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RESEARCH ARTICLE

Global trends and future prospects of acid mine drainage research

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Abstract
The uncontrolled release of acid mine drainage (AMD) results in the ongoing deterioration of groundwater and surface water, along with harmful impacts on aquatic ecosystems and surrounding habitats. This study employed a bibliometric analysis to examine research activities and trends related to AMD from 1991 to 2021. The analysis demonstrated a consistent growth in AMD research over the years, with a notable surge in the number of publications starting from 2014. *Applied Geochemistry* and *Science of the Total Environment* emerged as the top two extensively published journals in the field of AMD research. The USA held a prominent position, achieving the highest *h*-index (96) and central value (0.36) among 111 countries/territories, with China and Spain following closely behind. The author keyword analysis provides an overview of the main focuses in AMD research. Furthermore, the co-citation reference analysis reveals four primary domains of AMD research. Moreover, the prevention and remediation of AMD, including source prevention and migration control, as well as the hazards posed by heavy metals/metalloids and the mechanisms and techniques employed for their removal, are discussed in detail.

Keywords Acid mine drainage · Bibliometric analysis · Research trend · Co-citation analysis · Hotspots analysis · Remediation technology · Heavy metal removal

Introduction

Acid mine drainage (AMD) is a significant environmental problem that is associated with mining activities. AMD occurs when metal sulfide minerals, such as pyrite, are exposed to air, water and microorganisms, causing the sulfides to oxidize and produce sulfuric acid (Kefeni et al. 2017). The acidic water can then dissolve other metals and minerals, resulting in contaminate groundwater and surface water, as well as damage aquatic ecosystems and surrounding habitats (Tabelin et al. 2018). AMD has been recognized as a major environmental issue since the nineteenth century, but despite decades of research and management efforts, it continues to be a significant problem in many mining regions (España et al. 2005; Chen et al. 2015). Particularly, in regions where mining activities have been historically prevalent, such as the Appalachian Mountains in the United States and the Witwatersrand Basin in South Africa (Akcil and Koldas 2006; Vass et al. 2019).

The environmental impacts of AMD are far-reaching and can have long-lasting effects (Park et al. 2019). Acidic waters can mobilize heavy metals and other toxins, which can accumulate in the food chain and have harmful effects on human health (Ouyang et al. 2015). AMD can also alter the pH of soil and water sources, making it difficult for vegetation to grow and thrive (Simate and Ndlovu 2014). In addition to the environmental effects, AMD can also have social and economic impacts on local communities. AMD, stemming from mining activities, has the potential to displace indigenous communities and disrupt local economies (Zobrist et al. 2009). Given the widespread impact of AMD, efforts have been made to understand and mitigate the problem. This has involved a range of approaches, including passive and active treatment methods, and the development of policies and regulations to prevent AMD from occurring in the first place (Simate and Ndlovu 2014). Despite these efforts, AMD remains a significant environmental issue around the world.

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Bibliometric analysis serves as a potent tool capable of offering valuable insights into the development and evolution of research across diverse scientific disciplines (Zheng et al. 2015; Zhang et al. 2018a). The objective of this paper is to utilize bibliometric analysis for a comprehensive overview of the present state of AMD research. The analysis focused on publication outputs, journals, institutions, countries/regions, author keywords, and co-citation to explore research tendencies and hotspots associated with AMD. By synthesizing the findings of the bibliometric analysis, our objective is to provide insights into the current state of research in this field, as well as future research directions. Ultimately, this paper aims to contribute to the development of more effective and sustainable approaches to AMD treatment and management, with the goal of mitigating its environmental and public health impacts.

Methods

Data sources

Scientific output dates were extracted from the Science Citation Index Expanded (SCI-EXPANDED) database and the 2021 Journal Citation Reports (JCR) of Web of Science on March twenty-second, 2023. The 2021 JCR indexes 21,494 journals across 254 scientific disciplines and 111 countries/regions. For this study, "acid mine drainage" was used as topics for the period from 1991 to 2021. There were 6470 publications related to acid mine drainage research identified from SCI-EXPANDED. As articles represented the core category of documents, the 5298 articles were analyzed in the next steps.

Content analysis

CiteSpace is a visual analytic tool for analyzing trends and patterns in the scholarly literature of certain disciplines for a given period (Chen 2006). This article used CiteSpace Software (version is 6.2.R2 Advanced (64-bit)) to draw various knowledge maps of acid mine drainage field, showing research overview, research trends, and hotspots through elements such as co-citation network and citation bursts. The co-authors' institution network and co-authors' country/region network were visualized in Gephi (0.9.7) by the Force Atlas2 layout (Zhang et al. 2018a). The reported journal impact factor (JIF) was obtained from the 2021 JCR. The *h*-index is one of the common indicators of the influence of an institution or country in a specific research field, and *h*-index was defined by the *h* of the total article (TA) having at least h citations each and the other (TA-*h*) papers having $\leq h$ citations each (Zhang et al. 2018a, b).

Results and discussions

Publication characteristics

Characteristics of publication outputs

The inaugural research on acid mine drainage (AMD), titled "The role of microorganisms in acid mine drainage: A preliminary report," was published in the journal Science in 1947. The author discovered that microorganisms present in mine waste could oxidize sulfide minerals, resulting in the release of sulfuric acid and heavy metals into water. This finding underscores the pivotal role of microorganisms in the genesis of AMD. (Colmer and Hinkle 1947). Figure 1 shows the number of publications on AMD research during 1991–2021. The number of AMD research slowly increased from 1991 to 2001 with a growth rate of 7.43 article/year, since most of the relevant research was in the initial stage. Following the stricter legislation regarding heavy metal discharge worldwide (Chinese National Standard 2010; European Union 2010), the number of AMD research grew moderately between 2002 and 2013 with a growth rate of 20.32 article/year. The annual publication numbers rose dramatically after 2014 with a growth rate of 31.75 article/year, a growing number of researchers focus on environmental and ecological impacts of AMD, microbial ecology and microbiology of AMD, and prevention, remediation and resource recovery of AMD. From 1991 to 2021, the number of annual publications grew from 18 to 499. It is notable that annual articles account for a high proportion of annual all

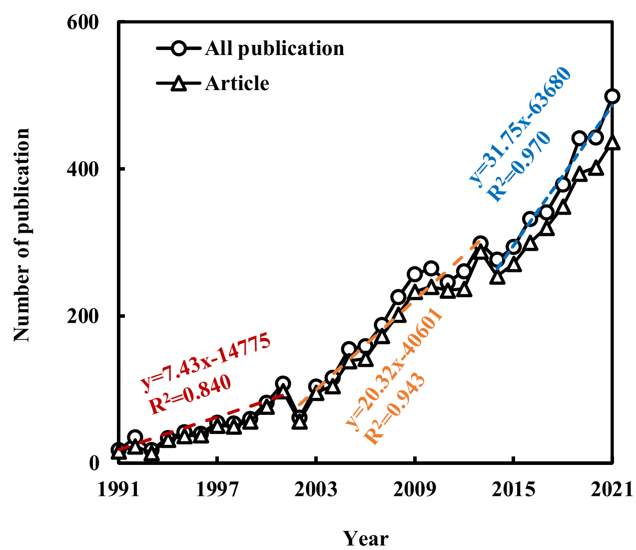

Fig. 1 Number of publications on acid mine drainage research during 1991–2021 (Fitting with piecewise function composed of three linear segments)

publications throughout, the annual article/annual all publications ratio reached 87.58% in 2021.

The distribution of journals

A total of 5,298 articles were published across 753 journals. Notably, a significant portion of these journals (659 or 87.51%) had contributed less than 10 articles each to AMD research. In contrast, the top 40 most prolific journals constituted over half (55.42%) of the entire article count, indicating that AMD research is predominantly concentrated within a limited set of journals. Table 1 displays the performance of the top 10 productive journals in terms of *h*-index, citations per article, journal impact factor, and country of publication. Given the imbalance in the number of publications across journals, the *h*-index may not be the most suitable indicator for reflecting research level. Therefore, citations per article is used for inter-journal comparison. Four of the top 10 productive journals were from the UK, three were from Germany, two were from the Netherlands, and one was from the USA, highlighting the dominant status of developed countries in journal publications. Together, these top 10 most productive journals accounted for 26.99% of all AMD research articles.

Applied Geochemistry published the highest number of articles with 223 (4.21%), followed by *Science of the Total Environment* with 190 (3.59%) articles, *Mine Water and the Environment* with 158 (2.98%) and *Environmental Science & Technology* with 144 (2.72%). By comparing the number of *h*-index, citations per article, and journal impact factor, some interesting phenomena can be revealed. Despite ranking fourth and fifth in total publications, *Environmental Science & Technology* and *Journal of Hazardous Materials* are ranked second and third in *h*-index (54 and 49, respectively), and occupy the first and second place in citations per article (56.78 and 47.54, respectively). This indicates that *Environmental Science & Technology* and *Journal of Hazardous Materials* are undoubtedly the most influential and widely recognized journals for AMD research. *Minerals Engineering*, which ranks tenth with 109 articles, has a relatively high *h*-index of 35 (5), citations per article (31.61), and impact factor (5.479). This result reveals that although *Minerals Engineering* contains a relatively small number of AMD research articles, these articles draw a lot of attention and are highly regarded.

The output of institutes

A total of 5,188 articles, spanning the years 1991 to 2021, included author address information from 3,379 institutes. The network diagram, illustrating the largest connected components (Fig. 2), comprised 135 nodes (3.93% visible) and 545 links (18.39% visible). These 135 institutions can be categorized into three distinct clusters. Cluster I mainly include institutions from the USA, with the central nodes being *US Geol Survey*, USA, *Univ Calif Berkeley*, USA, and *Oak Ridge Natl Lab*, USA, which collaborated with 57, 30, and 23 institutions, respectively. Cluster II is mainly composed of institutions from China, Japan, and South Korea with the *Chinese Academy of Sciences*, China and *South China University of Technology*, China collaborating with 42 and 11 institutions, respectively, as the central nodes. Cluster III is mainly composed of institutions from European countries with the *University of Huelva* and *CSIC* in Spain as the central nodes, collaborating with 57 and 66 institutions, respectively. Notably, only a few institutes from Canada appear in these three clusters, which indicates that the AMD research in Canada is more evenly distributed among institutions.

Table 2 presents the top 10 most productive institutions from 1991 to 2021. Within these institutions, three originated from the USA, two from Spain and China respectively, and one each from South Africa, Portugal, and Canada. This highlights the prominent role of US institutes in AMD research. *Univ Huelva,* Spain holds the top position

Table 1 Performance of the top 10 most productive journals

Journal	TP (%)	*h*-index (R)	TC/TP	JIF	Country
Applied Geochemistry	223 (4.21)	57 (1)	45.44	3.841	UK
Science of the Total Environment	190 (3.59)	49 (3)	43.78	10.754	Netherlands
Mine Water and the Environment	158 (2.98)	23 (9)	13.04	2.688	Germany
Environmental Science & Technology	144 (2.72)	54 (2)	56.78	11.357	USA
Journal of Hazardous Materials	138 (2.60)	49 (3)	47.54	14.224	Netherlands
Chemosphere	125 (2.36)	33 (6)	30.57	8.943	UK
Environmental Earth Sciences	117 (2.21)	23 (9)	13.72	3.119	Germany
Water, Air, & Soil Pollution	114 (2.15)	26 (7)	20.11	2.984	UK
Environmental Science and Pollution Research	112 (2.11)	24 (8)	17.57	5.190	Germany
Minerals Engineering	109 (2.06)	34 (5)	31.61	5.479	UK

TP: total publication; R: the rank, out of the top 10 most productive journals; TC/TP: total citation/total publication; JIF: journal impact factor

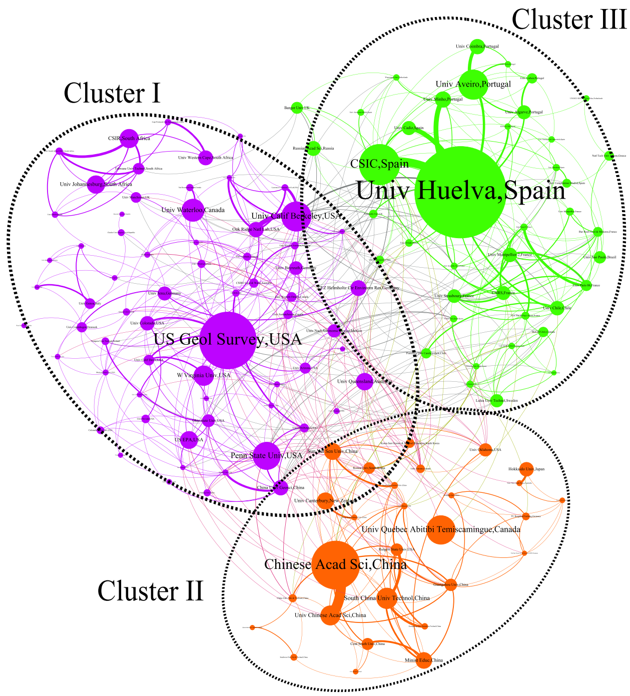

Fig. 2 The cooperation between institutions with a minimum of 10 articles

in terms of total publication (216) and collaborated institution (57), is ranked second in terms of *h*-index (46) and fourth in terms of citations per article (33.19). It started the AMD research relatively late and published its first AMD article in 2003. *US Geol Survey*, USA is ranked second in the total publication (134), collaborated institution (57), and citations per article (47.07), and is ranked third in *h*-index (45), demonstrating its crucial role in the AMD field. *Univ Witwatersrand,* South Africa is ranked fifth of total publication (70), whereas it only cooperated with a few institutions (10), showing a low level of inter-institutional cooperation. A similar phenomenon can be also observed in the institution ranked sixth of *Univ Aveiro,* Portugal. Notably, *Univ Calif Berkeley*, USA, the institution ranked seventh, had the highest citations per article (78.73), showing its high-quality output in AMD research. Betweenness centrality is a measure of the impact of research objects in the entire field, with higher central values indicating greater influence. According to this metric, *CSIC,* Spain ranks first with a value of 0.11, followed by *Chinese Acad Sci, China* (0.08), *US Geol Survey*, USA (0.07), and *Univ Huelva*, Spain (0.05), indicating the high influence of the above institutions in the AMD field.

Contribution of country/region

From 1991 to 2021, a total of 5,188 articles containing author address information were published across 111 countries/regions. Table 3 outlines the top 10 most productive countries in AMD research, collectively contributing to 65.53% of the total publications. This selection encompasses one African country, one country from Oceania, one from Asia, three from the Americas, and four from Europe. The USA and China are the leading contributors, publishing 1184 and 697 articles, respectively, which is far more than other countries. The USA ranks first in the year of first occurrence (1991), central value (0.36), international cooperation (65), and *h*-index (96), and third in citations per article (37.90), indicating its comprehensive influence and high-quality output in the field of AMD research. China ranks eighth in the year of first occurrence (1997), third in central value (0.16), seventh in international cooperation (39), fourth in *h*-index (57), and eighth in citations per article (23.93). These rankings suggest that China has conducted significant research in AMD but needs to improve its overall level of research. South Africa ranks fifth in the total publication (360) but is ninth in international cooperation (35), *h*-index (42), and citations per article (18.18), the result

Table 2 Performance of the top 10 most productive institutions

Institution	TP (%)	YFO	BC	CI	*h*-index (R)	TC/TP
Univ Huelva, Spain	216 (4.16)	2003	0.05	57	46 (2)	33.19
US Geol Survey, USA	134 (2.58)	1994	0.07	57	45 (3)	47.07
Chinese Acad Sci, China	113 (2.18)	1997	0.08	42	30 (5)	24.07
CSIC, Spain	95 (1.83)	2000	0.11	66	47 (1)	42.09
Univ Witwatersrand, South Africa	70 (1.35)	2003	0.01	10	16 (10)	16.76
Univ Aveiro, Portugal	69 (1.33)	1999	0.02	18	27 (6)	25.94
Univ Calif Berkeley, USA	69 (1.33)	1999	0.01	30	40 (4)	78.73
Univ Quebec Abitibi Temiscamingue, Canada	67 (1.29)	2008	0.01	23	25 (8)	19.65
Penn State Univ, USA	64 (1.23)	1994	0.01	30	26 (7)	32.98
Cent S Univ, China	58 (1.12)	2002	0.02	17	22 (9)	18.00

TP: total publication; YFO: year of first occurrence; BC: betweenness centrality; CI: collaborated institution number; R: the rank, out of the top 10 most productive institutions; TC/TP: total citation/total publication

Table 3 Performance of the top 10 most productive countries

Country	TP (%)	YFO	BC	CC	*h*-index (R)	TC/TP
USA	1184 (17.16)	1991	0.36	65	96 (1)	37.90
China	697 (10.10)	1997	0.16	39	57 (4)	23.93
Spain	498 (7.22)	1997	0.11	43	62 (2)	33.57
Canada	484 (7.02)	1991	0.12	43	60 (3)	31.10
South Africa	360 (5.22)	1995	0.14	35	42 (9)	18.18
UK	286 (4.15)	1992	0.13	50	57 (4)	48.54
Germany	283 (4.10)	1994	0.14	47	47 (8)	30.08
Australia	280 (4.06)	1991	0.08	39	52 (7)	32.49
France	243 (3.52)	1996	0.22	48	53 (6)	38.79
Brazil	205 (2.97)	1998	0.02	24	32 (10)	17.42

TP: total publication; YFO: year of first occurrence; BC: betweenness centrality; CC: collaborated country number; R: the rank, out of the top 10 most productive countries; TC/TP: total citation/total publication

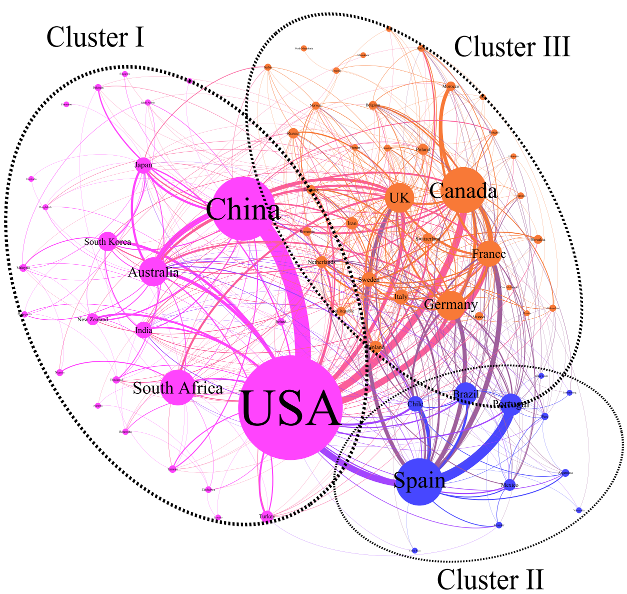

Fig. 3 Network diagram showing cooperation between countries/regions

suggesting that the quality of AMD research in South Africa needs to be strengthened. Notably, the UK has the highest citations per article (48.54) and ranks second in international cooperation (50), indicating its high-quality output and a high level of international cooperation in AMD research. France ranks ninth in total publication (243) and is in second place for citations per article (38.79), demonstrating its high overall level of AMD research.

Figure 3 depicts three clusters that vary in the size of countries/regions and publications. Cluster I is the largest and most complex group, consisting of 26 countries/regions, with the USA, China, South Africa, and Australia being the most productive. Cluster II comprises 12 countries/regions, with Spain, Brazil, and Portugal as the central nodes of this group and having close cooperation among them. Cluster III is composed of 35 countries/regions, mostly European countries, with Canada, Germany, France, and the UK as the central nodes. China-USA collaboration ranks first, with 101 cooperative publications, followed by Spain-Portugal (63), Canada-USA (44), Spain-USA (41), and France-USA (38). Significantly, collaborative countries/regions often exhibit geographic and political correlations, and this phenomenon is also observable in various other research fields..

Research tendencies and hotspots

Author keywords analysis

Analyzing author keywords is an important aspect of bibliometric research as it provides valuable insights into the research interests and themes of authors in a particular field or discipline. Author keywords are typically chosen by authors themselves and reflect their own perception of the main topics and concepts covered in their work. They provide the main information in the article, and therefore, research trends can be obtained by analyzing these keywords (Chen et al. 2016). Table 4 presents the temporal evolution of the 30 most frequently used author keywords and the year of their first occurrence in five periods.

In this paper, "acid mine drainage" was used as the search phrase to acquire the data. As a result, "acid mine drainage" consistently appears as the most frequently used keyword in all periods, with a frequency of 3351 and a relative frequency ranging from 10.45% to 13.64%. The next three most commonly used author keywords are "heavy metals", "water", and "removal". These keywords indicate a significant amount of literature on the removal of heavy metals from AMD (Fu and Wang 2011; Pat-Espadas et al. 2018). Of particular interest, the author keyword "removal" has demonstrated a consistent rise in frequency and ranking, reaching the third position during the 2016–2021 period. "Iron" and "oxidation", the sixth and seventh ranked author

Table 4 Top 30 most frequently used substantives in author keywords in five periods

Keywords	TP	YFO	91–21 R(%)	91–97 R(%)	98–03 R(%)	04–09 R(%)	10–15 R(%)	16–21 R(%)
Acid mine drainage	3351	1991	1 (10.95)	1 (13.64)	1 (12.68)	1 (10.99)	1 (10.99)	1 (10.45)
Heavy metals	800	1992	2 (2.61)	2 (2.65)	6 (1.96)	3 (2.23)	2 (2.84)	2 (2.69)
Water	585	1991	3 (1.91)	10 (0.88)	4 (2.34)	2 (2.29)	3 (1.91)	4 (1.75)
Removal	562	1992	4 (1.83)	19 (0.63)	17 (0.87)	10 (1.19)	6 (1.64)	3 (2.39)
Iron	548	1992	5 (1.78)	9 (1.14)	3 (2.94)	4 (2.08)	4 (1.82)	5 (1.53)
Oxidation	513	1991	6 (1.67)	3 (2.53)	2 (3.05)	5 (2.03)	5 (1.65)	8 (1.31)
Adsorption	441	1991	7 (1.44)	6 (1.77)	7 (1.80)	7 (1.23)	7 (1.32)	6 (1.52)
Metals	325	1993	8 (1.06)	11 (0.76)	13 (1.20)	7 (1.23)	8 (1.12)	10 (0.96)
Drainage	301	1994	9 (0.98)	11 (0.76)	17 (0.87)	6 (1.39)	12 (0.87)	11 (0.92)
Remediation	300	2006	10 (0.98)	NA	NA	50 (0.45)	18 (0.74)	7 (1.52)
Reduction	291	1993	11 (0.95)	114 (0.13)	11 (1.25)	12 (1.13)	9 (0.92)	12 (0.90)
Wastewater	259	2001	12 (0.84)	NA	134 (0.11)	50 (0.45)	20 (0.72)	9 (1.22)
Sediments	253	1992	13 (0.82)	6 (1.77)	14 (1.14)	11 (1.15)	26 (0.66)	17 (0.70)
Sulfate	246	1991	14 (0.80)	11 (0.76)	9 (1.31)	13 (0.95)	11 (0.88)	25 (0.63)
Sulfate reducing bacteria	244	2002	15 (0.79)	NA	42 (0.44)	18 (0.86)	10 (0.90)	13 (0.80)
Tailings	222	1999	16 (0.72)	NA	23 (0.76)	17 (0.87)	20 (0.72)	17 (0.70)
Pollution	215	2003	17 (0.70)	NA	106 (0.16)	28 (0.65)	13 (0.80)	14 (0.77)
Schwertmannite	211	1998	18 (0.69)	NA	17 (0.87)	19 (0.78)	13 (0.80)	28 (0.60)
pH	210	1993	19 (0.68)	114 (0.13)	23 (0.76)	22 (0.71)	20 (0.72)	21 (0.68)
Geochemistry	208	1992	20 (0.68)	59 (0.25)	42 (0.44)	13 (0.95)	19 (0.73)	28 (0.60)
Kinetics	207	1992	21 (0.67)	19 (0.63)	14 (1.14)	21 (0.74)	43 (0.54)	21 (0.68)
Pyrite oxidation	203	1991	22 (0.66)	40 (0.38)	16 (1.09)	29 (0.61)	31 (0.62)	23 (0.67)
Waters	201	1992	23 (0.65)	4 (2.40)	5 (2.12)	16 (0.91)	34 (0.59)	77 (0.30)
River	201	1995	23 (0.65)	19 (0.63)	27 (0.71)	15 (0.93)	17 (0.75)	40 (0.48)
Precipitation	182	1992	25 (0.59)	40 (0.38)	29 (0.65)	47 (0.46)	28 (0.64)	26 (0.62)
Thiobacillus ferrooxidans	173	1991	26 (0.56)	5 (1.89)	11 (1.25)	7 (1.23)	47 (0.50)	130 (0.18)
Water quality	173	1999	26 (0.56)	NA	36 (0.54)	36 (0.52)	16 (0.76)	37 (0.49)
Microbial community	172	2006	28 (0.56)	NA	NA	50 (0.45)	37 (0.58)	20 (0.70)
Copper	171	1999	29 (0.56)	NA	27 (0.71)	39 (0.50)	20 (0.72)	37 (0.49)
Diversity	171	2000	29 (0.56)	NA	76 (0.22)	39 (0.50)	42 (0.55)	24 (0.66)

TP: total publication; YFO: year of first occurrence; R: the rank; NA: no appear

keywords, are consistently ranked among the top ten author keywords in all periods, emphasizing their crucial roles in AMD research. This is due to the fact that AMD formation occurs through the oxidation of metal sulfide minerals, such as pyrite, which produces sulfuric acid. Ferric iron also plays a critical role in promoting the ongoing oxidation of these minerals (Johnson and Hallberg 2005).

"Adsorption" as a method for removing heavy metals from AMD has consistently received significant attention and ranks seventh among the top author keywords from 1991–2021. The author keyword "remediation" was not frequently used and did not even appear before 2006. However, its ranking has significantly increased and now ranks seventh among the top author keywords during the period of 2016–2021. This indicates that numerous studies have focused on removing or reducing the harmful effects of AMD on the environment, which involves various techniques such as passive treatment systems, active treatment systems, and bioremediation (Hogsden and Harding 2012; Simate and Ndlovu 2014).

The author keyword "sediments" has exhibited fluctuations in its ranking over time. Sediments play a crucial role in AMD processing as they can act as both sources and sinks of metals and metalloids (Nieto et al. 2007; Han et al. 2017). The fourteen-ranked author keyword, "sulfate", is a major component of AMD and contributes to its acidic nature, which is a significant environmental issue resulting from mining activities. Therefore, understanding the behavior of sulfate and how to control it is essential for the effective management of AMD. Tailings are a major source of pollutants that contribute to the acidity of AMD. The first tailings-related AMD research appeared in 1999, which focused on the control of AMD using alkaline paper mill waste (Bellaloui et al. 1999). Since then, a large body of research has emerged in the management and remediation of tailings (Johnson et al. 2002; Kefeni et al. 2017; Park et al. 2019). Schwertmannite is an iron oxyhydroxysulfate mineral formed through the oxidation of pyrite or other sulfide minerals. Research on schwertmannite in AMD began in 1998 and has since focused on its formation and stability, its role in controlling metal mobility, and its potential use as an indicator mineral for AMD (Acero et al. 2006; Asta et al. 2010).

Research on the "microbial community" in AMD aims to explore the diversity, composition, and function of microorganisms present in the system, including important families such as *Desulfovibrionaceae* and *Acidithiobacillaceae* (Johnson et al. 2002; Baker and Banfield 2003). By investigating microbial communities in AMD, researchers can gain insights into the interactions between microorganisms and their environment. Studies have revealed the influence of environmental factors such as pH, temperature, and nutrient availability on microbial diversity and function, which can help to better understand the complex relationships between microorganisms and their environment in AMD systems (Sánchez-Andrea et al. 2014; Méndez-García et al. 2015). The author keyword "sulfate reducing bacteria" (SRB) first appeared in 2002 and has since been widely studied in AMD research due to their potential for bioremediation. These bacteria, mainly from *Desulfovibrionaceae* family, can use sulfate as a terminal electron acceptor, resulting in the production of sulfide that can precipitate heavy metals in AMD (Kaksonen and Puhakka 2007; Gonzalez et al. 2019). *Acidithiobacillus ferrooxidans* is a type of bacteria that belongs to the *Acidithiobacillaceae* family. It was previously known as *Thiobacillus ferrooxidans* and has been studied extensively in the context of AMD. This acidophilic chemolithotrophic bacterium can generate energy by oxidizing ferrous iron, sulfur, and reduced sulfur compounds. It contributes to the production of acidity by oxidizing ferrous iron that is released from sulfide minerals during mining activities (Schrenk et al. 1998). However, it can also be used for the remediation of AMD. Researchers have developed bioleaching technologies that utilize *A. ferrooxidans* to extract valuable metals from sulfide ores while minimizing the environmental impact of mining activities (Johnson et al. 2002). Due to its taxonomic reclassification (Kelly and Wood 2000), the author keyword "*Thiobacillus ferrooxidans*" has become less commonly used in recent years.

Notably, the author keywords "waters" and "river" have shown a decreasing trend in their rankings and relative percentages over the past ten years. The reasons for this decline may be due to the evolution in the research field, the increasing diversity in research focus, or the emergence of new technologies and approaches that have shifted the research towards different topics. This tends to dilute the dominance and significance of these traditional research fields (Zhang et al. 2018a).

Co-citation reference analysis

The CiteSpace software was used to generate a co-citation network based on articles published between 1991 and 2021, with each year representing one time slice (Fig. 4). The Modularity score and Silhouette score are two metrics commonly used to evaluate the effectiveness of clustering algorithms (Sabe et al. 2022). The Modularity score measures the significance or meaningfulness of the clustering structure, with values above 0.3 indicating a significant clustering structure (Newman 2006; Chen 2012). The Silhouette score measures the similarity of data points within a cluster and the dissimilarity of data points in different clusters, with values above 0.7 indicating a highly reliable clustering structure (Rousseeuw 1987). In the context of the AMD co-citation clustering analysis (Fig. 4), the Modularity score is 0.8153, which suggests that the clustering structure is significant. The Silhouette score is 0.8604, which indicates that the clustering is both reasonable and highly reliable. Moreover, the Silhouette score of the top 15 co-citation clusters (Table 5) are higher than 0.8. These scores collectively suggest that the clustering algorithm employed in the analysis was effective in identifying meaningful groups within the data.

Table 5 presents information on the top 15 co-citation clusters in the form of the number of clusters, their size, Silhouette score, mean year of publications, and Log-likelihood ratio cluster labels. The top 15 co-citation clusters representing four major research trends related to AMD. These trends include the environmental and ecological impacts of AMD, microbial ecology and microbiology of AMD, prevention, remediation, and resource recovery of AMD, and geochemistry and mineralogy of AMD. To identify the most influential references, citation burst analysis was used, which takes into account both the frequency and timing of citations since publication (Busygina and Rykova 2020). Figure 5 highlights the top 25 references with the strongest citation bursts of at least 5 years, which can be used as representative references for each cluster.

The identified research trend pertains to the environmental and ecological impacts of AMD, encompassing five distinct clusters with an average timeframe from 2001 to 2015. These clusters were numbered and labeled and were characterized by their silhouette score, size, and mean year of publication. Cluster #3, labeled as the "mixing zone" (Silhouette score = 0.859; 179; 2001), highlights that mining activities lead to the release of AMD (Akcil and Koldas 2006), which can contaminate rivers and other water bodies, such as the Odiel River and Tinto River (España et al. 2005; Olías et al. 2006). When AMD mixes with natural water in the mixing zone, it can lead to elevated concentrations of pollutants

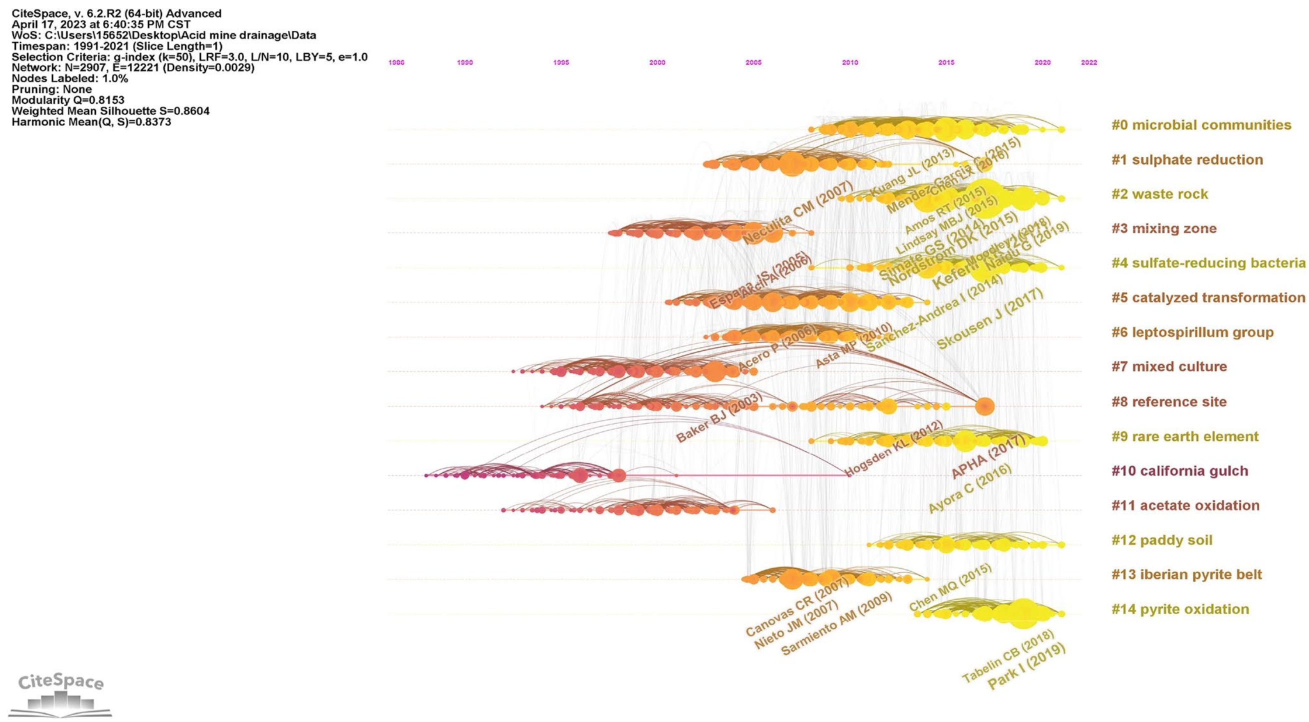

Fig. 4 Reference network view of the research on acid mine drainage (Timeline view, with lighter colors representing closer time and darker colors representing more distant time)

Table 5 References co-citation cluster analysis

Cluster ID	Size	Silhouette	Mean (year)	Log-likelihood ratio (LLR)
0	233	0.905	2013	Microbial communities; bacterial communities; strain ja12; microbial diversity; nitrogen fixation
1	198	0.834	2007	Sulphate reduction; wine waste; municipal wastewater; passive co-treatment; copper removal
2	192	0.863	2015	Waste rock; reactive tailing; valuable mineral; chemical species; drinking water
3	179	0.859	2001	Mixing zone; Odiel River; global gross flux; wet season; oxidation process
4	160	0.855	2016	Sulfate-reducing bacteria; sulfate removal; carbon source; sulfate reduction; sulfate ratio
5	151	0.869	2006	Catalyzed transformation; Schwertmannite transformation; ochreous precipitate; natural Schwertmannite; waterfall section
6	149	0.893	2007	*Leptospirillum* group; ISME journal; AMD microbial communities; genome signature; mature biofilm
7	137	0.925	1999	Mixed culture; oligonucleotide probe; anaerobic growth; total cell; pure culture
8	126	0.951	2001	Reference site; lethal level; acute toxicity; reference stream; laboratory assay
9	119	0.899	2014	Rare earth element; heavy REE; river reach; light REE; REE y
10	107	0.903	1993	California Gulch; hyporheic exchange; dynamic surface; stream tracer approach; oxy hydroxy sulfate
11	99	0.925	1999	Acetate oxidation; permeable reactive barrier; yellow jacket river; poor water quality; municipal compost
12	87	0.920	2015	Paddy soil; Hengshi river; secondary iron mineral; reductive dissolution; calcareous soil
13	85	0.915	2009	Iberian pyrite belt; Odiel River; Tinto River; receiving milieu; generating milieu
14	66	0.965	2017	Pyrite oxidation; catecholate complexe; coating formation; toxic arsenic; Al-based CME

and metal ions in the water column (Lee et al. 2002). The global gross flux of AMD is a major concern, and it tends to increase during the wet season due to the elevated flow rate of water (Olías et al. 2004). This research trend then vanished and reappeared with cluster #13, labeled as the "Iberian pyrite belt" (Silhouette score = 0.915; 85; 2009), which mainly focused on seasonal influence and river pollution by AMD in Iberian pyrite belt (Cánovas et al. 2007;

Fig. 5 Top 25 references with the strongest citation bursts of at least 5 years

References	Year	Strength	Begin	End	1991-2021	Cluster
Kuang JL, 2013, ISME J, V7, P1038	2013	18.67	2014	2018		#0
Mendez-Garcia C, 2015, *Front Microbiol*, V6, P0	2015	20.87	2016	2021		
Neculita CM, 2007, *J Environ Qual*, V36, P1	2007	29.27	2008	2012		#1
Nieto JM, 2007, *Environ Int*, V33, P445	2007	19.94	2008	2012		
Canovas CR, 2007, *Sci Total Environ*, V373, P363	2007	19.47	2008	2012		
Sarmiento AM, 2009, *Appl Geochem*, V24, P697	2009	19.57	2010	2014		
Simate GS, 2014, *J Environ Chem Eng*, V2, P1785	2014	32.42	2015	2019		#2
Nordstrom DK, 2015, *Appl Geochem*, V57, P3	2015	27.63	2016	2021		
Lindsay MBJ, 2015, *Appl Geochem*, V57, P157	2015	14.14	2016	2021		
Lee G, 2002, *Appl Geochem*, V17, P569	2002	14.17	2003	2007		#3
Espana JS, 2005, *Appl Geochem*, V20, P1320	2005	25.11	2006	2010		
Akcil A, 2006, *J Clean Prod*, V14, P1139	2006	17.05	2007	2011		
Olias M, 2006, *Appl Geochem*, V21, P1733	2006	15.63	2007	2011		
Sanchez-Andrea I, 2014, *J Hazard Mater*, V269, P98	2014	24.6	2015	2019		#4
Regenspurg S, 2004, *Geochim Cosmochim Ac*, V68, P1185	2004	14.17	2005	2009		#5
Johnson DB, 2005, *Sci Total Environ*, V338, P3	2005	33.63	2006	2010		
Jonsson J, 2005, *Appl Geochem*, V20, P179	2005	14.74	2006	2010		
Acero P, 2006, *Geochim Cosmochim Ac*, V70, P4130	2006	20.86	2007	2011		
Asta MP, 2010, *Chem Geol*, V271, P1	2010	15.96	2011	2015		
Schrenk MO, 1998, *Science*, V279, P1519	1998	12.53	1999	2003		#7
Baker BJ, 2003, *Fems Microbiol Ecol*, V44, P139	2003	24.75	2004	2008		
Johnson DB, 2003, *Res Microbiol*, V154, P466	2003	14.50	2004	2008		
Hogsden KL, 2012, *Freshw Sci*, V31, P108	2012	17.68	2013	2017		#8
Webster JG, 1998, *Environ Sci Technol*, V32, P1361	1998	13.79	1999	2003		#10
Chen MQ, 2015, *Chemosphere*, V119, P734	2015	14.14	2016	2021		#12

Nieto et al. 2007; Sarmiento et al. 2009). Cluster #8, labeled as the "reference site" (Silhouette score = 0.951; 126; 2001), showing that benthic stream communities, as a reference site, are critical indicators of water quality, and AMD significantly affects them, leading to decreased biodiversity and productivity, and even causing high mortality rates (Hogsden and Harding 2012). Cluster #2, labeled as the "waste rock" (Silhouette score = 0.863; 192; 2015), reflecting that AMD generated from waste rock and reactive tailings can contaminate drinking water (Lindsay et al. 2015), but it can also be treated to recover valuable minerals and water resources (Masindi 2017). Cluster #12, labeled as the "paddy soil" (Silhouette score = 0.920; 87; 2015), suggesting that AMD in the Dabaoshan mining area seriously affected the Hengshi River, leading to the formation of secondary iron minerals in the watershed (Chen et al. 2015), which in turn affected the terrestrial ecosystem in the area, including soil quality and vegetation (Bao et al. 2018). It can be seen that the impact of AMD on the environment and ecology is multifaceted and complex, and its improper treatment will cause significant environmental and ecological losses.

The microbial ecology and microbiology of AMD can be categorized into four distinct clusters, with the average publication timeframe spanning from 1999 to 2016. Cluster #7, labeled as the "mixed culture" (Silhouette score = 0.925; 137; 1999), represents the first cluster that emphasizes the role of microorganisms in AMD generation. This cluster focuses on the identification of microorganisms that promote AMD generation by using mixed culture, purified culture, and techniques such as oligonucleotide probes (Baker and Banfield 2003). It sheds light on the microbiology of AMD, with *T. ferrooxidans* and *Leptospirillum ferrooxidans* being two of the most commonly studied microbial species in this cluster (Schrenk et al. 1998; Johnson and Hallberg 2003). Cluster #6, labeled as the "*Leptospirillum* group" (Silhouette score = 0.893; 149; 2007). The *Leptospirillum* group is an important component of AMD microbial communities. The studies in this cluster have examined the genome signature and metabolic potential of *Leptospirillum* species in biofilms, clarifying their role in AMD generation, and their potential for bioremediation (Aliaga Goltsman et al. 2009; Denef et al. 2010). Cluster #0, labeled as the "microbial communities" (Silhouette score = 0.905; 233; 2013), the largest cluster, emphasizing the significant role of microbial communities in AMD. This cluster centers on the utilization of various techniques to investigate microbial communities associated with AMD, including 16S rRNA gene amplicon sequencing and metagenomic sequencing (Kuang et al. 2013). The research also delves into the metabolic networks and functional diversity of microorganisms involved in processes such as nitrogen fixation, metal resistance, and metal transformation (Méndez-García et al. 2015; Sun et al. 2018). Cluster #4, labeled as the "sulfate-reducing bacteria" (Silhouette score = 0.855; 160; 2016), is the most recent cluster under this trend. SRB play a significant role in sulfate removal from AMD (Chen et al. 2015). Studies have investigated the impact of carbon source (Tsukamoto et al. 2004) and COD/sulfate ratio (Sahinkaya and Gungor 2010) on sulfate reduction efficiency by these microorganisms. Understanding the mechanisms underlying sulfate reduction can aid in developing effective bioremediation strategies for AMD treatment (Sánchez-Andrea et al. 2014). Microorganisms are crucial in both the formation and management of AMD. It's essential to comprehend their metabolic processes and interactions within microbial communities to develop effective strategies for AMD treatment and prevention.

The prevention, remediation, and resource recovery of AMD can be categorized into four main clusters. Cluster #11, labeled as the "acetate oxidation" (Silhouette score = 0.925; 99; 1999), is the earliest cluster in this trend. Researchers have investigated the use of municipal compost and waste sludge as carbon sources in permeable reactive barriers (PRBs) for AMD remediation (Benner et al. 1997; Blowes et al. 2000). Studies have shown that sulfidogenic acetate oxidation is the rate-limiting step in the process by the SRB involved (Sahinkaya 2009). This research trend appears to have temporarily disappeared and then resurfaced with cluster #1, labeled as the "sulphate reduction" (Silhouette score = 0.834; 198; 2007), delves into the important processes of sulphate reduction and heavy metal removal in AMD treatment. The research focuses on exploring different methods, such as using wine waste and municipal wastewater as carbon sources for passive co-treatment (Strosnider and Nairn 2010; Strosnider et al. 2011), and studying the efficient removal of heavy metal, such as copper from AMD by SRB (Neculita et al. 2007). Cluster #9, labeled as the "rare earth element" (Silhouette score = 0.899; 119; 2014), focuses on studying the behavior of rare earth elements (REEs) in AMD and their recovery (Grawunder et al. 2014; Ayora et al. 2016). Ayora et al. (2016) found that schwertmannite does not accumulate REEs, which are instead retained in basaluminite residue. Additionally, Vass et al. (2019) reported that REEs distribution in precipitate samples favored heavy REEs over traditional REE ores. Cluster #14, labeled as the "pyrite oxidation" (Silhouette score = 0.965; 66; 2017), the most recent cluster, focused on source prevention techniques aimed at reducing the generation of AMD. Catecholate complexes are effective in inhibiting iron oxidation and preventing the oxidation of pyrite and arsenopyrite (Park et al. 2019). Coating formation creates a physical barrier that blocks the contact between these minerals and oxygen, reducing their oxidation rates (Dong et al. 2020). The use of aluminum-based carrier-microencapsulation can also help suppress pyrite and arsenopyrite oxidation, thus reducing the production of toxic substances (Tabelin et al. 2018; Park et al. 2019). The prevention, remediation, and resource recovery of AMD not only alleviate environmental and ecological problems but also enable the recovery of various resources from AMD.

The research on the geochemistry and mineralogy of AMD is categorized into two distinct clusters, with an average publication timeframe of 1993 and 2006, respectively. Cluster #10, labeled as the "California Gulch" (Silhouette score = 0.903; 107; 1993), pertains to a site in Colorado where AMD has emerged as a notable environmental concern linked to mining activities. Researchers have utilized stream tracer approaches to study the hyporheic exchange and dynamic surface water interactions (Harvey et al. 1996). The mineralogy of oxyhydroxysulfate minerals and ochreous sediments has been analyzed extensively to gain a better understanding of the impacts of AMD (Bigham et al. 1996; Webster et al. 1998). Cluster #5, labeled as the "catalyzed transformation" (Silhouette score = 0.869; 151; 2006), involves catalyzed transformations, such as the schwertmannite transformation and the subsequent formation of goethite and jarosite (Acero et al. 2006). It is worth noting that the precipitation of schwertmannite from supersaturated solutions through the oxidation of Fe (II) to Fe (III) can remove heavy metals and metalloids, such as lead and arsenic, through adsorption (Regenspurg et al. 2004; Asta et al. 2010). Jönsson et al. (2005) reported schwertmannite precipitated from AMD, regarding phase transformation, sulphate release and surface properties. They concluded that the duration, pH value, sulfate concentration, and temperature all play important roles in schwertmannite precipitation and subsequent transformations. By understanding the mineralogy and geochemistry of AMD, researchers can identify the sources of heavy metals and metalloids in affected water bodies and develop effective remediation strategies.

Hot issues

Author keywords and publication titles provide valuable information for analyzing research themes, trends, and hotspots (Baskerville 1904). In addition, keywords plus, generated by an algorithm from referenced or cited titles, offer further insights (Garfield 1990). The combination of author keywords, article titles, and keywords plus has enabled the successful application of the "word cluster analysis" method in identifying research hotspots (Mao et al. 2010).

Research tendencies for AMD research were extracted and separated into three categories:

(1) Abiotic and biological remediation technologies: this category includes various techniques such as limestone, lime addition, constructed wetlands, sulfidogenic bioreactors, and PRBs. These methods aim to remediate AMD through chemical and biological processes.
(2) Heavy metal-related research: this category encompasses studies specifically focused on understanding and addressing the behavior and effects of specific heavy metals in AMD. Copper, lead, arsenic, zinc, manganese, cadmium, chromium, and mercury are among the key metals of interest in these investigations.
(3) Heavy metal removal mechanisms: this category focuses on the development of methods for removing heavy metals from AMD-contaminated water. Mechanisms such as precipitation, adsorption, and membrane are investigated to effectively reduce the concentration of metals.

Prevention and remediation of AMD

Over the years, as the environmental impact of AMD has become more apparent, numerous studies have been conducted to develop techniques for prevention and remediation. These efforts primarily concentrate on source prevention and migration control measures (Fig. 6) (Johnson and Hallberg 2005; Simate and Ndlovu 2014). Source prevention techniques aim to prevent the formation of AMD at the source. These techniques include reducing sulfide exposure by covering or encapsulating reactive mine wastes (Yuniati et al. 2015), controlling oxygen levels through capping, sealing, or utilizing oxygen barriers (Park et al. 2019), managing water through diversion and flow control, implementing proper waste management practices such as lined containment and waste treatment, reclaiming and restoring disturbed areas by rehabilitating and recontouring (Akcil and Koldas 2006), and adopting sustainable mining practices known as green mining (Li et al. 2022). Migration control techniques primarily aim to address the resulting AMD. These techniques can be classified based on whether they rely on biological activities or not (Simate and Ndlovu 2014). Within these two categories, there are processes that can be considered as either active or passive. Some of the techniques employed for AMD remediation involve aeration and lime addition, anoxic limestone drains (Akcil and Koldas 2006), off-line sulfidogenic bioreactors (Neculita et al. 2007), aerobic wetlands, compost reactors/wetlands, PRBs (Naidu et al. 2019), and packed bed iron-oxidation bioreactors (Johnson et al. 2002). These methods effectively reduce the migration and negative effects of AMD through the application of diverse chemical, biological, and physical processes.

Figure 7a illustrates the publication trends of abiotic and biological remediation technologies from 1991 to 2021. Constructed wetlands have gained significant attention, with articles increasing from one in 1991 to 23 in 2021. They offer cost-effective maintenance and solid-phase product retention but face challenges such as high installation costs, land area requirements, unpredictable performance, and uncertain fate of deposits (Johnson and Hallberg 2005). Limestone and lime addition, two abiotic technologies, rank second and third in publications. Limestone is widely used in passive systems like anoxic limestone drains, limestone ponds, and open limestone channels, aiding in AMD neutralization and metal precipitation. Furthermore, limestone can be used as a filler material in combination with biological remediation

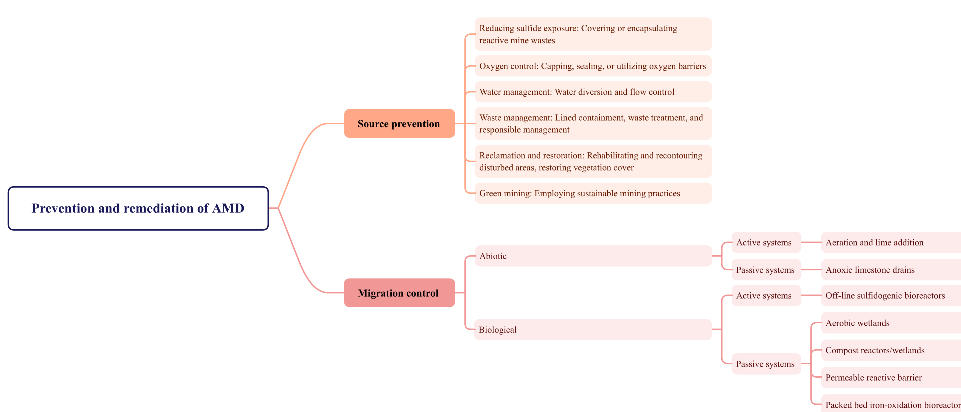

Fig. 6 The prevention and remediation technologies for acid mine drainage (adapted from Johnson and Hallberg 2005; Simate and Ndlovu 2014)

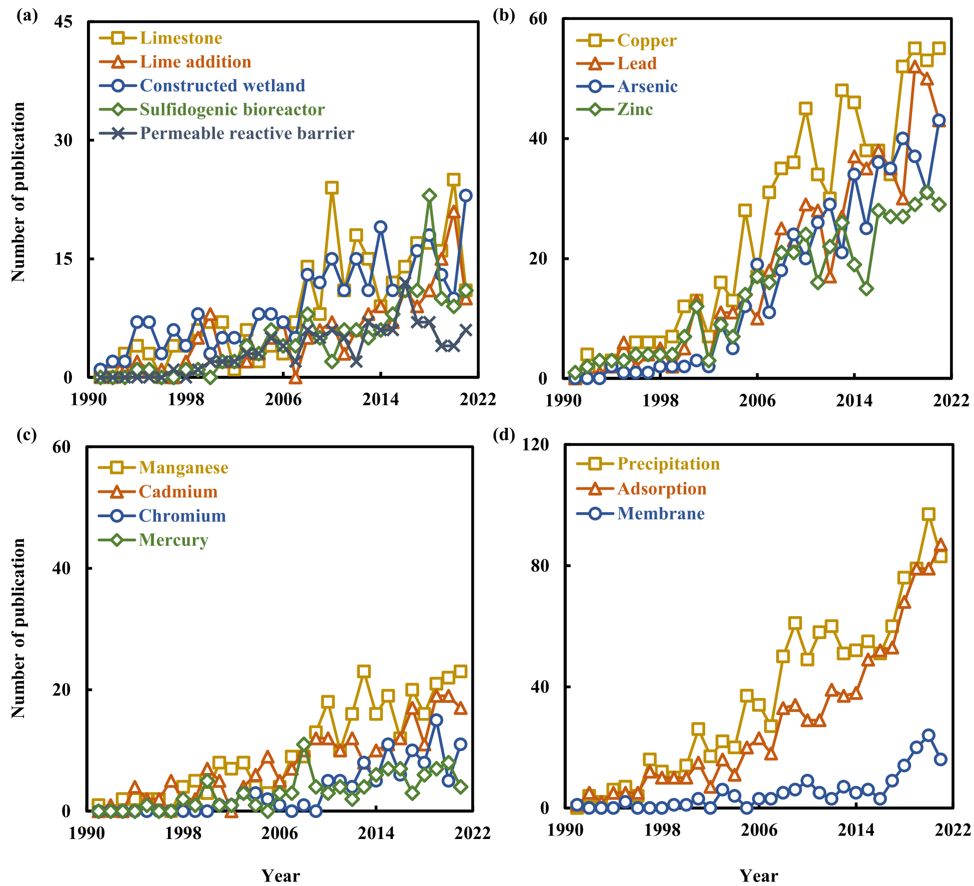

Fig. 7 Growth trends of hotpot-related articles of acid mine drainage: **a** abiotic and biological remediation technologies, **b**, **c** heavy metal-related research, and (**d**) heavy metal removal mechanisms from 1991 to 2021

technologies like anaerobic wetlands and PRBs, enhancing their performance in treating AMD (Skousen et al. 1998). However, limestone's reactivity diminishes over time, necessitating replacement, and anoxic limestone drains can experience reduced permeability (Johnson and Hallberg 2005; Akcil and Koldas 2006). Lime addition achieves efficient pH adjustment and metal precipitation similar to limestone but is limited by high cost and sludge generation (Johnson and Hallberg 2005). Recent studies have highlighted the important role of lime in integrating various processes and technologies to effectively address the challenges associated with AMD (Simate and Ndlovu 2014). PRBs effectively remove contaminants, provide long-term treatment, but have design challenges, potential clogging, limited effectiveness on mobile contaminants, and site-specific limitations (Naidu et al. 2019). Packed bed iron-oxidation bioreactors remove heavy metals, utilize natural microbial communities, but face design complexity, clogging, limited effectiveness for some contaminants, and site-specific requirements (Naidu et al. 2019). Recent research explores waste/by-product utilization, waste co-treatment, and systemic treatment as innovative approaches for sustainable AMD solutions (Strosnider et al. 2011; Simate and Ndlovu 2014; Moodley et al. 2018). These advancements offer promising opportunities to tackle AMD challenges holistically.

Heavy metal/metalloid removal

Heavy metal/metalloid pollutants in water pose a danger to humans and animals due to their persistence in natural ecosystems and ability to accumulate in biological chains, causing acute and chronic diseases (Akpor and Muchie 2010). Additionally, soil contamination by heavy metals is a major environmental concern, adversely affecting ecological health. Elevated levels or combinations of heavy metals in plants can lead to diverse effects on their growth (Yadav 2010). Moreover, aquatic organisms, such as fish, accumulate heavy metals directly and indirectly, potentially causing severe oxidative stress (Tao et al. 2012). Simate and Ndlovu (2014) summarized the effects of various heavy metals on humans and animals, soil and plants, and aquatic organisms.

Figure 7(b, c) illustrates the publication trends of key heavy metals/metalloids in AMD research from 1991 to 2021. Copper has gained significant attention, with articles increasing from 0 in 1991 to 55 in 2021. It enters AMD mainly through the oxidation of copper-bearing ores like chalcopyrite and chalcocite. Excessive copper levels (> 0.10 mg/L) harm humans by causing anaemia, liver/kidney damage, and stomach/intestinal irritation. It inhibits photosynthesis, plant growth, reproduction, and impacts thylakoid surface (Singh et al. 2011). Copper also poses severe toxicity to aquatic life (Solomon 2008). Lead in AMD originates from the oxidation of lead-bearing ores like galena and boulangerite. Lead levels above 0.10 mg/L are highly hazardous, causing mental retardation and organ damage. Lead exposure inhibits plant growth, reduces chlorophyll production, and increases the activity of superoxide dismutase (Singh et al. 2011). Arsenic and zinc, ranking third and fourth among AMD contaminants, primarily originate from the oxidation of arsenopyrite and sphalerite. Elevated arsenic concentrations (> 0.02 mg/L) lead to bronchitis, dermatitis, and poisoning, while zinc concentrations (> 15 mg/L) damage the nervous membrane (Simate and Ndlovu 2014). Manganese, cadmium, and chromium are typically found as associated minerals in sulfide metal ores, and they enter AMD as a result of the oxidation of these ores. Elevated manganese levels (> 0.26 mg/L) cause central nervous system damage, cadmium levels (> 0.06 mg/L) result in renal dysfunction and lung disease, and chromium exposure (> 0.05 mg/L) leads to nervous system damage (Singh et al. 2011). Mercury in AMD is due to the oxidation of mercury-bearing minerals like cinnabar. Elevated mercury levels (> 0.01 mg/L) can cause neurological disorders and reproductive issues (Singh et al. 2011). Therefore, the removal of heavy metals from AMD is of utmost importance.

Figure 7d depicts the publication trends in research on heavy metal removal mechanisms from 1991 to 2021. Precipitation emerges as the predominant mechanism, with a notable surge in publications from 0 in 1991 to 83 in 2021, resulting in a cumulative total of 1140 publications. It involves the addition of precipitants or the generation of anions that react with heavy metal ions for their removal from AMD (Johnson and Hallberg 2005). Lime addition and anoxic limestone drains are AMD remediation techniques that use lime and limestone as precipitants to effectively remove heavy metals (Skousen et al. 1998). Adsorption is the second-ranked mechanism, with a significant increase in publications from 1 in 1991 to 87 in 2021, totaling 881 publications. Adsorbents have a strong affinity for heavy metal ions, binding to their surface through interactions like electrostatic attraction, ion exchange, and complexation (Kefeni et al. 2017). Membrane separation has also gained attention, with publications rising from 1 in 1991 to 16 in 2021, resulting in a cumulative total of 156 publications. Reverse osmosis and nanofiltration membranes are commonly employed as secondary treatment of heavy metal from AMD (Zhong et al. 2007). Importantly, most AMD treatment techniques involve multiple mechanisms to ensure effective removal of heavy metals. The off-line sulfidogenic bioreactor uses SRB to reduce sulfate and generate sulfide ions that react with heavy metal ions through adsorption, precipitation, and co-precipitation mechanisms (Gonzalez et al. 2019). Constructed wetlands utilize plants and microbial communities to remove heavy metals through mechanisms such as phytoextraction, rhizofiltration, as well as microbial-mediated processes like adsorption and precipitation (Pat-Espadas et al. 2018). PRBs are subsurface barriers composed of reactive materials that intercept the flow of contaminated groundwater, facilitating reactions for the immobilization or removal of heavy metals through processes such as adsorption, precipitation, and redox reactions (Scherer et al. 2010). Packed bed iron-oxidation bioreactors employ iron-oxidizing bacteria to convert ferrous iron into ferric iron, which then interacts with heavy metals through adsorption, precipitation, and co-precipitation mechanisms (Johnson et al. 2002). The efficient removal of heavy metals from AMD brings significant environmental and ecological benefits.

Challenges, opportunities, and prospects

AMD is generated in and around mining areas, predominantly in locations such as abandoned and active mines. Abandoned mines, in particular, are susceptible to AMD generation due to inadequate maintenance and supervision. Additionally, secondary sources of AMD encompass mine waste dumps, ore stockpiles, tailings dumps, tailings dams, haul roads, quarries, pit lakes, and sludge ponds (Moodley et al. 2018). A pivotal strategy for mitigating AMD pollution is the proactive approach of source prevention. In the "Hot Issues" section, we delve into the comprehensive discussion of common source prevention methods, as illustrated in Fig. 6. It's worth noting that when considering the covering or encapsulation of reactive mine wastes, it often involves the development of new materials, necessitating careful consideration of both environmental sustainability and economic feasibility of these novel materials (Si et al. 2023). Carrier-microencapsulation technology, emerging as a promising source prevention technique, has demonstrated notable control efficacy and applicability (Chen et al. 2021). However, there remains room for research in enhancing stability, timeliness, and the development of novel passivation materials.

The application of treatment technology represents the most direct approach to mitigating the harm caused by AMD. The common methods for AMD treatment are presented in Fig. 6 and elaborated upon in detail in the "Hot Issues" section. Due to heavy metals being one of the most common pollutants in AMD, recent research has focused extensively on the efficient removal of heavy metals. The efficient removal of heavy metals from AMD holds promise through the utilization of bioremediation (Du et al. 2022) and the application of cost-effective, high-performance adsorption materials (Dovorogwa and Harding 2022). Although significant progress has been made in these areas, there is still a considerable distance to go before achieving widespread large-scale implementation. Recent research has made significant progress in the synergistic treatment of AMD alongside urban sewage (Masindi et al. 2022), the resource recovery of REEs from AMD (Hermassi et al. 2022; Wilfong et al. 2022), and the holistic resource recovery throughout the entire AMD processing cycle (Ighalo et al. 2022). Currently, the prevention, management and treatment of AMD face numerous opportunities and challenges, primarily driven by increasingly stringent environmental policies and the continuous advancements in treatment technologies and functional materials. It is widely held that as efforts to prevent, manage, and treat AMD are continually refined, they will progressively align with the demands of sustainable development.

Conclusions

A comprehensive overview of research in the field of AMD was presented, including information on publication outputs, journals, institutions, countries, research tendencies, and hotspots. From 1991 to 2021, the number of annual publications grew sharply from 18 to 499. *Applied Geochemistry* and *Science of the Total Environment* stood out as the two most extensively published journals in the field of AMD research. *Univ Huelva,* Spain takes the top spot in terms of total publication (216) and collaborated institution (57), ranking second in terms of *h*-index (46), indicating a high-quality output in AMD research. The USA ranks first in the year of first occurrence (1991), central value (0.36), international cooperation (65), and *h*-index (96), highlighting its significant influence and high-quality contributions in AMD research. The author keywords analysis revealed a consistent focus on the remediation of AMD and the removal of heavy metals. The co-citation reference analysis identified four key domains of AMD research, providing insights into the advancements made in each area. These domains encompass the environmental and ecological impacts of AMD, microbial ecology and microbiology of AMD, prevention, remediation, and resource recovery of AMD, as well as the geochemistry and mineralogy of AMD. Furthermore, the prevention and remediation of AMD, including source prevention and migration control, are discussed in detail, highlighting the advantages and disadvantages of different migration control methods. Also, the risks posed by prevalent heavy metals/metalloids present in AMD to humans, animals, soil, plants, and aquatic organisms are described, along with mechanisms for removing heavy metals. Addressing the temporal limitations of bibliometric analysis, the study concluded with a consideration of the challenges, opportunities, and prospects associated with AMD. This will contribute to the effective prevention and management of AMD, thereby mitigating its impact on the environment and public health.

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Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to disclose.

References

Acero P, Ayora C, Torrentó C, Nieto JM (2006) The behavior of trace elements during schwertmannite precipitation and subsequent transformation into goethite and jarosite. Geochim Cosmochim Acta 70:4130–4139. https://doi.org/10.1016/j.gca.2006.06.1367

Akcil A, Koldas S (2006) Acid mine drainage (AMD): causes, treatment and case studies. J Clean Prod 14:1139–1145. https://doi.org/10.1016/j.jclepro.2004.09.006

Akpor OB, Muchie M (2010) Remediation of heavy metals in drinking water and wastewater treatment systems: Processes and applications. Int J Phys Sci 5:1807–1817

Aliaga Goltsman DS, Denef VJ, Singer SW et al (2009) Community genomic and proteomic analyses of chemoautotrophic iron-oxidizing “*Leptospirillum rubarum*” (Group II) and “*Leptospirillum ferrodiazotrophum*” (Group III) bacteria in acid mine drainage biofilms. Appl Environ Microbiol 75:4599–4615. https://doi.org/10.1128/AEM.02943-08

Asta MP, Ayora C, Román-Ross G et al (2010) Natural attenuation of arsenic in the Tinto Santa Rosa acid stream (Iberian Pyritic Belt, SW Spain): The role of iron precipitates. Chem Geol 271:1–12. https://doi.org/10.1016/j.chemgeo.2009.12.005

Ayora C, Macías F, Torres E et al (2016) Recovery of rare earth elements and yttrium from passive-remediation systems of acid mine drainage. Environ Sci Technol 50:8255–8262. https://doi.org/10.1021/acs.est.6b02084

Baker BJ, Banfield JF (2003) Microbial communities in acid mine drainage. FEMS Microbiol Ecol 44:139–152. https://doi.org/10.1016/S0168-6496(03)00028-X

Bao Y, Guo C, Lu G et al (2018) Role of microbial activity in Fe(III) hydroxysulfate mineral transformations in an acid mine drainage-impacted site from the Dabaoshan Mine. Sci Total Environ 616–617:647–657. https://doi.org/10.1016/j.scitotenv.2017.10.273

Baskerville C (1904) The titles of papers. Science (80-) 19:702–703

Bellaloui A, Chtaini A, Ballivy G, Narasiah S (1999) Laboratory investigation of the control of acid mine drainage using alkaline paper mill waste. Water Air Soil Pollut 111:57–73. https://doi.org/10.1023/a:1005017912012

Benner SG, Blowes DW, Ptacek CJ (1997) A full-scale porous reactive wall for prevention of acid mine drainage. Gr Water Monit Remediat 17:99–107

Bigham JM, Schwertmann U, Traina SJ et al (1996) Schwertmannite and the chemical modeling of iron in acid sulfate waters. Geochim Cosmochim Acta 60:2111–2121. https://doi.org/10.1016/0016-7037(96)00091-9

Blowes DW, Ptacek CJ, Benner SG et al (2000) Treatment of inorganic contaminants using permeable reactive barriers. J Contam Hydrol 45:123–137. https://doi.org/10.1016/S0169-7722(00)00122-4

Busygina T, Rykova V (2020) Scientometric analysis and mapping of documentary array on the issue "Oil and petroleum products in soil and groundwater." Environ Sci Pollut Res 27:23490–23502. https://doi.org/10.1007/s11356-020-08717-0

Cánovas CR, Olías M, Nieto JM et al (2007) Hydrogeochemical characteristics of the Tinto and Odiel Rivers (SW Spain). Factors controlling metal contents. Sci Total Environ 373:363–382. https://doi.org/10.1016/j.scitotenv.2006.11.022

Chen C (2006) CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. J Am Soc Inf Sci Technol 57:359–377. https://doi.org/10.1002/asi.20317

Chen C (2012) Predictive effects of structural variation on citation counts. J Am Soc Inf Sci Technol 64:431–449. https://doi.org/10.1002/asi

Chen M, Lu G, Guo C et al (2015) Sulfate migration in a river affected by acid mine drainage from the Dabaoshan mining area, South China. Chemosphere 119:734–743. https://doi.org/10.1016/j.chemosphere.2014.07.094

Chen D, Liu Z, Luo Z et al (2016) Bibliometric and visualized analysis of emergy research. Ecol Eng 90:285–293. https://doi.org/10.1016/j.ecoleng.2016.01.026

Chen G, Ye Y, Yao N et al (2021) A critical review of prevention, treatment, reuse, and resource recovery from acid mine drainage. J Clean Prod 329:129666. https://doi.org/10.1016/j.jclepro.2021.129666

Chinese National Standard (2010) Emission standard of pollutants for copper, nickel, cobalt industry (GB 25467–2010). Technology Standards Department, China

Colmer AR, Hinkle ME (1947) The action of certain microorganisms in acid mine drainage: A preliminary report. Science (80-) 106:253–256

Denef VJ, Mueller RS, Banfield JF (2010) AMD biofilms: Using model communities to study microbial evolution and ecological complexity in nature. ISME J 4:599–610. https://doi.org/10.1038/ismej.2009.158

Dong Y, Zeng W, Lin H, He Y (2020) Preparation of a novel water-soluble organosilane coating and its performance for inhibition of pyrite oxidation to control acid mine drainage at the source. Appl Surf Sci 531:147328. https://doi.org/10.1016/j.apsusc.2020.147328

Dovorogwa H, Harding K (2022) Exploring the use of tobacco waste as a metal ion ddsorbent and substrate for sulphate-reducing bacteria during the treatment of acid mine drainage. Sustain 14:4–14. https://doi.org/10.3390/su142114333

Du T, Bogush A, Edwards P et al (2022) Bioaccumulation of metals by algae from acid mine drainage: a case study of Frongoch Mine (UK). Environ Sci Pollut Res 29:32261–32270. https://doi.org/10.1007/s11356-022-19604-1

España JS, Pamo EL, Santofimia E et al (2005) Acid mine drainage in the Iberian Pyrite Belt (Odiel river watershed, Huelva, SW Spain): Geochemistry, mineralogy and environmental implications. Appl Geochemistry 20:1320–1356. https://doi.org/10.1016/j.apgeochem.2005.01.011

European Union (2010) Directive 2010/75/EU of the European Parliament and of the council on industrial emissions (integrated pollution prevention and control). European Union

Fu F, Wang Q (2011) Removal of heavy metal ions from wastewaters: A review. J Environ Manage 92:407–418. https://doi.org/10.1016/j.jenvman.2010.11.011

Garfield E (1990) Key-words-plus takes you beyond title words. 2. Expanded journal coverage for current-contents-on-diskette includes social and behavioral-sciences. Curr Contents 33:5–9

Gonzalez D, Liu Y, Gomez DV et al (2019) Performance of a sulfidogenic bioreactor inoculated with indigenous acidic communities for treating an extremely acidic mine water. Miner Eng 131:370–375. https://doi.org/10.1016/j.mineng.2018.11.011

Grawunder A, Merten D, Büchel G (2014) Origin of middle rare earth element enrichment in acid mine drainage-impacted areas. Environ Sci Pollut Res 21:6812–6823. https://doi.org/10.1007/s11356-013-2107-x

Han YS, Youm SJ, Oh C et al (2017) Geochemical and eco-toxicological characteristics of stream water and its sediments affected by acid mine drainage. CATENA 148:52–59. https://doi.org/10.1016/j.catena.2015.11.015

Harvey JW, Wagner BJ, Bencala KE (1996) Evaluating the reliability of the stream tracer approach to characterize stream-subsurface water exchange. Water Resour Res 32:2441–2451

Hermassi M, Granados M, Valderrama C et al (2022) Recovery of rare earth elements from acidic mine waters: An unknown secondary resource. Sci Total Environ 810:152258. https://doi.org/10.1016/j.scitotenv.2021.152258

Hogsden KL, Harding JS (2012) Consequences of acid mine drainage for the structure and function of benthic stream communities: A review. Freshw Sci 31:108–120. https://doi.org/10.1899/11-091.1

Ighalo JO, Kurniawan SB, Iwuozor KO et al (2022) A review of treatment technologies for the mitigation of the toxic environmental effects of acid mine drainage (AMD). Process Saf Environ Prot 157:37–58. https://doi.org/10.1016/j.psep.2021.11.008

Johnson DB, Hallberg KB (2003) The microbiology of acidic mine waters. Res Microbiol 154:466–473. https://doi.org/10.1016/S0923-2508(03)00114-1

Johnson DB, Hallberg KB (2005) Acid mine drainage remediation options: A review. Sci Total Environ 338:3–14. https://doi.org/10.1016/j.scitotenv.2004.09.002

Johnson DB, Dziurla MA, Kolmert A, Hallberg KB (2002) The microbiology of acid mine drainage: genesis and biotreatment. S Afr J Sci 98:249–255

Jönsson J, Persson P, Sjöberg S, Lövgren L (2005) Schwertmannite precipitated from acid mine drainage: Phase transformation, sulphate release and surface properties. Appl Geochem 20:179–191. https://doi.org/10.1016/j.apgeochem.2004.04.008

Kaksonen AH, Puhakka JA (2007) Sulfate reduction based bioprocesses for the treatment of acid mine drainage and the recovery of metals. Eng Life Sci 7:541–564. https://doi.org/10.1002/elsc.200720216

Kefeni KK, Msagati TAM, Mamba BB (2017) Acid mine drainage: Prevention, treatment options, and resource recovery: A review. J Clean Prod 151:475–493. https://doi.org/10.1016/j.jclepro.2017.03.082

Kelly DP, Wood AP (2000) Reclassification of some species of *Thiobacillus* to the newly designated genera *Acidithiobacillus* gen. nov., *Halothiobacillus* gen. nov. and *Thermithiobacillus* gen. nov. Int J Syst Evol Microbiol 50:511–516

Kuang JL, Huang LN, Chen LX et al (2013) Contemporary environmental variation determines microbial diversity patterns in acid mine drainage. ISME J 7:1038–1050. https://doi.org/10.1038/ismej.2012.139

Lee G, Bigham JM, Faure G (2002) Removal of trace metals by coprecipitation with Fe, Al and Mn from natural waters contaminated with acid mine drainage in the Ducktown Mining District, Tennessee. Appl Geochem 17:569–581. https://doi.org/10.1016/S0883-2927(01)00125-1

Li S, Yu L, Jiang W et al (2022) The recent progress China has made in green mine construction, Part I: Mining groundwater pollution and sustainable mining. Int J Environ Res Public Health 19:5673. https://doi.org/10.3390/ijerph19095673

Lindsay MBJ, Moncur MC, Bain JG et al (2015) Geochemical and mineralogical aspects of sulfide mine tailings. Appl Geochemistry 57:157–177. https://doi.org/10.1016/j.apgeochem.2015.01.009

Mao N, Wang MH, Ho YS (2010) A bibliometric study of the trend in articles related to risk assessment published in science citation index. Hum Ecol Risk Assess 16:801–824. https://doi.org/10.1080/10807039.2010.501248

Masindi V (2017) Recovery of drinking water and valuable minerals from acid mine drainage using an integration of magnesite, lime, soda ash, CO_2 and reverse osmosis treatment processes. J Environ Chem Eng 5:3136–3142. https://doi.org/10.1016/j.jece.2017.06.025

Masindi V, Foteinis S, Chatzisymeon E (2022) Co-treatment of acid mine drainage and municipal wastewater effluents: Emphasis on the fate and partitioning of chemical contaminants. J Hazard Mater 421:126677. https://doi.org/10.1016/j.jhazmat.2021.126677

Méndez-García C, Peláez AI, Mesa V et al (2015) Microbial diversity and metabolic networks in acid mine drainage habitats. Front Microbiol 6:1–17. https://doi.org/10.3389/fmicb.2015.00475

Moodley I, Sheridan CM, Kappelmeyer U, Akcil A (2018) Environmentally sustainable acid mine drainage remediation: Research developments with a focus on waste/by-products. Miner Eng 126:207–220. https://doi.org/10.1016/j.mineng.2017.08.008

Naidu G, Ryu S, Thiruvenkatachari R et al (2019) A critical review on remediation, reuse, and resource recovery from acid mine drainage. Environ Pollut 247:1110–1124. https://doi.org/10.1016/j.envpol.2019.01.085

Neculita C-M, Zagury GJ, Bussière B (2007) Passive treatment of acid mine drainage in bioreactors using sulfate-reducing bacteria. J Environ Qual 36:1–16. https://doi.org/10.2134/jeq2006.0066

Newman MEJ (2006) Modularity and community structure in networks. Proc Natl Acad Sci U S A 103:8577–8582. https://doi.org/10.1073/pnas.0601602103

Nieto JM, Sarmiento AM, Olías M et al (2007) Acid mine drainage pollution in the Tinto and Odiel rivers (Iberian Pyrite Belt, SW Spain) and bioavailability of the transported metals to the Huelva Estuary. Environ Int 33:445–455. https://doi.org/10.1016/j.envint.2006.11.010

Olías M, Nieto JM, Sarmiento AM et al (2004) Seasonal water quality variations in a river affected by acid mine drainage: The Odiel River (South West Spain). Sci Total Environ 333:267–281. https://doi.org/10.1016/j.scitotenv.2004.05.012

Olías M, Cánovas CR, Nieto JM, Sarmiento AM (2006) Evaluation of the dissolved contaminant load transported by the Tinto and Odiel rivers (South West Spain). Appl Geochem 21:1733–1749. https://doi.org/10.1016/j.apgeochem.2006.05.009

Ouyang Y, Liu Y, Zhu R et al (2015) Pyrite oxidation inhibition by organosilane coatings for acid mine drainage control. Miner Eng 72:57–64. https://doi.org/10.1016/j.mineng.2014.12.020

Park I, Tabelin CB, Jeon S et al (2019) A review of recent strategies for acid mine drainage prevention and mine tailings recycling. Chemosphere 219:588–606. https://doi.org/10.1016/j.chemosphere.2018.11.053

Pat-Espadas AM, Portales RL, Amabilis-Sosa LE et al (2018) Review of constructed wetlands for acid mine drainage treatment. Water (switzerland) 10:1–25. https://doi.org/10.3390/w10111685

Regenspurg S, Brand A, Peiffer S (2004) Formation and stability of schwertmannite in acidic mining lakes. Geochim Cosmochim Acta 68:1185–1197. https://doi.org/10.1016/j.gca.2003.07.015

Rousseeuw PJ (1987) Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. J Comput Appl Math 20:53–65. https://doi.org/10.1016/0377-0427(87)90125-7

Sabe M, Chen C, Sentissi O et al (2022) Thirty years of research on physical activity, mental health, and wellbeing: A scientometric analysis of hotspots and trends. Front Public Heal 10:943435. https://doi.org/10.3389/fpubh.2022.943435

Sahinkaya E (2009) Microbial sulfate reduction at low (8 °C) temperature using waste sludge as a carbon and seed source. Int Biodeterior Biodegrad 63:245–251. https://doi.org/10.1016/j.ibiod.2008.09.006

Sahinkaya E, Gungor M (2010) Comparison of sulfidogenic up-flow and down-flow fluidized-bed reactors for the biotreatment of acidic metal-containing wastewater. Bioresour Technol 101:9508–9514. https://doi.org/10.1016/j.biortech.2010.07.113

Sánchez-Andrea I, Sanz JL, Bijmans MFM, Stams AJM (2014) Sulfate reduction at low pH to remediate acid mine drainage. J Hazard Mater 269:98–109. https://doi.org/10.1016/j.jhazmat.2013.12.032

Sarmiento AM, Nieto JM, Olías M, Cánovas CR (2009) Hydrochemical characteristics and seasonal influence on the pollution by acid mine drainage in the Odiel river Basin (SW Spain). Appl Geochemistry 24:697–714. https://doi.org/10.1016/j.apgeochem.2008.12.025

Scherer MM, Richter S, Valentine RL et al (2010) Technology chemistry and microbiology of permeable reactive barriers for in situ groundwater clean up chemistry and microbiology of permeable reactive barriers for in situ groundwater clean up. Crit Rev Environ Sci Technol 30:363–411

Schrenk MO, Edwards KJ, Goodman RM et al (1998) Distribution of *Thiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*: Implications for generation of acid mine drainage. Science 279:1519–1522. https://doi.org/10.1126/science.279.5356.1519

Si M, Chen Y, Li C et al (2023) Recent advances and future prospects on the tailing covering technology for oxidation prevention of sulfide tailings. Toxics 11:1–13. https://doi.org/10.3390/toxics11010011

Simate GS, Ndlovu S (2014) Acid mine drainage: Challenges and opportunities. J Environ Chem Eng 2:1785–1803. https://doi.org/10.1016/j.jece.2014.07.021

Singh R, Gautam N, Mishra A, Gupta R (2011) Heavy metals and living systems: An overview. Indian J Pharmacol 43:246–253. https://doi.org/10.4103/0253-7613.81505

Skousen J, Rose A, Geidel G et al (1998) Handbook of technologies for avoidance and remediation of acid mine drainage. The National Mine Land Reclamation Centre, West Virginia

Solomon F (2008) Impacts of metals on aquatic ecosystems and human health. Environ Communities 14–19

Strosnider WH, Nairn RW (2010) Effective passive treatment of high-strength acid mine drainage and raw municipal wastewater in Potosí, Bolivia using simple mutual incubations and limestone. J Geochem Explor 105:34–42. https://doi.org/10.1016/j.gexplo.2010.02.007

Strosnider WH, Winfrey BK, Nairn RW (2011) Biochemical oxygen demand and nutrient processing in a novel multi-stage raw municipal wastewater and acid mine drainage passive co-treatment system. Water Res 45:1079–1086. https://doi.org/10.1016/j.watres.2010.10.026

Sun W, Xiao E, Häggblom M et al (2018) Bacterial survival strategies in an alkaline tailing site and the physiological mechanisms of dominant phylotypes as revealed by metagenomic analyses. Environ Sci Technol 52:13370–13380. https://doi.org/10.1021/acs.est.8b03853

Tabelin CB, Igarashi T, Villacorte-Tabelin M et al (2018) Arsenic, selenium, boron, lead, cadmium, copper, and zinc in naturally contaminated rocks: A review of their sources, modes of enrichment, mechanisms of release, and mitigation strategies. Sci Total Environ 645:1522–1553. https://doi.org/10.1016/j.scitotenv.2018.07.103

Tao Y, Yuan Z, Xiaona H, Wei M (2012) Distribution and bioaccumulation of heavy metals in aquatic organisms of different trophic levels and potential health risk assessment from Taihu lake, China. Ecotoxicol Environ Saf 81:55–64. https://doi.org/10.1016/j.ecoenv.2012.04.014

Tsukamoto TK, Killion HA, Miller GC (2004) Column experiments for microbiological treatment of acid mine drainage: Low-temperature, low-pH and matrix investigations. Water Res 38:1405–1418. https://doi.org/10.1016/j.watres.2003.12.012

Vass CR, Noble A, Ziemkiewicz PF (2019) The occurrence and concentration of rare earth elements in acid mine drainage and treatment byproducts: Part 1-Initial survey of the northern Appalachian Coal Basin. Mining, Metall Explor 36:903–916. https://doi.org/10.1007/s42461-019-0097-z

Webster JG, Swedlund PJ, Webster KS (1998) Trace metal adsorption onto an acid mine drainage iron(III) oxy hydroxy sulfate. Environ Sci Technol 32:1361–1368. https://doi.org/10.1021/es9704390

Wilfong WC, Ji T, Duan Y et al (2022) Critical review of functionalized silica sorbent strategies for selective extraction of rare earth elements from acid mine drainage. J Hazard Mater 424:127625. https://doi.org/10.1016/j.jhazmat.2021.127625

Yadav SK (2010) Heavy metals toxicity in plants: An overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. South African J Bot 76:167–179. https://doi.org/10.1016/j.sajb.2009.10.007

Yuniati MD, Kitagawa K, Hirajima T et al (2015) Suppression of pyrite oxidation in acid mine drainage by carrier microencapsulation using liquid product of hydrothermal treatment of low-rank coal, and electrochemical behavior of resultant encapsulating coatings. Hydrometallurgy 158:83–93. https://doi.org/10.1016/j.hydromet.2015.09.028

Zhang M, Gao M, Yue S et al (2018) Global trends and future prospects of food waste research: a bibliometric analysis. Environ Sci Pollut Res 25:24600–24610. https://doi.org/10.1007/s11356-018-2598-6

Zhang M, Gao Z, Zheng T et al (2018) A bibliometric analysis of biodiesel research during 1991–2015. J Mater Cycles Waste Manag 20:10–18. https://doi.org/10.1007/s10163-016-0575-z

Zheng T, Wang J, Wang Q et al (2015) A bibliometric analysis of industrial wastewater research: current trends and future prospects. Scientometrics 105:863–882. https://doi.org/10.1007/s11192-015-1736-x

Zhong CM, Xu ZL, Fang XH, Cheng L (2007) Treatment of acid mine drainage (AMD) by ultra-low-pressure reverse osmosis and nanofiltration. Environ Eng Sci 24:1297–1306. https://doi.org/10.1089/ees.2006.0245

Zobrist J, Sima M, Dogaru D et al (2009) Environmental and socioeconomic assessment of impacts by mining activities-a case study in the Certej River catchment, Western Carpathians, Romania. Environ Sci Pollut Res 16:14–26. https://doi.org/10.1007/s11356-008-0068-2