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REVIEW ARTICLE

Scientometric analysis on the review research evolution of tailings dam failure disasters

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Abstract
As the most severe damage form of tailings ponds, dam failure causes a serious threat and damage to the surrounding lives and environment. Therefore, based on the systematic collection and consultation of relevant data at home and abroad, the literature source analysis on tailings dam failure disasters is conducted using the CiteSpace scientometric tool. The research on tailings dam failure disasters can be classified into two stages: the preliminary germination stage and rapid development stage. Based on the scientometric knowledge map, the research hotspots of tailings dam failure disasters are analyzed and summarized as three main research directions: environmental impact, risk assessment, and mechanical behavior. With the maturity of the research on ecological problems caused by tailings leakage, ecological restoration has also gradually become a hot research topic. Through the analysis of keyword bursts and co-cited bursts, the research frontier of tailings dam break disaster is explored. "Risk management," "real-time monitoring," and "tailings characteristic" represent the current research frontier. Among them, risk management is burst for the longest time and is expected to be a very important research direction in the future. Finally, a tailings pond risk management and control suggestion is proposed with risk management as the core, emphasizing risk monitor, and combined with dynamic risk control, which provides a foundation for the construction of tailings dam safety management and dynamic monitoring systems.

Keywords Scientometric analysis · Tailings dam failure · Disaster evolution · Risk control · Environmental impact

Introduction

Tailings ponds are an important facility in mine production. Among the many types of accidents that occur in tailings ponds, dam failure is the most harmful and accounts for 95% of tailings pond accidents. Dam failure of a tailings pond is easily caused by effects of seepage, overtopping, earthquakes, and so on. Damage to the tailings pond causes not only a large number of casualties and property losses but also great harm to the environment via soil pollution, plant destruction, etc., because the tailings contain a large amount of heavy metal elements (Punia 2021). Therefore, research on dam failure of tailings ponds is crucial for mine safety production, protection of downstream life, and safety of property and surrounding environment.

With regard to tailings dams, Stefaniak and Wróżyńska (2018) stated that the collapse of a tailings dam is no accident. Moreover, following the failure of the Brumadinho tailings dam in Brazil, Ligia Noronha, head of UNEP's economics department, commented that although the development of mineral resources is crucial, the premise should be to ensure the safety of people and ecosystems (Luo et al. 2021). Mining operation data show that the number of tailings from ore processing constitutes 97–99% of the total ore (Adiansyah et al. 2015). Advances in mining technology enables mining of lower-grade deposits, implying that more waste residue will be generated and handling of it will place more pressure on tailings ponds. By 2021, approximately 20,000 tailings dams have been constructed and approximately 1.2% tailings dam accidents have occurred (Azam and Li 2010). However, the actual accident rate may be much higher than this; this is

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because the lack of information and accident bias make some mining companies reluctant to publicly disclose information about the collapse of tailings ponds. In 2010, Azam and Li (2010) analyzed the regularity of tailings dam failure time, geography, and reasons based on the statistics of tailings dam failures that occurred in the past 100 years. They found that the main reasons for the tailings dam failure were abnormal rainfall and mismanagement. At the same time, tailings dam failure disasters have moved geographically from developed to developing countries over time. This was also confirmed by Islam and Murakami (2021). The updated global tailings dam failure database updated in 2020 reveals that the tailings dam failure accident is currently on the increase again. Lyu et al. (2019) also found that tailings dam failure is closely related to the country's economic situation. Although decades ago, most of the tailings dam failures occurred in developed countries, its proportion has been relatively high in developing countries in recent years. This shift poses a major challenge to the tailings pond disaster prevention and control capabilities of these developing countries. These countries should, therefore, learn from the experience of developed countries to mitigate the occurrence of dam failure accidents. The tailings dam failure disaster is affected by various factors, which signifies the disaster mechanism. Therefore, risk factor analysis and risk assessment of tailings dam failure are the starting points of tailings dam failure risk management. Only by having a clear understanding of the risk of tailings dam failure can we obtain accurate risk-related information and provide a basis for disaster prevention and control. Hence, it is essential to conduct relevant research on tailings dam failure disasters.

Researchers have studied the tailings dam failure from different perspectives and using different methods to obtain improved theoretical analysis and experimental research results. Cheng et al. (2021) pointed out that tailings dam risk assessment, monitoring, and early warning are necessary for tailings dam prevention and mitigation through a case study of the Brumadinho tailings dam disaster. Zheng et al. (2011) proposed the quantitative and grading standards of major hazard source evaluation indicators in tailings according to the internal safety mechanism of the mine tailings library. These standards provide not only a basis for companies to identify and classify hazard sources but also guidance to the government to achieve grading control of hazard sources. Jing et al. (2012) studied the displacement, infiltration line, stress, and damage process using a physical model test and a numerical simulation method. The results showed that physical model trials and numerical simulation analysis are effective means of studying tailings dams. Hatje et al. (2017) suggested that acid mine drainage (AMD) and mine tailings are the most important issues that lead to environmental pollution in mining activities. Accordingly, by considering the world's largest tailings dam failure event as an example, they analyzed the spatial distribution of main trace elements and the characteristics of water, sediments, and suspended particulate matter in the tailings dam failure area. Finally, the exploration of bioavailability and enrichment causes was realized, and the effect of mine drainage and mine tailings on the surrounding environment was outlined. The above-mentioned studies on tailings dam failure based on different perspectives and methods have laid a theoretical foundation for accurately obtaining tailings pond risk information and realizing the risk management and control of tailings dam failure. For the current study, Dong et al. (2020a) believed that it is necessary and significant to conduct research on tailings dams. However, there are relatively few literature reviews on tailings dams, and most of them are not systematic and comprehensive. Therefore, a systematic review and summary of the existing research are necessary.

Although some scholars have combined the research progress of the mine tailings library, the previous literature reviews focus on the research on the dam-related disasters in the mine tailings, which is mostly based on the subjective experience of experts and lacks time, space, institution, and quantitative analysis based on scientific measurement using research hotspots and cutting edges. Knowledge map analysis based on scientometrics is a visual presentation method and is widely used in literature scientometric research in recent years (Dong et al. 2020b). Scientometrics, the quantitative study of science, can access a wide and highly diverse range of related topics, making it superior to traditional qualitative expert-compiled reviews. Chen et al. (2014) pointed out that scientometric-assisted literature reviews are not intended to replace expert-produced reviews but provide additional reference points, for which deep and keen insights from experts in the relevant field and understanding of complex topics are essential. Based on the quantitative analysis of scientific measurement and the subjective experience of experts, scientometrics combines qualitative and quantitative analysis to more efficiently analyze the evolution of research on tailings dam failure disasters and grasp the research progress and research frontier more accurately. Therefore, in this paper, through the CiteSpace literature scientometric analysis tool, we use a combination of qualitative and quantitative methods to conduct scientometric analysis of tailings pond dam failure disaster research hotspots, frontiers, and trends; reveal the research progress in the field of tailings pond dam failure disaster research; analyze the problems faced by tailings pond dam failure disaster research; and propose relevant recommendations, with a view to provide references for the theoretical research and technological innovation to realize tailings pond disaster prevention and mitigation.

General characteristics of tailings dam failure disaster research

Overview of CiteSpace

CiteSpace, developed by Chen (2017), is a Java-based scientific visualization software package used for analyzing and visualizing co-citation networks; it is a multi-dimensional, time-sharing, dynamic citation visualization tool. CiteSpace uses time-sliced snapshots to show the evolution of research fields and integrates citation and co-citation analysis methods to build a theoretical model from "knowledge base" to "research frontier" (Chen et al. 2009), as shown in Fig. 1.

Chen (2006) believed that if a research front is defined as the development status of a research field (e.g., research ideas), then the citations of the research front would form the corresponding knowledge base. A research area can be conceptualized as a temporal mapping $\Phi(t)$ from the research front $\psi(t)$ to the knowledge base $\Omega(t)$, as follows:

$$\Phi(t) : \psi(t) \rightarrow \Omega(t) \quad (1)$$

$$\psi(t) = \left\{ \text{term} | \text{term} \in S_{\text{title}} \cup S_{\text{abstract}} \cup S_{\text{descriptor}} \cup S_{\text{identifier}} \bigwedge \text{IsHotTopic}(\text{term}, t) \right\} \quad (2)$$

$$\Omega(t) = \{ \text{article} | \text{term} \in \psi(t) \bigwedge \text{term} \in \text{article}_0 \bigwedge \text{article}_0 \rightarrow \text{article} \} \quad (3)$$

where $\psi(t)$ is a group of words and phrases (i.e., terms) associated with emerging trends and sudden changes at time t, and these terms are called research-front terms; $\Omega(t)$ consists of groups of articles cited by articles in which research-front terms are found; S_{title} denotes a set of title terms; $\text{IsHotTopic}(\text{term}, t)$ denotes a Boolean function; and $\text{article}_0 \rightarrow \text{article}$ denotes that article_0 cites article.

Based on scientometrics and visualization technology, CiteSpace integrates the co-occurrence network, association rules, and clustering analysis algorithms to analyze relevant data in literature and perform visual analysis of information via intuitively displaying the structure, distribution rules, and correlation of scientific knowledge.

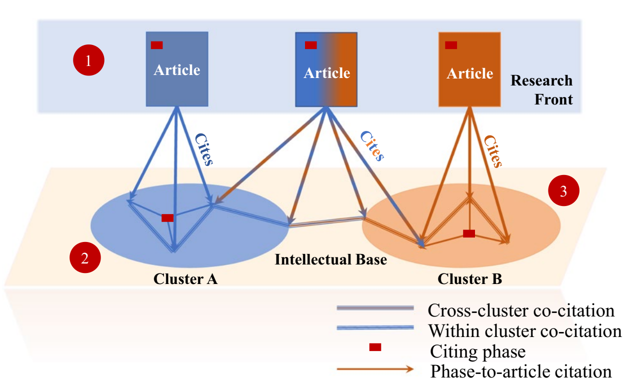

Fig. 1 Conceptual model of CiteSpace

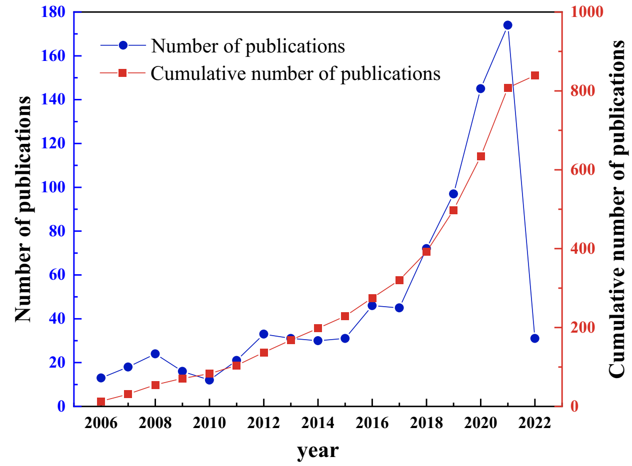

Fig. 2 Statistics of literature published in the field of tailings dam failure disasters

Based on the "Web of Science" core database, the related publications on the tailings dam failure were searched with "tailings dam failure" and "stability of tailings dam" as the subject words. After screening, a total of 839 publications were obtained from 2006 to 2022. A scientometrics analysis was conducted on these publications, and the research hotspots, evolution trends, and research frontiers in the research field of tailings dam failure disasters were determined by combining qualitative and quantitative methods. Thus, a theoretical and application reference could be provided for in-depth research on tailings dam failure disasters in the new era.

Statistical analysis of publications

The number of published papers can to some extent reflect the research heat of relevant fields in a certain stage. The statistical analysis of the annual number of publications and the cumulative number of publications according to time was performed for 839 publications from 2006 to 2022, and a statistical chart of the number of publications related to tailings dam failure disasters was obtained, as shown in Fig. 2.

The overall development process and research progress in the research field of tailings dam failure disasters can be understood through the analysis of the time characteristics of the number of publications. As can be seen from Fig. 1, the research on tailings dam failure disasters can be divided into two stages:

1. Preliminary germination stage (2006–2015). At this stage, the research on tailings dam failure disasters is

in the preliminary germination stage with slow development, and the average annual number of published papers is also small, with the cumulative number of published papers accounting for 23.60%. The research at this stage is mainly based on the basic theory of tailings dam failure disasters.

2. Rapid development stage (2016–2022). At this stage, the research on tailings dam failure disasters grows rapidly and increases significantly, which is the peak period of the research on tailings dam failure disasters. This stage is also the peak period of tailings dam failure accidents, which also promotes the academic field to pay attention to the safety of tailings dam failure to some extent.

It is worth noting that the growth rate of the number of publications decreased from 2020 to 2021. Although research on tailings dam failure has relatively matured, it remains to be further observed whether it is about to enter a period of fluctuation and decline due to the effect of COVID-19. However, in general, from the cumulative number of publications, the academic research on tailings dam failure disasters is still in the process of gradual in-depth and stable development. This further illustrates the importance of summarizing the research on tailings dam failure disasters.

Analysis of international cooperation network

The cooperation of research scholars for the common purpose of generating new scientific knowledge is called scientific collaboration (Katz and Martin 1997). Based on the analysis of international cooperation networks, research on tailings dam failure by countries or regions and cooperation by countries or regions can be obtained. The map of the international cooperation network is shown in Fig. 3.

Figure 3 shows the cooperation network of countries in tailings dam failure disaster research. The size of each node in the map indicates the number of publications in each country or region. The larger the node is, the more publications are made in the country or region. The connection between the nodes represents the cooperative relationship between countries. The thicker the connection is, the closer the cooperation is. It has established a network of cooperation centered on China, Brazil, Canada, Australia, the USA, South Africa, and Spain, including Germany, Italy, France, Romania, Turkey, Iran, Sweden, Chile, and Source Korea. The regions should continue to strengthen cooperation to further promote the healthy development of the tailings dam failure disaster research system. It can be clearly seen from Fig. 2 that China and Brazil are the two largest nodes among them. These two countries have more research on tailings dam failure disasters, and the problems of tailings dam failure disasters in these two countries are also the most prominent. The prevention and control of tailings dam failure disasters have obvious realistic demand. Therefore, scholars in these countries have the most extensive research on tailings dam failure disasters, which also shows that practice and theory are inseparable to a certain extent.

The red node in Brazil reflects the highest burst intensity, indicating that Brazil is the most active country in the research field of tailings dam failure disaster in recent years. This is because after the occurrence of the major failure accidents of Fundão and Brumadinho tailings dams, research on tailings dam failure disasters in Brazil has entered the explosive growth stage. In addition, although China also exhibits high enthusiasm for tailings dam failure disaster research, there is a lack of cooperation with other countries or regions. Scholars of tailings dam failure disaster research should continue to strengthen cooperation to further promote the healthy development of tailings dam failure disaster research systems.

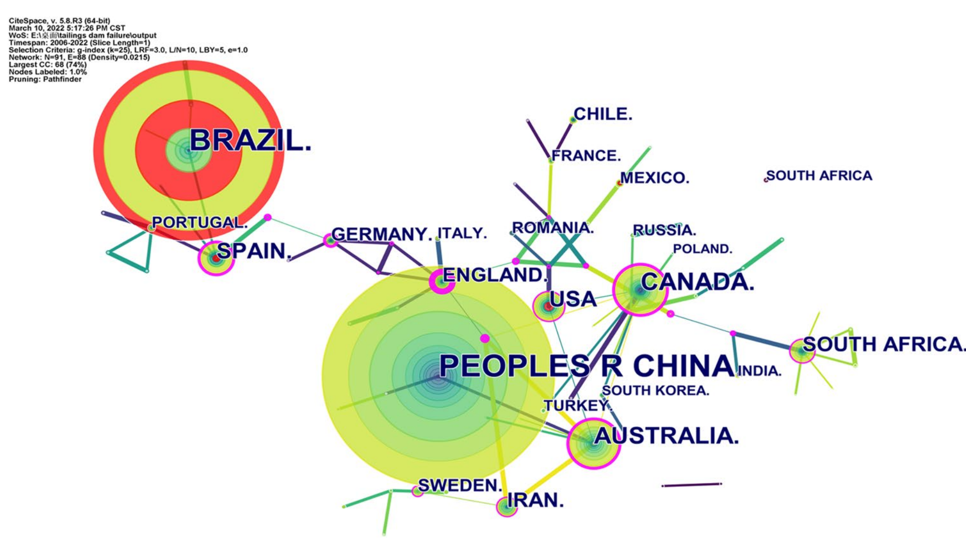

Fig. 3 Cooperation network of countries

Analysis on research hotspots of tailings dam failure disaster

Keyword co-occurrence and cluster analysis

Keywords are the summary of the main content of the literature and the author's intention and are the core and essence of the literature. Therefore, the scientific econometric analysis of keywords of relevant literature in the research field of tailings dam failure disasters is beneficial to ascertain the research status of tailings dam failure disasters and quantitatively extract research hotspots and research frontiers of tailings dam failure disasters. By drawing the co-occurrence network map of keywords and conducting cluster analysis of keywords, the research hotspots and current research frontiers that are most concerned by academia in the study of tailings dam failure disasters can be extracted. In CiteSpace, the node type was set as "Keyword" and the time slice was selected as 1, so as to obtain the keyword co-occurrence and clustering network map of tailings dam failure disaster research, as shown in Fig. 4.

In the keyword co-occurrence graph shown in Fig. 4, each node represents a unique keyword. The larger the keyword node and the more the connections between nodes, the higher the frequency of co-occurrence of the keyword. The thickness of the connection indicates the closeness between the two keywords. The frequencies of "tailings dam", "heavy metal", and "mine tailings", i.e., 199, 141, and 109, respectively, are considerably higher than those of other keywords. Among them, "tailings dam" and "mine tailing" are the basis of literature retrieval, which is not analyzed. High-frequency keywords in the research field of tailings dam failure disasters are determined using the critical determination model of high-frequency keywords proposed by Xu and Feng (2021) (formula (4)).

$$T = 1/2(-1 + \sqrt{1 + 8I_1}) \quad (4)$$

where T is the critical value of high-frequency keywords; I_1 is the number of keywords with frequency 1.

The number of keywords with a frequency of 1 is 231. According to formula (1), it can be obtained that the critical value of high-frequency keywords in the study of tailings dam failure disasters is 21, so the keywords with word frequency more than 21 are selected as high-frequency keywords for tailings dam failure disaster research. Delete the retrieval words such as "tailings dam", "mine tailing" and "dam failure", the high-frequency keywords and their frequencies of tailings dam failure disaster research are "heavy metal" (141), "soil" (92), "environmental impact" (79), "environmental pollution" (75), "acid mine drainage" (58), "behavior" (51), "stability analysis" (50), "risk assessment" (44), "iron ore tailing" (42), "sediment" (36), "shear strength" (34), "management" (28), "trace element" (26), and "waste" (24). Through the analysis of high-frequency keywords, the focus of tailings dam failure disaster research can be roughly divided into three main directions: environmental impact, mechanical behavior, and risk assessment. In addition, iron ore tailing is one of

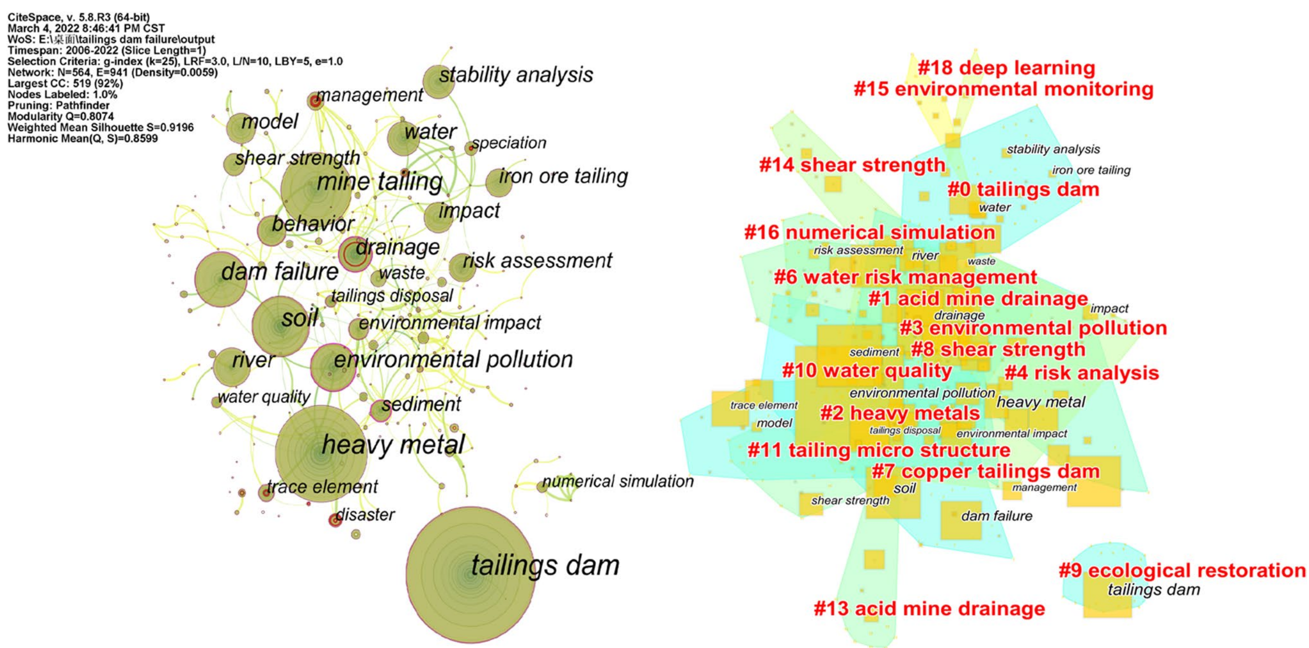

Fig. 4 Keyword co-occurrence and clustering network map

the high-frequency keywords, indicating that iron ore is one of the main research objects.

In the keyword clustering map shown in Fig. 4, modularity Q is 0.81 > 0.3 and mean silhouette is 0.92 > 0.5, indicating that the partition structure is significant and the clustering is efficient and convincing. The keyword clustering results are as follows: “tailings dam”, “acid mine drainage”, “heavy metals”, “environmental pollution”, “risk analysis”, “remote sensing”, “water risk management”, “copper tailings dam”, “shear strength”, “ecological restoration”, “water quality”, “tailing micro structure”, “hydrometallurgical waste”, “acid mine drainage”, “shear strength”, “environmental monitoring”, “numerical simulation”, “flotation”, and “deep learning”. The results of keyword clustering and keyword co-occurrence are basically the same and can be divided into three main aspects: environmental impact, mechanical behavior, and risk assessment. It is worth noting that the clustering results of “remote sensing”, “ecological restoration”, “tailing micro structure”, “numerical simulation”, and “deep learning” are not reflected in high-frequency keywords, which also represent the current research hotspot. This indicates that as the research on tailings pollution mechanisms gains maturity, the research on ecological restoration is gradually becoming a new research hotspot.

Co-occurrence and cluster analysis of co-cited articles

The citation relationship among scientific documents shows that scientific documents are not isolated but interrelated and ever-extending systems. The mutual citation of scientific literature reflects the objective regularity of scientific development and embodies the accumulation, continuity, and inheritance of scientific knowledge as well as the cross and penetration between disciplines. Therefore, the source can be traced forward and the development can be traced backward through the citation network.

The evolutionary networks and co-citation trajectories formed by the co-cited articles are the knowledge base of the research field. Cluster analysis was performed on the co-cited articles, and the clustering network of the co-cited articles was obtained, as shown in Fig. 5. The extracted themes were named for the clustering results, and the themes and trends in tailings dam failure disaster research were further analyzed according to the clustering results of the co-cited articles.

The largest node in Fig. 5 is “The environmental impact of one of the largest tailings dam failure worldwide,” published in Scientific Report by Hatje et al. (2017); it shows the highest citation frequency of 65 times. Hatje et al. (2017) analyzed the effect of the SAMARCO iron tailings leakage accident on the environment and demonstrated that the tailings dam failure disasters pose long-term and unknown risks to the surrounding environment. Moreover, it was pointed out that it is necessary for the academia to conduct in-depth research on tailings dam failure disasters with the highest speed and the most urgent attitude so as to reduce environmental damage and realize the restoration of the ecosystem. This reemphasizes the importance and significance of research on tailings dam failure disasters. In addition, the main contents of the top 5 highly co-cited articles are as follows:

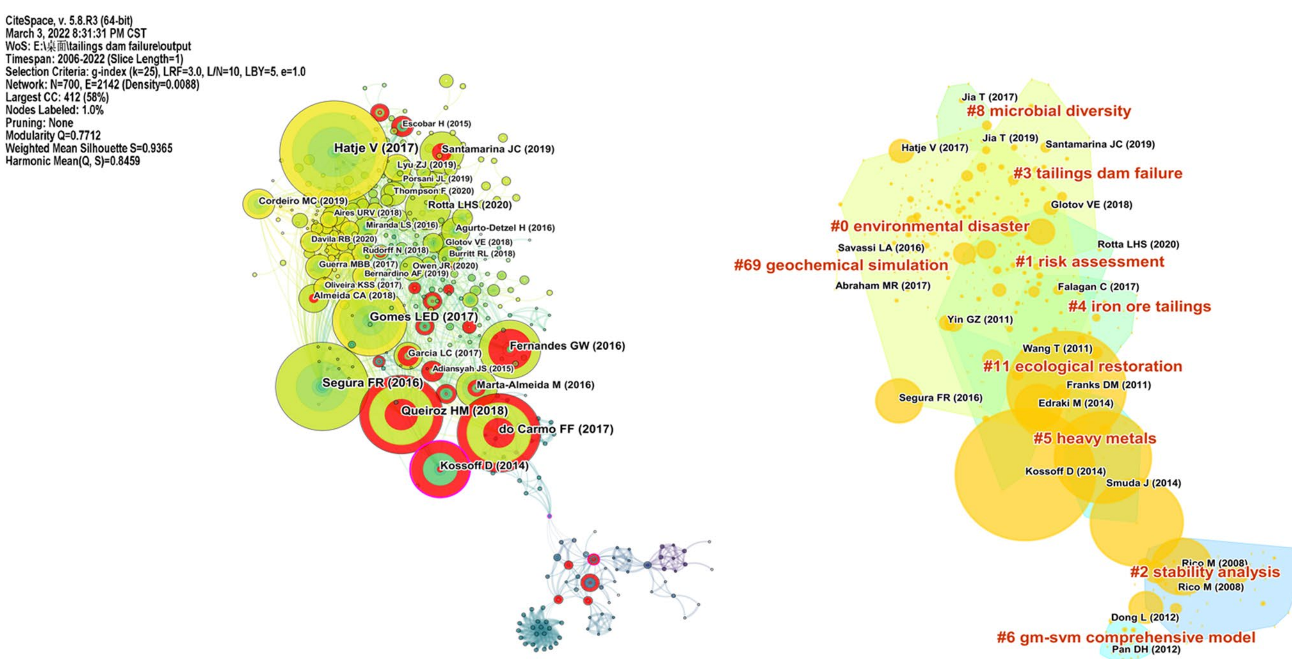

Fig. 5 Co-citation network of tailings dam failure disaster research

Segura et al. (2016) studied the element composition, microbial count, leaching/extraction capacity, and toxicological bioassay of tailings after SAMARCO iron tailings leakage, in order to provide reference for monitoring and risk assessment of SAMARCO iron tailings.

Queiroz et al. (2018) collected and analyzed the soil and tailings samples from the area affected by SAMARCO iron tailings dam failure and determined the pH value, particle size, mineralogical composition, total metal content, and organic content of the samples. Fractionation of metals was carried out to elucidate the kinetic mechanism of trace metals.

Fernandes et al. (2016) analyzed the impact of SAMARCO iron tailings dam failure on social economy and ecological environment and proposed a long-term monitoring framework and mitigation measures. At the same time, it is also pointed out that catastrophic accidents such as SAMARCO iron tailings dam failure may become more frequent.

Kossoff et al. (2014) analyzed the characteristics, types, scale, and environmental impact of tailings dam failure and proposed corresponding remedial measures.

From the content of highly co-cited articles, most of them are based on the study of SAMARCO iron tailings leakage accident. In the context of global tailings dam failure disasters, this accident is more prominent. The SAMARCO iron tailings leakage accident in Brazil occurred in 2015. More than 43 million cubic meters of iron ore tailings contaminated 668 km of waterways from the Doc River basin to the Atlantic Ocean, with an unprecedented number of pollutants and the extent of the affected ecosystem. The tailings dam failure accident sounded the alarm for the mining industry, and many international scholars began to focus on the related research of the tailings dam failure disasters. The research on the tailings dam failure disasters has entered a period of rapid growth from the preliminary germination stage. It is also pointed out in the section of "General characteristics of tailings dam failure disaster research" that since 2015, the research on tailings dam failure disasters has entered the stage of rapid growth. In addition, the emergent intensity of Brazil is the strongest. Brazil is one of the most active countries in the research field of tailings dam failure disasters in recent years. The reasons behind these phenomena all point to the SAMARCO iron tailings leakage accident. Through this accident, we should reflect on whether lessons have been learned and whether tragedies can be prevented from happening again.

From the co-cited clustering results of literature, modularity Q is $0.77>0.3$ and mean silhouette is $0.94>0.5$, indicating that the partition structure is obvious and clustering is efficient and convincing. On the basis of the clustering topics extracted from co-cited clustering (Fig. 5), the network is divided into 10 co-cited clusters. The cluster results that the number of cluster members exceeds 40 are summarized as follows. The clustering topics and representative articles are detailed in Table 1.

These representative studies reflect different research hotspots of tailings dam failure disasters. The important articles in each co-cited clustering theme play a key role in the knowledge evolution of tailings dam failure disaster research and are the most important knowledge base in this clustering field. Different clustering themes represent different hot research directions in the field of tailings dam failure disaster research. Among them, the number of members in the cluster theme of "environmental disaster" is the largest, indicating that the research on environmental disaster in tailings dam failure disasters dominates, followed by "risk assessment", "stability analysis", "iron ore tailing", and "heavy metals". This is also consistent with the keyword analysis results. The research hotspots of tailings dam failure disasters can be summarized into three main research directions: environmental impact, risk assessment, and mechanical behavior. Among the research objects, relatively many publications on iron tailings exist.

In addition, the co-occurrence and clustering results of the co-cited articles show that the literature review accounts for a high proportion, indicating the importance of the literature review in scientific research, and is the research basis for tailings dam failure disasters. However, most of these reviews are based on the qualitative analysis of researchers and lack the quantitative guidance of scientometric analysis. Therefore, a comprehensive analysis of tailings dam failure combining qualitative and quantitative analysis is crucial.

Research frontier analysis of tailings dam failure disaster

Using the detection technology and algorithm of mutation words provided by CiteSpace, combined with the time distribution characteristics of word frequency (the changing trend

Table 1 Cluster themes and representative articles

Cluster ID	Clustering theme	Size	Silhouette	Representative articles
#0	Environmental disaster	62	0.902	(Sá et al. 2021)
#1	Risk assessment	61	0.945	(Lyu et al. 2019)
#2	Stability analysis	55	0.964	(Bird et al. 2008)
#3	Tailings dam failure	52	0.854	(Tian et al. 2021)
#4	Iron ore tailings	45	0.949	(Fontes et al. 2019)
#5	Heavy metals	44	0.965	(Dold 2014)

of word frequency and not just the frequency), the subject words with a high-frequency change rate are detected from a large number of subject words, called mutation words. Through the extraction of emergent words, the recent and future research trends in tailings dam failure disaster research can be identified. To study the frontier knowledge of tailings dam failure disaster research, the keywords bursts were extracted, and the frontier evolution trend of tailings dam failure disaster research locally and abroad was obtained. Table 2 shows the information of the extracted burst keywords.

The *k*nowledge base will evolve over time. To study the frontier knowledge in and explore the frontier evolution trend of the research on tailings dam failure disasters, co-cited articles were taken as nodes to extract the emergent information of co-cited articles in the research on tailings dam failure disasters, as shown in Table 3.

Since 2015, the research enthusiasm of scholars on tailings dam failure disasters has been increasing, the number of relevant articles published has increased rapidly, and many new achievements have emerged in the frontier field.

Tables 2 and 3 respectively show the keyword emergence and co-cited literature emergence obtained from the burst detection of keywords and co-cited articles in the research field of tailings pond dam failure disasters. Each lattice in the table corresponds to a year. "Begin" and "end" represent the beginning and ending years of the corresponding keywords burst, respectively.

Table 2 shows that in the early stage of tailings dam failure research, "trace element and mechanism" represents the research frontier at this stage. The representative literature of this stage is Rico et al. (2008), which conducted a statistical analysis of tailings dam failure cases. The study found that the main causes of tailings dam failure disasters are "abnormal rainfall" and "seismic liquefaction". Furthermore, it pointed out that more than 90% of the accidents occur in mining mines, and formulating relevant regulations and standards for tailings disposal is very urgent. "Acid mine drainage" has the highest burst strength and the longest duration. The burst of "impact areas, mobility" also lasted for a long time, from the preliminary germination stage to the rapid development stage of tailings dam failure disaster research, indicating that the academic community has continuously tracked research on them, representing the research frontier in the preliminary germination stage and rapid development stage of tailings dam failure disaster research. Among the co-cited literature burst at this stage, Kossoff et al. (2014), Edraki et al. (2014), and Villavicencio et al. (2014) studied the characteristics, dam failure mechanisms, and environmental impact of tailings pond, respectively.

In addition, "sediment characteristics" and "environmental remediation" began to emerge from 2016 to 2020, which are largely related to the ecological restoration and environmental governance after the SAMARCO iron tailings leakage accident. Among them, "environmental remediation" lasted for a long time, to a certain extent, indicating that the research on ecological problems caused by tailings leakage has increasingly matured, and the role of "environmental remediation" research has begun to gradually emerge,

Table 2 Keywords with the strongest bursts

Keywords	Year	Strength	Begin	End	2006-2022
acid mine drainage	2006	8.51	2006	2017	
trace element	2006	5.06	2009	2012	
impact areas	2006	4.41	2009	2016	
mechanism	2006	3.59	2011	2012	
mobility	2006	3.83	2012	2017	
sediment characteristic	2006	2.58	2016	2017	
environmental remediation	2006	2.96	2016	2020	
risk management	2006	5.48	2017	2022	
real-time monitoring	2006	4.93	2020	2022	
tailings characteristic	2006	3.62	2020	2022	

Table 3 Co-cited with the strongest citation bursts

Keywords	Year	Strength	Begin	End	2006-2022
Rico M (2008)	2008	6.77	2011	2013	
Kossoff D (2014)	2014	17.05	2016	2019	
Edraki M (2014)	2014	5.76	2016	2019	
Villavicencio G (2014)	2014	5.28	2016	2019	
Adiansyah JS (2015)	2015	4.51	2018	2020	
Zhang QG (2015)	2015	4.41	2018	2021	
Fernandes GW (2016)	2016	4.52	2019	2021	
do Carmo FF (2017)	2017	5.79	2020	2022	
Queiroz HM (2018)	2018	5.79	2020	2022	
Santamarina JC (2019)	2019	8.30	2020	2022	

which represents the evolution of the research frontier at this stage. Most of the emergent articles from 2016 to 2020 adopted the SAMARCO iron tailings leakage accident as an example to explore the effect of tailings dam failure on the ecological environment, social economy, and life safety; for example, Fernandes et al. (2016), do Carmo et al. (2017), and Queiroz et al. (2018). In this stage, "sediment characteristic" and "environmental remediation" became the research frontier for a long period of time due to the impact of the SAMARCO iron tailings leakage accident.

Since 2020, "risk management", "real-time monitoring", and "tailings characteristic" have the highest burst strengths of 5.48, 4.93, and 3.62, respectively. "Real-time monitoring" and "tailings characteristic" began to burst in 2020, which is the research frontier in the recent two years. Zhang et al. (2015) used a tri-axial soil mechanics device and a self-designed "observation device for micromechanics and deformation of tailings" to explore the mechanical properties of the layered structure of tailings dam from the macroscopic and microscopic perspectives. Clarkson et al. (2021) pointed out the importance of consistent, real-time, and online tailings dam monitoring equipment and analyzed the significance of integration from a single instrument to a comprehensive monitoring system. In addition, the burst time of "risk management" has continued from 2017 to the current year, indicating that the safety management of tailings ponds is the most prominent research content at the current stage; it is the current research frontier and is expected to be an important research direction in the future period. Now that engineering science has developed to analyze and mitigate almost all technical risks, why does the dam failure accident of tailings ponds still happen? Based on the analysis of the accident characteristics of tailings ponds with upstream, centerline, and downstream damming modes, Santamarina et al. (2019) pointed out that no construction method can avoid the effect of poor management and bad engineering practice. It can be seen that the risk management of tailings dam is an extremely important aspect in tailings dam failure disasters management.

Evolution analysis of tailings dam failure disaster research

On the basis of scientometric analysis, the research evolution of tailings dam failure disasters is extended and analyzed to further explore the research evolution process of tailings dam failure disasters.

Preliminary germination stage

In the preliminary germination stage of research on tailings dam failure disasters, most scholars have conducted basic theoretical analysis on tailings dam failure disasters, focusing on aspects such as disaster mechanism, disaster evolution characteristics, and trace elements in tailings. Among them, understanding the mechanism and evolution characteristics of tailings dam failure disasters are the core and foundation of disaster prevention and mitigation. The research on the mechanism of tailings dam failure disasters is mainly reflected in the following three aspects: (1) static stability of a tailings dam and its influencing factors; (2) in terms of tailings dam seepage instability; and (3) study on the stability of tailings dams under earthquakes.

1. Static stability of a tailings dam and its influencing factors

   Yin et al. (2011) conducted a physical similarity model test to explore the effect of tailings dam height on dam stability, demonstrating that the dam height of the tailings dam must be less than the design height to ensure the stability of the dam. Lyu et al. (2019) compared the stability of tailings dams with different dam-building types, and they suggested that the stability of upstream tailings dams is worse than that of other dam-building methods, and upstream tailings dams account for 58% of tailings dam failure accidents. Sun et al. (2012) studied the evolution model of tailings dam failure based on a physical model test method. The results showed that the dam displacements depend on the dam saturation degree during tailings dam flood overtopping failure. The higher the saturation lines, the larger the sliding displacements. In addition, as ways to effectively reduce the probability of tailings dam failure in flood season, they suggested reducing the height of the infiltration line, increasing the length of the dry beach, and setting a drainage channel.
2. In terms of tailings dam seepage instability

   The seepage instability of the tailings dam is one of the factors of instability failure of the tailings dam. The seepage field directly induces the instability of the tailings dam (seepage and internal erosion). The current research is mainly based on the numerical simulation and analysis of the seepage field in the tailings dam. Yin et al. (2012) analyzed the effect of seepage on the microstructure of tailings. The results showed that the deformation response to the microstructure of tailings is rapid under load. The deformation of the tailings microstructure caused by seepage was considered to be the main factor leading to the failure and instability of the tailings dam. Zhang et al. (2020) established two-dimensional and three-dimensional finite element models to simulate the seepage field changes under different working conditions. The results showed that the longer the length of the dry beach, the lower the phreatic line and the greater the safety factor. The higher the upstream slope ratio, the lower the phreatic line and the greater the safety factor.

3. Study on the stability of tailings dams under earthquakes
   Relevant literature points out earthquakes as the second major cause of tailings dam failure. According to statistics, 57% of tailings dams are stacked by the upstream method (Islam and Murakami 2021), which is more sensitive to earthquakes. Mayoral and Romo (2008) used the Mohr–Coulomb failure criterion coupled with an incremental pore pressure generation scheme to construct a model that can predict pore pressure and shear strength of fine-grained saturated materials caused by seismic load. Seid-Karbasi and Byrne (2004) studied the seismic response characteristics and corresponding seismic measures of a tailings dam based on the finite-difference algorithm principle. Ishihara et al. (2015) analyzed the maximum possible crest settlement and transverse displacement that small- and medium-sized tailings dams can withstand during earthquakes. The results of the case studies suggested a lateral or vertical deformation of 1.5–2.0 m as a threshold value differentiating between limited deformation and complete failure of the dams.

Statistical analysis of the main causes of tailings dam failures from 2000 to 2022. The main disaster-causing factors of tailings dam failures are seepage, slope instability, earthquake liquefaction, etc. The proportion of disaster-causing factors is shown in Fig. 6.

It can be seen from Fig. 6 that among the disaster-causing factors of tailings dam failure accidents, seepage accounts for the highest proportion, followed by slope instability, earthquake liquefaction, and flooding. The main disaster causing factors of tailings dam failure disaster correspond to the main research directions in tailings dam failure disaster mechanism research, which shows that theory and practice are complementary, practice is the basis of theory, and theory reacts to practice.

Research on the disaster-causing mechanism of tailings dam failure is a long-term process with deepening understanding. An in-depth study on the disaster-causing mechanism and evolution characteristics of the tailings dam will contribute to the comprehensive cross-integration between different basic disciplines. At the same time, it can greatly enhance the theoretical cognitive level of disaster prevention and mitigation of tailings dam failures and realize the significant transformation from “passive disaster relief” to “active disaster prevention.”

At this stage, the environmental disaster caused by trace elements is also one of the key directions of tailings pond disaster research. Antwi-Agyei et al. (2009) pointed out that a large amount of trace element (As, Cu, Zn, and Pb) pollution in soil is related to the tailings dam of metal mines and revealed the transport mechanism of trace elements in the tailings dam. Kossoff et al. (2012) analyzed the effect of

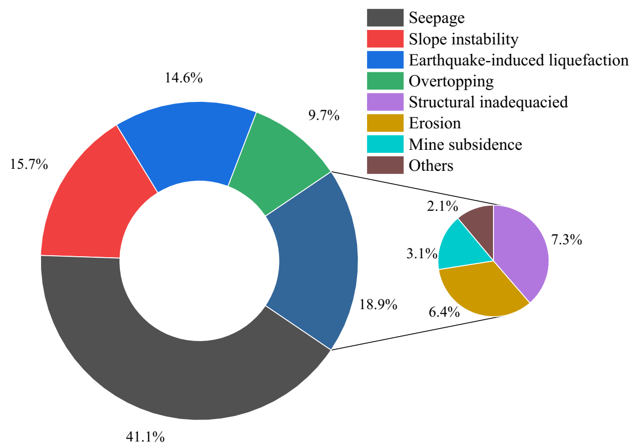

Fig. 6 The proportion of disaster-causing factors in tailings dam failure

tailings leaked due to tailings dam failure on the floodplain environment, and they strongly emphasized that every effort should be made to limit or completely prohibit the release of tailings to floodplain soils. These studies showed that the threat to environmental safety and ecological environment caused by tailings dam failure is also one of the research directions that need to be focused in the future.

Although these basic theoretical studies are in the early stage of tailings dam failure disasters research, they have laid the theoretical foundation for the research on tailings dam failure disasters. In these studies, problems were constantly found, analyzed, and solved, and the implementation plan was summarized and improved, thereby playing a guiding role in the future practice of tailings dam failure disasters.

Rapid development stage

In the rapid development stage, with the deepening of the understanding of tailings dam failure disasters and the improvement of essential safety requirements, the research on tailings dam failure disasters has entered a prosperous period, and an increasing number of theories have been widely applied in the research on tailings dam failure disasters. In addition, the research focus has gradually shifted from disaster mechanisms, evolution characteristics, and environmental impact of tailings dam failure disasters to ecological restoration, tailings characteristics, monitoring and early warning, safety management, and other directions.

Previous studies pointed out that the environmental problems caused by tailings leakage are reaching maturity, and the research on ecological restoration is attracting research attention. The movement and migration of toxic and metalloid metals from soils, sediments, and mining wastes to water systems through natural weathering processes place ecosystems and human health at high risk. Cross and Lambers (2017) believed that achieving successful ecological restoration outcomes on tailings landforms is likely one of the greatest challenges faced by restoration ecologists and the mining industry. Xu et al. (2019) believed that the principle of geochemical evolution provided a new perspective for further studies on pollution control and risk management and suggested that greater attention should be paid to the identification and selection of candidate plants for tailings reclamation in the future. To solve the competition problem of acidophilic bacteria and sulfate-reducing bacteria of mine tailings bioremediation, Zhang et al. (2017) explored the mechanisms of using different nutrients to adjust the microbial community. Nguyen et al. (2021) comprehensively considered the effect of the economy and environment and suggested bioleaching as the best choice for the removal of toxic metals and metalloids from soils.

The engineering characteristics of tailings are of great significance to the safety evaluation and engineering design of the tailings dam. Huang et al. (2014) studied the mechanical properties and microstructure of tailings consolidation and revealed the cementation mechanism of tailings solidified by different cementing materials. In addition, with the continuous mining of mineral resources and the increasing improvement of mineral processing technology, especially the large-scale development of lean ore, resulting in a sharp increase in the content of fine tailings, the fine tailings dam has gradually become the future development trend of tailings dam engineering. Suazo et al. (2016) analyzed the effects of confining pressure, initial static shear stress, and porosity on the anti-liquefaction performance of fine-grained tailings. Cao et al. (2019) tested the effect of particle size distribution on the shear wave velocity of unsaturated tailings. The test results showed that the soil–water characteristic curve of the unsaturated tailings soil is similar to that of other sandy soil and spatially related to effective stress, grain size, and void ratio. Shi et al. (2020) analyzed the evolution characteristics of the microstructure of tailing sand samples with different seepage failure types in the process of seepage failure. The results showed that there are obvious differences in the microstructure characterization of fluid soil and piping-type infiltration failures.

In terms of monitoring and early warning, the development and application of special monitoring devices and new technologies for the tailings dam are imperative. Clarkson and Williams (2021) pointed out that new literature, mining regulatory authorities, insurance companies, and mining practitioners are calling for the supervision of the tailings dam to be strengthened in the form of real-time monitoring and hoping industry suppliers will build innovative monitoring systems to monitor different failure modes and mechanisms of tailings dams. Wang et al. (2018) designed a tailings dam safety monitoring system based on the Internet of Things (IoT) and built a software platform integrated with a geographic information system. Dong et al. (2017) constructed a multi-source information monitoring system for tailings dams based on IoT and wireless networks by using multiple sensors to monitor the stability index such as saturation line, reservoir water level, and dam displacement. Dong et al. (2020a) recommended the establishment of a joint real-time monitoring and early warning system for sound–light–electricity and underground–surface–sky to avoid deficiencies in traditional monitoring methods and some coupled monitoring systems. The real-time monitoring technology of tailings dam failure can improve the accuracy of tailings dam safety monitoring and the timeliness of safety warning as well as realize the intelligent and efficient development of tailings dam safety disaster warning and disaster prevention and mitigation. Scholars use high-resolution remote sensing, unmanned aerial vehicle aerial photography, photogrammetry, three-dimensional laser scanning, and many other online monitoring technologies to monitor the changes in the saturation line, dry beach length, rainfall, dam displacement, and reservoir water level. It can be seen that the real-time dynamic monitoring of tailings dams has been paid increasing attention. Relevant researchers organically combine computer technology, communication technology, monitoring technology, and other means with tailings pond monitoring theory to realize scientific and automatic online safety monitoring of tailings ponds.

It is not difficult to infer that each tailings dam failure involves management factors, and these factors can be avoided. We should focus on methods to prevent accidents rather than perform repairs after the accident. Improving the level of safety management before the occurrence of dam failure accidents can effectively reduce the probability of dam failure accidents. After the occurrence of dam failure accidents, the triggering mechanisms and potential factors of tailings dam failure should be identified, which is crucial to prevent future accidents. Risk assessment is the research focus and frontier for a long time in this stage. Engineering risks are well known, and engineering science has developed to deal with these technical risks. However, the risks that are more easily overlooked are non-technical risks. In almost all cases, the root cause of tailings dam failure is risk management, and timely and effective risk control measures are needed to prevent and control accidents. Brown (2019) developed a historical database of tailings dam cases and analyzed the dam failure modes as well as causes and probability of dam failure. The results showed that most of the tailings dam failure accidents could be avoided. This is a disappointing conclusion. Lyu et al. (2019) also showed that timely and effective management of tailings, monitoring risk factors of tailings ponds, finding problems, and timely repair can effectively reduce the probability of accidents. Through investigation and analysis of tailings dam failure cases, Van Niekerk and Viljoen (2005) found that due to economic pressure, the number of personnel and management input were reduced, and management negligence was the root cause of many tailings dam failure. In view of the increasing number of tailings dams around the world and the high rate of dam failure in history, it can be predicted that there will still be more tailings dam failure accidents for a long time in the future.

The above analysis elucidates that although scholars have conducted considerable work in many aspects of tailings dam failure disaster research and many achievements have been realized, some problems still exist:

1. Tailings dam construction is a constantly changing process. The complexity of the dam construction method, the complexity of the internal structure of the tailings dam, the uncertainty of the discharge process, the physical characteristics of the tailings material, and the dynamic changes in the seepage field and the deformation field will affect the stability of the dam; however, it is difficult to comprehensively consider these problems in numerical simulation and field experiments.
2. There is uncertainty of the monitoring index and evaluation index of the tailings dam failure disaster risk. The relevant normative and technical standard documents do not clearly define the monitoring index and specific parameters of the tailings pond, and many indexes are still in the stage of qualitative analysis and theoretical research.
3. The key indicators of tailings dam safety monitoring, such as the saturation line, dry beach length, dam displacement, and rainfall, are dynamic indicators. Because no specific standard exists for setting monitoring points, there is certain subjectivity in setting, and monitoring data are organically linked with safety management. Realizing the real-time dynamic monitoring of the tailings pond based on information requirements is also a difficult problem that needs to be solved emphatically.

Based on the above, research on the stability of the tailings dam, dynamic monitoring of safety indicators, and dynamic warning technology is crucial for providing theoretical support and control basis for the safe operation of tailings ponds.

Analysis of prevention and control measures of tailings dam failure disaster

Compared with engineering risks, non-technical risks are easily ignored. In almost all cases, the root cause of accidents is risk-management problems, with most of the risks being caused by mismanagement. "Rapid development stage" shows that most of the management factors that lead to tailings dam failure can be avoided, and we should focus on methods to avoid accidents rather than emergency rescue after an accident. In response to tailings dam failure disasters, many countries have formulated a series of control measures in terms of organizations, laws, and policies, realizing the transformation from individual disaster prevention to comprehensive disaster prevention, post-event rescue to pre-event control (Asif and Chen 2016). Schoenberger (2016) analyzed the causes of two tailings dam failures in Ok Tedi and MoutPolley and noted that although the design and construction of tailings ponds are technically challenging, the root cause of tailings dam failures is management rather than technical. In addition, Chen et al. (2022) pointed out that the root causes of tailings dam failure disasters are human risk and facility management risk. In engineering practice, the safety awareness of managers should be improved to enhance the safety management level of tailings ponds.

The above-mentioned studies agree on the fact that scientific and reasonable safety management methods are the basic guarantee for the safe operation of tailings ponds. Therefore, it is of great significance to improve the safety management level of tailings ponds and establish a perfect safety management system. However, most of the previous studies (e.g., Burritt and Christ 2021; Stefaniak and Wróżyńska 2018) focus on the research on "human safety awareness", "management style", "system implementation", and so on and lack in-depth research on enterprise safety regularity, accident characteristics, production systems, and other such aspects. To this end, on the basis of systematically reviewing the related studies on tailings pond risk management, a tailings pond risk management and control suggestion is proposed with risk management as the core, emphasizing on risk monitoring, combined with dynamic risk control.

1. Consider risk management as the core. Enterprises should identify the potential risks involved in the key positions of the tailings pond and ensure that personnel in hazardous places (including operators and those within the downstream endangerment range) should be aware of the risks and take precise control measures corresponding to the risk patterns. Supervisory departments should carry out targeted supervision to promote the continuous improvement of risk control by enterprises. The problems of tailings pond risks such as "unclear, unexpected, and uncontrollable" should be effectively solved.
2. Emphasis on risk monitoring. The accurate grasp and evaluation of the operation status of tailings ponds is in line with the safety production and economic interests of mining enterprises and can provide decision support for the operation and planning of tailings ponds. In recent years, new technologies and new equipment such as satellite remote sensing, photogrammetry, slope radar,

unmanned aerial vehicles, and intelligent robots have emerged, and a large number of successful cases have been accumulated in disaster prevention and control; these can be introduced into the disaster prevention and control of tailings ponds, thereby expanding the safety monitoring perspective of tailings ponds and improving the safety guarantee level of tailings ponds from the technical equipment level.

3. Dynamic risk control. The safety status of a tailings pond is dynamic and will change with the risk management status of the tailings pond and the results of the external natural environment. Most of the previous studies focus on the inherent property indicators or static indicators of tailings ponds, which cannot reflect the real-time status of tailings pond safety risks. To this end, a unified early warning standard for dynamic monitoring indicators (personnel positioning, high and steep slope, dry beach length, saturation line depth, dam displacement rate, reservoir water level, precipitation, etc.) should be established.

It should be noted that the construction of a tailings pond safety management system is a complex task that needs to be continuously improved in engineering practice. Therefore, the construction of tailings dam failure disaster prevention and control systems is still an important topic that needs continuous improvement.

Conclusions

A combination of qualitative and quantitative methods was used to systematically distinguish the tailings pond dam failure disaster research by conducting scientometric analysis of 839 published articles on tailings dam failure disasters using CiteSpace and on the basis of information visualization, combined with atlas evolution analysis of scientific knowledge frontier. The following conclusions are drawn:

1. According to the statistical analysis of the number of published articles, research on tailings dam failure disasters can be roughly divided into two stages: the preliminary germination stage and the rapid development stage. Currently, although the growth rate of the number of published articles has reduced, it remains to be further observed in terms of whether it is about to enter the period of fluctuation decline. In the international cooperation network, China, Brazil, Canada, Australia, the USA, South Africa, and Spain as the center, including Germany, Italy, France, Romania, Turkey, Iran, Sweden, Chile, and South Korea, have formed collaboration on the research on dam failure disasters of tailings ponds. All relevant regions should spare no efforts to strengthen cooperation in the study of tailings dam failure disasters so as to further promote the healthy development of the research system on tailings dam failure disasters.
2. Through the co-occurrence and cluster analysis of tailings dam failure disaster research, the hotspots of the tailings dam failure were explored in this review. The research hotspots of tailings dam failure disaster can be roughly summarized as three main research directions: environmental impact, risk assessment, and mechanical behavior. There are relatively abundant researches on iron tailings among the research objects. Furthermore, as the research on ecological problems resulted from tailings leakage is attaining maturity, the research on ecological restoration has gradually become a hotspot as well as one of the main research directions at present.
3. Through the keyword burst analysis and co-cited burst analysis, the relevant research frontiers of tailings dam failure disasters in different periods were explored. At present, “risk management”, “real-time monitoring”, and “tailing characteristics” have the highest burst strength. “Real-time monitoring” and “tailing characteristics” began to burst frequently since 2020, becoming the research frontier rising in recent 2 years. Furthermore, the burst time of “risk management” has continued from 2017 to the current time, indicating that the safety management of tailings ponds is the most prominent research content at the current stage and the research frontier in the research of tailings dam failure disaster for a long time. This is expected to be a very important research direction in the future.
4. Through quantitative research in scientometric, combined with the subjective experience of experts, a broader and more diverse range of research themes has been explored. This combined qualitative and quantitative research method can better analyze the evolution of tailings dam failure disaster research, and more precisely grasp the research progress and research frontiers. It provides a theoretical reference for tailings pond dam failure disaster research.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no conflict of interest.

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