-curtain	CFD
Liu et al.[42]	**dust** air-curtain	CFD
Nie et al.[43]	**dust** multi-radial vortex airflow	a self-designed simulation system
D. Chen [44]	**dust** wet dust-collecting net	CFD
Hua et al.[45]	**dust** spatial and temporal evolution	CFD

article classifies these smaller sub-branches under the category of "additional topics". Spontaneous combustion in coal mines is one of these smaller sub-branches. The term "spontaneous combustion" appeared 178 times between 2010 and 2023, emerging as a research hotspot in 2015. In the keyword clustering, class Cluster #8 contains 46 items, ranking as the 8th largest class cluster in the entire field of mine ventilation. The thematic analysis reveals that research related to class Cluster #8 has continued to garner attention from 2010 to 2023, Particularly during this period, issues concerning underground fires and spontaneous combustion have become focal points in mine ventilation research.

Underground fires and spontaneous combustion primarily occur in coal mines. This is because coal reacts with air, leading to oxidation and the generation of heat. When the airflow within underground coal seams is restricted, the coal becomes susceptible to spontaneous combustion, potentially resulting in fires. Therefore, improving the ventilation conditions in underground mines is essential to prevent and suppress coal seam spontaneous combustion. Gu et al. used numerical simulations and on-site measurements to identify areas at risk of spontaneous combustion in the roof coal. They further analyzed the temperature rise patterns in these combustion-prone areas [105]. Liang et al. employed simulation software, Ventsim, to model air leakage in goaf areas, revealing that ventilation simulations are a valuable tool for researching coal mine underground fire control [106]. Hansen enhanced the climatic conditions in mine work and investigated the impact of the ventilation system on mine fires [107].

Therefore, spontaneous combustion of coal seams frequently occurs underground. Mitigating the risk of underground coal seam spontaneous combustion through mine ventilation is a primary focus for scholars in mine ventilation. It is also a key area of study for mine ventilation scholars now and in the future.

Furthermore, "longwall" appeared twice in the theme research Cluster #9, indicating that longwall ventilation is also a research hotspot in the field of mine ventilation. For instance, Gangrade et al. developed a similar geometric model and conducted simulation analyses of longwall ventilation under different caving scenarios [108]. However, it's important to note that underground mine disasters often involve multiple hazards occurring simultaneously. For example, coal seam spontaneous combustion and gas explosions frequently happen together, and gas and dust are commonly found in the same areas. Therefore, scholars should consider other potential risks while studying a specific hazard. Multi-field coupling research is a significant trend in the future development of mine ventilation research.

For instance, Zheng et al. conducted a study through numerical simulations and similar experiments to explore the multi-field evolution and composite hazard levels during coal spontaneous combustion in goaf areas containing gas [109]. Cheng et al. used CFD simulation methods to perform a coupled analysis of gas and coal spontaneous combustion, determining the optimal approach for controlling underground gas disasters and fire risks [110]. Zhou et al. employed CFD numerical simulations to analyze the issue of excessive gas and dust in a certain mine, achieving effective dust containment within a low gas concentration range [111]. Xue et al. investigated and analyzed the airflow, gas, and dust migration patterns in the development drift and identified the optimal ventilation rate for the drift [112]. Wang et al. optimized fan parameters and found that the control effectiveness for dust and gas on the fully mechanized working face is highly dependent on the installation position of wall-mounted air ducts [113]. Thus, research on the coupling of various hazards, such as high temperature, high humidity, gas, and dust, has become a focal point in the field of mine ventilation, representing an important direction that scholars need to explore. Multi-field, multi-phase coupled research is a major trend in the future development of mine ventilation.

For example, Huang et al. employed CFD simulations to analyze the temporal and spatial variations of CO in high-altitude mines under different operating conditions, determining the extent to which various factors influenced these variations [114]. Liu utilized FLUENT software to compare and analyze the migration characteristics of radon concentrations in single-heading roadways under different ventilation methods [115]. This research provides valuable guidance for selecting appropriate ventilation strategies in practical mining operations.

Numerical simulation and analysis are currently the primary research methods and tools in the field of mine ventilation. However, most studies are based on the assumption of static mine ventilation conditions. In reality, mine environments are complex and constantly changing. Static simulations and analyses cannot fully capture the dynamic nature of ventilation in mines. Therefore, a significant technological challenge in the field of mine ventilation is to make numerical simulation and simulation techniques dynamic, enabling them to accurately represent the real-time ventilation conditions in mines. For instance, Krawczyk used CFD simulations to analyze the impact of the shearer machine's operation on gas diffusion and ventilation conditions in longwall mining [116]. Li et al. employed CFD simulations to analyze the transport patterns of dust and gas flows during the coal loading and unloading processes [117].

5. Conclusions

This study utilized bibliometric analysis software, CiteSpace, to analyze literature related to mine ventilation from 2010 to 2023. The analysis encompassed studies of publication trends, co-authorship networks, co-citation patterns, and keyword analysis. Additionally, the research classified the key topics within the field of mine ventilation, aiming to uncover the primary areas of study, emerging trends, and prospects from 2010 to 2023. The following conclusions were drawn.

(1) The publication of literature on mine ventilation from 2010 to 2023 experienced three distinct phases: steady growth, slow progress, and rapid expansion. Analysis using CiteSpace revealed that China Univ Min & Technol was the institution with the highest publication output globally. Nie Wen and Li Z contributed significantly, each producing 56 papers during this period. Notably, seven out of the top ten institutions by publication volume were from China, and all the top ten authors in terms of publication volume also hailed from China. China's contributions to the field of mine ventilation accounted for 42% of the

global publication output. In contrast, while Canada and Poland exhibited high intermediary centrality, they had relatively lower publication output. Most countries directly or indirectly collaborated with them. Hence, there is a need for mutual collaboration and synergy. Consequently, strengthening collaboration among nations, institutions, and authors is essential. By sharing expertise, generating innovative ideas, and developing new technologies, these collaborative efforts can collectively address the challenges in the field of mine ventilation research.

(2) China's network structure in the field of mine ventilation is complex, with numerous contributing institutions and authors, and a high degree of collaboration among these institutions. In contrast, other countries have simpler network structures in the field of mine ventilation, with fewer authors and institutions involved, and limited collaboration between them. This has not led to the formation of comprehensive mine ventilation networks. Overall, research in the field of mine ventilation appears to lack expansion and extension. Research topics and content are not sufficiently focused. In future developments, there should be a concentrated effort to explore and expand research content and themes in the field of mine ventilation.

(3) The scarcity of shallow mineral resources and the advent of the digital and information age have brought unprecedented opportunities for deep mine ventilation and intelligent mine ventilation. Future research in mine ventilation will focus on deep mine ventilation and intelligent mine ventilation. For deep mine ventilation, the key challenge and a major focus of future research is how to reduce costs and improve ventilation efficiency while lowering temperatures in deep mine environments. In the case of intelligent mine ventilation, the primary directions and goals for future research are "unmanned monitoring and sensing, intelligent analysis and decision-making, and automated remote control and coordination".

(4) The coupling of multiple disaster research is a new direction in the field of mine ventilation, and it has gained significant attention despite having fewer researchers involved. It's an area that the future of mine ventilation research needs to develop. In addition, numerical simulation and analysis are the primary research methods and tools in the field of mine ventilation. How to make numerical simulation and simulation technology dynamic to accurately reflect the actual ventilation conditions in mines is a technical challenge that the field of mine ventilation needs to overcome.

Additional information

No additional information is available for this paper.

Data availability statement

No data was used for the research described in the article.

CRediT authorship contribution statement

Yan Xue: Writing – review & editing, Writing – original draft. **Jinmiao Wang:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Jun Xiao:** Writing – review & editing.

Declaration of competing 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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