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Research progress on acid mine drainage treatment based on CiteSpace analysis

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Abstract: Acid mine drainage has always been of global concern, primarily due to its low pH, high concentration of heavy metals and toxic substances, and serious impact on the surrounding environment and ecology of mines. However, the research progress and hotspots in this field of acid mine drainage processing are still unclear. To better understand the research hotspots and trends of acid mine drainage processing from 2004 to 2023, we used CiteSpace bibliometric software to visually analyze 1142 English-language research articles and reviews from the Web of Science core database. Results indicated that this field has received increas-ing attention from researchers worldwide, especially since 2017. The USA and China stand out as major contributors, yet their international collaboration doesn't match South Africa robust partnerships. Strengthening cooperation with other nations should be a priority for both the USA and China. The University of Quebec and University of South Africa were the most production institution. Vhahangwele Masindi from South Africa was the most active author. The top two core journals in this field were Science of the Total Environment and Water Re-search. Additionally, through keyword co-occurrence, clustering, and burst analysis, it is evi-dent that research on heavy metal mechanisms and resource recovery will be the future re-search hotspots in this field of acid mine drainage. This study provides researchers with an opportunity to understand the hotspots and trends in acid mine drainage research from a bibliometric perspective, and serves as a reference for future studies.

Introduction

Acid mine drainage (AMD) is the acidic water discharged from a mining pit (Anekwe and Isa 2023). It originates from active and abandoned mines, mainly gold and coal mines. AMD is commonly encountered in developed countries, such as Canada, China, Russia, South Africa, and USA (Masindi, Foteinis et al. 2022, Tong, Fan et al. 2021). In most cases, it is produced by the oxidation of pyrite (FeS_2, also known as pyrite) with water and oxygen (Lazareva, Myagkaya et al. 2019, Tabelin, Park et al. 2021). AMD exerts an environmental impact. Primarily, it can alter the pH levels of the surrounding environment and affect the dissolution concentration of various chemical substances (Masindi, Akinwekomi et al. 2017). Moreover, AMD also contains a significant amount of toxic substances, such as cyanide, harmful heavy metals (e.g., Cu, Zn, Cd, Mn, Pb, Cr, Ni, Fe), and toxic metalloids (e.g., As, Se) (Azapagic 2004, Johnson and Hallberg 2005). Once it leaks, AMD poses a long-term and large-scale threat to the surrounding environment of the mining area, particularly to surface water, groundwater, and soil, it thereby affects the health of residents and the biodiversity of the ecosystem (Anawar 2015, Si, Chen et al. 2023). Hence, the pollution caused by AMD has emerged as the predominant environmental challenge confronting the mining industry today.

With the unrestrained development and utilization of mineral resources, a significant amount of sulfur-containing minerals (such as pyrite, pyrrhotite) are exposed to the environment. These minerals react with oxygen, water, and bacteria to form strongly acidic sulfates, which constitutes the main cause for the acidity of mine water. Taking pyrite as an example, the specific process for the production of AMD is as follows (Tong, Fan et al. 2021):

(a)

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$$

(b)

$$2Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$$

(c)

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$$
$$14Fe^{3+} + FeS_2 + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

The oxidation of pyrite to produce acid can be divided into two stages. The first stage mainly involves the reaction of pyrite in contact with oxygen and water mainly reacts to generate sulfuric acid and ferrous sulfate. Under sufficient oxygen conditions, ferrous sulfate oxidizes to trivalent iron, and the first stage reaction is very slow. In the second stage, bacteria participate in the oxidation of pyrite, which accelerates the dissolution rate of reaction products and generates a large amount of sulfate. The bacteria involved in this stage mainly include *Thiobacillus ferrooxidans*, *Thiobacillus ferrooxidans*, *Bacillus ferrooxidans*, and *metal bacteria* (Jiao, Zhang et al. 2023). Therefore, the reaction mechanism between iron, sulfur oxidizing bacteria and sulfide minerals has always been a hot research topic.

In order to prevent the further impact of AMD on the environment, a large number of treatment methods have been actively proposed, such as neutralization, vulcanization, artificial wetland, and microbial methods (Benassi, Laus et al. 2006). Hongzong et al.(Tyulenev, Gvozdkova et al. 2017) employed calcium carbonate and calcium hydroxide to neutralize AMD. The pH of the wastewater was neutralized to 7.5, consequently leading to a reduction in sulfate and total iron content. The removal of heavy metals from AMD has always been a hot topic of concern for researchers. By utilizing sodium hydrogen sulfide as a sulfide agent, heavy metal ions in AMD can be effectively removed through the formation of sulfide precipitation. In this process, the removal rate of zinc ions can reach an impressive 96.85% (Ming 2006). The anaerobic wetland of passive treatment plays a good role in the leaching of heavy metals from AMD. Under anaerobic conditions, bacterial sulfates are reduced to sulfides, which form insoluble metal precipitates and produce alkalinity, leading to metal precipitation into hydroxides (Skousen, Ziemkiewicz et al. 2019). Bioremediation functions by reducing the concentration of pollutants in AMD through microorganisms in a controlled environment. Relying on the ability of natural microorganisms to mineralize organic compounds, ultimately forming CO_2, H_2O, and biomass. Utilizing wood chips and fermented chicken manure products as carbon sources for sulfate-reducing bacteria (SRB) in AMD treatment led to a removal rate exceeding 90% for both Fe^{2+} and Cu^{2+} (Li-Pinga, Wen-Yingb et al. 2008). Kiiskila et al (Kiiskila, Li et al. 2020). studied the efficiency of vetiver to treating AMD in the TabSimco mining area in southern Illinois, USA. The results showed that the removal rate of SO_4^{2-} in AMD was 91%, and the removal rate of metals was 90-100%. Continuous research has demonstrated the sustainability and cost-effectiveness of vetiver in the treatment of AMD wetland systems. Previous research has mainly concentrated on different treatments of AMD from limited perspectives, often lacking a systematic induction and review to describe common characteristics, progress in scientific methods, and research focuses. Additionally, the evolution of research hotspots in this field over time has not been thoroughly examined. Therefore, a comprehensive analysis of the entire development trajectory of AMD treatment and utilization research is crucial for accurately and evidence-based prediction of future trends. This approach has important theoretical guiding significance for water pollution control and the sustainable high-quality development of the mining industry.

Therefore, based on the Web of Science (WoS) core collection database, this study uses bibliometric analysis of emerging research tools and visualization analysis based on CiteSpace software to systematically summarize and analyze literature related to AMD treatment. The purposes of this review include: (i) studying the application background and principles of AMD treatment methods; (ii) identifying research hotspots and emerging trends in the AMD research field; (iii) determining important contributors in this field and clarifying effective ways for the future of AMD treatment.

Materials and methods

Data sources and screening

In order to increase the objectivity of the data and reflect the true level and quality of papers, this study is based on the WoS core collection database, using data collected on October 9, 2023. The retrieval formula of this study was TS = (treatment OR utilization) AND acid mine drainage, and obtained 2705 records. By using the refining function of Web of Science classification, excluding non review and article types, the time was selected from 2004 to 2023, and the language was English, and 2078 papers were obtained. To ensure the reliability and credibility of the data, the article information was reviewed one by one, and non academic literature that was not closely related to the research topic was manually deleted. In addition, after removing 22 duplicate papers, 1142 papers were ultimately obtained. The selected literature was downloaded in the format of "Full Records and Cited References" and saved as plain text files as data samples for analysis.

Research methods

Citespace uses mathematical and statistical methods to deeply mine scientific literature, and draws corresponding graphs for perform visual analysis to obtain the current research progress, hotspots, and future development trends of a certain field of study (Chen 2006). In this study, we used CiteSpace 6.2. R4 version to transform and deduplicate the literature obtained from the WoS core collection database. The time slice was set to one year, and the node type was selected as country, institution, author and keyword. Selection criteria, g-index, scale factor k = 25 or 15 and Top N = 50. Finally, draw a collaborative network of countries, institutions, authors, Journal and keyword co-occurrence clustering analysis to analyze the basic overview and research trends of acid mine drainage treatment process field.

Knowledge graph analysis using CiteSpace

Trends in the number of published papers

The annual variation in the quantity of articles published can directly reflect the current development status and trends in a certain field. Figure 1 presents the statistical analysis results of the relevant literature in the field of AMD treatment obtained from the WoS database. The number of publications on the relationship AMD showed an overall upward trend from 2004 to 2023, which could be divided into three periods. Slow growth period (2004-2010), during which the quantity of publications accounted for 17.08% of the total. Fluctuating increase period (2011-2016), the number of related publications has shown a

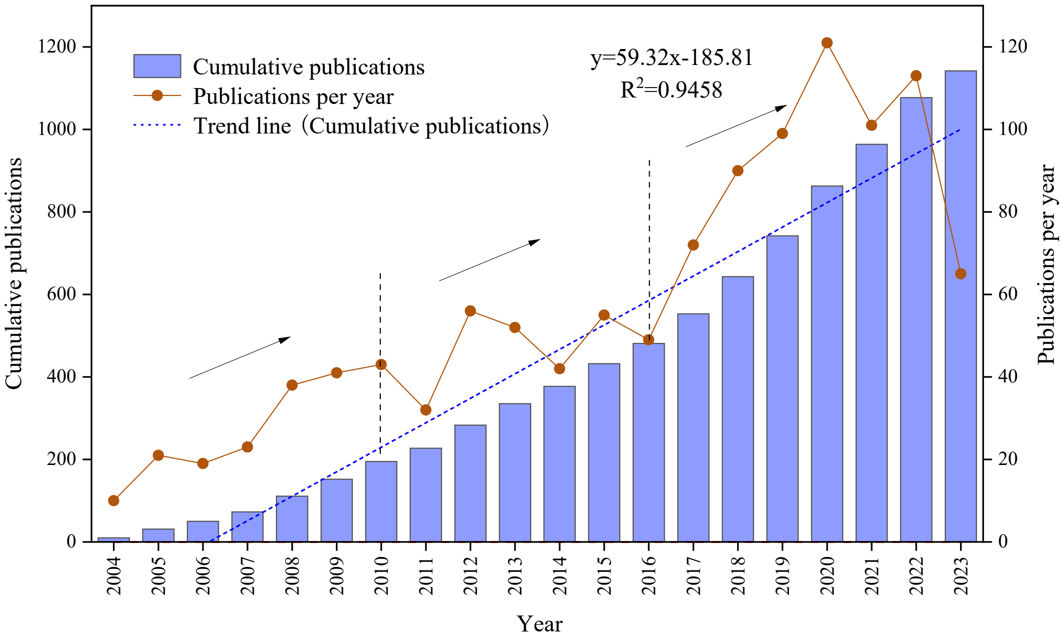

Figure 1. Annual trends of publications on AMD

fluctuating growth, with countless articles published during this period accounting for 25.04% of the total. Rapid growth period (2017-2023), the volume of publications constitutes 57.88% of the total, which is over three times that of the first stage. Correspondingly, the number of articles related to AMD rose sharply from 2017 to 2020. As the data was collected in October 2023, the quantity in 2023 was relatively small and only reflects some of the publications in 2022. However, we can optimistically assume that the publication trend was on the rise. In summary, this ascending trend proves that research on the treatment of AMD is still prevalent.

Overall, the cumulative publications has grown exponential in the past 20 years. This result can be attributed to the application of new materials or technologies in AMD treatment methods, such as biochar, sulfate reducing bacteria (SRB), and artificial wetlands (Agboola 2019, Ali, Basheer et al. 2019, Xiang, Zhang et al. 2020), as well as a greater emphasis on the reuse of AMD and the restoration and management of mining environments. In addition, significant support and funding from the government and industry have contributed this trend. A linear fitting analysis was conducted on the trend line and cumulative publications, leading to a quadratic curve fitting with an extremely impressive R^2 value of 0.9458. The fitting was determined to be highly accurate, affirming the reliability of the trend line. These findings suggest that the total number of publications will continue to increase at an accelerated pace in the future.

Cooperation network analysis

Country cooperation network analysis

The node type was set as country, and visual analysis was performed on literature on AMD treatment in Figure 2. The international cooperation among various countries was relatively close, generating a total of 77 nodes and 206 connecting lines,

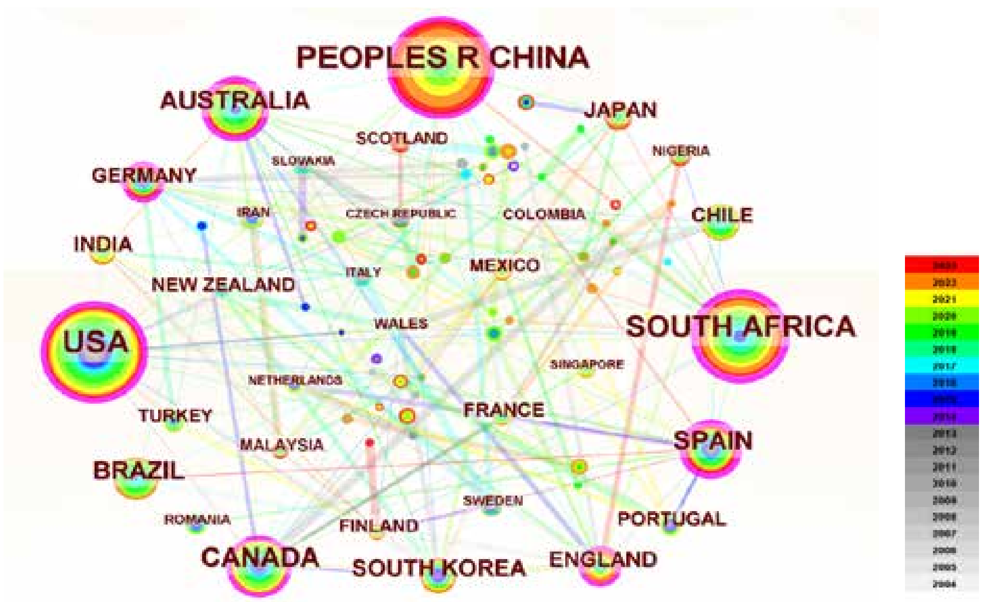

Figure 2. The cooperation network of the countries.

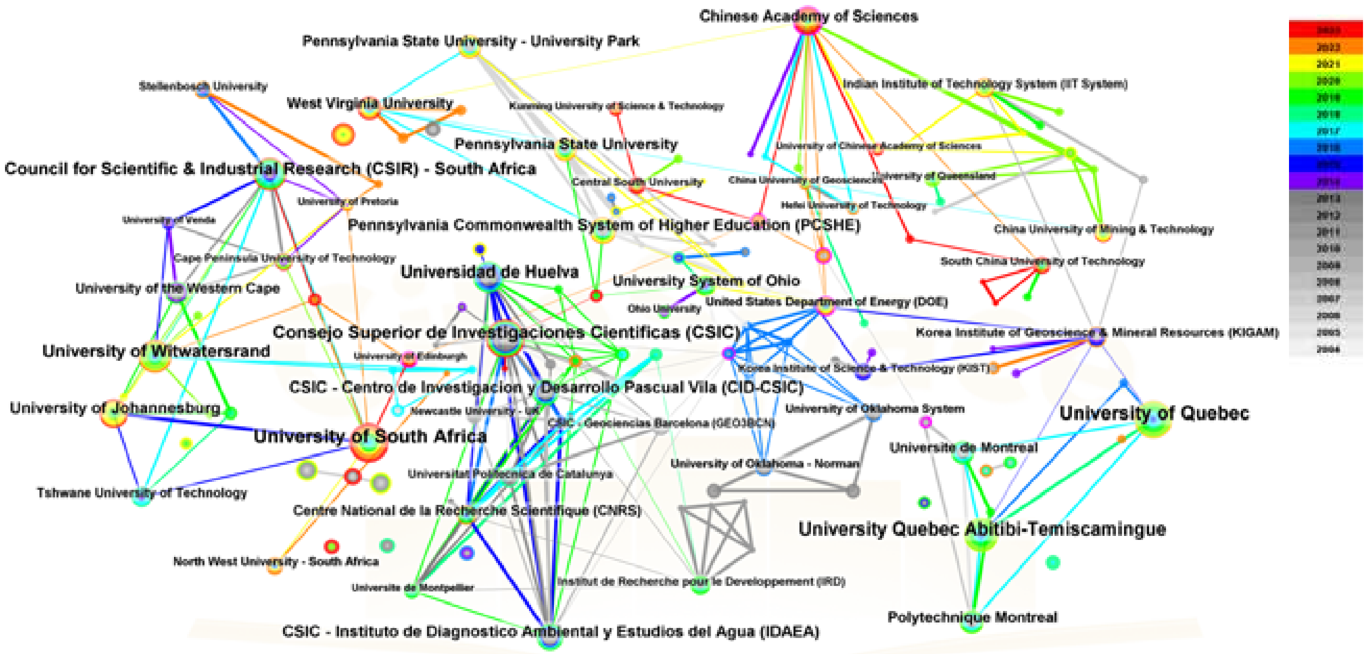

Figure 3. The cooperation network of the institutions

with a density of 0.0704. As shown in Table 1, the country with the highest number of publications on this top was USA (213), accounting for 18.65% of the total, followed by the China (191), South Africa (179), Canada (96), Australia (72), Spain (71), Brazil (69). The prominent roles of the United States, China, and South Africa in the field of AMD treatment was reflected in the large volume of publications and numerous connections with other countries, indicating extensive international cooperation. In addition, collaborative efforts in addressing global environmental issues such as carbon dioxide emission reduction and the Convention on the Protection of Biological Diversity, serve as models and a foundation for international cooperation in the field of AMD treatment (Edgar, Stuart-Smith et al. 2014, Zhang, Yang et al. 2014). A thicker line indicates closer cooperation between countries (He, Lan et al. 2022). Wales cooperated more with Chile and the South Korea in the early years, but in the mid-term had begun cooperated with England and the New Zealand. Additionally, the USA had early collaborations with India, Finland, and South Korea (Figure 2). Notably, the centrality of South Africa nodes (Centrality = 0.49) was much higher than that of the USA (Centrality = 0.25) and Australia (Centrality = 0.29), which indicating that South Africa has a higher international influence in the domain of AMD. However, although China ranks second in the number of papers (191), its centrality was very low (0.15), indicating weak international cooperation. China and other countries with similar problems should enhance their influence in the international academic community.

Institution cooperation network analysis

Analysis institutions distribution and the number of publications can reflect the level of academic support between institutions, promoting communication and cooperation among scholars between institutions (Qin, Zhu et al. 2021, Yan, Xue et al. 2020).Using institutions as the node type, a cooperation network analysis of institutions publications on AMD treatment was performed, generating a total of 276 nodes and 398 connecting lines, with a density of 0.0087 (Figure 3). Within this framework, the University of Quebec and University of South Africa has published more articles in this field, with a total of 44 essays, accounting for 3.85 of all literature (Table 2). Followed by the University Quebec Abitibi-Temiscamingue (40), Consejo Superior de Investigaciones Cientificas (35), Council for Scientific & Industrial Research (CSIR) - South Africa and University of Witwatersrand (30). From this perspective, South Africa has played a crucial role in promoting research on AMD treatment. Notably, the institution with the highest influence was not the University of Quebec (Centrality = 0.08), but rather the United States Department of Energy (Centrality = 0.18). In recent years, the University of South Africa has cooperated with many universities, such as Council for Scientific & Industrial Research (CSIR) - South Africa, University of Johannesburg, North West University-

Table 1. Top 10 countries in terms of publications on A MD research

Rank	Country	Centrality	Number of publications	Percentage (%)
1	USA	0.25	213	18.65
2	Peoples R China	0.15	191	16.73
3	South Africa	0.49	179	15.67
4	Canada	0.19	96	8.41
5	Australia	0.29	72	6.30
6	Spain	0.23	71	6.22
7	Brazil	0.01	69	6.04
8	South Korea	0.04	50	4.38
9	England	0.2	41	3.59
10	India	0.09	39	3.42

Table 2. Top 10 research institutions in the field of AMD treatment

Rank	Institution	Country	Centrality	Number of publications	Percentage (%)
1	University of Quebec	Canada	0.05	44	3.85
2	University of South Africa	South Africa	0.06	44	3.85
3	University Quebec Abitibi-Temiscamingue	Canada	0.04	40	3.50
4	Consejo Superior de Investigaciones Cientificas (CSIC)	Spain	0.08	35	3.06
5	Council for Scientific & Industrial Research (CSIR) - South Africa	South Africa	0.01	30	2.63
6	University of Witwatersrand	South Africa	0.03	30	2.63
7	Universidad de Huelva	Spain	0.02	28	2.45
8	University of Johannesburg	South Africa	0.01	25	2.19
9	Pennsylvania Commonwealth System of Higher Education (PCSHE)	USA	0.03	24	2.10
10	CSIC - Instituto de Diagnostico Ambiental y Estudios del Agua (IDAEA)	Spain	0.03	23	2.01

South Africa and University of Edinburgh. In contrast, the collaboration among the top 10 institutions with the highest number of publications is relatively loose and would benefit from being strengthened.

Author collaboration network analysis

The number of published papers by an author can reflect their contributions to a specific field. The results of the author collaborative network analysis were depicted in Figure 4, demonstrating strong collaboration among researchers in this field. Among them, the authors with the most publications were Vhahangwele Masindi (19), Gerald J Zagury (17), Carmen M Neculita (15), Thomas Genty (15), Carlos Ayora (14), Bruno Bussiere (14), Mostafa Benzaazoua (13), Jose Miguel Nieto (11). Overall, there were more authors from Canada and Spainin (Table 3). Meanwhile, among these authors, Gerald J Zagury, Carmen M Neculita, Mostafa Benzaazoua, Thomas Genty, Bruno Bussiere and others form a closely collaborative core team, while Jose Miguel Nieto, Francisco Macias, Manuel A Caraballo and Carlos Ayora form another core team (Figure 4). Chinese authors have historically had fewer publications than their foreign counterparts. However, in recent years,

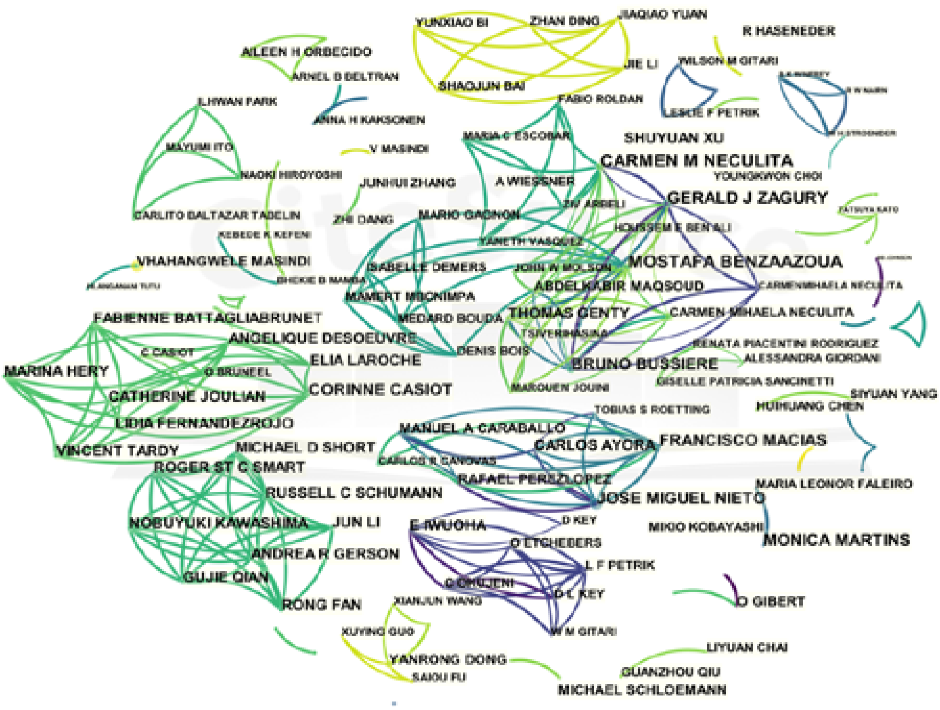

Figure 4. The cooperation network of authors

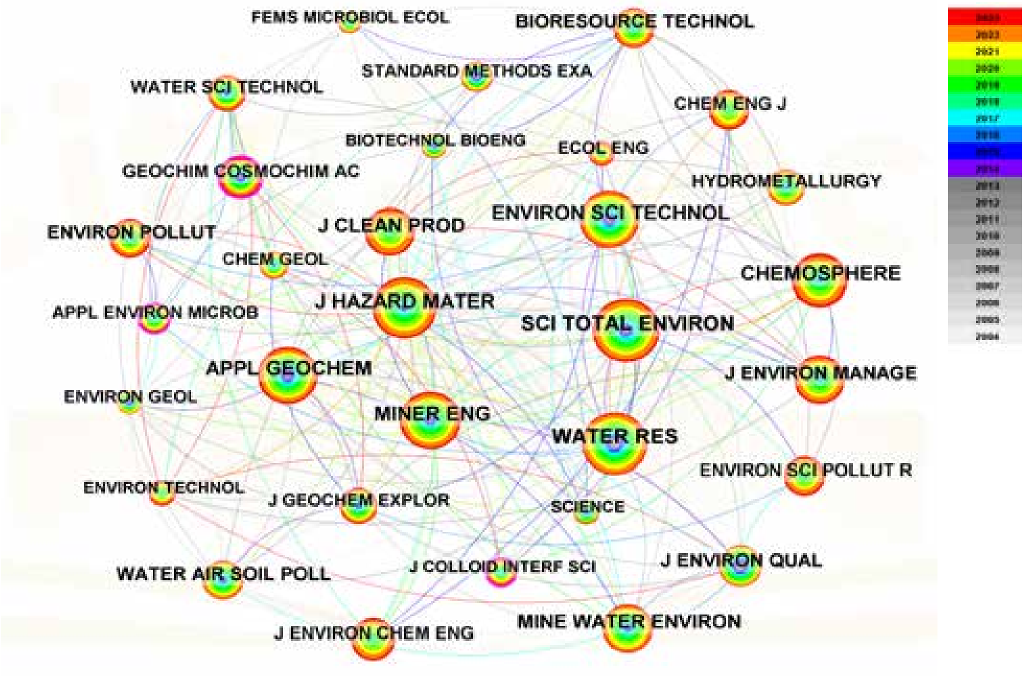

Figure 5. The cooperation network of cocited journals

Chinese authors have also established collaborative teams, predominantly comprised of Zhang Ding, JiaQiao Yuan, Jie Li, YunXiao Bi and ShaoJun Bai. On the whole, the cooperation between foreign authors in the field of AMD treatment was closer, while the cooperation among Chinese authors was relatively loose. In the future, it is essential to enhance communication and foster stronger cooperation between domestic and foreign author teams.

Cocited journal network analysis

Citation analysis was an effective method that can reflect the influential journals in the development and research of this field. Based on Figure 5, it is apparent that 298 cited journals had a close citation relationship, with a total of 1128 links. This distribution indicates that research on AMD treatment was widely distributed across various journals rather than being limited to a few. However the two core journals with the highest citation counts in this field were *Science of the Total Environment* (704) and *Water Research* (675), followed by *Journal of Hazardous Materials* (660), *Environmental Science and Technology* (628), *Applied Geochemistry* (591), *Minerals Engineering*(556), *Chemosphere*(554). See Table 4. These journals cover different interdisciplinary fields such as environmental science, chemistry, materials, minerals, and water treatment. Diversity of citations among different journals reflects the strong interest of researchers from different disciplines in AMD treatment.

The h-index and impact factor of journals were key indicators that reflect the level and influence of journals in a certain field. In this study, among the top 10 journals in the environmental field with the highest citation frequency, Water Research (263) and Environmental Science and Technology (345) had the highest h-index in 2022. Additionally, Water Research (12.3) and Journal of Hazardous Materials (13.6) had the highest impact factors. Most notably, although *Chemosphere* does not have the highest citation frequency, it exhibits a high centrality (0.1), indicating a strong collaborative relationship between journal citations.

Keyword knowledge graph analysis

Keyword co-occurrence clustering analysis

Keywords serve to condense and summarize the main content and core viewpoints of a research field. They also reflect the hotspots and trends within the field, providing researchers with a means to quickly grasp the dynamic evolution of relevant knowledge. In this study, relevant literature on AMD treatment

Table 3. The top 10 authors with the largest numbers of publications

Rank	Author	Country	publications	Percentage (%)
1	Vhahangwele Masindi	South Africa	19	1.73
2	Gerald J Zagury	Canada	17	1.55
3	Carmen M Neculita	Canada	15	1.36
4	Thomas Genty	Canada	15	1.36
5	Carlos Ayora	Spain	14	1.27
6	Bruno Bussiere	Canada	14	1.27
7	Mostafa Benzaazoua	Morocco	13	1.18
8	Jose Miguel Nieto	Spain	11	1.00
9	Francisco Macias	Spain	11	1.00
10	Manuel A Caraballo	Chile	10	0.91

Table 4. The top 10 journals with the largest numbers of citations

Rank	Journal	Citation count	Centrality	H-inder	Impact factor in 2022
1	Science of the Total Environment	704	0.04	205	9.8
2	Water Research	675	0.01	263	12.3
3	Journal of Hazardous Materials	660	0.02	235	13.6
4	Environmental Science and Technology	628	0.02	345	11.4
5	Applied Geochemistry	591	0.03	114	3.4
6	Minerals Engineering	556	0.03	88	4.8
7	Chemosphere	554	0.1	212	8.9
8	Mine water and the Environment	435	0.05	29	2.8
9	Journal of Cleaner Production	432	0.01	150	11.1
10	Journal of Environment Management	374	0.01	146	8.7

was obtained from the WOS database and imported into CiteSpace for visual analysis. Keywords were used as node types to generate a co-occurrence network graph, as depicted in Figure 6. The graph comprises a total of 295 keywords, 1250 lines, and exhibits a co-occurrence network density of 0.0288.

Considering that the surveyed literature mainly focuses on the treatment of AMD, it is not surprising that the compound keyword "acid mine drainage" appearing the most frequently (618 times) (Table 5). "Removal" (281 times) ranks second in frequency. The removal of pollutants in AMD treatment is particularly important and has accordingly received a great deal of attention from scholars (Tabelin, Veerawattananun et al. 2017). The keyword "heavy metals"(228 times) has a frequency ranking of third in this study, indicating that it has become a prominent research hotspot in the field of AMD treatment. Indeed removal of heavy metals is a key link to treating AMD (Aydin, Yuzer et al. 2019). In recent years, in-depth research in the field of pollutant removal from AMD has mainly focused on treatment methods such as adsorption and sulfate-reducing bacteria (SRB) (Bogush and Voronin 2011, Masindi, Foteinis et al. 2022). At present, the most widely used method for scholars to study AMD treatment is mainly bioremediation. Therefore, the keyword "sulfate-reducing bacteria" has important and lasting research value. This indicates that the application of

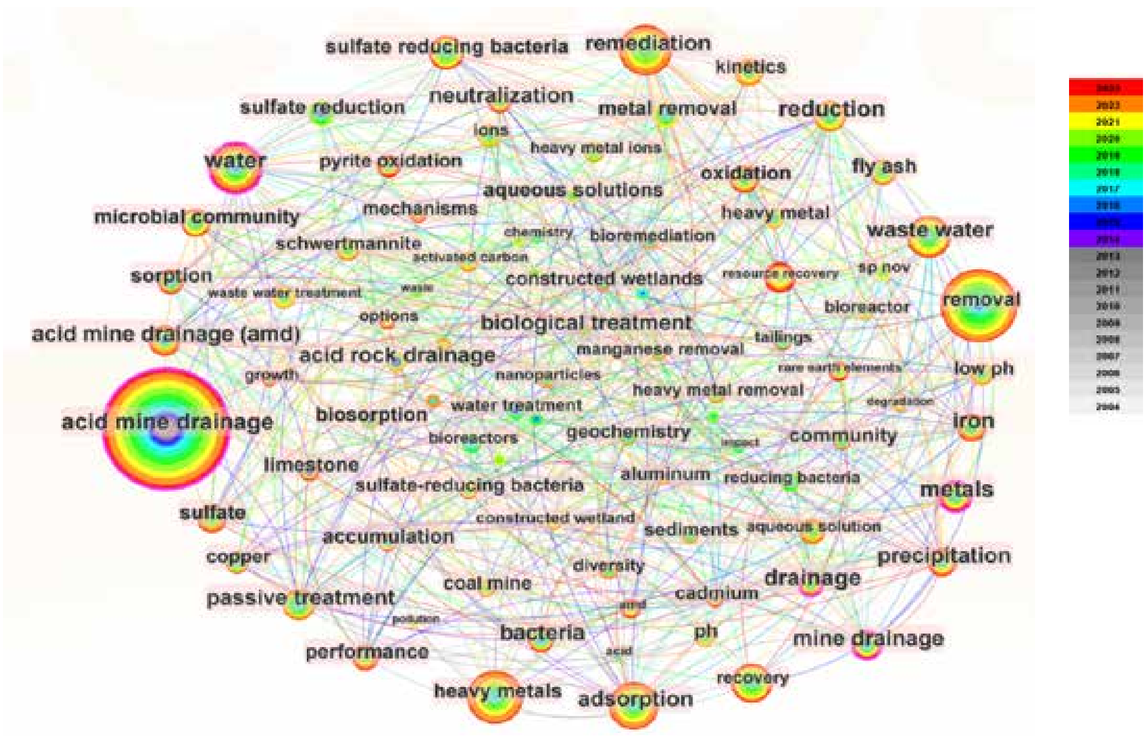

Figure 6. Keyword co-occurrence clustering analysis

sulfate reduction method for treating AMD will continue to substantial research space in the future and warrants further in-depth exploration (Papirio, Villa-Gomez et al. 2013).

Heavy metals ions (such as, Ni, Cd, Fe, Pb) were released during the mineral oxidation and mine water acidification (Yang, Lu et al. 2021). Subsequently, these metals were dissolved in AMD. At present, a green technology, namely the adsorption method, can effectively remove heavy metals from AMD (Motsi, Rowson et al. 2009, Rahman, Wong et al. 2021). By using free radical initiation to graft acrylic acid onto pine cone powder for modification, the modified adsorbent was employed to adsorb (Fe^{3+}), (Cu^{2+}), (Mn^{2+}), (Zn^{2+}), and (Pb^{2+}) in AMD (Mzinyane 2022). Therefore, "adsorption" keyword will become a research hotspot. The microbial remediation of AMD by sulfate reducing bacteria was a promising research direction. Microorganisms reduce sulfates to hydrogen sulfide, which stabilizes and precipitates with heavy metals (McCauley, O'Sullivan et al. 2009). In order to effectively treat AMD with sulfate reducing bacteria in high concentration sulfate and heavy metal environments, Fe^0 was added to the wastewater to enhance the activity of sulfate reducing bacteria. In earlier years, fly ash was also a significant topic in the field of AMD treatment. Specifically, fly ash zeolite garnered attention due to its high cation exchange performance and crystalline structure. This material effectively retains a majority of the metals present in AMD at the surface position (Prasad and Mortimer 2011).

Timeline visualization of keyword co-occurrence clustering analysis

Keyword timeline visualization consisted of 289 nodes and 1203 connected lines. Cluster analysis revealed variations in the research focus on AMD across different time stages ($Q=0.3922>0.3$, $S=0.6934>0.5$; Figure 7.). In the early stages of the study (2004-2005), researchers concentrated on Clusters # 0 (mental removal), Clusters # 1 (acid mine drainage), Clusters

Table 5. Keyword co-occurrence of AMD treatment

Number	Keyword	Word frequency	Year	Centrality
1	acid mine drainage	618	2004	0.15
2	removal	281	2007	0.05
3	heavy metals	228	2005	0.05
4	water	184	2004	0.12
5	remediation	177	2006	0.06
6	adsorption	155	2006	0.08
7	waste water	129	2006	0.07
8	sulfate reducing bacteria	124	2004	0.04
9	reduction	113	2004	0.07
10	iron	105	2004	0.09
11	passive treatment	103	2007	0.09
12	metals	95	2005	0.14
13	recovery	87	2011	0.03
14	oxidation	84	2008	0.04
15	fly ash	81	2005	0.09
16	performance	80	2007	0.05
17	sulfate	78	2010	0.07
18	neutralization	69	2006	0.07
19	precipitation	65	2008	0.06
20	mine drainage	63	2007	0.11

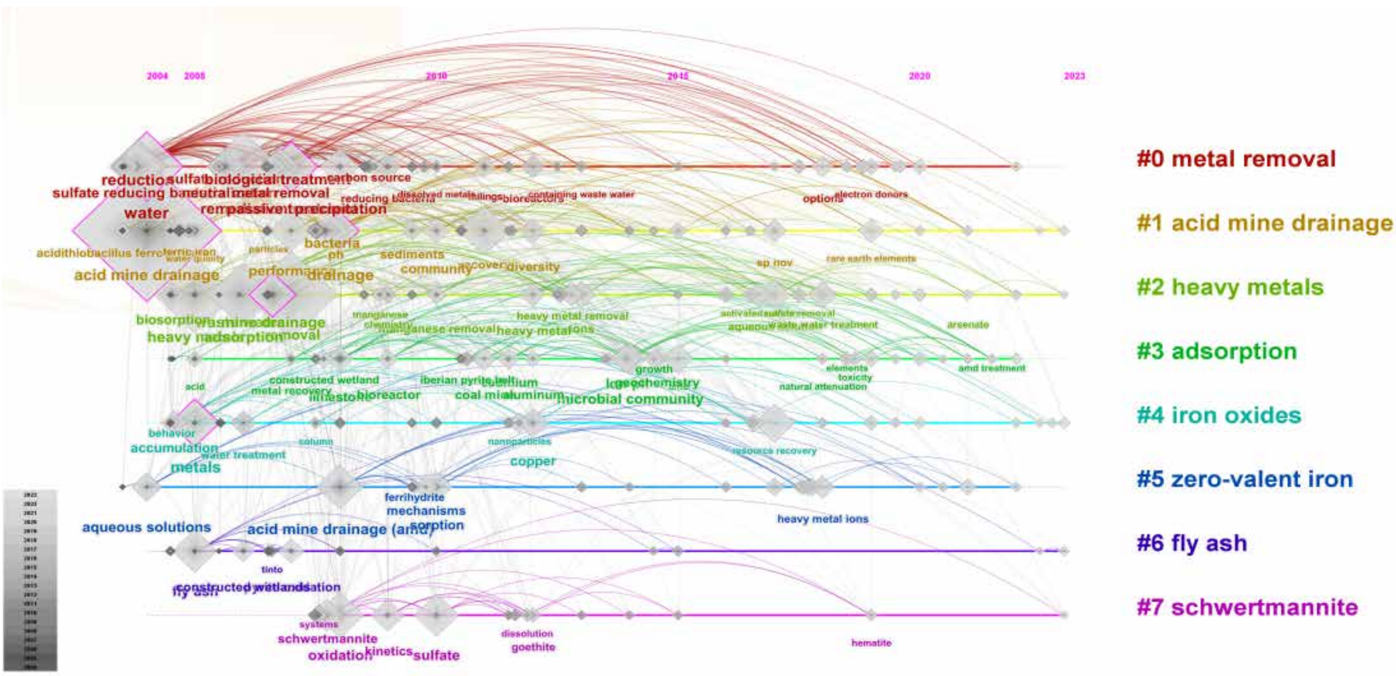

Figure 7. Timeline visualization of keyword co-occurrence clustering analysis in the study of AMD treatment

4 (iron oxides) and Clusters # 6 (fly ash). Clusters # 6 (fly ash) has consistently played a significant role in mitigating AMD sources (Qureshi, Jia et al. 2016, Sephton, Webb et al. 2019). Notably, the issue of heavy metal removal from AMD has consistently been a research hotspot in this field. The most significant heavy metals in AMD, such as Cd, Pb, and Cu, pose a challenge for removing heavy metals from mine water due to their high concentrations and resistance to degradation (Núñez-Gómez, Rodrigues et al. 2019). Researchers have used inorganic materials such as zeolite (Joshiba, Kumar et al. 2021), activated carbon (Lo, Wang et al. 2012), and titanium dioxide (Zhang, Han et al. 2015) as adsorbents, aiming to effectively remove heavy metal ions from mine water. However, the removal efficiency was limited by the cost, efficiency, and speed of the adsorbent. To address this, subsequent researchers considered combining phosphoric acid modified TiO_2 with zero valent iron to investigate the adsorption capabilities of modified TiO_2 for Cd (II), Pb (II), and Cu (II) ions in AMD (Ren, Zheng et al. 2022). In recent years, research of AMD treatment has gradually shifted from Clusters # 0 (mental removal), Clusters # 1 (acid mine drainage), and Clusters # 2 (heavy mental) to the study of the biased mechanisms of Clusters # 4 (iron oxides) and Clusters # 5 (zero-valent iron).

Keyword burst analysis

By analyzing the time series of keyword frequencies, we can clearly observe the evolution of research hotspots in AMD treatment (Table 6). This method can provide insights into the dynamic development of research trends, thereby predicting the possible future development directions of this research (Nageshwari and Balasubramanian 2022). In Table 6, the blue line represents the time span, and the red line represents the burst period of keywords. The start and end points of the red line represent the start and end of the burst time (Zhou and Zhao 2015). Greater intensity of keyword occurrence indicates stronger research in that period and higher output of research results (Ouyang, Wang et al. 2018).

As can be seen from Table 6, during the period from 2006 to 2016, the burst strength of the keywords "biological treatment", "sulfate reducing bacteria" and "limestone" were 5.57, 5.14, and 4.71 respectively. Thus, it can be seen that the biological method and neutralization method for treating AMD were prominent research hotspots during this period. During the period from 2016 to 2021, the keywords "bioreactors", "sp nov", and "zero valent iron" became new research frontiers. It can be seen that research on the treatment of AMD has shifted from initial biological treatment (Pagnanelli, De Michelis et al. 2008, Sierra-Alvarez, Karri et al. 2006) to sp nov, heavy metals (Varvara, Popa et al. 2013) and zero valent iron (Zhao, Fu et al. 2018). In recent years, the keywords "resource recovery", "rare earth elements" and "groundwater" have high burst intensities, and researchers are increasingly paying attention to resource recycling and the impact on groundwater (Chen, Ye et al. 2021) (Liu, Xie et al. 2023, Nishimoto, Yamamoto et al. 2021). This progress indicates that the research in the field of mine water has shifted from advanced treatment to recycling and more in-

Table 6. Top 15 keywords with the strongest citation bursts on AMD treatment

Keywords	Year	Strength	Begin	End	2004-2023
acid mine drainage	2004	6.92	2004	2005	
biological treatment	2007	5.57	2007	2016	
sulphate-reducing bacteria	2008	5.14	2008	2011	
limestone	2008	4.71	2008	2012	
pH	2008	5.67	2012	2013	
bioreactors	2012	7.12	2016	2018	
impact	2016	4.44	2016	2019	
sp nov	2017	4.35	2017	2021	
reducing bacteria	2009	4.31	2017	2020	
zero valent iron	2018	4.58	2018	2019	
heavy metal ions	2018	4.58	2018	2020	
rare earth elements	2019	4.5	2019	2021	
resource recovery	2017	12.15	2020	2023	
kinetics	2009	6.31	2021	2023	
groundwater	2021	4.34	2021	2023	

depth environmental impact research. In addition, keywords with a long time span such as "biological treatment" and "heavy metal ions" indicate that the removal of heavy metals in AMD and biological treatment still pose challenges, and more effective treatment methods need to be sought to solve them.

Conclusions and future prospect

In the study, we based on CiteSpace software to visualize and analyze the relevant literature on AMD treatment from the Web of Science (WoS) database from 2004 to 2023 over the past two decades. By constructing a network graph, we analyzed the cooperation among countries, authors, institutions and journals during this time period. Additionally, we further excavated the research trends highlighted by keywords, and gained a preliminary understanding of the current research status and development trends of AMD. In terms of international cooperation networks, the United States leads in the number of publications within the AMD research field (213), followed closely by China (191) and South Africa (179). Notably, South Africa exhibits the highest centrality, indicating stronger international cooperation and greater global influence. Our analysis of publishing institutions revealed a research network centered around the University of South Africa, Consejo Superior de Investigaciones Cientificas (CSIC) and Chinese Academy of Sciences. Among the top 10 authors with the highest number of published papers, those from Canada and Spain account for 70% of the total. Science of the Total Environment (704) and Water Research (675) were the most cited core journals in the field of AMD research. In terms of keywords, current research hotspots in the AMD field mainly focuses on acid mine drainage, heavy metal removal, bacterial bioremediation, neutralization precipitation and adsorption treatment.

Based on extensive research articles and review analysis, in order to effectively address the challenges faced in AMD treatment, future research should consider the following key aspects:

(1) Technology integration and collaborative governance have become the mainstream. In the future, it is expected to see various AMD treatment technologies (e.g., membrane technology, adsorption technology, bioremediation technology.) more closely integrated to form a collaborative governance model. Through the complementary advantages of different technologies, deep removal of various pollutants in AMD and efficient recycling and utilization of resources can be achieved. For example, first use constructed wetland + phytoremediation technology to preliminarily degrade some organic pollutants, then use membrane technology for fine separation and recycling of useful substances, and finally use adsorbents to deeply remove residual trace pollutants. Thus, a high-standard AMD treatment effect can be achieved and meet increasingly strict environmental emission standards.

(2) AMD governance will no longer be limited to eliminating pollution, but will pay more attention to the recycling of resources and the sustainable restoration of the ecological environment. The generation and governance of AMD will be considered from the mine exploitation planning stage. By optimizing mining processes and taking preventive measures, the generation amount of AMD can be reduced. At the treatment stage, valuable resources in AMD (e.g., rare earth elements, precious metals, sulfates) are fully recovered and transformed into new economic growth points. At the same time, the treated AMD effluent can be used for irrigation and industrial reuse around the mine to realize the recycling of water resources and promote the benign restoration and sustainable development of the ecological environment in mining areas. In short, the concept of sustainable development should be deeply integrated throughout the entire process of AMD governance.

(3) In the future, greater financial support should be considered to be directed towards aspects such as technology research and development, resource recycling and utilization, application of sustainable development indicator frameworks, and international cooperation and exchanges in the field of AMD treatment. This includes the research and development of new strains and integrated equipment, as well as international discussions on advanced technologies and cooperation exchanges, all with the aim of achieving effective treatment of AMD and sustainable utilization of resources and contributing to environmental protection.

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