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RESEARCH ARTICLE

Spatial and temporal evolution of mine dust research: visual knowledge mapping analysis in Web of Science from 2001 to 2021

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Abstract
Dust pollution control is the basic guarantee of mine safety production, which has been widely concerned by scholars. Based on a total of 1786 publications collected by the Web of Science Core Collection (WOSCC) from 2001 to 2021, this paper analyzes the spatial–temporal distribution characteristics, hot topics, and frontier trends of the international mine dust field during the past 20 years by using Citespace and VOSviewer knowledge graph technology. The research shows that the study of mine dust can be divided into three stages: initial period (2001 ~ 2008), stable transition period (2009 ~ 2016), and boom period (2017 ~ 2021). The journals and disciplines which belong to mine dust research mainly focus on environmental science and engineering technology. A stable core group of authors and institutions have been preliminarily formed in the dust research field. The main themes of the study contained the whole process of mine dust generation, transport, prevention, and control, as well as the consequences of disaster. At present, the hot research fields mainly focus on mine dust particle pollution, multi-stage dust prevention, and emission reduction technologies, and mine occupational protection, monitoring, and early warning. In the future, the research should focus on the mechanism of dust production and transportation, the theory of efficient prevention and control, the technology and equipment of precise prevention and control of dust, and the high-precision monitoring and early warning of dust concentration. Future research should be concerned with dust control in underground mines and deep concave open-pit mines with complicated and treacherous environments, and strengthen research institutions, interdisciplinary cooperation, and interaction so as to promote the integration and application of mine dust and automation, information, and intelligent technology.

Keywords Mine · Dust · Bibliometrics · Knowledge mapping · VOSviewer · Citespace

Introduction

The mining of coal and metalliferous mines are the fundamental industries for the production of raw materials (Wang et al. 2019c), which play an important role in the world energy structure and economic development strategy (Liu and Liu 2020). With the improvement of mechanization, automation, and intelligence in mines, the degree of ore crushing is significantly increased, which aggravates the dust pollution in the mine workplaces and the occupational health risk of miners (Qi et al. 2020; Ullah et al. 2018). Simultaneously, with the gradual depletion of shallow mineral resources (Wang et al. 2022d), the exploitation of mineral resources step by step develops towards the environment with harsh geological and structural conditions such as high altitude, high ground temperature, and large buried depth (Wang et al. 2022e). The complexity of processes in the mine workplaces, the differentiation of equipment control strategies, and the perturbation of equipment coordination have raised higher requirements for clean (Nie et al. 2022) and healthy mining (Jordanova et al. 2021; Peng et al. 2022).

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Analysis of the sources and hazards of mine dust

The sources of mine dust in different mine working environments are different, and dust is often generated when mine ore is crushed. The main sources of dust in ore mining are drilling (Jiang et al. 2021a; Paluchamy et al. 2021; Wang et al. 2022c), blasting (Xie et al. 2022), unloading (Wang et al. 2020c), crushing (Chaulya et al. 2021; Silvester et al. 2007), transportation (Tian et al. 2019), lifting (Wang et al. 2019d), and screening (Chen et al. 2015c). The main dust sources of underground coal mining are coal mining (Chen et al. 2022a), tunneling (Wang et al. 2017), transportation (Chen et al. 2015b), and shotcreting (Chen et al. 2018b). The main dust sources in open-pit coal mines are perforation (Chen et al. 2015a), blasting (Wang et al. 2020a), loading (Zhao et al. 2021), transportation (Sinha and Banerjee 1997), and soil dumping (Du et al. 2022). All these operations are prone to generate a large amount of dust. Fine dust particles suspended in the air do not sediment with ease and cause air pollution (Lv et al. 2015). According to the data of the World Health Organization (WHO), mining, vehicle exhaust emissions, and industrial dust from construction are the main industries that cause air pollution, and the environmental pollution effect causes more than 4 million deaths worldwide every year (Guo et al. 2020). The heavy metals attached to the particles will flow into the soil, rivers, and biota with precipitation (Du et al. 2014; Liu et al. 2021; Zhang et al. 2021c), which causes soil contamination and ecosystem damage (Yang et al. 2018, 2021) and affects the marine biogeochemical cycle (Choobari et al. 2014).

Respiratory dust particles are easily inhaled into the respiratory system of miners (Cheng et al. 2023, Zeng and Li 2022), threatening the safety and health of miners, as shown in Fig. 1. Dust produced in the process of mining can enter the human body through the mouth, nose and throat (Morman and Plumlee 2013), and accumulate in the human lungs by virtue of gravity sedimentation, inertial impaction, diffusion, interception, and electrostatic deposition (Kreyling and Scheuch 2000). According to the particle size, the deposition area of dust in the respiratory system can be divided into head region, tracheobronchial region, and alveolar region (Lippmann and Albert 1969; Stahlhofen et al. 1980). In normal breathing environment, the structure of the mouth or nose and throat determines that particles with a particle size greater than 50 μm cannot enter the human body. Particles with a particle size of about 10 μm will be inhaled into the nose and deposited in the head region due to gravity settlement and inertial collision. Particles with a particle size of 5 ~ 10 μm are mainly deposited in tracheobronchial region. Dust particles with a particle size less than 5 μm will be sucked into the alveolar region and deposited in this region (Clayton and Clayton 1981; McIvor and Johnston 2016). Figure 1 also shows the functional relationship between the probability of dust particle deposition and the aerodynamic diameter of particles in different areas of the respiratory system (Hinds and Zhu 2022). It can be found that when the aerodynamic diameter of dust particles is greater than 4.5 μm, the deposition probability of dust particles in the lungs decreases rapidly (Stahlhofen et al. 1980). Dust particles smaller than 0.2 μm are mainly deposited in alveolar area of human lung (Shekarian et al. 2021).

Accumulation of mine dust particles in the human respiratory system will lead to an increased incidence of respiratory infections, atrophic rhinitis, and other respiratory diseases (Cheng et al. 2023; Liu et al. 2022). More importantly, the respiratory tract is a channel for gas exchange between the human body and the external environment. The dust deposited in the upper respiratory tract and the dust entering the

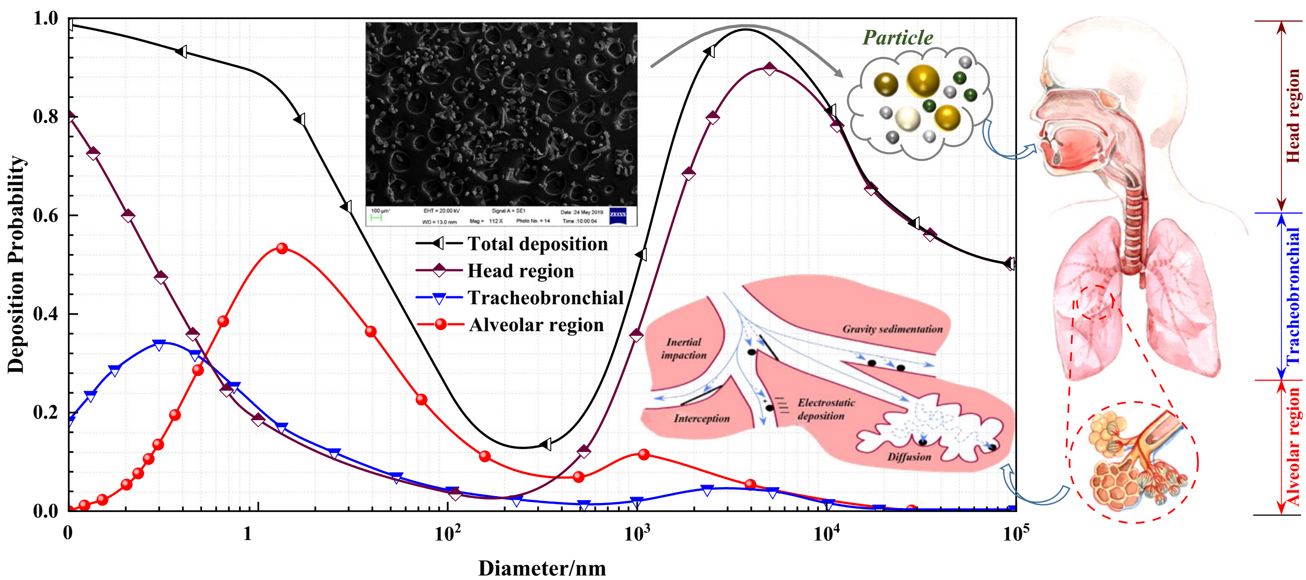


Fig. 1 Probability of sedimentation of mine dust in the human respiratory tract (Lippmann and Albert 1969, Stahlhofen et al. 1980)

lungs will cause fibrous lesions in human alveolar tissue and cause pneumoconiosis (Yu et al. 2018). According to the Annual Report on Occupational Disease Statistics issued by the National Health and Family Planning Commission, Fig. 2 shows the number and proportion of new occupational diseases and pneumoconiosis in China since 2001 (Jiang et al. 2021b). In 2021, the number of new occupational cases reported in China was 15,407, and the number of occupational pneumoconiosis was 11,809, accounting for 76.66%. It can be predicted that pneumoconiosis will remain the most harmful occupational disease in China in the next few years.

Apart from adverse health effects, the corrosive effect of dust particles will shorten the service life of lubricants in machinery and equipment and increase their maintenance costs due to excessive wear or premature failure (Wang et al. 2019d). Furthermore, excessively high dust concentration will affect the visibility of ore transport vehicles and increase the probability of traffic accidents (Ma et al. 2020, Wang and Jiang 2021). These hazards seriously threaten the safety of production and the health of mine operators. As a result, it is crucial to dilute and suppress the mine dusts to a safer level for preserving a safe and productive workplace environment in the process of mining.

Analysis of mine dust pollution and prevention technology

In the past two decades, research scholars have continuously explored and practiced the mechanism of dust generation, dust migration laws, and the environmental pollution effects of dust during the mining and transportation processes (Csavina et al. 2012, Fan and Liu 2021, Peng et al. 2018, Zhang et al. 2021a). Noble et al. (2017) analyzed the sources of dust emissions from metal-containing mines. Csavina et al. (2012) summarized the generation, dispersion, and deposition of dust particles in mining operations. Farmer (1993) summarized the physical and chemical properties of dust types in underground mining and open-pit mining, and also deeply analyzed the influence of dust particles on vegetation. Wang et al. (2020b) investigated the mechanism of impact airflow generation and the factors influencing the variation of dust concentration during unloading of the multi-level in high ore pass. Cheng et al. (2016) studied diffusion and pollution mechanisms of airborne dust in a fully mechanized excavation face at mesoscopic scale. Nie et al. (2022) simulated the dynamic dispersion pattern of dust in coal mine excavation working surface on the basis of computational fluid dynamics (CFD). Zhou et al. (2018) utilized numerical simulation to analyze the variation characteristics of airflow-dust diffusion rules during coal cutting in a fully mechanized coal mining face. Balabanova et al. (2011) revealed the distribution of atmospheric particulate matter concentrations and the extent of regional deposition of heavy metal elements in copper mining operations. Wang et al. (2019b) researched the source apportionment of heavy metals and their health risks in a soil-dustfall-plant system nearby a typical non-ferrous metal mining area of Tongling. Doney et al. statistically and systematically analyzed the hazard effects of respirable coal mine dust in underground mining (Doney et al. 2019)versus open-pit mining (Doney et al. 2020) in the USA from 1982 to 2017. The practical results of international mine dust control projects show that relying on a single dust control technology to completely prevent mine dust pollution is very difficult to be realized, and various measures need to be taken to jointly control (Zhou et al. 2022).

The most fundamental way to prevent and control dust pollution is to reduce the generation of dust and the inhalation of

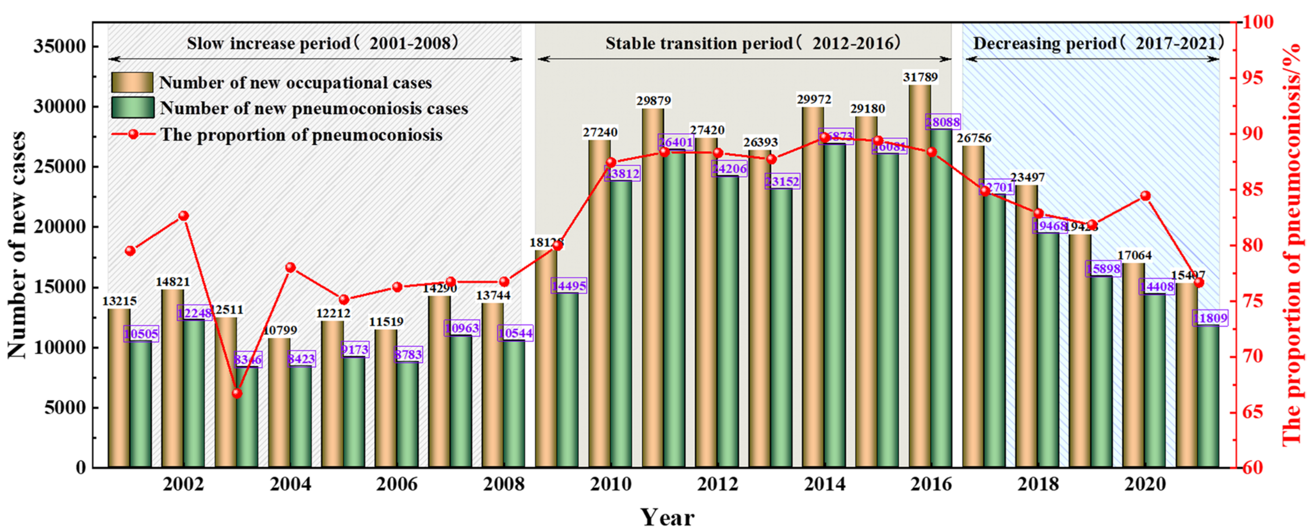


Fig. 2 Number and proportion of occupational diseases in China from 2001 to 2021

human body. Therefore, researchers have deeply explored the multi-stage dust control and emission reduction linkage control technology. As of now, an integrated dust control system is being developed in mining, such as ventilation and dust discharge (Jiang et al. 2021a; Yu et al. 2017; Zhou et al. 2022), wet dust reduction (Peng et al. 2020; Wang et al. 2020d; Xu et al. 2018; Zhang et al. 2021c), airtight dust extraction (Chen et al. 2022b; Nie et al. 2016), purified wind flow (Wang et al. 2014), and dust suppressant (Li et al. 2021; Wang et al. 2014; Zeng et al. 2023; Zhou et al. 2020b; Zhu et al. 2021). Cai et al. studied the influence of exhaust air volume and forced ventilation height on dust suppression performance of mixed ventilation system (Cai et al. 2019, 2021). Chen et al. studied the effects of inlet area (Chen et al. 2022b), inlet volume flow (Chen et al. 2018a), and cyclone outer diameter (Chen et al. 2019) on the dust removal performance of cyclone separator. Zeng et al. (2023) studied the dust pollution control of high tunnel by pre-injection foam dust removal technology in ore bin. Wang et al. (2022c) studied the coordinated control effect of ventilation and dust removal and spray dust removal in fully mechanized mining face, and determined the best ventilation parameters and dust removal parameters. Lu et al. (2022) studied the multi-level linkage control technology of air curtain dust isolation and spray dust suppression in coal mine heading face by using cyclone theory.

With the continuous development of precision mining in mines and the popularization of the coverage of Internet of Things in mines, more and more researchers are using the multi-source and massive dynamic information of mine dust to carry out research on high-precision monitoring and early warning technology of dust. Zhang et al. (2021b) developed a high-precision optical sensor for dust concentration based on Michaelis scattering theory. Amoah et al. (2022) used linear regression model to calibrate the low-cost light scattering particle sensor for coal dust monitoring. Ye et al. (2022) proposed a visual measurement algorithm of dust concentration based on the calculation of image transmittance characteristic value. Wang et al. (2022b) proposed a visual digital monitoring system for dust pollution assessment and monitoring based on the improved gray average (IGSA) and fractal dimension (FD) theory. Miao et al. (2023) developed a hidden danger analysis and risk early warning system for coal mines by using data mining technology. Gong et al. (2021) established an intelligent control system of air flow at the air outlet of heading face driven by digital twins, which can realize real-time collection and intelligent prediction of dust concentration.

Overview of bibliometrics and knowledge mapping techniques

Bibliometrics is a discipline that takes literature information and spatial–temporal characteristics as the research objects, and adopts the quantitative method of mathematical statistics to analyze the distribution of information, quantitative relationship, and change the law of existing literature in specific research fields (Chen 2017). The traditional bibliometric methods mainly utilize the insights and knowledge stock of scholars to find literature metadata, such as titles, abstracts, keywords, authors, and number of citations, which explore the evolution of the research field by means of semantic analysis (Liu et al. 2020), content analysis (Peng et al. 2018), and topic modeling (Li and Lei 2021). However, in the age of industrial information explosion, these technical methods cannot accurately and clearly show the network connections between literature metadata (Wang et al. 2022a). For instance, what are the characteristics of the knowledge production model of literature metadata? How do research content and subject areas influence each other? What are the hot topics and cutting-edge directions in the research field?

With the emergence of visual knowledge mapping technology, these questions mentioned above can be effectively addressed. Up to now, the mainstream bibliometric mapping tools for scientific and technical papers using, citing, and disseminating are VOSviewer and Citespace (Pan et al. 2018), which are widely applicable in the field of mining energy. Dong et al. (2020) used Citespace to study the water inrush disaster in the coal mine, who obtained technical problems such as hidden water disasters, quantitative evaluation of aquicludes, and rapid identification of water inrush sources currently unresolved. Yang and Qiu (2019) found that coal spontaneous combustion has shifted from the early topic of oxidation mechanism to the present fire prevention and control technology on the foundation of literature metrology. Shao et al. (2022) investigated coal porosity with the help of VOSviewer and gained that the structure number, internal development mechanism, and microcosmic chemical evolution law of coal porosity are the main research trends in this field.

To sum up, researchers have undertaken a lot of studies on the law of mine dust generation and transportation, pneumoconiosis pathogenesis and mine dust pollution prevention technology by means of theoretical analysis, numerical simulation, and field experiments. The studies on mine dust are widespread and multifarious, and the research hotspots are in a continuous state of evolution. However, there have been few research advances in analyzing mine dust with the visual knowledge mapping methodology. In order to accurately grasp the research results and research directions in the field of mine dust, with Web of Science Core Collection (WOSCC) from 2001 to 2021 as the data source, VOSviewer and Citespace were used to conduct statistical analysis and data mining for analyzing the temporal characteristics of the literature volume, demonstrating the distribution characteristics of journals and disciplines, tracing research subjects and hot fronts of mine dust. The practical contribution for this study is to provide reference and information on the knowledge framework, dynamic evolution, and development trend in the field of mine dust.

Data acquisition and research methods

Data source

In this paper, the Web of Science Core Collection was selected as the data source. Web of Science has been recognized by many academicians as one of the most comprehensive digital literature resources covering disciplines in the world (Ding and Yang 2020), and contains more than 12,000 authoritative and high-impact academic journals in various research fields such as natural science, engineering, and technology from poles to poles (Thelwall 2008; Zeng and Li 2022), which deemed to be the most suitable database for bibliometric analysis. The search terms included TS (Topic Search) = [((metal mine) OR (coal mine)) AND (dust)]. The retrieval time span is from Jan 1st to Dec 31st, 2021. Duplicate documents were filtered and irrelevant documents (e.g., conferences, newsletters, information, patents) were excluded. As demonstrated in Fig. 3, a total of 1786 publications were obtained, including 1684 articles (94.89%) and 102 reviews (5.71%).

Methods of scientometric analysis

Bibliometric analysis is a quantitative method for retrospecting and portraying published papers that enables academic scholars to assess the research in a specific field (Abdeljaoued et al. 2020; Ding and Yang 2020; Nascimento et al. 2022). In recent years, there is an increasing number of scientists who exploit modern computer visualization techniques to diagnose the dynamics of the evolution of a particular field of study. Among them, VOSviewer and Citespace are the two mainstream knowledge mapping visualization and analysis tools at present. The former is a method for visualizing similarities between objects developed by Dr. NeesJan van Eck and Prof. Ludo Waltman at the Center for Science and Technology (CWTS) of Leiden University in 2009 (van Eck and Waltman 2007), which provides convenient and esthetically impressive networks of knowledge mappings by means of data normalization methods in probability theory (Van Eck and Waltman 2010). The latter is an open source software for data mining and visual analysis of scientific literature developed by Prof. Chaomei Chen's team at Drexel University on the basis of Java language (Chen 2017; Chen et al. 2010), which is able to present the hot spots and the evolution of the research field on the network mapping.

In this paper, 1786 valid papers retrieved in the field of mine dust research are exported in plain text file format (records contain full metadata and references). VOSviewer (version 1.16), Citespace (version 6.2), and Python (version 3.10) were used to perform the topology of collaborative networks, co-occurrence analysis of keywords, and detection of salient keywords. More importantly, this paper has analyzed the chronological characteristics of journal literature, the distribution characteristics of literature carriers, research subjects, and hot frontiers in both temporal and spatial dimensions, with a view to systematically and comprehensively recapitulating the evolutionary process of the domain of mine dust research.

In the periodical co-citation knowledge mapping generated by VOSviewer (Van Eck and Waltman 2010), the node size denotes the co-citation frequency of the journal. The color of the node denotes the average time of journal co-citation, the line connecting the nodes denotes the existence of co-citation between these two journals in the same article, and the thickness of the line indicates the co-citation intensity between these two journals. In the cooperative network mapping, the size of nodes indicates the number of papers published by authors, institutions, or countries. The link is a connection or a relation between two items. Each link has a strength, represented by a positive numerical value (Van Eck and Waltman 2011). The higher this value, the stronger the link. The thickness of node connection reflects the strength of cooperative relationship between nodes, and the color of nodes indicates the average time for publishing papers. In the co-occurrence network mapping of keyword, the size of the node indicates the frequency of co-occurrence of the keyword, the color of the node indicates the average time of keyword co-occurrence, the line between nodes indicates the co-occurrence relationship between two keywords, and the thickness of the line indicates the intensity of co-occurrence between these two keywords.

When explaining the knowledge mapping generated by CiteSpace, as shown in Table 1, the selection of core keywords of mine dust is judged by the value range of centrality (Chen 2017), and the clarity and clustering scale of clustering boundary are measured by the clustering module value and average silhouette degree (Chen 2017; Chen et al. 2010). When explaining the knowledge mapping of discipline co-occurrence generated by Python (Muppidi and Reddy 2020), the size of the node indicates the frequency of the discipline, the color of the node indicates the category of the discipline clustering, the line between nodes indicates the co-occurrence relationship between two disciplines, and the thickness of the line is proportional to the frequency of co-occurrence.

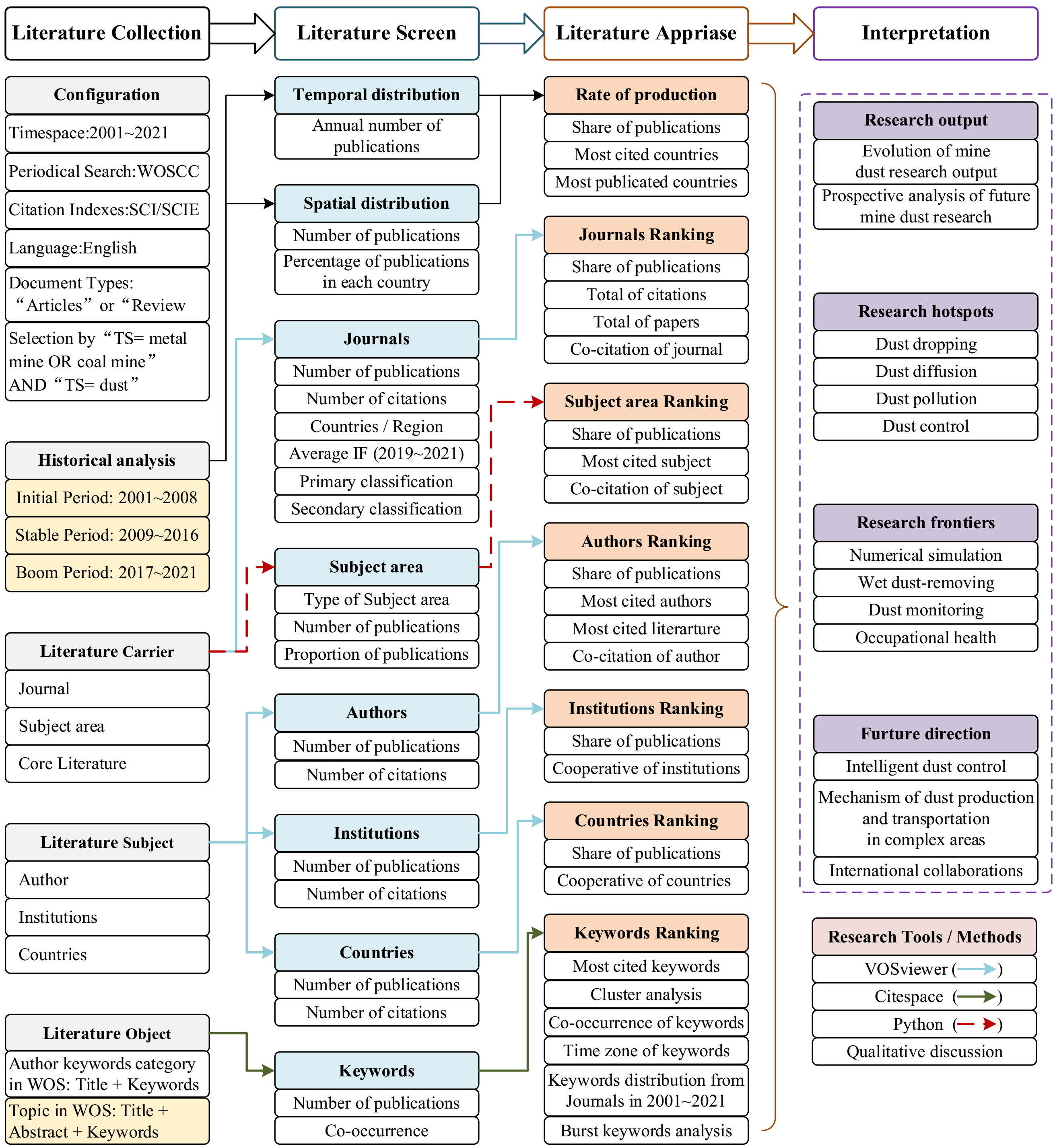


Fig. 3 Knowledge framework of mine dust research

Results and discussion

Temporal and spatial characteristics of mine dust research

The time-series characteristics of the number of publications on mine dust research can reflect the level and development of research in the field of dust control. Figure 4 represents the number of publications within the WOSCC database in the field of mine dust and the contribution of the cumulative literature from the main output countries for the period 2001 to 2021. Figure 5 shows the temporal distribution of the number of papers in the top 10 countries in terms of the number of articles published. Global research on mine

Table 1 Parameter description of knowledge mapping technology

Technology	Name	Meaning	Standard	
VOSviewer (version 1.16)	Links	Number of links of an item with other items	> 0	The higher this value, the stronger the link
	Total link strength	Total strength of the links of an item with other items	> 0	The higher this value, the stronger the link
Citespace (version 6.2)	Modularity	Clarity of clustering boundary	Q > 0.3	Significant clustering structure
	Weighted Mean Silhouette	Scale of the clustering subject	S > 0.7	Clustering is convincing
	Centrality	Connection strength of different clustering paths	≥ 0.1	Core keywords

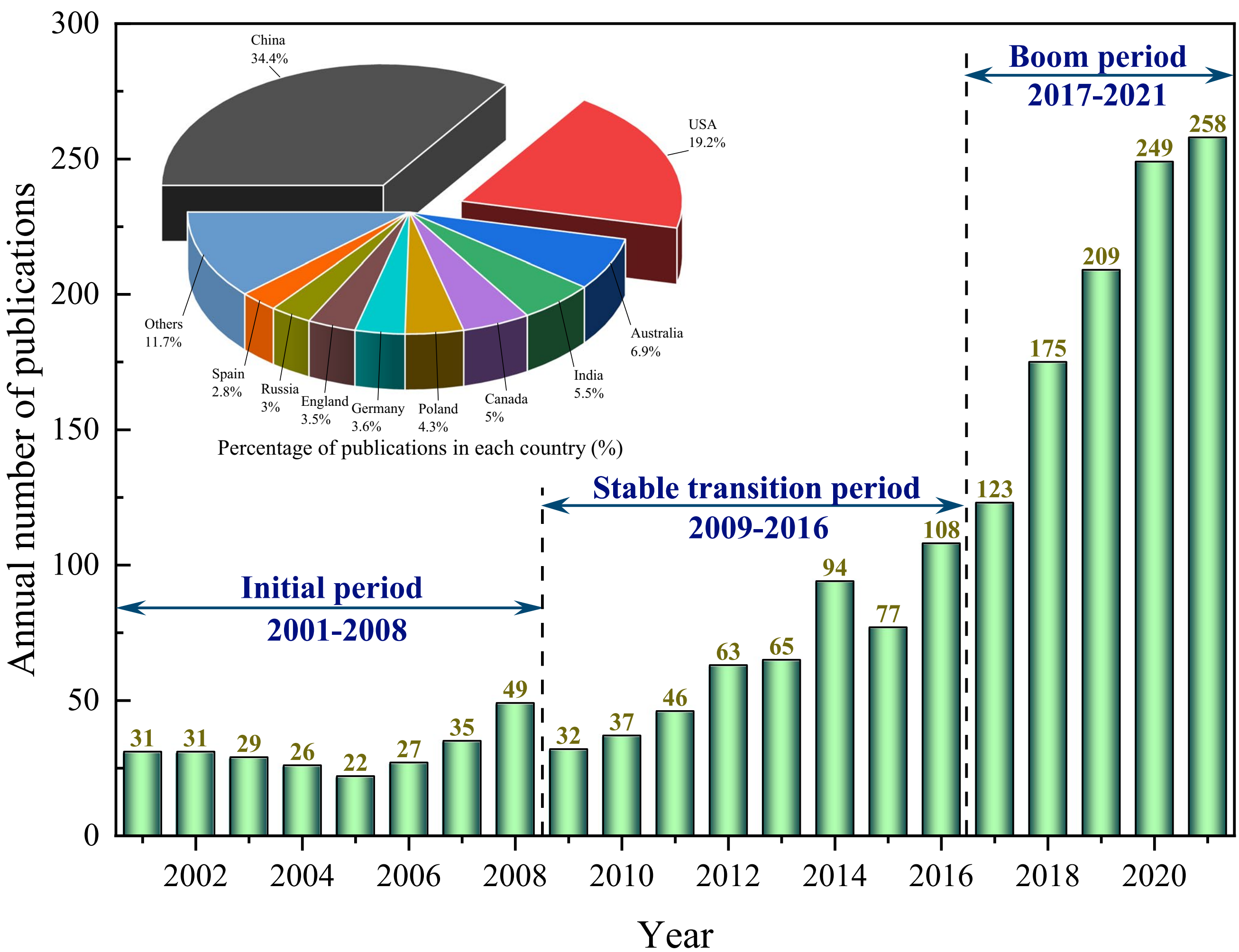


Fig. 4 Temporal distribution of publication volume of mine dust

dust can be approximately divided into three periods: ① Initial period (2001 ~ 2008). The average annual number of papers published internationally on mine dust research was less than 32 (total, 250). The main output countries of the literature in this period were developed countries such as the USA, Germany, Canada, and the UK, while developing countries such as China and India had a low average annual volume of publications. This may be attributed to the fact that communication and internet technology were not yet sophisticated enough to upload all the papers (Wang et al. 2022a). Besides, the investigation and comprehension of mine dust in each country were not profound as limited by the dust concentration detection technology at that time. ② Stable transition period (2009 ~ 2016). In the

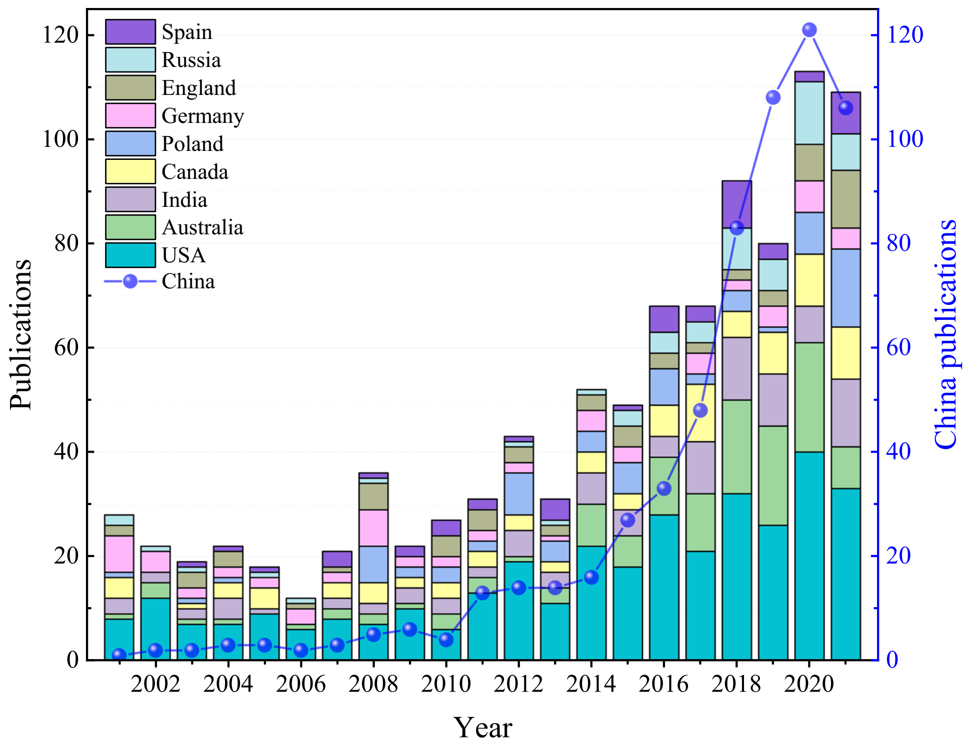


Fig. 5 Number of publications on mine dust in various countries

wake of the global financial crisis in 2008, the economy had fully recovered and rebounded, and the demand for mineral resources had been on the rise year after year. The number of mine production accidents was also augmented (Zheng et al. 2009), and the mine-safety mining issue needed to be addressed urgently (Chen et al. 2012). Consequently, there was a tremendous increase in the research literature on mine dust during this period, with an annual average of around 65 publications (total, 522), an increase of 108.8% YoY, among which the USA, China, Australia, Poland, India, Canada, and other countries had been paying more and more attention to the research of mine dust. ③ Boom period (2017 ~ 2021). Mine dust research worldwide is showing a dramatic rise. The number of publications rapidly increased from 108 in 2016 to 258 in 2021, with an annual average of about 203 publications (total, 1014), which was a 3.11-fold increase compared to the previous period. There are two main reasons for this phenomenon. On the one hand, with the development of economic globalization, cultural and technological exchanges are also colliding constantly. The availability of high-precision instruments (such as microcomputer laser dust monitor, high-speed camera, scanning electron microscope, dust particle size analyzer) has made it possible to gain further insight into the physical and chemical (such as microscopic morphology, dust particle size, dust concentration) properties of mine dust (Wang et al. 2018). On the other hand, with the continuous maturity and improvement of numerical simulation technology (Xiu et al. 2020), there is an in-depth awareness of the mechanism of dust generation and transportation law. From this, a series of dust control measures are carried out (Yao et al. 2020) to ensure the cleanliness and health of the work surface.

Figure 4 also shows the proportion of the total number of articles on mine dust research from the top 10 countries in terms of number of articles published. It can be found that scholars in the field of mine dust mainly from 92 countries and regions. Among them, China ranked first in terms of the number of articles published with 614, accounting for 34.4% of the total number of articles. The USA ranked second with 343 articles, accounting for 19.2%. Australia ranks third with 124 articles, accounting for 6.9%. The following countries are India, Canada, Poland, Germany, Britain, Russia, and Spain. As can be seen from Fig. 5, the main publishing countries in the field of mine dust research in recent years were China, USA, Australia, Russia, and Poland. The decline in dust research articles in China and other countries in 2021 may be due to the impact of the COVID-19 epidemic (Jiang et al. 2021b). The number of annual publications in China was in line with the global trend of annual publications, reaching a historical peak of 121 publications in 2020, accounting for 48.59% of the total number of publications worldwide in the same year, it can be presumed that China will remain the main site of research in the domain of mine dust for a long period of time in the future.

In addition, the comprehensive national power of the country, the reserves of mineral resources, and the technical problems facing the development of mineral resources are important and major constraints factors to the development of the mine dust field. For example, mine dust research in China has a strong policy orientation and tendency. With the accession of China to the World Trade Organization in 2001, Chinese economy has developed rapidly, and the demand for mineral resources has gradually increased, as well. The number of publications in the field of mine dust exhibits an ascendant trend, with Chinese scholars publishing 21, 127, and 466 articles in the above three phases, respectively. In particular, the stable transition period is known as the flourishing phase of mining in China. The demand for mineral resources had reached 3500Mt per year (Dai et al. 2022). At this stage, coal dust explosion (Zheng et al. 2009) and metal mine production accidents (Li et al. 2016; Yin et al. 2011) (such as high sulfur mine asphyxiation, aluminum, and magnesium mine explosion) occurred frequently. Therefore, how to avoid dust explosion and ensure safe production is an important topic in China at that stage. During the boom period, workers suffered from pneumoconiosis with a certain incubation period, reaching a historical peak in the number of new pneumoconiosis cases in 2016 at 28,088 between 2001 and 2021 (Wang et al. 2019d). To ensure that mining is towards the direction of cleanliness and health, the Chinese government had issued the "Health China 2030 Program" and the "National Occupational Disease Prevention and Control Plan (2021–2025)" document. Chinese scholars have undertaken numerous studies on how to reduce dust pollution and decrease the number of pneumoconiosis patients. In the future, with the introduction and implementation of the Chinese government's carbon neutrality and carbon emission peak, the innovation of dust prevention and control technology in China will step forward into a sophisticated field.

Carrier characteristics of mine dust research

Analysis of major source journals and co-citations

Academic journals play a pivotal position in the dissemination of research results. Dzikowski asserted that the main source journals in a certain field can be distinguished by the number of articles published and the trend of change (Dzikowski 2018). From 2001 to 2021, the distribution of journals in mine dust research was more decentralized, with a total of 463 journals. Table 2 lists the 10 journals with the most published articles, which cover 24.47% of the papers on mine dust research. The journals are distributed in developed countries, with four journals from the Netherlands, three from the UK, and one each from Germany, Switzerland, and the USA. In terms of the number of articles carried, Powder Technol ranked first with 85 articles, followed by Environ Sci Pollut R and Sci Total Environ with 62 and 50 articles, respectively.

Co-citation analysis is a literature-based analysis method proposed by American intelligence scientist Henry Small in 1973 (Small 1973). He believed that the co-citation frequency of two scientific papers can be determined by comparing lists of citing documents in the Science Citation Index and counting identical entries. As illustrated in Fig. 6, the largest node is *Environ Sci Pollut R*, followed by *Powder Technol*, *Sci Total Environ*, indicating that these three journals are the most frequently cited journals in the field of mine dust from the rest of the journals. In regard to co-citation intensity, *Environ Sci Pollut R* and *Process Saf Environ* have the thickest linkage, indicating that both of them have the highest co-citation frequency, followed by *Environ Sci Pollut R* and *Adv Powder Technol*, *Environ Sci Pollut R*, and *J Clean Prod*, respectively. From the aspect of time span, in the initial period (2001 ~ 2008), mine dust-carrying journals were mainly related to air pollution, occupational health, and dust monitoring, such as *Atmos Environ*, *Environ Monit Assess*, *Am J Ind Med*. Under the stable transition period (2009 ~ 2016), the contained journals are mainly associated with environmental pollution and dust explosion, such as *Sci Total Environ*, *J Hazard Mater*. In recent years (2017 ~ 2021), the published journals mainly focus on dust pollution and prevention technologies, such as *Environ Sci Pollut R*, *Powder Technol*, *J Clean Prod*.

Analysis of discipline categories and co-occurrence

The discipline classification in the WOSCC database is one of the most comprehensive and objective of the many discipline classification systems, where the included journals each contain at least one discipline category (Ding and Yang 2020). The 1786 articles retrieved from 2001 to 2021 covered a total of 201 disciplines. Figure 7 demonstrates the top 15 disciplines with the highest number of papers published in mine dust. The top discipline in terms of number of publications was *Environmental Sciences* (777, 44%), followed by *Engineering, Chemical* (260, 15%), *Public, Environmental & Occupational Health* (247, 14%), and *Engineering, Environmental* (206, 12%). The disciplines ranked 5th to 9th had the similar number of publications, all of which are mainly in the direction of energy, geology, and mining, accounting for 7%, 6%, 5%, and 5% of the total number of publications, respectively. In general, it can be found that the research content of mine dust is mainly based on environmental science, supplemented by engineering technology, and there is a trend towards multidisciplinary structure and diversification.

The relationship between different disciplines within the field of mine dust is studied. With the bridge role of intermediate disciplines, new insights and ideas can be captured from different approaches and perspectives (Deng and Xia 2020). Discipline category co-occurrence analysis was

Table 2 Statistical information of the main source journals from 2001 to 2021

Rank	Disciplines	Publications	Citations	Average citation	Countries/region	Primary classification (JCR)	Secondary classification (JCR)	Average IF (2019 ~ 2021)
1	*Environ Sci Pollut R*	85	3317	39.02	Germany	Environmental Science and Ecology Q3	Environmental Sciences Q3	3.397
2	*Powder Technol*	62	870	14.03	Netherlands	Environmental Science and Ecology Q2	Environmental Sciences Q2	6.701
3	*Sci Total Environ*	50	1213	24.26	Switzerland	Engineering Technology Q2	Engineering: Chemical Q2	4.23
4	*Process Saf Environ*	46	1549	33.67	The United Kingdom	Environmental Science and Ecology Q2	Engineering: Chemical Q2 Engineering: Environmental Q3	5.169
5	*Environ Pollut*	42	1022	24.33	The United Kingdom	Environmental Science and Ecology Q2	Environmental Sciences Q2	6.859
6	*Environ Geochem Hlth*	41	659	16.07	Netherlands	Environmental Science and Ecology Q3	Engineering: Environmental Q3 Environmental Sciences Q3 Public: Environmental & occupational Health Q2 Water Resources Q2	3.778
7	*Environ Monit Assess*	31	707	22.81	Netherlands	Environmental Science and Ecology Q4	Environmental Sciences Q4	2.125
8	*J Loss Prevent Proc*	29	846	29.17	The United Kingdom	Engineering Technology Q3	Engineering: Chemical Q4	2.841
9	*Fuel*	27	1130	41.85	Netherlands	Engineering Technology Q2	Energy and Fuels Q2 Engineering: Chemical Q2	5.772
10	*J Clean Prod*	27	814	30.15	the United States	Environmental Science and Ecology Q1	Engineering: Environmental Q2 Environmental Sciences Q2 Green & Sustainable Science & technology Q2	7.646

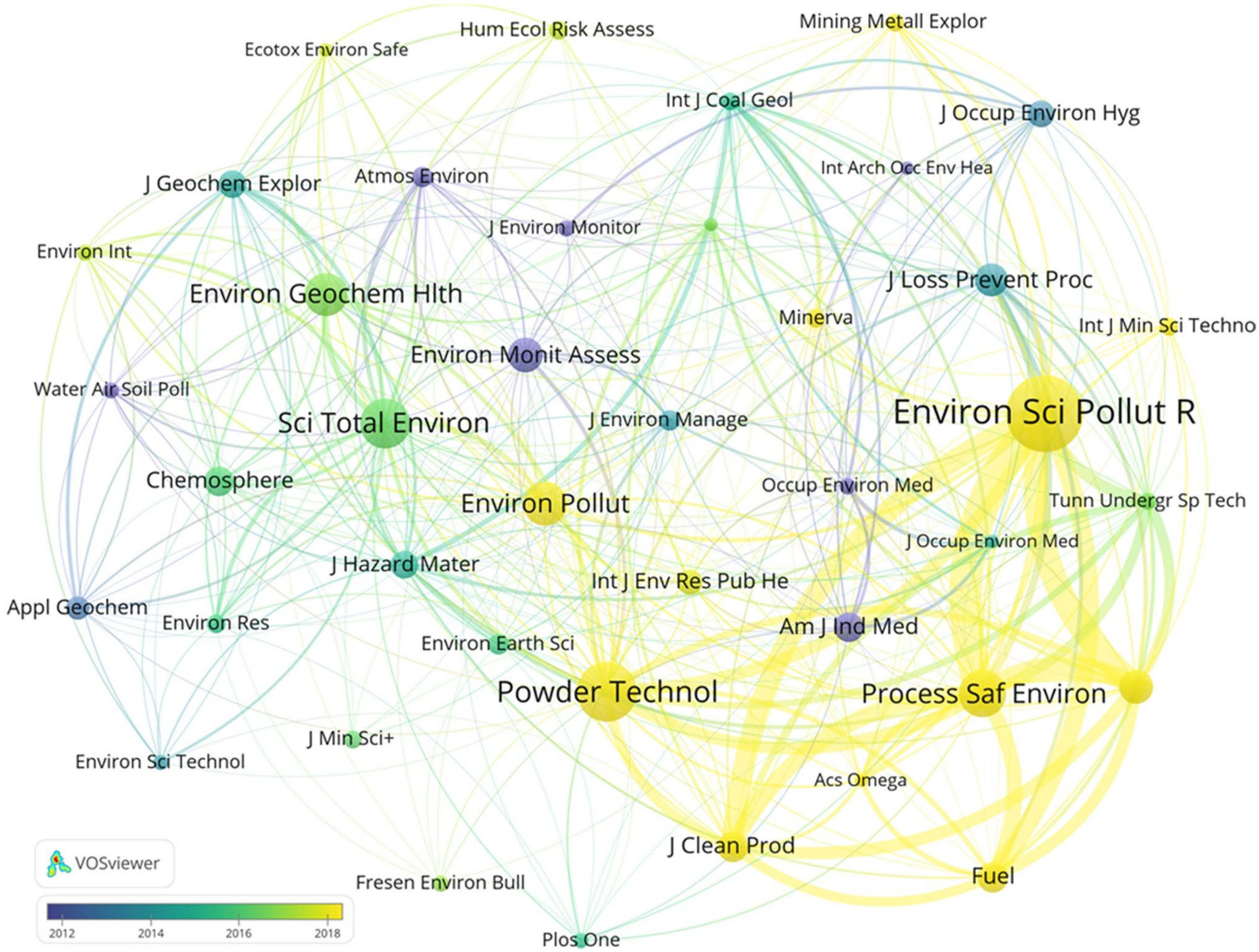


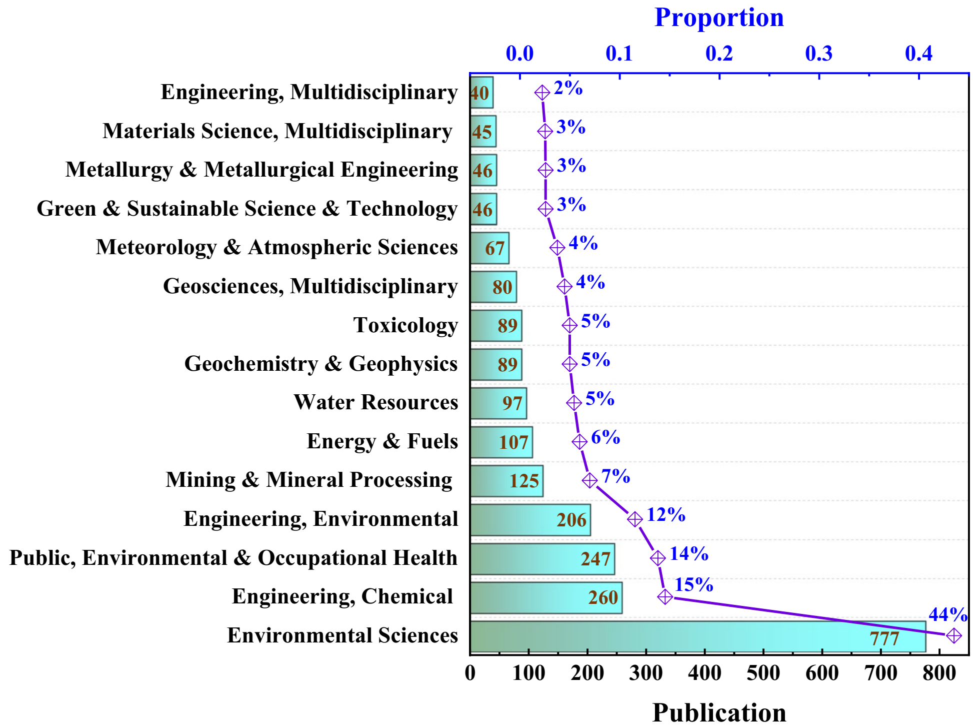
Fig. 6 Co-citation knowledge mapping of main source journals for mining dust research

performed in conjunction with the network open-source class library using Python. It was found that 849 out of 1786 publications contain at least two disciplines, accounting for about 47.53% of the total publications. The co-occurrence matrix was constructed for the disciplines of these 849 publications, and 102 disciplinary categories were obtained, as displayed in Fig. 8. In general, mine dust research is focused on three disciplines. First of all, it is clustering with environmental science as the core. As an intermediate discipline, *Environmental Sciences* (green group) is closely related to other disciplines such as *Engineering, Environmental*, *Water Resources*, and *Public, Environmental, & Occupational Health*. The second one is the clustering of energy technology as the centerpiece. *Engineering, Chemical* (red group) is more closely associated with *Energy & Fuels*, *Engineering*, *Chemical*, and *Thermodynamics* as a connection carrier. The third one is the clustering focused on medicine and chemistry. *Toxicology* (blue group) and *Chemistry, Multidisciplinary* are the main disciplines that are not yet as strongly interconnected with other disciplines as the previous two. All in all, the discipline area of mine dust research involves various aspects of the environment, energy, medicine, engineering, and technology. The diversity of research in interdisciplinary fields is initially being characterized. In the future, there is a need to continue to explore the interaction and integration of disciplinary areas in mine dust research.

Analysis of co-citations in core literature

The distribution characteristics of the citation frequency of the literature can reflect the scientific value and contribution of the paper in the corresponding field (Small 1973). To ascertain the most influential literature in the field of mine dust, the top 10 high-cited literature in terms of frequency of citations were tabulated as listed in Table 3.

Fig. 7 Proportion distribution of major disciplines in mine dust field



Among them, 8 articles are co-authored by different institutions and 2 by one institution. The total citations of these 10 articles reached 1961, with an average of 196.1 citations per article and a single maximum of 503 citations, indicating that these articles have received a high peer acknowledgment from mine dust research scholars at an international level. The published journals are mainly classic and authoritative journals in the fields of environmental science and powder technology, such as Process Saf Environ, J Environ Manage, and Adv Powder Technol. The research mainly includes three aspects, namely, heavy metal pollution and its distribution during mining, the health hazards of mine dust to workers, and the prevention and control technology of mine dust. Besides, there were five papers published during the boom period (2017 ~ 2021). The research content of these papers indicates that analyzing the pollution distribution of dust in mining processes on the basis of numerical simulation techniques and proposing dust control measures which are economical, efficient, and environment-friendly are the current research hotspots and development trends of mine dust.

Subjects characteristics of mine dust research

Analysis of core authors and co-authorship

Representative scholars and core authors can be informed by statistical analysis of authors in the field of mine dust. The well-known American scientometrics Price believed that half of the papers on the same research topic were produced by a group of high-productivity authors who were numerically equal to the square root of the total number of authors (Price 1963). And there was:

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

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

According to VOSviewer statistics, $n_{max} = 45$ and $N = 6340$. The minimum number of publications m for the core authors is represented by Eq. (2):

$$m = 0.749 \times \sqrt{n_{max}} = 0.749 \times \sqrt{45} \approx 5.02 \tag{2}$$

Therefore, authors who had published more than 5 articles (including 5 articles) are positioned as the core authors in mine dust field. According to the statistics, there were 167 core authors, and the total number of published articles was 1377, accounting for 77.1% of the total number of published articles, which exceeded the threshold of 50% proposed by Price. As a result, it was considered that the core author group in the research field of mine dust prevention and control had initially appeared.

Figure 9 illustrates the core group of authors in the field of mine dust. On the whole, the international partnership

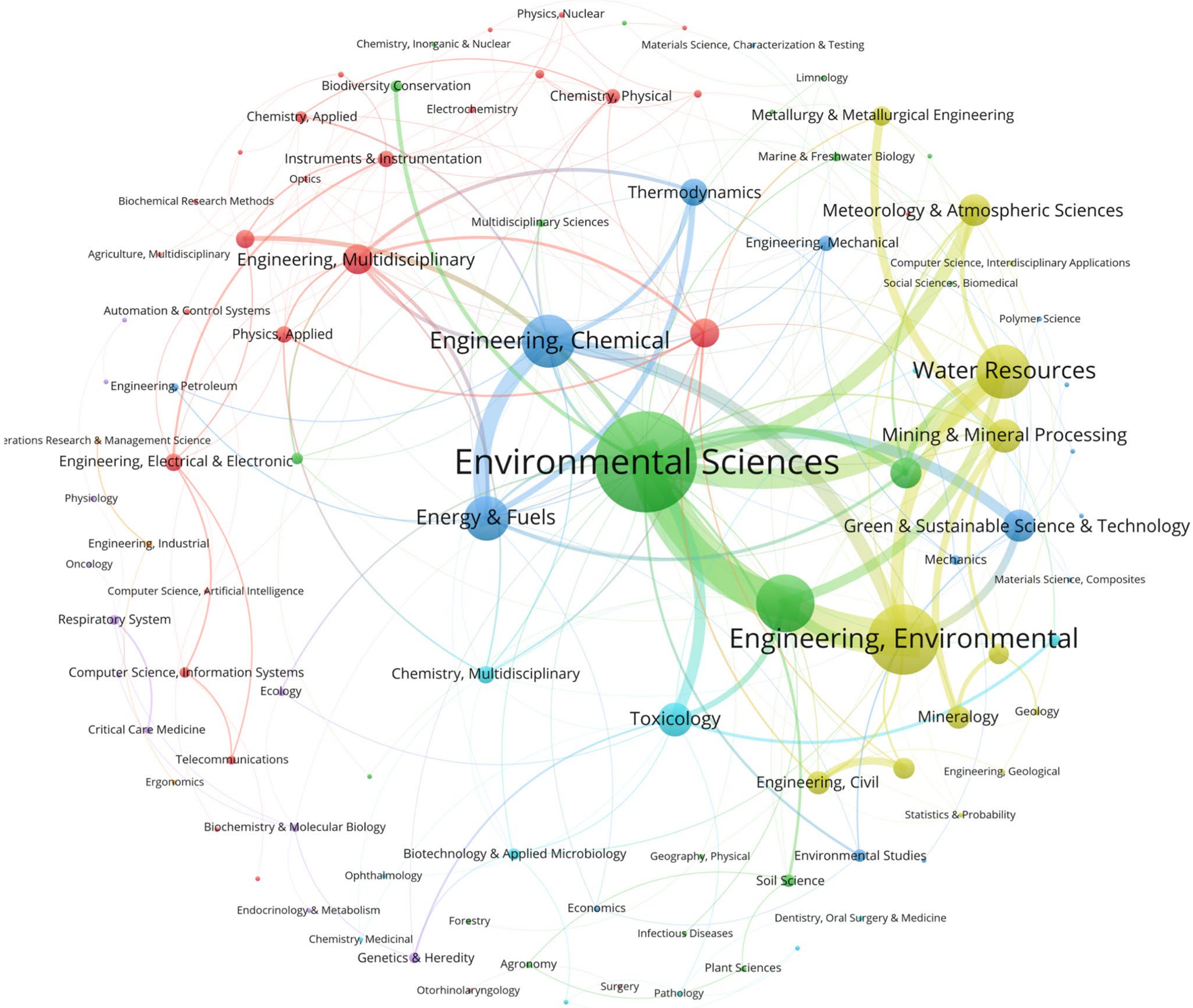


Fig. 8 Co-occurrence knowledge map of the major disciplines in the field of mine dust

in the field of mine dust is relatively fragmented. The connectivity of the collaboration network of authors is not well established. The characteristics of small groups among the authors are more obvious. More specifically, the collaboration among emerging and highly productive authors is evident and relatively close. The concentration of the sub-network authors (e.g., Gang Zhou, Wen Nie, Weimin Cheng) in the central location of the network is characterized by a high degree of cooperation and close collaborative relationships. On the contrary, several other sub-networks have a relatively smaller scale of authorship and limited mutual collaboration between authors. In addition, the sub-networks have fewer connections and are more independent from each other.

Figure 10 displays 15 high-productivity authors with more than 12 articles in this field. In view of publication numbers, the top three authors are Gang Zhou, Wen Nie, and Weimin Cheng, with 45, 43, and 30 articles, respectively. These three scholars are all affiliated with the Shandong University of Science and Technology and have cooperated with each other many times. From the published papers, it can be observed that these three scholars focus mainly on the generation mechanism and dispersion law of mine dust. For example, the dust transport law of different coal mining heights in the comprehensive mining face has been explored (Nie et al. 2022), the mechanism of macroscopic dynamic dispersion of coal dust has been identified (Wang et al. 2018), and the dust and pollution effects of coal dust on a fine-scale have been explored (Cheng et al. 2016). Following closely behind were Hetang Wang and Deming Wang who work at the China University of Mining and Technology with 26 and 25 articles, respectively. These two scholars are more concerned with the microscopic properties and dust

Table 3 Statistical information of the core literature from 2001 to 2021

Rank	Literature	Disciplines	Authors	Year	units	Co-citation	Country
1	Heavy metal distribution and chemical speciation in tailings and soils around a Pb–Zn mine in Spain	Journal of Environmental Management	Rodriguez et al.)	2009	3	503	1
2	Health impacts of coal and coal use: possible solutions	International Journal of Coal Geology	Finkelman et al.	2002	5	306	4
3	Mine wastes: past, present, future	Elements	(Hudson-Edwards et al.)	2011	3	178	3
4	Auxiliary ventilation in mining roadways driven with roadheaders: Validated CFD modeling of dust behavior	Tunnelling and Underground Space Technology	Torano et al.	2011	1	159	1
5	The diffusion behavior law of respirable dust at fully mechanized caving face in coal mine: CFD numerical simulation and engineering application	Process Safety and Environmental Protection	Zhou et al.	2017a	2	158	1
6	Assessment of air pollution around coal mining area: Emphasizing on spatial distributions, seasonal variations and heavy metals, using cluster and principal component analysis	Atmospheric Pollution Research	Pandey et al.	2014	2	143	1
7	Effect of air flowrate on pollutant dispersion pattern of coal dust particles at fully mechanized mining face based on numerical simulation	Fuel	Cai et al.	2019	2	141	1
8	Effects of air volume ratio parameters on air curtain dust suppression in a rock tunnel's fully mechanized working face	Advanced Powder Technology	Wang et al.	2018	1	137	1
9	Preparation and characterization of a wetting-agglomeration-based hybrid coal dust suppressant	Process Safety and Environmental Protection	Fan et al.	2018	2	120	1
10	Multi-factor numerical simulation study on spray dust suppression device in coal mining process	Energy	Xu et al.	2019	2	116	1

suppression mechanism of mine dust. For instance, they have studied the influence of cutting parameters of tunnel boring machine (Zhou et al. 2020a) and coal mass structure on dust generation characteristics (Zhou et al. 2020b), as well as explored the foaming mechanism and dust suppression effect of foam polymer (Wang et al. 2019a). The average citations of the above scholars all exceeded 29, demonstrating that the research results of these scholars have significant influence in the field of mine dust.

In summary, a stable and mature core group of authors has initially formed in the field of mine dust. However, the internal members of the same institution are a cooperative team, and there are few studies on cross-institutional cooperation. The collaborative research atmosphere among authors from different institutions is not strong, and collaborative cross-citation relationships are weak. The limited cooperation is often attributed to various factors such as research areas, research directions, work patterns, and geographic locations, which are not propitious to the progress of mine dust research. Nowadays, scientific cooperation has become a trend. Author-to-author collaboration can effectively facilitate the exchange and development of relevant knowledge in society, universities, and academia. Therefore, cooperation between authors in the field of mine dust has to be strengthened.

Analysis of core institutions and co-authorship

Analyzing the cooperative institutions of mine dust research can clarify the information of the most productive organizations in this field and how they collaborate with each other. Globally, a total of 1810 institutions were involved in mine dust research and published papers, and the top 15 research institutions with the highest number of publications are

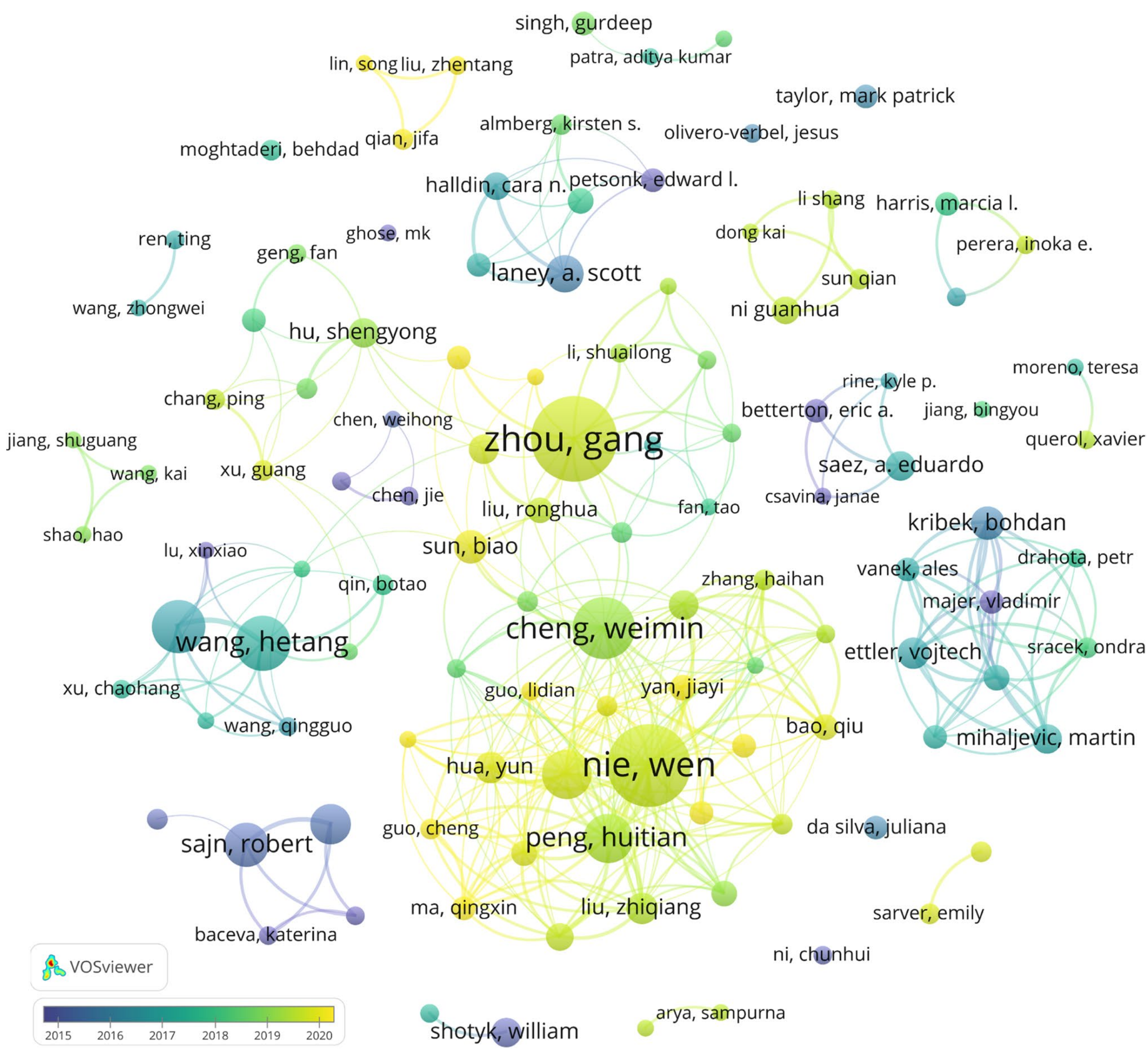


Fig. 9 Co-authorship network of core authors in the field of mine dust

displayed in Table 4. It can be observed from Table 4 that 9 institutions are from China, accounting for 60% of the total, which is mainly accounted for by the fact that China is one of the leading countries in the world in terms of mineral resources extraction (Shao et al. 2022). Furthermore, it suggests that the demand of energy and the protection of ecological environment facilitate the sustainable development of mine dust research. In terms of the number of publications, Shandong University of Science and Technology, China University of Mining and Technology, and National Institute for Occupational Safety and Health ranked the top three institutions, with 153, 138, and 95, respectively. With regard to average citations, Shandong University of Science and Technology ranked first with 33.82, and Charles University, Chinese Academy of Sciences, and University of Arizona ranked second to fourth with 27.42, 27.28, and 26.73, respectively. From the perspective of the urban distribution of the mine dust institutions, the core institutions are mainly located in the capitals of various countries, such as Beijing in China, Washington in the USA, and Moscow in Russia.

In the knowledge mapping of collaborating institutions through VOSviewer, there are 45 institutions with more than 10 publications, as shown in Fig. 11. The number of institutions involved in mine dust research is enormous and widespread, and the institutions have pronounced characteristics of the times. In initial period

Fig. 10 Statistical information of core authors in the field of mine dust

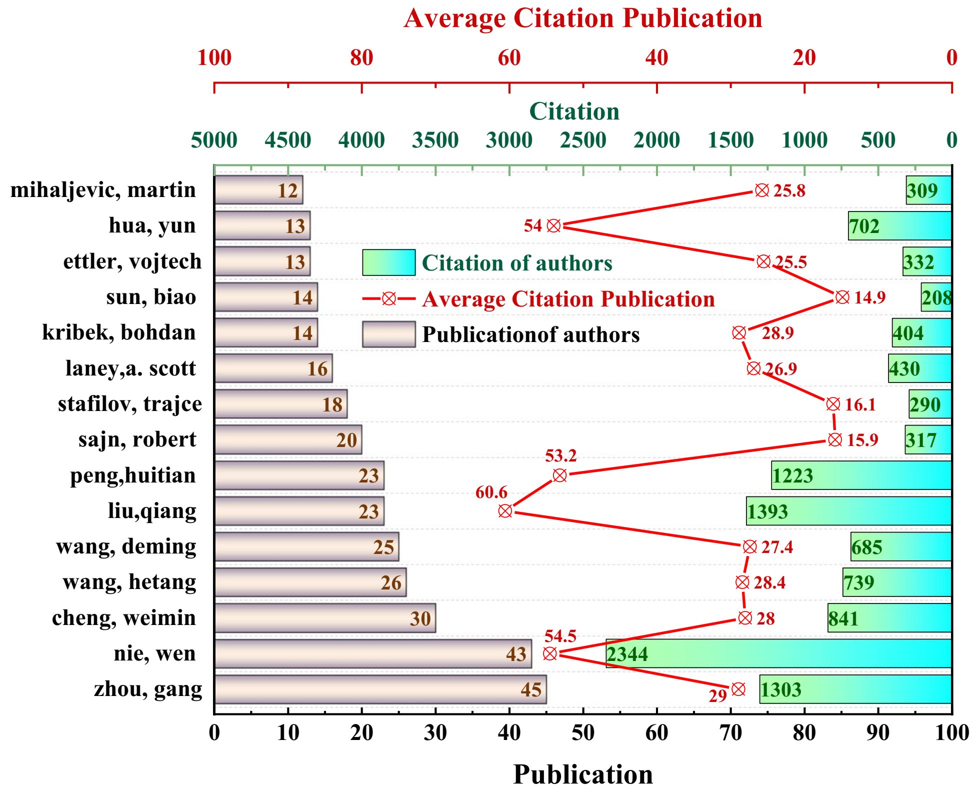


Table 4 Statistical information of core research institutions for mine dust research

Rank	label	Countries	Cities	Documents	Citations	Avg. citations	Proportion
1	Shandong University of Science & Technology	China	Qingdao	153	5174	33.82	8.6%
2	China University of Mining & Technology	China	Xuzhou	138	2672	19.36	7.7%
3	National Institute for Occupational Safety & Health	The United States	Washington	95	2093	22.03	5.3%
4	Chinese Academy of Sciences	China	Beijing	58	1582	27.28	3.2%
5	Geological Survey of Slovenia	Slovenia	Ljubljana	34	588	17.29	1.9%
6	University of Arizona	The United States	Arizona	30	802	26.73	1.7%
7	Russian Academy of Sciences	Russia	Moscow	28	247	8.82	1.6%
8	Taiyuan University of Technology	China	Taiyuan	24	369	15.38	1.3%
9	University of the Chinese Academy of Sciences	China	Beijing	24	355	14.79	1.3%
10	Indian Institute of Technology	Indian	Mumbai	23	511	22.22	1.3%
11	Xi'an University of Science and Technology	China	Xi'an	23	154	6.70	1.3%
12	China University of Mining and Technology (Beijing)	China	Beijing	22	279	12.68	1.2%
13	Anhui University of Science and Technology	China	Huainan	19	410	21.58	1.1%
14	Charles University	Czech Republic	Prague	19	521	27.42	1.1%
15	Henan Polytechnic University	China	Jiaozuo	18	178	9.89	1.0%

(2001 ~ 2008), most of the research on mine dust is concentrated upon research institutions with the theme of occupational hygiene and health, such as the National Institute for Occupational Safety and Health, University of Virginia, and US Geological Survey. In stable transition period (2009 ~ 2016), research on mine dust has mostly specialized in institutions that are characterized by ecological environment pollution, such as Chinese Acad Sci, Russian Acad Sci, and Geological Survey of Slovenia. In recent years (2017 ~ 2021), the research on mine

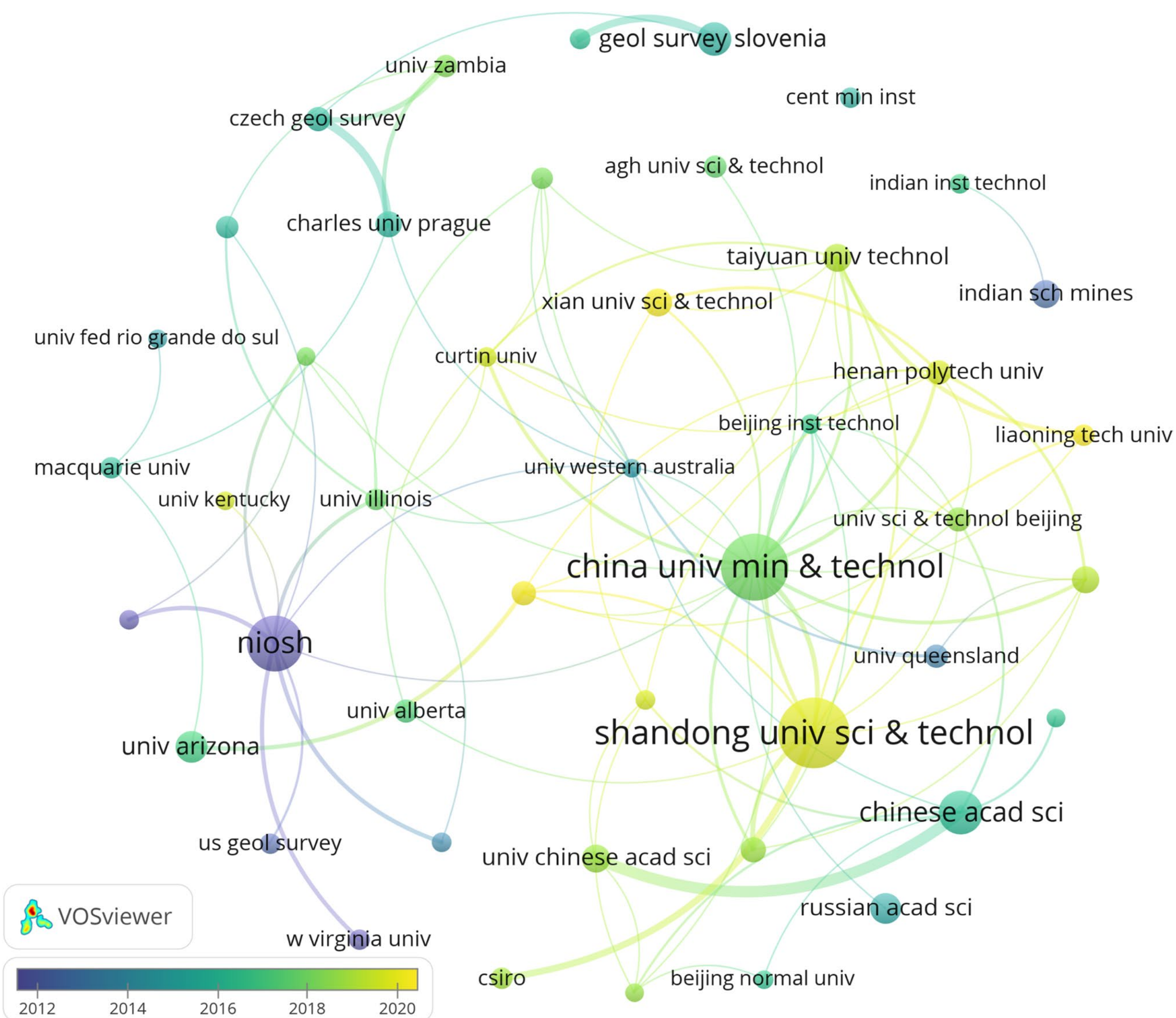


Fig. 11 Co-authorship network of research institutions in the field of mine dust

dust has been focused on mining dust pollution prevention in universities of science and engineering, such as Shandong University of Science and Technology, China University of Mining and Technology, and University of Science and Technology Beijing. In summary, the cooperation among international mining dust research institutions has formed a relatively well-developed model. That is to say, it has gradually developed a cooperative relationship centered on "Shandong University of Science & Technology," "China University of Mining & Technology," and "National Institute for Occupational Safety & Health." These institutions have played a bridging role in promoting international cooperation, which are of great significance in accelerating the development of mine dust research.

Analysis of core countries and co-authorship

Cooperation between countries has been an important contributor to the development of mine dust research, with as many as 92 countries from all over the world engaged in mine dust research. As shown in Fig. 12, from the regional distribution as a whole, the research on mine dust is mainly concentrated in mineral resource–producing countries such as China, the USA, Australia, India, and Canada, where the supply of energy plays a crucial role in the economic development of these countries and drives the development of mineral dust research. Specifically, as can be observed in Fig. 13, three distinct camps of regional cooperation have formed in terms of time span. *Purple Camp* mainly consists of developed

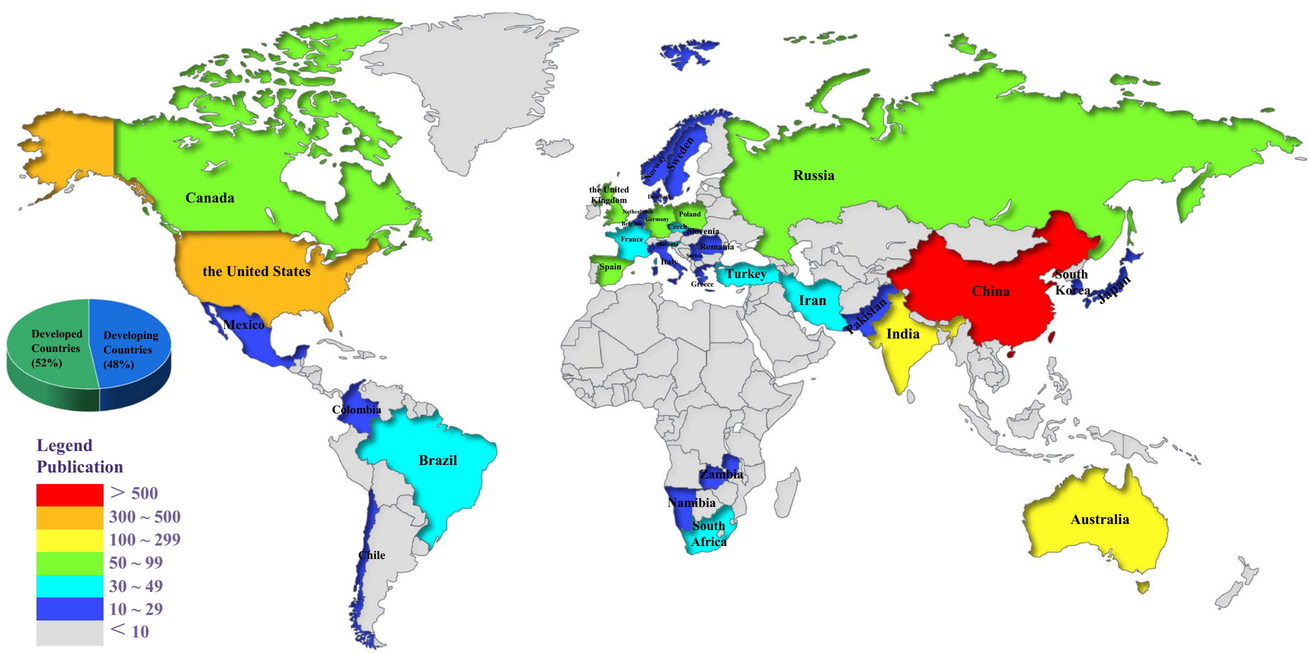


Fig. 12 Distribution of global publishing countries

European countries, such as Germany, France, Norway, and the Netherlands, with the UK as the centerpiece, where research primarily emphasizes on the contamination effects of mineral dust particles containing heavy metals. *Indigo camp* is dominated by countries with the USA around the core, such as Canada, Mexico, Chile, and India, where most of the research priority is devoted to occupational health and environmental protection. *Lime Green Camp* is composed principally of countries with China and Australia as the keystone, such as Spain, Russia, Poland, South Africa, Zimbabwe, and Iran, where the research focus is essentially on pollution prevention technologies for mine dust.

Furthermore, in order to analyze the countries with high productivity in mine dust research, Table 5 presents the top 15 countries with the highest number of publications in this field, of which 5 are developing countries and 10 are developed countries. China (641 articles, 34.4%), the USA (343 articles, 19.2%), and Australia (124 articles, 6.9%), the three countries with the most published papers, are currently the core force in the field of mine dust internationally. The total link strength of the USA, China, Australia, and the UK are 193, 164, 118, and 89, respectively, which shows that these countries have played an important role as a bridge in international cooperation. The number of articles published in the UK, Spain, and France is only 63, 50, and 48, while the average number of citations per article is 44.52, 35.5, and 34.29. It demonstrates that these developed countries have achieved relatively little in mine dust research, while the impact has been tremendous.

Hot topics and frontier trends of mine dust research

Analysis of co-occurrence of hot keywords

The keywords in the literature reflect the research theme and core of the paper, and the keywords can be used to explore the hot topics and frontier trends in the research field. VOSviewer was used for statistical analysis of the selected articles, with a total of 7417 keywords. There are 139 keywords with a co-occurrence frequency greater than 20, as shown in Fig. 14, which is the co-occurrence network map of these keywords. It can be seen that heavy metals, dust, soil, and pollution belong to the research branch of environmental pollution. Exposure, pneumoconiosis, and health belong to the research branch of occupational health and medicine. Numerical simulation, diffusion, and suppression belong to the research branch of dust prevention. These keywords are all representative terms in the field of mine dust. From the network layout, these keywords are also the critical nodes in the field of mine dust research, around which other nodes together form the research themes and research directions in the field of mine dust.

The top 20 keywords with frequencies over 67 were extracted using Citespace as summarized in Table 6. According to Prof. Chaomei Chen, keywords with centrality greater than or equal to 0.1 can be considered as the core keywords for research in the field (Chen 2017). Dust ranked first with a centrality of 0.81, followed by pollution, exposure, coal dust, and pneumoconiosis with the centrality of 0.4, 0.26, 0.25, and 0.23, respectively. This reveals that mine dust pollution

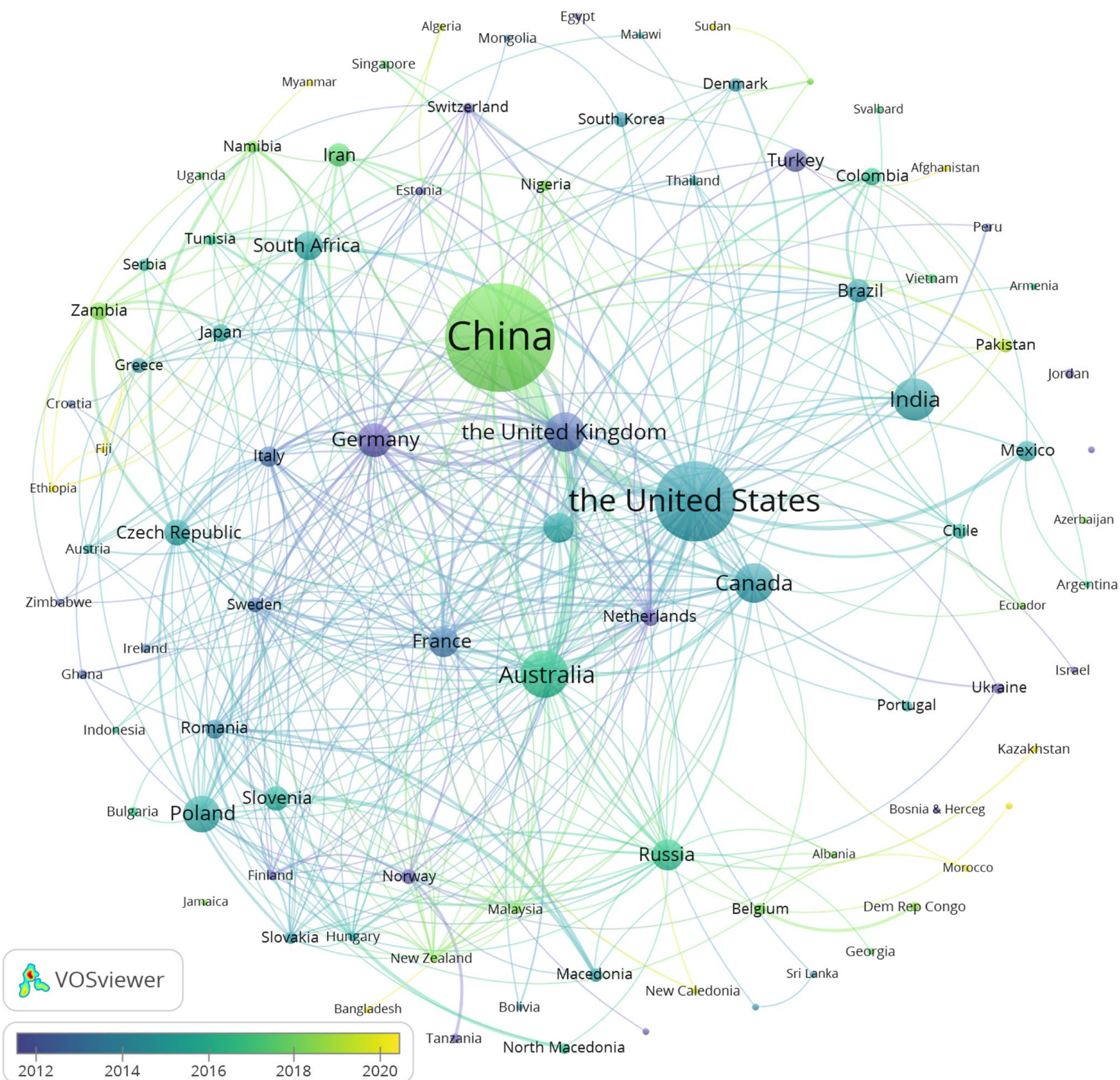


Fig. 13 Co-authorship network of research countries in the field of mine dust

and occupational health protection are the main research directions in the field of mine dust. At the same time, mine dust research has a strong disciplinary, contemporary, and subjectivity. The high citations of emerging keywords such as numerical simulation, performance, respirable dust, mine, and particulate matter have illustrated that more and more research scholars pay more attention to the control methods and technologies of respirable dust from the source of dust generation and dispersion process in mines, promoting the development of dust control towards automation, intelligence and diversification directions.

Analysis of clustering subjects of hot keywords

On the basis of high-frequency keyword statistics, the clustering subjects analysis of mine dust research is further carried out, and the K value (keyword) is selected to extract 17 clusters as shown in Fig. 15. The modularity ($Q > 0.3$) and weighted mean silhouette ($S > 0.7$) reflect the clarity of keyword clustering boundaries and the cluster size (Chen 2017; Chen et al. 2010), respectively. As can be seen from Fig. 15, the analysis of 337 nodes was calculated to obtain $Q = 0.8646$ and $S = 0.9235$, all of which

Table 5 Statistical information of the top 15 countries in terms of number of publications

Rank	Countries	Type	Documents	Citations	Avg. citations	Proportion	Total link strength
1	China	Developing	614	14,488	23.60	34.4%	164
2	The United States	Developed	343	6662	19.42	19.2%	193
3	Australia	Developed	124	3236	26.10	6.9%	118
4	India	Developing	99	2027	20.47	5.5%	14
5	Canada	Developed	88	2002	22.75	4.9%	70
6	Poland	Developed	78	703	9.01	4.4%	35
7	Germany	Developed	65	1285	19.77	3.6%	78
8	The United Kingdom	Developed	63	2805	44.52	3.5%	89
9	Russia	Developing	54	490	9.07	3.0%	37
10	Spain	Developed	50	1775	35.50	2.8%	63
11	France	Developed	48	1646	34.29	2.7%	70
12	South Africa	Developing	45	659	14.64	2.5%	32
13	Czech Republic	Developed	36	758	21.06	2.0%	48
14	Slovenia	Developed	35	626	17.89	2.0%	35
15	Brazil	Developing	30	624	20.80	1.7%	22

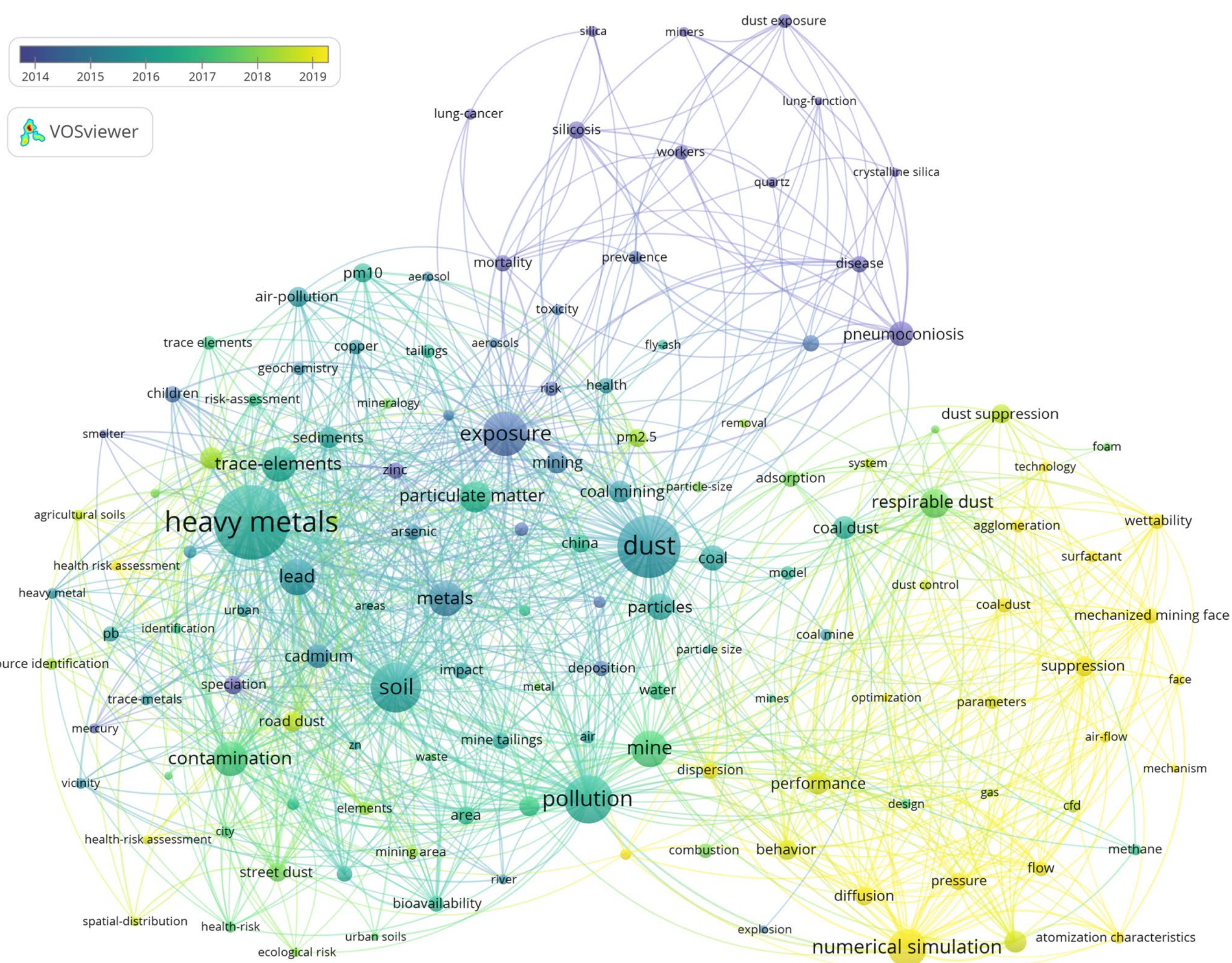


Fig. 14 Co-occurrence knowledge map of the major keywords in the field of mine dust

Table 6 Statistical information of the top 20 high-frequency keywords

Rank	Keywords	Occurrences	Centrality	Avg. pub. Year	Avg. citations
1	Heavy metals	402	0.19	2016	22.9088
2	Dust	238	0.81	2016	18.5587
3	Soil	187	0.08	2016	18.7914
4	Pollution	179	0.4	2016	25.8492
5	Exposure	162	0.26	2015	21.0556
6	Numerical simulation	132	0.22	2019	27.6818
7	Mine	125	0.14	2017	25.024
8	Lead	124	0.18	2016	22.4194
9	Metals	117	0.09	2015	22.0513
10	Trace-elements	116	0.14	2016	26.1552
11	Contamination	115	0.10	2017	20.8783
12	Particulate matter	103	0.08	2017	17.4951
13	Respirable dust	95	0.21	2018	27.4105
14	Particles	85	0.14	2016	21.4471
15	Coal	79	0.12	2016	18.9494
16	Pneumoconiosis	76	0.23	2013	15.1711
17	Cadmium	72	0.11	2015	23.3333
18	Coal dust	71	0.25	2016	20.9718
19	Performance	71	0.12	2019	27.9718
20	Coal mining	67	0.18	2016	15.3284

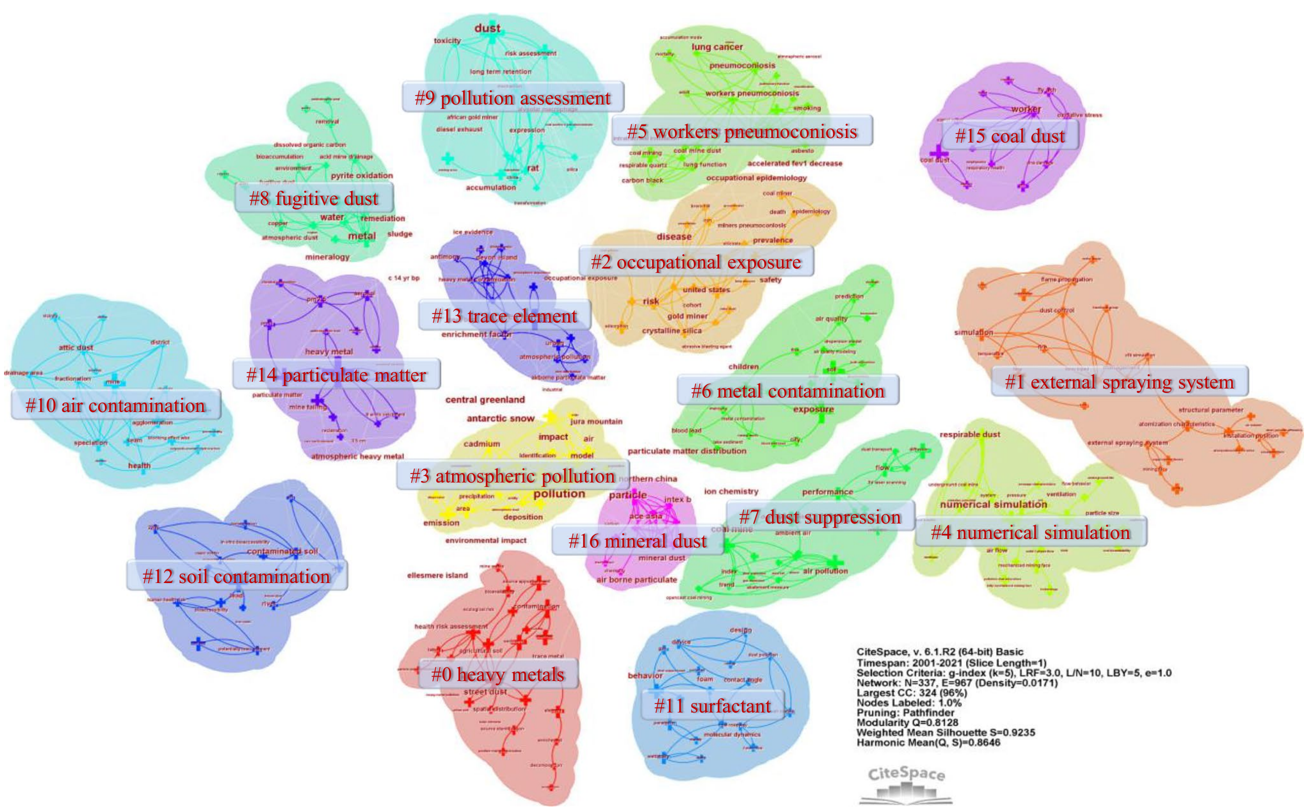


Fig. 15 Cluster mapping of keywords of mine dust research

Table 7 Statistical information on keyword clustering

ID	Cluster	Silhouette	MY	Top terms
0	Heavy metals	0.94	2015	Heavy metals; spatial distribution; health risk; ecological risk; street dust; sediment; source apportionment
1	External spraying system	0.986	2019	External spraying system; spraying pressure; nozzle caliber; structural parameter; combustion; atomization characteristics; optimal dust-removal air flow rate; dust suppression efficiency;
2	Occupational exposure	0.852	2006	Prevalence; disease; silicosis; exposure; dust exposure; epidemiology; crystalline silica; adsorption
3	Atmospheric pollution	0.894	2007	Heavy metals; mining area; multivariate statistics; distribution characteristics; typical steppe; lead; pollution; northern hemisphere; deposition; emission
4	Numerical simulation	0.938	2017	Numerical simulation; ventilation; underground coal mine; fully mechanized mining face; mechanized mining face; particle size; air flow; pollution characteristics; CFD; solid 2 phase flow
5	Workers pneumoconiosis	0.926	2004	Coal mining; pneumoconiosis; lung cancer; black lung; respirable dust; diesel exhaust; particle characterization; occupational epidemiology
6	Metal contamination	0.904	2012	Metal contamination; heavy metals; regression model; surface soil; open coal field; pollution sources; health risk; urban environment; mercury source; mining waste; air quality modeling
7	Dust suppression	0.946	2011	Dust suppression; dust generation; dust diffusion; dust transport; coal mine; air suction; fully mechanized mining face; installation angle; numerical simulation; multiple dust sources; abatement measure; foam generator; foaming agent;
8	Fugitive dust	0.976	2014	Atmospheric dust; giant mine; fugitive dust; land reclamation; dissolved organic carbon; commercial blasting; metal mesh filter; metal; water; copper; acid mine drainage; mineralogy;
9	Pollution assessment	0.9	2003	Dust; risk assessment; mining area; atmospheric particle; sequential extraction; statistical analysis; mechanism; accumulation; blood lead levels; integrated exposure uptake;
10	Air contamination	0.909	2014	Mine area; speciation; attic dust; reflection; drainage area; river sediment; shotcretes; health risk; indoor dust; microsomal epoxide; vicinity; permeability; seam
11	Surfactant	0.939	2018	Surfactant; dust pollution; dust suppressant; behavior; analysis of dust suppression mechanism; particle size; wind resistance; engineering application; dust pollution;
12	Soil contamination	0.911	2013	Bio accessibility; potentially toxic elements; contaminated soils; human health risk; contaminated soil; potentially toxic element; zinc; sequential extraction; copper smelter; iron oxide
13	Trace element	0.939	2010	Trace element; urban; enrichment factor; size distribution; enrichment factor; trace element; ecotoxicity; traffic dust; heavy metal contamination
14	Particulate matter	0.924	2010	Particulate matter; pm10; pm2.5; aerosol; mine tailings; heavy metals; numerical simulation
15	Coal dust	0.849	2009	Occupational exposure; coal dust; heavy metals; sentinel species; air particles; mineral coal; coal mining
16	Mineral dust	0.95	2010	Mineral dust; size distribution; particle; whistler; air borne particulate; mining wastes; land degradation; wind erosion; surface coal mines; air borne particulate

Note that the silhouette denotes the closeness of clustering members or homogeneity of members (> 0.7 is better), MY (mean year) denotes the average year of citations, and top terms denote the clustering members

passed the clustering test, indicating a significant clustering structure. It can be concluded from the clustering results that the research in the field of mine dust in the nearly 20 years encompasses the whole process of mine dust generation (#0 *heavy metals*, #8 *fugitive dust*, #13 *trace element*, #14 *particulate matter*, #15 *coal dust*, #16 *mineral dust*), migration (#4 *numerical simulation*, #6 *metal contamination*, #10 *air contamination*, #12 *soil contamination*), prevention and control (#1 *external spraying system*, #7 *dust suppression*, #9 *pollution assessment*, #11 *surfactant*), and disaster-causing consequences (#2 *occupational exposure*, #3 *atmospheric pollution*, #5 *workers pneumoconiosis*).

The statistical information of the 17 clusters extracted with Citespace is listed in Table 7. It can be found that with the iterative updating of research techniques, the focus of mine dust research has been varied at different times. The three stages are mainly manifested as follows.

- In initial period (2001 ~ 2008), the theme of the study is "*Occupational exposure and pneumoconiosis pathogenesis*", and the representative clusters are as follows: #2 *occupational exposure*, #5 *workers pneumoconiosis*, etc. For instance, Finkelman et al. (2002) analyzed the links between potential environmental problems and human health during coal mining and use. Kuempel et al. (2003) studied the relationship between lung inflammation and silica dose in respiratory coal mine dust. Beeckman et al. (2001) and Antao et al. (2005) successively investigated the changing trend of respiratory diseases among coal miners (2001) and the influencing factors of pneumoconiosis (2005) in the USA.

- In stable transition period (2009 ~ 2016), the study of mine dust mainly focuses on "*Pollution effects of mining dust particles containing heavy metals*," and the representative clusters are as follows: #6 *metal contamination*, #10 *air contamination*, #12 *soil contamination*, etc. For example, Rodriguez et al. (2009) studied the distribution of heavy metals in soils from lead and zinc mining areas in Spain. Csavina et al. (2011) conducted a study of metal and metalloid contaminants in atmospheric aerosols from mining operations. Pandey et al. (2014) investigated the quantitative assessment of air pollution around coal mining areas using clustering and principal component analysis methods.
- In recent years (2017 ~ 2021), the research scholars are increasingly concerned with the "*Mining dust generation and transportation mechanism and prevention technology*," and the representative clusters are as follows: #1 *external spraying system*, #4 *numerical simulation*, #7 *dust suppression*, #11 *surfactant*, etc. For instance, Zhou et al. (2017a) researched the diffusion behavior law of respirable dust at a fully mechanized caving face in coal mine by using numerical simulation. Jiang et al. (2017) investigated the mechanism of dust generation during rock cutting in the mining process and the performance of water jets to suppress dust. Zhou et al. (2017b) studied the synergistic dust reduction technology of surfactant-magnetized water in underground coal mines. Ren et al. (2017) analyzed the effect of dust particles on the stability of dust-proof foams.

All in all, the microscopic physicochemical characteristics and macroscopic transportation laws of mine dust are the themes of research that exist in every period, and how to

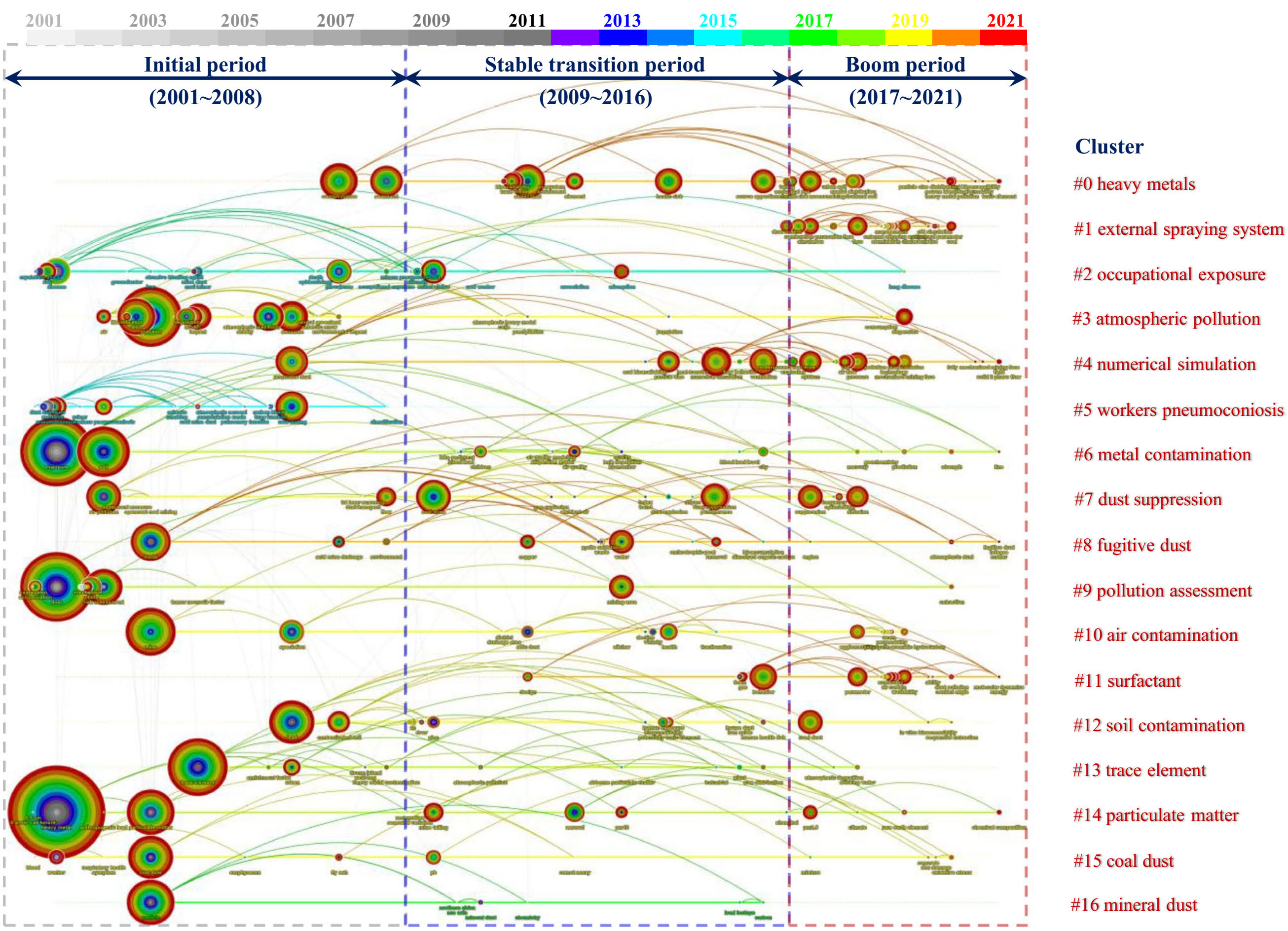


Fig. 16 Timeline of mine dust research hotspots. Note that each node represents a keyword, and the concatenation of nodes indicates the existence of co-occurrence of keywords. The radius size of the node represents the frequency of the keyword (i.e., the number of articles containing the keyword). The evolution pattern of the keyword at different times is represented in the form of the annual rings of the tree, where the width of each ring represents the frequency of the keyword in a certain year, and the annual rings from inside to outside represent the time from far to near

take effective dust removal measures to reduce the hazards of mine dust to the atmosphere and dust exposed workers have been the core of research.

Analysis of time line evolutionary trends of keywords

To further analyze the evolutionary trends in the field of mine dust, the hotspot timeline of 17 clusters of mine dust research was obtained using Citespace's built-in LLR algorithm, as shown in Fig. 16. Among them:

- Heavy metals (cluster 0), coal dust (cluster 15), and mineral dust (cluster 16) are mainly concerned with the source distribution, physicochemical properties, spatial distribution, and ecological risks of mine particulate pollutants.
- External spraying system (cluster 1) and surfactant (cluster 11) pay more attention to the analysis of dust parameters of wet dust suppression by means of laboratory experiments and field experiments, which is the research focus of international scholars at present.
- Occupational exposure (cluster 2) and workers pneumoconiosis (cluster 5) were the research focuses in the initial period (2001 ~ 2008), mainly investigating the hazard of mine dust on workers, occupational exposure and damage quantification method, and epidemiological characteristics of pneumoconiosis.
- Numerical simulation (cluster 4) is currently the mainstream research method for analyzing dust migration rules and dust control parameters, and numerical simulation for dust distribution based on gas–solid two-phase flow theory is the key and symbolic research direction for dust research in mines.
- The research on the pollution effect of mine dust runs through the whole period. For one thing, the clusters represented by atmospheric pollution (cluster 3), metal contamination (cluster 6), and soil contamination (cluster 12) focus more on the pollution effect of open-pit mining, and the spatial pollution distribution characteristics of mineral dust particles containing heavy metals generated by this process are the priority of researchers. For another, the clusters represented by pollution assessment (cluster 9) and air contamination (cluster 10) are more concerned with the distribution pattern of aerosols in the underground mining process, occupational hazard assessment, and health protection mechanism.
- Dust suppression (cluster 7) and particulate matter (cluster 14) are the core themes of mine dust research. These clusters have more nodes with a prominent degree of centrality and have appeared throughout the entire duration of the study. This indicates that scholars have conducted a lot of research surrounding them, and as shown by the timeline, which mainly includes the mechanism of mine dust generation, diffusion and transportation laws, and dust reduction and dust abatement technologies.
- Fugitive dust (cluster 8) and trace element (cluster 13) are presently clustered to a relatively low degree, and the research mainly focuses on the pollution effect of mine dust particles containing heavy metals and trace elements on the surface water circulation system, which is the potential direction for future research.

In order to reveal the evolutionary themes of mine dust control in the three periods from 2001 to 2008, 2009 to 2016, and 2017 to 2021, a co-occurrence relationship analysis of keywords was performed on the collected literature using Citespace, respectively, as displayed in Fig. 17. The parameters were set as follows: time slicing was set to "2001.01 ~ 2008.12," "2009.01 ~ 2016.12," and "2017.01 ~ 2021.12." Years per slice was set to 1. Node types were set to "Keyword." Selection criteria was set to "g-index, k = 10." The "Pathfinder," "Puring sliced network,"

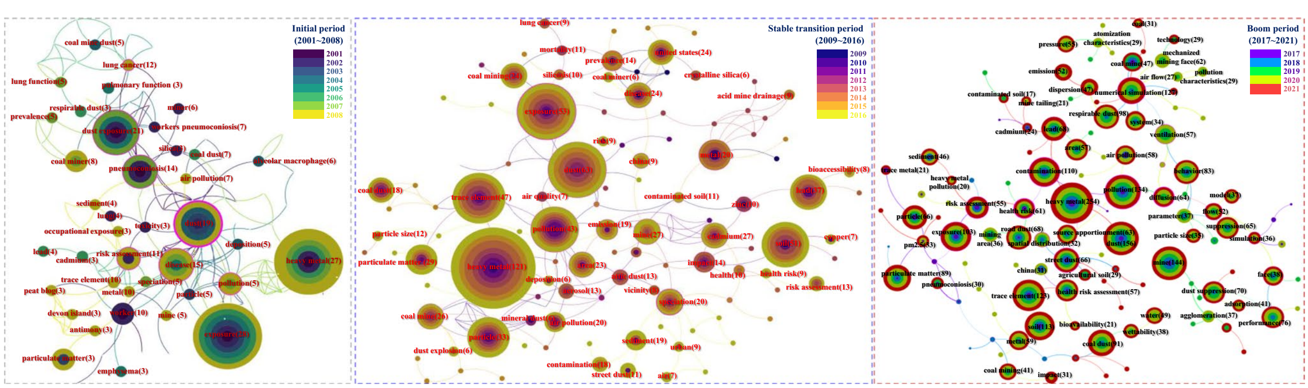


Fig. 17 Evolution trend of keywords in mine dust research. Note that a red circle of a node indicates that the node has exploded or increased sharply in a certain period of time, and this indicates that the frequency of this keyword suddenly changes (surges) in this time interval, and it is at the forefront of research. A purple circle surrounds the node, which indicates that the node has a high degree of betweenness centrality (i.e., the node has a strong connection ability in the clustering network)

and "Pruning the merged network" options in the Puring settings were checked.

It can be observed from Fig. 17 that:

- In initial period (2001 ~ 2008), the keywords with high frequency are as follows: exposure, heavy metal, dust exposure, dust, disease, etc. The keywords with high intermediary center are as follows: dust, pneumoconiosis, dust exposure, pollution, disease, etc. The research field of mine dust in this period is wide but not deep, which laid the overall research pattern of mine dust prevention and control. The characteristics of mine dust research in this period present a wide but not deep research field, which has established the overall research pattern of mine dust pollution prevention.
- In stable transition period (2009 ~ 2016), as the economy recovers in an all-around way and develops rapidly, the problem of safe mining in mines needs to be solved urgently. The research on mine dust in this period has a strong directivity, that is, the pollution effect of mine dust particles containing heavy metals. The hot keywords are heavy metal, dust, exposure, soil, trace element, pollution, etc. Studies in this period mainly focused on the spatial distribution characteristics of heavy metal-bearing mine dust, the pollution prediction of the soil and water around the mine, the migration laws of heavy metals in the soil, and the remediation methods for heavy metal pollution to meet the increasing demand for mineral resources.
- In recent years (2017 ~ 2021), the keywords with co-occurrence times of more than 100 in this period are as follows: heavy metal, dust, mine, polarity, numerical simulation, trace element, soil, contamination, exposure, etc. With the gradual maturity and improvement of numerical simulation software, more and more research scholars tend to analyze the dust dispersion (such as PM1, PM2.5, PM10), the dust production and transportation law of each dust generating process, various dust reduction techniques (such as spray dust reduction, ventilation and dust discharge, dust suppression by dust-rising suppressant, dust removal by dust collector), and their dust reduction efficiency so as to ensure the clean and healthy air of the operating environment.

Analysis of frontier trends in burst keywords

The burst keywords for mine dust research reflect the change in frequency of keywords between 2001 and 2021, which enables analysis of emerging theoretical trends and the emergence of new topics. Citespace was used for the analysis of the highlighted keywords with the following specific parameters: $\alpha 1/\alpha 0 = 2$, $\alpha i/\alpha i\text{-}1 = 2$, $\gamma = 0.7$. States and minimum duration were set to 2 and 4, respectively, as shown in Table 8. It can be found that in the early stages, the technology of mining dust research was not mature enough, and research scholars were more concerned with the environment of pneumoconiosis, occupational exposure, and methods of quantifying damage. Subsequently, with the vigorous exploitation of mining resources, the pollution effects of mine dust studies had received wide attention from scholars, such as heavy metal, silicosis, and occupational hazard. In recent years, with the continuous improvement of numerical simulation software and the appearance of comprehensive dust control system, it is the focus of current research to adopt numerical simulation to analyze the spatial and temporal transport law of mine dust and the linkage control of various dust prevention, control, and reduction technologies to ensure the occupational health and environmental cleanliness of mine construction workers.

Research orientation analysis of mine dust field

The harsh environmental workplace makes ventilation more difficult and increases the time and intensity of fine dust suspended in the air, which becomes an important factor limiting safe, clean, and healthy production in mines. In order to ensure the cleanliness and health of mine workplaces, combined with the international frontier in the field of mine dust, the following recommendations are made for the development of mine dust research.

1) Mechanism of generation and migration and effective theory of prevention and control in mine dust

It is the basis and premise to master the mechanism of mine dust production to realize dust source control. The main research contents in this direction include the following three aspects (Yuan 2020). Firstly, the mechanism of mine dust production under different working conditions will be studied around underground mines and deep concave open-pit mines with complex geological formations (e.g., high altitude, high ground temperature, large depth of burial) (Jiang et al. 2021b). Secondly, the experimental platform of three-dimensional large-scale physical simulation of different working procedures in mines will be constructed to deeply explore the real laws of dust generation, migration, settlement, and other process in each working procedure in mines (Yuan 2020). Thirdly, the three-dimensional numerical simulation software of multi-phase and multi-field coupling will be developed, and the numerical simulation model of dynamic evolution of different types of dust under different working conditions will be constructed to realize the real inversion of mine dust migration and settlement.

Table 8 Top 25 keywords with the strongest citation bursts

Bursts Keywords	Year	Strength	Begin	End	2001-2021
dust exposure	2001	16.28	2001	2012	
disease	2001	13.78	2001	2016	
exposure	2001	12.93	2001	2017	
lung cancer	2001	10.91	2001	2014	
pneumoconiosis	2001	7.54	2001	2007	
coal miner	2001	6.55	2004	2016	
trace element	2001	9.34	2006	2017	
heavy metal	2001	11.25	2007	2016	
dust remover	2001	8.53	2009	2017	
silicosis	2001	7.69	2009	2017	
coal mine	2001	7.39	2009	2018	
occupational hazard	2001	6.73	2010	2014	
foam dust removal	2001	7.71	2011	2016	
tunneling face	2001	6.93	2011	2014	
mechanized mining face	2001	7.33	2012	2017	
dust reduction efficiency	2001	6.89	2013	2016	
dust suppressant	2001	9.68	2014	2018	
particulate matter	2001	7.8	2016	2018	
influencing factor	2001	6.99	2018	2019	
spatial distribution	2001	6.66	2018	2021	
numerical simulation	2001	19.23	2019	2021	
external spraying system	2001	7.08	2019	2021	
respirable dust	2001	6.58	2019	2021	
atomization characteristics	2001	6.23	2019	2021	
pollution characteristics	2001	6.23	2019	2021	

Note that the year denotes the time of bursts keywords appearance. Strength denotes the strength of the keyword prominence, with higher strength indicating greater influence. Begin and end denote the start and end of bursts keywords, respectively

2) Accurate prevention and control technology and equipment of mine dust

Accurate mine dust prevention and control technology and equipment are the core guarantee to achieve the dust-free standard of mine environment (Li et al. 2019). Hence, in order to ensure the occupational health of mine construction workers, we should establish and improve the comprehensive prevention and control technology and equipment system for mine dust, develop high-performance, low-cost environmentally friendly dust suppressants, design spray nozzles with excellent atomization performance, optimize ventilation air flow purification technology, study high-efficiency, low-energy mining dust collectors, and utilize the linkage control of multiple preventions, reduction, exhaust, and dust removal technologies.

3) High precision monitoring and early warning of dust concentration in mines

Continuous and high-precision monitoring and real-time early warning of dust mass concentration provide technical support for mine dust prevention and control and miners' health. The physical and chemical properties of mine dust in different mine environments are quite different. With the help of SEM scanning, laser scattering, charge fusion, and other technologies, the physical and chemical properties of typical mine dust are determined and the corresponding database is established (Jiang et al. 2021b, Yu and Zahidi 2022). Combined with online dust monitoring, digital information control, and dynamic data transmission system, the dust working environment evaluation system, monitoring, and early warning platform are established to monitor and control the dust concentration of workers in real time.

4) Interdisciplinary and institutional cooperation of mine dust

Cooperation and interaction between multi-institutions and disciplines in the field of mine dust research should be strengthened. With the continuous integration and application of information technologies such as big data, artificial intelligence, and digital twinning, the continuous intersection and mutual learning among disciplines (such as environmental science, engineering technology, mining, and medicine) will make mine dust research present an intelligent, automatic, and diversified development trend. For example, it is necessary to strengthen the cross-fertilization and synergistic innovation of science, engineering, and medicine, and to build a large sample database of pneumoconiosis patients' genomes, proteomes, cell groups, biomarkers, and mine dust environments (Yuan 2020). Around the screening of susceptible genes and biochemical indicators of pneumoconiosis, different stages of the injury process of miners' pneumoconiosis will be identified, so as to achieve non-invasive diagnosis and accurate treatment of miners' pneumoconiosis.

Conclusions

This paper makes a statistical analysis of 1786 publications in the field of mine dust research in the Web of Science Core Collection database, and captures knowledge domain mapping through VOSviewer and Citespace software. Up to now, mine dust research has the following characteristics:

(1) Global research on mine dust can be divided into three stages: initial period (2001 ~ 2008), stable transition period (2009 ~ 2016), and boom period (2017 ~ 2021). China is the most active country in the field of mine dust research, accounting for 34.4% of the total global publications. Nevertheless, studies from developed countries such as the USA, Australia, and the USA have been more impactful. The comprehensive national power of the country, the reserves of mineral resources, and the technical problems facing the development of mineral resources are important and major constraints factors to the development of the mine dust field.

(2) *Environ Sci Pollut R*, *Powder Technol*, *Sci Total Environ*, and *J Clean Prod* are the mainstream journals in the field of mine dust. The journals and disciplines of mine dust are mainly in the field of environmental science and engineering technology. The topic of mine dust research includes the whole process of mine dust generation, migration, control, and disaster consequence.

(3) A stable core group of authors has been initially formed in the field of mine dust research. The top 15 most published institutions are mainly from China, the USA, Slovenia, Arizona, Russia, Indian, and Prague. Among these institutions, "Shandong University of Science & Technology," "China University of Mining & Technology," and "National Institute for Occupational Safety & Health" act as a bridge to promote inter-institutional cooperation in dust research.

(4) At present, hot research fields of mine dust mainly focus on mine dust particle pollution, multi-stage combined control technology of dust prevention and emission reduction, and mine occupational protection, monitoring, and early warning. Future research will focus on dust production and transport mechanism and efficient prevention and control theory, precise dust control technology and equipment, and high-precision monitoring and early warning of dust concentration. Attention should be paid to dust control in underground mines and deep concave open-pit mines under complex and dangerous environments. Cooperation and interaction between research institutions and interdisciplinary should be strengthened to promote the integration and application of mine dust and automation, information, intelligent, and other technologies.

Author contribution Fabin Zeng, writing—original draft, conceptualization, methodology.

Professor Zhongan Jiang, supervision, funding acquisition, writing—review and editing.

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

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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