Applied Water Science (2024) 14:204
https://doi.org/10.1007/s13201-024-02259-3

REVIEW ARTICLE

Global advancements in the management and treatment of acid mine drainage

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Received: 20 December 2023 / Accepted: 28 July 2024 / Published online: 17 August 2024

Abstract

Acid mine drainage (AMD) is a mining-associated environmental problem that mainly pollutes water resources worldwide, making it imperative to find sustainable remediation solutions. To find effective treatment solutions for AMD, it will be beneficial to understand how this area of research has evolved over the years. Thus, this work provides a bibliometric analysis and narrative review of previous research articles that have focused on AMD treatment and management over the past 47 years and highlights the associated challenges and how to overcome them. Research articles addressing the treatment and management of AMD were retrieved from the Scopus database, using specific search criteria. The Scopus Analyze Tool and VOSviewer were used to analyze the publications to provide information on the publication distribution, countries of publication, authorship, keywords, field of study, and author affiliations, while the narrative review provides an overview of how AMD treatment technologies have evolved over these years. The top ten most published countries are developed countries except for South Africa (ranking number 4). This review revealed that several approaches have been developed for AMD treatment and management. It was observed that AMD treatment methods have not drastically changed over the years. Instead, earlier treatment techniques are being improved to develop new and more effective ones. The most recent remediation approach involves the valorization of AMD for the recovery of new materials in economically viable amounts. This is a sustainable approach to AMD treatment; however, it comes with challenges that can be overcome through more research in this area.

Keywords Acid mine drainage (AMD) · Water · Mining · Bibliometric analysis · Treatment · Remediation

Introduction

Background

Mining is an important aspect of our daily lives, with its many benefits ranging from the production of essential raw materials for several industries to the economic empowerment of communities and nations where mining takes place. Mining improves economies, creates jobs, and improves infrastructure, education, and social and public health services (Hosseinpour et al. 2022). Mining is also known to have many negative impacts on the environment. Some of these include land degradation, erosion, pollution of soil, air, and water, displacement of human beings from their original/native habitats, etc., thus preventing sustainable use of natural resources (Fu and Zhang 2022; Otunola et al. 2022; Hosseinpour et al. 2022). A major environmental problem largely associated with mining is acid mine drainage (AMD). Although AMD can be a natural process, it is often aggravated by mining leading to pollution of air, soil, and water as well as surrounding ecosystems.

Acid mine drainage is a process that occurs when water flows through abandoned or active mines, rock surfaces, mine spoils, or mine tailings that contain sulfide minerals in the presence of oxygen (Akcil and Koldas 2006; Angelov et al. 2023). This process lowers water pH (making it acidic), and this condition releases or mobilizes heavy metals, which are very toxic to many living organisms (Palmerton 2023). Also, acidic conditions threaten the lives of most aquatic organisms. AMD is characterized by high acidity, sulfates, and toxic heavy metals and metalloids (Angelov et al. 2023). The characteristics of AMD and the extent of its negative

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impacts vary widely depending on the nature of impacted rocks or ore bodies, climatic conditions, flow rate of water, and the mining processes, pH, oxygen, surface area of exposed sulfide mineral, and bacterial activity (Akcil and Koldas 2006).

As a result of its toxicity, much attention is being given to research in the area of AMD treatment and management For example, heavy metals are not biodegradable, meaning that they are persistent in the environment and are very toxic to living organisms in minute quantities (Dong et al. 2019; Otunola et al. 2022). The process of AMD formation can also be accelerated by certain naturally occurring bacteria such as Acidithiobacillus ferrooxidans (Akcil and Koldas 2006; Natarajan 2008). Many authors have provided details on the major chemical reactions that produce AMD (Akcil and Koldas 2006; Bwapwa et al. 2017; Anekwe and Isa 2023). According to Akcil and Koldas (2006), the acid generation reactions are best described by the oxidation of pyrite (FeS_2), a common sulfide mineral. The reaction will be the oxidation of the sulfide mineral (in this case FeS_2) to produce dissolved iron (Fe), sulfate ($SO_4{}^2$), and hydrogen ions, represented in equation 1 below:

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \tag{1}$$

Later, most of the ferrous iron (Fe^{2+}) will oxidize to ferric iron (Fe^{3+}), as in equation

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

At a low pH of about 2.3 to 3.5, the ferric iron precipitates as iron (III) hydroxide ($Fe(OH)_3$) and jarosite and thus some Fe^{3+} in solution while further lowering pH as shown in equation 3.

$$4Fe^{3+} + 12H_2O \rightarrow 4Fe(OH)_3(\text{solid}) + 12H^+ \tag{3}$$

At this point, all Fe^{3+} that did not precipitate in equation 3 may cause additional pyrite oxidation as in equation 4.

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \tag{4}$$

Finally, the overall reaction for the formation of AMD through pyrite weathering (as the sulfide mineral) is given in Equation 5.

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8H_2SO_4 \tag{5}$$

Some reported case studies on the negative effects of AMD on the environment and human beings

AMD is of much concern worldwide because it negatively affects all environmental compartments, and it is mostly inevitable wherever mining takes place. AMD can pose a risk to human beings in so many ways. For instance, through pollution of water and plants, and consumption by animals, contaminants (such as heavy metals) from AMD can easily become introduced into the food chain, posing a direct health risk to human beings. Another source of risk is through physical contact with polluted soil and water or inhalation of polluted air. Jiao et al. (2023) indicate that hydrogen sulfide gas produced from AMD often causes skin irritation, respiratory problems, and eye irritation (Jiao et al. 2023). The harmful pollutants released by AMD into soil and waterbodies also cause plant and animal health to depreciate, resulting in a loss of biodiversity. As a result of oxidation in rivers, AMD has particularly been responsible for the massive death of aquatic organisms in many parts of the world (Lin et al. 2007; Neuman et al. 2014; Jiao et al. 2023). According to Lukacs and Ortolano (2015), AMD arising from abandoned coal mines has affected several hundred miles of streams, leaving the residents of West Virginia with polluted waters (Lukacs and Ortolano 2015; Palmerton 2023).

In Brazil, a stream and river affected by AMD were investigated by Galhardi and Bonotto (2016). They found that the pollution source was a nearby tailings pile, causing the release of iron and aluminum metals. Seasonality also causes a variation in the release of these toxic elements, while the extent of pollution is also affected by the pH, oxidation of sulfide minerals oxygen and iron content, and microbial activity in the affected water bodies (Galhardi and Bonotto 2016). A case of AMD in Poland indicated that pyrite exists in a sedimentary formation. As a result of mining, arsenic-rich pyritiferous rocks are exposed, resulting in highly acidic solutions that contaminate water bodies (Migaszewski et al. 2019). Excessive coal mining in China has resulted in the abandonment of several mines. These mines hold water and result in rock dissolution from which AMD is generated. This has led to a shortage of potable water (Wang et al. 2021). Pyrite was also indicated as the major mineral responsible for the formation of AMD, under oxidized environments. The major mining areas in Nigeria also face the problem of AMD, rendering most of the freshwater sources useless as they are unsafe for domestic use (Mallo 2011). Akpan et al. (2021) studied the chemical composition of soil and water (that empties into water bodies that serve as municipal water supply) in abandoned coal mines and confirmed that the water was acidic, with an abundance of iron, copper, lead, and zinc, while sediment quality was deteriorating (Akpan et al. 2021).

In the arid area of Potosí (Bolivia), AMD has polluted local water resources, making them unfit for agricultural and domestic use, although, because of water shortage, the farmers make use of this contaminated water for irrigation. This poses huge environmental and health risks to all that consume any produce that was irrigated by AMD-affected water. The agricultural soils contained high levels of total metal concentrations which exceeded the Dutch, Canadian, and German guidelines. Also, the levels of cadmium, lead, and zinc in potatoes farmed in that area exceeded commercially sold vegetable guidelines (Garrido et al. 2009). In South Africa (a country recognized as a leader in the mining sector), there have been several cases of AMD, especially in abandoned mines. In the Witwatersrand gold mining region of the country, the tailings dams contain very high levels of heavy metals and oxides, with very low pH (pH ranges from 2.4 to 5.8). These result in about 202 million liters per day in discharge volume of AMD, although this can serve as a supply of safe water if adequately treated (Abiye and Ali 2022). In the Mpumalanga region of South Africa, AMD-affected sediments were tested for metal release. It was deduced that metals such as iron, uranium, and nickel are bioavailable (Fosso-Kankeu et al. 2017), indicating that they can easily be absorbed by plants or taken in by animals, posing a risk to the food chain.

Sustainability advocates a balance between economic, social, and environmental prosperity; therefore, sustainability in mining is of utmost importance to reduce the negative impacts of mining (Chris 2023). One of the ways to achieve sustainability in mining is through planned and consistent remediation of polluted areas, prevention and mitigation of pollution, and frequent environmental monitoring, to understand how mining impacts different compartments of the environment. With sustainability in mind, it is important to seek the most appropriate solutions to AMD. For this reason, this paper seeks to highlight the advancements that have been made worldwide in the treatment and management of AMD. This was achieved through a bibliometric analysis and narrative review of studies focused on the remediation and management of AMD.

This study acknowledges that some authors have previously published reviews on the treatment of AMD. For instance, Jiao et al. (2023) reviewed the methods for AMD treatment, although published very recently, it leaves out remediation options such as phytoremediation in the discussed methods (Jiao et al. 2023). Also, there are a low number of studies that have provided a bibliometric analysis of research on the treatment and management of AMD. A certain study researched the treatment of AMD through phytoremediation (using Eichornia crassipes and Pistia stratiotes) and also undertook a bibliometric analysis of studies that have applied phytoremediation for AMD treatment (Wibowo et al. 2022). In their experiment, they found that the plants were effective, removing 69 and 62% of heavy metals, respectively, within 40 days of treatment. The bibliometric study revealed that the use of phytoremediation for AMD treatment is rare. Zhang et al. (2023) also present a very recent bibliometric study on the treatment of AMD, but the review captured only research published from the year 1991 to 2021, limiting the number of included studies (Zhang et al. 2023). Another review article reviewed the prevention, treatment, and generation of new products from AMD, with more emphasis on prevention, but only covered the years 1980 to 2016 (Kefeni et al., 2017). In the present bibliometric study, all studies that could be retrieved from the Scopus database up to the year 2022 were included. Also, some other reviews focused on only a specific type of treatment. For example, the use of chemicals such as lime, caustic soda, soda ash briquettes, and ammonia (Skousen 2014), treatment by biosorption (Kim and Park 2022), ion exchange (Gaikwad), and phytoremediation (Wibowo et al. 2022). The present study is unique because it considers the gaps in these previous review articles and provides updated and complementary knowledge in the research area of AMD treatment and management by conducting a bibliometric analysis and narrative review that critically evaluates and discusses previous studies over a longer period (1976 to 2022) and considers different treatment types for AMD and how they have evolved over the years. Thus, this study provides a more robust overview of research in the area of AMD treatment which will offer guidance on sustainable AMD treatment and give future researchers the state of the art of research on the techniques that have been applied for AMD treatment, and management. It also points out possible research collaboration opportunities within and outside relevant institutions and countries. The bibliometric analysis will help to quantify the impact, distribution and performance of articles related to the treatment and management of AMD.

Material and methods

Article search strategy

For this study, all research articles around the topic of management and treatment of acid mine drainage that exists on the Scopus database were retrieved. Scopus was selected because it boasts a large range of high-quality, reliable publications on several research topics from over 17 million authors (“About | Elsevier Scopus Blog,”, 2023). Also, unlike other databases such as Google Scholar, PubMed, and Web of Science (which are also reliable), Scopus covers a wider range of journals and provides tools for citation analysis. The article search was carried out on specific keywords that are related to the treatment and management of AMD (more details in Figure 1), using Boolean operators “AND” and “OR”. Only original research papers (and not review papers) were considered in this study because the focus is on actual research on the treatment and management of AMD. Conference papers and book chapters were excluded to avoid duplication of studies and the inclusion of unpublished conference papers. Moreover, research papers

Fig 1 The search and selection criteria used to retrieve relevant articles from Scopus

(TITLE-ABS-KEY ("treatment of acid mine drainage") OR TITLE-ABS-KEY ("Management of acid mine drainage") OR TITLE-ABS-KEY ("treatment of acid rock drainage") OR TITLE-ABS-KEY ("management of acid rock drainage") OR TITLE-ABS-KEY ("treatment of polluted mine water") OR TITLE-ABS-KEY ("Management of mine water") OR TITLE-ABS-KEY ("mitigation of acid mine drainage") OR TITLE-ABS-KEY ("mitigatio* of acid mine drainage") OR TITLE-ABS-KEY ("control of polluted mine water") OR TITLE-ABS-KEY ("solution for acid mine drainage") OR TITLE-ABS-KEY ("Remediatio*" of "acid mine drainage")) AND (EXCLUDE (DOCTYPE , "cp") OR EXCLUDE (DOCTYPE , "re") OR EXCLUDE (DOCTYPE , "ch") OR EXCLUDE (DOCTYPE , "cr") OR EXCLUDE (DOCTYPE , "bk") OR EXCLUDE (DOCTYPE , "er") OR EXCLUDE (DOCTYPE , "sh") OR EXCLUDE (DOCTYPE , "no") OR EXCLUDE (DOCTYPE , "ed") OR EXCLUDE (DOCTYPE , "dp")) AND (EXCLUDE (LANGUAGE , "Chinese") OR EXCLUDE (LANGUAGE , "Spanish") OR EXCLUDE (LANGUAGE , "German") OR EXCLUDE (LANGUAGE , "Portuguese") OR EXCLUDE (LANGUAGE , "Korean") OR EXCLUDE (LANGUAGE , "Undefined") OR EXCLUDE (LANGUAGE , "Japanese") OR EXCLUDE (LANGUAGE , "French") OR EXCLUDE (LANGUAGE , "Finnish") OR EXCLUDE (LANGUAGE , "Turkish") OR EXCLUDE (LANGUAGE , "Polish") OR EXCLUDE (LANGUAGE , "Malay")) AND (LIMIT-TO (SRCTYPE , "j"))

provide a high level of detail for better comprehension of the research area of interest (Matyukira and Mhangara 2023). The retrieved articles were stored in CSV format and uploaded to VOSviewer for bibliometric analysis. The Scopus Analyze Tool also assisted in the bibliometric analysis.

Analysis of the retrieved articles

Bibliometric analysis has been employed by several studies to analyze the distribution and properties of publications around a particular research area of interest (Wang et al. 2009; Derviş 2020; Guo et al. 2020; Donthu et al. 2021; Okolie et al. 2023). The bibliometric analysis approach is not new, but in recent years, its usage/application has increased in many fields (Wang et al. 2009; Donthu et al. 2021). It can provide information concerning article authors, collaborations, country of publication, citation, and several bibliometric networks (Matyukira and Mhangara 2023) and mitigate interpretation bias since it relies on quantitative techniques (Donthu et al. 2021). VOSviewer enabled realistic analysis of large data, to explore and understand relationships based on publication properties through scientific mapping to give the structural and dynamic details of the research topic. A total of 1,109 articles were retrieved from the article search in Section 2.1. These were uploaded in CSV format to the VOSviewer Platform. Density and network visualization maps, collaboration, and keyword analysis were retrieved from VOSviewer. Online published articles were explored for relevant studies. This study carefully selected and reviewed all relevant literature from 1976 to 2022. The timeframe was considered because research on the treatment and management of AMD started around the 1970s, while the selection stops at the year 2022 because the research was done in the year 2023 and not all relevant publications were available at this time. Also, the information related to the papers published in 2023 was not yet complete and stable, although review studies from all the years were considered because they have no impact on the analysis of research articles. Also, the years were grouped into 20-year segments, and the most cited papers for each segment were analyzed and detailed in a table. The 20-year segments were chosen because it is considered that 20 years would be enough time difference to show the changes in a particular field, while the most cited articles were selected because not all the thousands of retrieved articles can be individually analyzed.

Results and discussion

Analysis of publications on acid mine drainage treatment and management

A total number of 1109 research-based publications on the topic of acid mine drainage treatment and management were retrieved. Publication in this area started in the year 1976, and these articles were published in the English language by various journals. Only one article was published about treating or managing AMD in the years 1976 and 1977, followed by zero publication on the subject matter in the following two years (1978 and 1979). A fluctuation between no publication and one publication continued until the year 1991, which records two publications; thereafter, there was a gradual, but consistent, increase in yearly publications about AMD treatment and management. The highest number of yearly publications was 83, achieved in the year 2020, and a mean yearly publication of 23.6. Considering the steady rise in yearly publications on AMD treatment and management as seen in the current growth trends presented in Figure 2, as well as the associated known environmental risks, it is expected that the coming years will see an increase in publications on this subject matter.

Authorship and citation

A total of 890 authors contributed to the 1109 publications in the research area of AMD treatment and management. The top ten leading and most published authors in the field are presented in Table 1. Ayora, C. is the most published

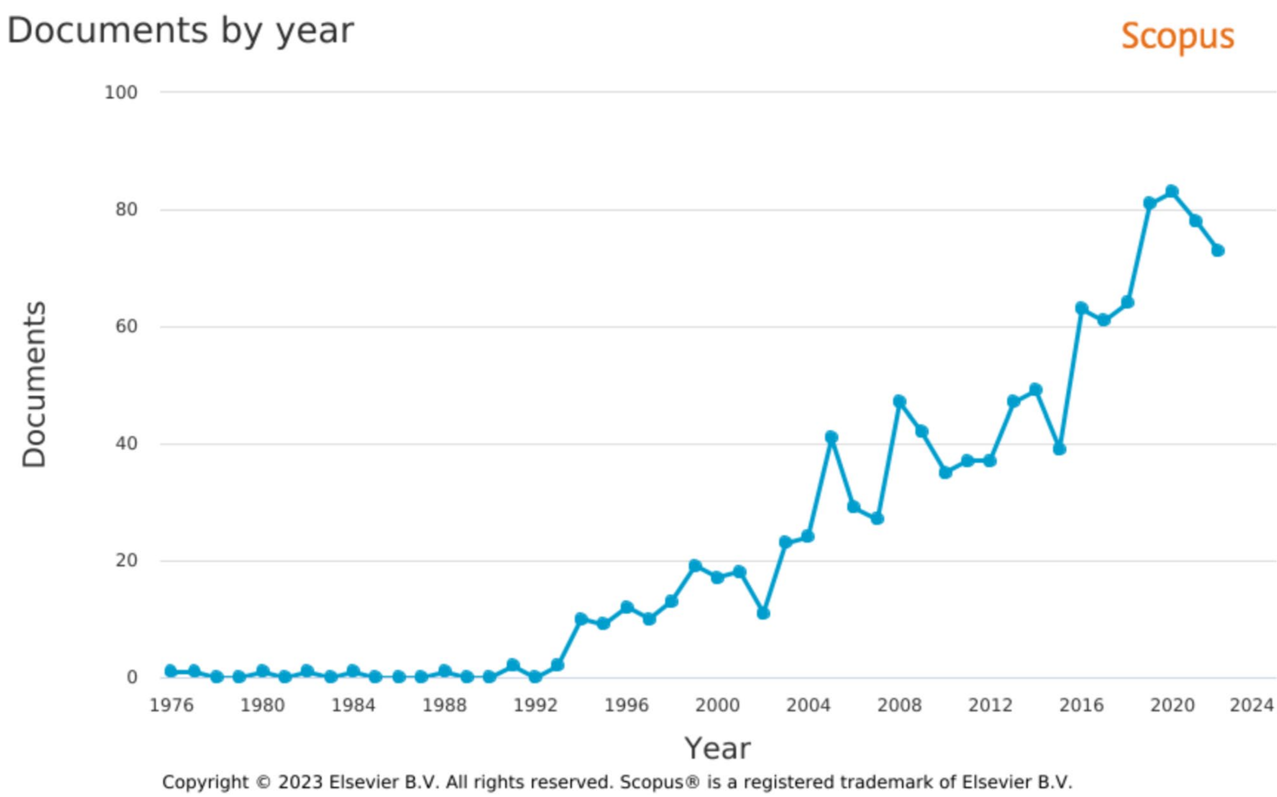

Fig 2 Distribution of yearly publications on the treatment and management of acid mine drainage

Table 1 : The first 20 leading authors in the field and the number of published documents per author.

Author	Documents
Ayora, C.	30
Nieto, J.M.	20
Neculita, C.M.	18
Blowes, D.W.	17
Benzaazoua, M.	16
Johnson, D.B.	14
Masindi, V.	14
Caraballo, M.A.	13
Macías, F.	13
Ptacek, C.J.	13
Runkel, R.L.	13
Dang, Z.	11
Pérez-López, R.	11
Öhlander, B.	11
Bussière, B.	10
Younger, P.L.	10
Cortina, J.L.	9
Gibert, O.	9
Lu, G.	9
Maurice, C.	9

author, with 30 research papers, followed by Nieto, J.M., with 20 research papers. The last published authors on the topic have at least three articles. The topmost published authors are affiliated with institutions in developed countries: Masindi, V. (an Africa-based researcher) is number seven (7) among the ten topmost authors on the topic.

Word distribution/keywords

A total of 2649 keywords (based on the 1109 articles) were retrieved for this bibliometric analysis. Figure 3 shows a network diagram for keywords that appear 10 times or more, and 49 keywords met this criterion. Details on the keywords related to AMD treatment and management are as follows: Acid mine drainage was used as keyword 449 times (red node), remediation appeared 95 times (blue node), heavy metals appeared 62 times (red node), bioremediation appeared 50 times (red node), and passive treatment appeared 36 times (yellow node). The key important terms (keywords) frequently used have larger nodes (Figure 3), the shorter the link, the stronger the relationship between the linked keywords. There is such a strong link between acid mine drainage and bioremediation, which indicates that the most frequently explored treatment/remediation method for AMD is bioremediation. Heavy metals are associated with

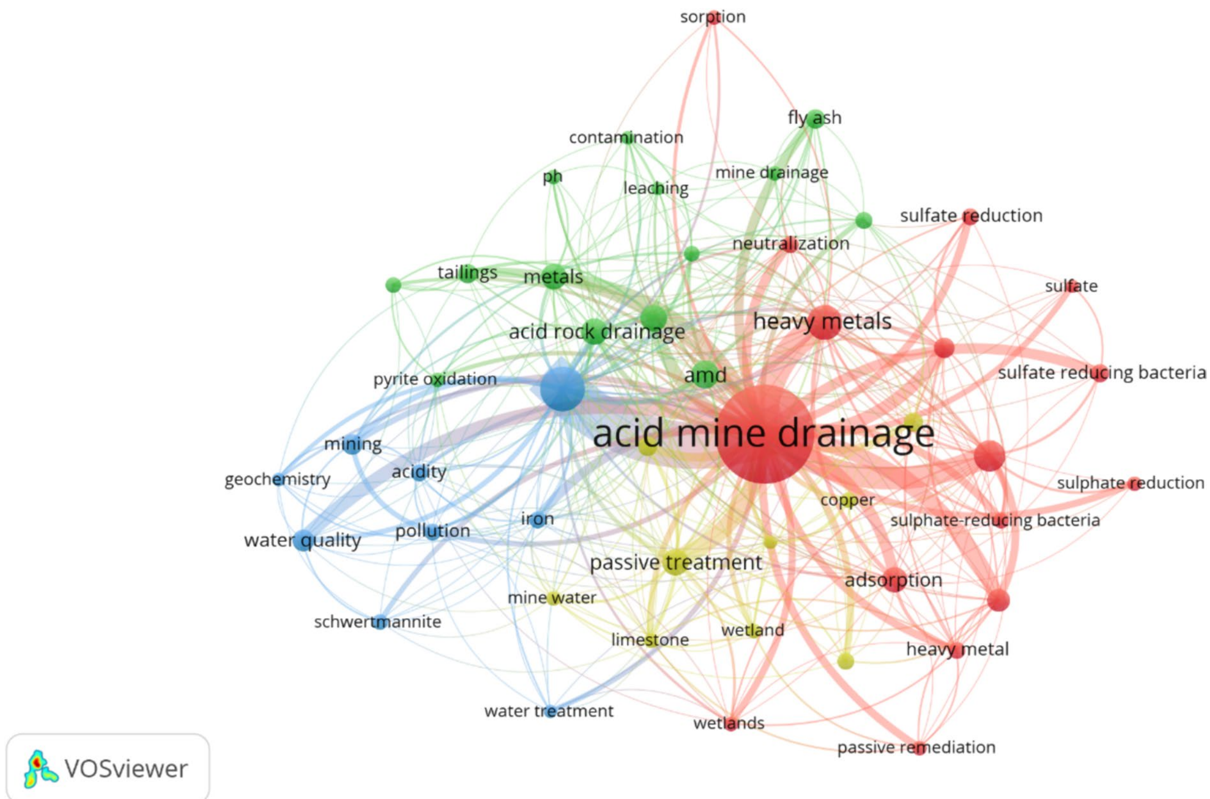

Fig 3 Network visualization for author keywords in studies on acid mine drainage treatment and management. Each node in the network represents individual keywords, while lines represent the pathways of association between keywords. The shorter the line, the stronger the association

AMD as seen in the medium-sized red nodes; as a result, treatment methods that can remove heavy metals are preferred. The most popular treatment approaches that have been used for AMD treatment include passive treatment (through wetlands, limestone drains and sulfate-reducing bacteria), adsorption, fly ash application, and neutralization. The major controlling factors include the level of acidity of AMD, pyrite oxidation, and the formation of schwertmannite.

Major findings on the current state of acid mine drainage treatment and management

Understanding the progress made over the years in the area of AMD treatment and management requires identifying publications that have contributed substantially in this area. This study found 1109 documents published from the year 1976 to the year 2022. Most of the articles were published from year 1997 to 2017. These years were grouped into 20-year segments, and the most cited papers for each segment are summarized and presented in Table 2 to provide an overview of the reviewed articles. The reviewed articles revealed that there are many difficulties with efforts to inhibit the generation of AMD, but several attempts have been made to treat or manage AMD (Figure 4). The treatment and management of AMD can be very tedious, difficult, and expensive because AMD affects large areas and the properties can be unique per scenario, therefore requiring unique treatment solutions. Also, most times, treatment is not once-off because AMD is frequently generated in active and passive mines.

Several techniques have been applied for the treatment of AMD over the years, and these treatment techniques are often grouped as active or passive treatment methods. Active treatment involves frequent/continuous neutralization using materials/chemicals such as sodium hydroxide (NaOH), biochar, limestone, clay minerals, and nanomaterials to precipitate metals from the solution (Mondale et al. 1995; Lee et al. 2002; Matlock et al. 2002). The most widely used treatment method in the 1990s was active treatment. The trend observed in this review is that the most common approach in the late 1970s was the neutralization of the AMD using limestone, carbonates, and clay minerals to reduce its acidity and heavy metals mobility and thus its toxicity. A disadvantage of applying these materials is that they can be a source of contamination on their own. For example, metals including Sr, Ba, and Al had higher concentrations in the effluent site (treated AMD-impacted water) as compared to the influent

Table 2: Research findings of the top ten most cited articles (for every 20-year segment from 1976 to 2022) in the area of acid mine drainage treatment and management.

Author(s)	Citations	Country	Study type (Field/ Laboratory/Desktop)	Method (technique)	Findings
1976–1996					
Gazea et al. (1996)	242	Greece	Desktop	Mixed	Passive treatment is most effective for AMD
Hedin (1994)	166	USA	Field	Passive (limestone drains)	Anoxic limestone drains are effective for removing heavy metals from AMD and have theoretical effective lifetimes of about 20 years.
Wunderly et al. (1996)	140	Canada	Laborator	Modeling (mathematical)	The MINTOX model can show the potential benefits of various remediation schemes before they are applied in real life.
Mondale et al. (1995)	131	USA	Laboratory	Active (adsorbents)	Several natural and synthetic zeolites such as Erionite, Chabazite, Clinoptilolite, and Mordenite are effective for AMD treatment.
Leblanc et al. (1996)	117	France	Laboratory	Passive (Microbial action)	Used ferruginous bacterial accretions to extract arsenic from AMD, thus controlling downstream pollution.
Sherlock et al. (1995)	105	Canada	Desktop	Active (neutralization)	Carbonates and silicates are effective for neutralizing AMD
Stollenwerk (1994)	87	USA4	Laboratory	Modeling (geochemical)	A geochemical model was developed to simulate the changes in the geochemical conditions of groundwater impacted by AMD.
Béchard et al. (1994)	71	Canada	Laboratory	Passive (microbial action)	A combination of aerobic and anaerobic microbes in the presence of cellulose is effective for AMD treatment.
Wang et al. (1996)	70	Canada	Laboratory	Active (adsorption)	The presence of calcium ions decreased the metal recovery from a simulated AMD under ambient conditions
Johnson (1995)	64	UK	Laboratory	Passive (microbial action)	Acidophilic microbial communities are effective for AMD treatment
1997–2016					
Johnson and Hallberg (2005)	1597	UK	Desktop	Mixed	Passive treatment involves a combination of adsorption, biological, oxidation, and reduction techniques
Lu et al. (2012)	863	China	Laboratory	Active (adsorption)	Sludge-derived biochar can be an alternative material to minimize the concentration of Pb^{2+} in AMD
Matlock et al. (2002)	624	USA	Field and Laboratory	Active (adsorption)	BDET can be applied as an additive to reduce metal concentrations in AMD

Table 2: (continued)

Author(s)	Citations	Country	Study type (Field/ Laboratory/Desktop)	Method (technique)	Findings
Xu et al. (2006)	540	USA	Laboratory	Modeling (geochemical)	Modeling helps to predict the effectiveness of the proposed AMD treatment
Blowes et al (2000)	494	USA and Canada	Laboratory	Passive (reactive barriers)	Permeable reactive barriers are good for AMD treatment
Motsi et al. (2009)	454	UK	Laboratory	Active (adsorption)	Natural zeolite can be effective in removing heavy metals from AMD
Nordstrom and Alpers (1999)	399	USA	Laboratory	Modeling (geochemical)	Geochemical modeling for decision-making saves time and cost. Although, surface-water diversions is proposed as an immediate solution to control AMD
Lee et al. (2002)	330	USA	Filed and Laboratory	Active (adsorption)	AMD can be neutralized by saturated NaOH
Sánchez-Andrea et al. (2014)	285	The Netherlands	Desktop	Passive (microbial)	Sulfate-reducing bacteria can produce alkalinity to neutralize AMD
Gray (1997)	261	Ireland	Desktop	Mixed	A systems management approach is necessary, to effectively manage the impacts of AMD
2017–2022					
Vital et al. (2018)	119	Chile	Laboratory	Passive (reactive membranes)	Forward osmosis removes heavy metals from AMD
Feng et al. (2019)	105	China	Laboratory	Active (adsorption)	Magnetic Fe_3O_4-chitosan@bentonite possesses high stability and good performance in the removal of Cr(VI) from AMD
Le Pape et al. (2017)	92	France	Laboratory	Passive (microbial action)	A composite of Fe_3O_4-CS@BT proved very effective for Cr(VI) from AMD
Luo et al. (2020)	82	China	Field and Desktop	Modeling (geochemical)	Geochemical modeling using PHREEQC is effective for AMD monitoring
Xu et al. (2020)	82	China	Field and Laboratory	Active (neutralization)	Valuable metals can be recovered from the AMD treatment process
Zhang et al. (2019)	80	China	Laboratory	Passive (microbial action)	Microalgae can be used to treat acidic waters with heavy metals, N, and low COD
Dutta et al. (2020)	64	India	Laboratory	Active (neutralization)	Limestone proved effective for reducing AMD toxicity
Willscher et al. (2017)	61	Germany	Laboratory	Passive (plants)	Phytoremediation using *Helianthus tuberosus* is effective for removing heavy metals from AMD
Pozo et al. (2017)	61	Australia	Laboratory	Hybrid	A combination of microbial action and electrical current showed good potential for treating AMD.
Macías et al. (2017)	60	Spain	Laboratory	Active (neutralization)	Sludge generated from AMD can be valorized

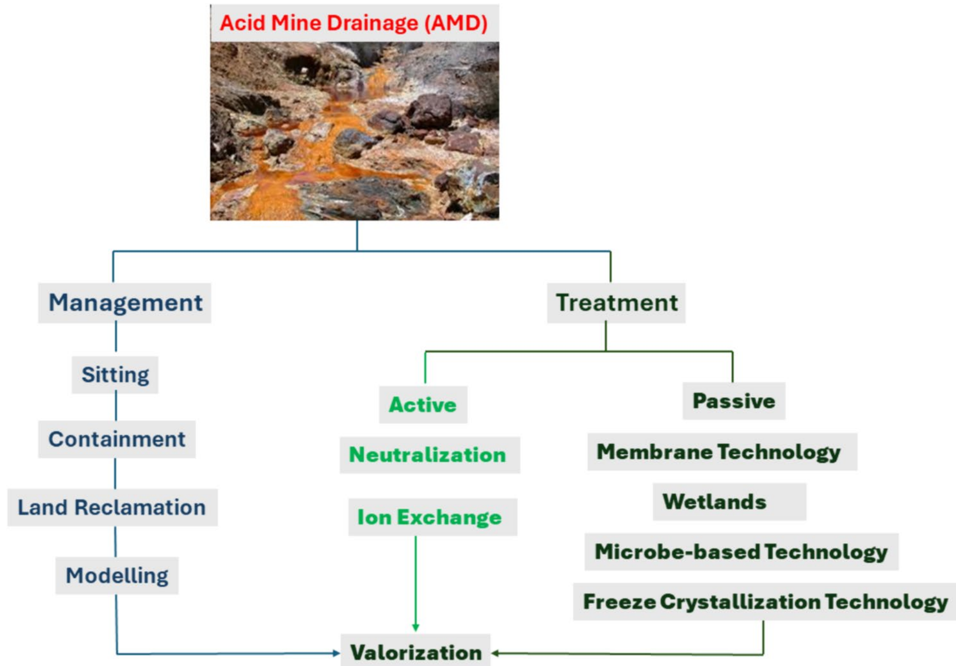

Fig 4 A graphical representation of advancements in the treatment and management of acid mine drainage. There are possibilities of generating economically valuable materials from the AMD treatment and management processes.

(untreated AMD-impacted water), which could be attributed to metal impurities in the added lime (Matlock et al. 2002), indicating that much care should be taken regarding additives to ensure that more or new contaminants are not introduced into the environment during AMD treatment.

Passive treatments, on the other hand, involve the use of permeable reactive barriers and wetlands (Ford 2003; Zipper and Skousen 2014) or living organisms (such as bacteria, plants, and algae) to remove contaminants from AMD (Béchard et al. 1994; Johnson 1995; Leblanc et al. 1996; Sánchez-Andrea et al. 2014; Willscher et al. 2017; Vital et al. 2018). This method is also more economical compared to active treatments. In some cases of passive treatment, hybrid treatment techniques can also be applied (Gazea et al. 1996; Pozo et al. 2017). It often requires a combination of several methods; therefore, the limitation of one method can be corrected by other methods used in combination. This method requires a relatively large expanse of land and requires critical evaluation of the water chemistry, flow rate, local topography, and site characteristics (West Virginia University, Morgantown et al. 2005; Skousen et al. 2017). Also, the method is relatively slow compared to active treatments, but esthetically pleasing and less costly.

Over the years, active and passive treatment methods have been improved to produce new and more effective AMD remediation techniques. Adsorption technologies are often applied for metal removal from AMD (Matlock et al. 2002; Motsi et al. 2009; Rodriguez-Galiano et al. 2012). The adsorption process in AMD treatment is simply a process in which adsorbent materials such as clays are applied to AMD and these attract the metals present in the AMD onto the surface of the adsorbent (Otunola and Ololade 2020). Technologies developed from biological methods (mainly based on the action of sulfate-reducing bacteria) include BioSURE—biological sulfate reduction process, IMPI—integrated managed passive treatment process, ASBR—anaerobic stirred batch reactor (Foucher et al. 2001; Mosai et al. 2024) have proven to be cost-effective and efficient for AMD treatment, although sometimes generates a huge amount of wastes. Membrane technologies are majorly based on the reverse and forward osmosis through the HIPRO—high recovery precipitating reverse osmosis, SPARRO—slurry precipitation and recycle reverse osmosis, SWRO—seawater reverse osmosis or ultrafiltration and nanofiltration through the NIC—Nanotechnology Innovation Center process (Mosai et al. 2024). Freeze crystallization technologies are used to remove salt from AMD (Randall and Nathoo 2015).

Precipitation technologies targeted at AMD containing high sulfate and metals using processes such as ABC—alkali–barium–calcium, HDS—high-density sludge (Motaung et al. 2008; Mackie and Walsh 2015) while ion exchange technologies are used to remove metals from AMD through the use of ion exchange resins (Mackie and Walsh 2015). Most of these techniques require several stages before the affected water reaches acceptable quality.

Based on the present review, in the 1980s and early 1990s, more research focused on passive biological treatment using microbial action and wetlands (Murayama et al. 1987; Gazea et al. 1996). The 1990s saw an increase in the research on reactive barriers, e.g, limestone drains and biological treatment such as rotating disk biological reactor

(Béchard et al. 1994; Johnson 1995), with a few research focusing on modeling for AMD management (Stollenwerk 1994; Wunderly et al. 1996). In the 2000s, it is observed that there is an increase in research on the valorization of AMD (Macías et al. 2017; Masindi et al. 2019; Ayora et al. 2022). Through valorization, other resources have been produced in economically valuable quantities from AMD treatment process. For example, studies have proved the valorization of AMD and wastes generated from the AMD treatment process (Macías et al. 2017; López et al. 2019; Firth et al. 2020; Muedi et al. 2021). This is very advantageous because AMD treatment generally generates huge amounts of waste products, but if new materials are generated from this process, it will reduce the quantity of waste produced, also reducing the costs of waste disposal. Mostly, valuable metals and compounds such as aluminum-enriched ferric oxide hydroxide (Fe/AlO(OH)), sulfuric acid, Zn, Cu, and water have been recovered from AMD treatment (López et al. 2019; Masindi et al. 2019; Muedi et al. 2021). This also ensures sustainability even in the AMD treatment process because it cleans up the environment while producing new materials. The major challenges to the adoption of the recently researched technique of valorization are the high cost and co-contamination of heavy metals with different recovery requirements. Also, these techniques can be expensive and technology intensive, and their commercial viability may be uncertain.

Mining operations have the tendency to generate AMD at some point (during or after mining), but this can be prevented or managed appropriately to minimize environmental impacts. It is very important to adopt strategies that prevent AMD generation or contain it. Well-known AMD management strategies include sitting (careful study of the characteristics of the mining site), source control (involves treating the acid-producing rock directly to stop or slow down acid production), containment (application of dry and wet barriers to ensure the AMD does not flow out of the source area), and adequate land reclamation (Skousen et al. 2017; Roy et al. 2017).

Mathematical, chemical, and geochemical modeling has been introduced for successful AMD management, aiding expertise for decision-making when planning and monitoring AMD treatment, and has remained fairly constant over the years (Ezzeldin and Bahr 2023). This management approach for AMD mostly involves modeling, predicting and continuous monitoring of the AMD. For example, modeling is required for monitoring the flow of AMD, validation of AMD treatment, determination of the characteristics and treatment requirements in different areas, and the fate of AMD (Stollenwerk 1994; Wunderly et al. 1996; Nordstrom and Alpers 1999; Xu et al. 2006; Luo et al. 2020).

Overall, it is observed that the AMD treatment methods have not drastically changed over the years. Instead, earlier treatment methods are being improved and combined to achieve better results, although with a consciousness about sustainability. A general challenge with the implementation of AMD treatment techniques is that only a few field and mesocosm tests have been conducted in this area, thus limiting real-life applications. A limitation of this study is that only articles published in English were included in the analysis because most journals publish in English. Another limitation of this study is that review articles were excluded from the search criteria, but upon reviewing the retrieved documents, there were a few review articles included in the search results, and thus, in this analysis, they are classified as "Desktop" study type. However, this limitation only affects the number of publications and not the general trend in research. Also, only Scopus was used as the article search database, although there is no single database that contains all articles that have ever been published on a particular topic.

Conclusion

The current study provides an overview of the patterns in research on acid mine drainage treatment and management. Based on data retrieved from the Scopus database, the outcome of this study indicates there has been progressive research on the treatment and management of AMD since the year 1976. It is observed that there has been a growing interest in the field of AMD treatment and management, with most of the studies done in Canada, the USA, China, South Africa, and the UK. A major challenge in the treatment and management of AMD is that most of the available studies have focused on laboratory experiments, which limits the knowledge about the true efficacy of the researched treatment technologies. It is encouraged that field or pilot studies should be promoted. This study also observed an increase in research investigating the valorization of AMD. This approach should be encouraged as it is more sustainable, although it comes with challenges such as being expensive, technology-intensive, and uncertain commercial viability of products. Also, in a world with water and resource scarcity problems, retrieval of portable water and metals from AMD treatment will be a breakthrough in solving water and resource decline problems in some areas. Therefore, more studies should focus on the most effective, less costly methods/techniques for generating portable water and metals from AMD treatment process. The results of this study will guide future researchers to grasp the global research scope of acid mine drainage treatment and management.

Acknowledgements The authors would like to thank the School of Geography, Archaeology, and Environmental Studies (GAES), University of the Witwatersrand Johannesburg, South Africa, for providing the consumables for this research.

Funding B.O. received funding from the University of the Witwatersrand URC Postdoctoral Fund. Grant number: B.O-2023 Postdoctoral Fellowship Funding. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Website: https://www.wits.ac.za/

Declarations

Conflict of interest The authors declare no known conflicts of interest. We declare no known financial or personal interests that could have influenced the work reported in this article.

Ethical Statement This article does not contain any study with human or animal participants, neither does it contain research on plant specimens performed by any of the authors.

Consent to participate All the authors consented to participate in drafting and submitting this manuscript.

Consent to publish All the authors consented to publish this manuscript.

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