Mining, Metallurgy & Exploration (2021) 38:315–327
https://doi.org/10.1007/s42461-020-00298-3

REVIEW

Development and Status of the Treatment Technology for Acid Mine Drainage

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Received: 14 January 2020 / Accepted: 27 August 2020 / Published online: 4 September 2020

Abstract

Acid mine drainage (AMD) is difficult to treat due to its physicochemical characteristics, such as high pH and high heavy metal concentrations, so it causes great harm to the environment and human health. If acid mine drainage is discharged arbitrarily without treatment, it will lead to a series of environmental problems and cause long-term environmental pollution. In this paper, the source and hazards of acid mine drainage are introduced in detail. And the principle, the mechanism, the application, and basic information of the current primary technology of the treatment for acid mine drainage are comprehensively introduced and summarized. The summarized treatment technologies for acid mine drainage mainly include neutralization, sulfidization, constructed wetland method, adsorption method, microbiological method, ion exchange method, membrane technology, and microbial fuel cell technology. Also, the primary technology of treatment for acid mine drainage is systematically compared and evaluated. Moreover, some suggestions on the development direction of water treatment technology in the future are put forward. This paper provides a scientific reference for scientific and technical works to treat acid mine drainage.

Keywords Acid mine drainage · Neutralization · Wastewater · Sulfidization · Environmental problems

1 Introduction

In recent years, the problem of water shortage and environmental pollution has intensified, and the world is facing mounting challenges posed by the intractable problems. With a total water resource of 2.81×10^{12} t, China ranks the 6th in the world, while its per capita water resource occupies the 108th place in the world. In the world, China is one of the 21 countries with the most water shortage; the average per capita water availability in China is lower than one-fourth of that of the world average and is one-fifth of America [1]. Mineral resources in the long-term mining process cause the waste of water resources, water pollution, and the tremendous potential safety hazard of water resources [2]. Acid mine drainage is produced in the process of mining and utilization of mineral resources. And the mass concentration of heavy metal ions ranges from a few milligrams to several hundred milligrams per liter, even thousands of milligrams. Heavy metals pollute the water, soil, and air, also which cause some diseases through the transmission of the food chain. It is no exaggeration to say that deterioration of the quality of the environment threatens the existence of mankind. Therefore, removing heavy metals from the environment is a significant scientific and practical task. Acid mine drainage has become the leading environmental issue of the mining industry today [3].

A large number of scholars, enterprises, and research institutions have introduced various treatment technologies of AMD. In this paper, researchers can screen and compare favorable treatment methods of acid mine drainage, and researchers will get a lot of information on treating acid mine drainage.

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2 Sources and Hazards of Acid Mine Drainage

2.1 The Sources of Acid Mine Drainage

Acid mine drainage is usually produced within and around mining areas. These locations typically include abandoned and active mines, both of which can be open-pit or underground. The secondary sources of acid mine drainage include mine waste dumps, tailing dumps, tailing dams, iron ore stockpiles, haul roads, quarries, pit lakes, and sludge ponds [4]. Furthermore, acid mine drainage is also produced in the process of oilfield production, such as drilling process, acid fracturing process, and well testing process [5].

With the development and utilization of various mineral resources, a large number of sulfur compounds, such as pyrite and pyrrhotite in a stable reducing environment, are exposed to the oxidation environment then they react with water, air, and organisms. Sulfur in minerals is oxidized and dissolved in water in the oxidation environment, so the concentration of SO_4^{2-} and other anions in groundwater increases. The produced sulfide and cation form sulfate which is the main component of groundwater. Sulfate is a strong acid salt, so it makes the water acidic. Taking pyrite as an example, the specific process of producing acidic wastewater is as follows.

a. Pyrite produces sulfuric acid and ferrous sulfate under the action of oxygen

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \quad (1)$$

b. Ferrous ions are oxidized to ferric irons in the presence of free oxygen or bacteria

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

c. Hydrolysis or oxidation of pyrite by ferric ions

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad (3)$$

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

The rate of the chemical reaction (1) is slow, while reaction (4) is fast. Therefore, pyrite oxidized by ferric ions is the main reason for the production of acid, while pyrite oxidized by oxygen is a minor factor, and reactions (2) and (4) form a cycle. The oxidation of pyrite to produce acid can be divided into two stages. The first stage is a reaction mainly involving oxygen in nature; the main products are sulfuric acid and ferrous sulfate, and ferrous sulfate is oxidized to ferric iron when the oxygen is sufficient, but this reaction is extremely slow. The second stage is that bacteria participate in the oxidation process of pyrite as the pH value drops to 4.5 or higher, and the reaction is much faster than the first stage. The bacterium in the second stage is mainly Thiobacillus ferrooxidans, Thiobacillus thiooxidans, Bacillus ferrooxidans, and metallobacteria [6]. And sulfur-oxidizing bacteria such as Thiobacillus ferrooxidans increases the dissolution rate of the reaction products. At present, the reaction mechanism of iron, sulfur-oxidizing bacteria, and sulfide minerals has always been one of the research highlights. Therefore, a key way to prevent acid mine drainage is to prevent the growth of these bacteria, actively kill them, and control environmental conditions so that they cannot reproduce. Some chemicals, such as anionic detergents, can inhibit iron-oxidizing bacteria and sulfur-oxidizing bacteria, but they are far from the requirements of field application.

2.2 Hazards of Acid Mine Drainage

With the mining and production of mineral resources, the acid mine drainage discharged without treatment causes tremendous water pollution. And the acidity and chroma of acid mine drainage severely exceed the industrial effluent discharge standard. Furthermore, the strong acidity of acid mine drainage accelerates the corrosion and damage of pipelines, steel rails, pumps, and other mine equipments near the mining area. If acid mine drainage directly discharges into rivers, lakes, and other waters, it will poison fish, plankton, and algae and kill them in large quantities. And Fe^{2+} in the water is oxidized to Fe^{3+}, then Fe^{3+} reacts with OH^- to produce $Fe(OH)_3$ which is red-brown precipitation. The produced $Fe(OH)_3$ makes the bottom and sides of the water appear red and affects esthetics.

For example, in the early stage of mining, the acid mine drainage is caused by the mining of sulfur ore and the exposure of sulfur residue. A rock dump in Mpumalanga, South Africa, polluted by a large amount of acid mine drainage is shown in Fig. 1 [7]. On April 25, 1998, a large amount of acid mine drainage and toxic mud flowed into the Agrio River in Spain. This tailing leakage caused the worst environmental pollution accident in Spanish history [8].

Acid mine drainage can corrode human skin and endanger human health. Once it enters the surface water, it will pollute the water source, break the soil structure, harden the soil, and inhibit the growth of crops. In serious case, large areas of crops die, which reduces grain production.

3 Treatment Technology for Acid Mine Drainage

Acid mine drainage is one of the most serious environmental problems in the world. At present, the treatment methods of

Fig. 1 A water pollution accident in Mpumalanga, South Africa

acid mine drainage include chemical treatment, physical treatment, and biological treatment. The commonly used treatment technologies for acid mine drainage include neutralization, sulfidization, constructed wetland, adsorption method, ion exchange method, and microbiological method [9]. The latest research status, comparison, and evaluation of the technologies are introduced below.

3.1 Neutralization

Neutralization is the most commonly used technology to treat acid mine drainage, and its application principle is very simple. This method is to add a certain amount of alkaline substances in the wastewater, such as limestone, lime milk, sodium hydroxide, sodium carbonate, and other substances, to increase pH of the wastewater, and the metal ions in the wastewater react with hydroxide and eventually form insoluble hydroxide precipitation. Common neutralizers to treat acid mine drainage mainly include quicklime, limestone, hydrated lime, and caustic soda. The comparison of conventional neutralization methods is listed in Table 1.

Zheng Yajie et al. [13] adopted a second-stage neutralization method of lime and sodium hydroxide to treat acid mine drainage. In this experiment, the removal rates of Fe^{2+}, Mn^{2+}, and Zn^{2+} reached 14.14%, 5.94%, and 13.91% respectively when the pH of the wastewater was neutralized to 5 by adding lime. Then adding sodium hydroxide in the second neutralization process, the removal rates of Fe^{2+}, Mn^{2+}, and Zn^{2+} reached up to 99.7% in the wastewater when pH was 10.20, the aeration flow was 50 mL/min, and the reaction time was 20 min. And the residual mass concentrations of Fe^{2+}, Mn^{2+}, and Zn^{2+} in the wastewater were 80 μg/L, 81 μg/L, and 30 μg/L respectively, which met the national integrated wastewater discharge standard (GB8978-1996) [10]. Wang Hongzhong et al. [11] adopted the neutralization method to treat acid mine drainage. Calcium carbonate was used to neutralize the wastewater to a ph of 4.5 then calcium hydroxide was added to neutralize the wastewater to a ph of 7.5. And the sulfate and total iron content met the discharge standard. Zhang Zhi et al. [12] adopted the neutralization method to treat acid mine drainage which contains lead, zinc, and antimony. The removal rates of the metal ions after treatment were high, and the water quality index met the discharge standard. Feng D et al. [14] used the iron slag and steel slag to remove copper, lead, and other metal ions in acid mine drainage. This method was also applied to treat acid mine drainage from a gold mine in South Africa and achieved a good removal effect. The components and removal effect of iron slag and steel slag are listed in Tables 2 and 3.

Steel slag is a by-product of industrial steelmaking, which is mainly composed of Ca_3SiO_5, Ca_2SiO_4, $Ca_2Fe_2O_5$, $CaFeO_4$, $MgFe_2O_4$, and FeO, and has some certain characteristics of absorption and the ability to neutralize acidity [16]. At present, steel slag has been proved to be able to effectively remove pollutants in acid mine drainage.

Steel slag can combine with small-scale secondary treatment system and other adsorbents to improve the treatment efficiency of the system [17]. The slag filter has some applications in the treatment of multi-component wastewater. For example, the abandoned McCarty mine site in Preston County, WV, established some steel slag leach beds to treat the acid mine drainage [15]. Steel slag leach beds were also widely used to treat acid mine drainage by neutralizing the acidity and precipitating the metals in southeastern Ohio [18]. In other applications, the combination of basic oxygen furnace (BOF) slag, lime, soda ash, and reverse osmosis (RO) system can recover minerals from acid mine drainage [19]. Therefore, in order to treat acid mine drainage efficiently, it is very meaningful to develop new adsorbents and filter materials.

He Xiaolei et al. [20] developed an alternative technology of high-density slurry (HDS) method, which made the solid content of sediment reach 20~30% by back-flow. This technology saved the cost of sludge treatment and effectively extended the service life of the equipment. Yang Xiaosong et al. [21] adopted the HDS method to treat acid mine drainage. This process accelerated the sedimentation and separation of sludge, made calcium sulfate easier to adhere to the slurry, and reduced the scaling of pipelines and equipments. And the quality of the treated wastewater met the secondary effluent standard of the integrated wastewater discharge standard. Zhuang Minglong [22] used sodium sulfide as a precipitant to separate copper and iron ions in acid mine drainage then used limestone to neutralize the acidity of the wastewater. The amount of precipitant has an important influence on the removal rate of heavy metals.

It should be noted that when calcium compounds are used to neutralize sulfuric acid, this results in gypsum ($CaSO_4 \cdot 2H_20$) which is sufficiently soluble in wastewater that it leaves

Table 1 Comparison of conventional neutralization methods

Method	Chemical formula	Efficiency of neutralization reaction	Bulk purchase price in 2020 ($/t)	Comparison of treatment cost	Demerits	Merits	Reference
Hydrated lime	$Ca(OH)_2$	90%	$90	Caustic alkali agent > limestone agent > Hydrated lime agent > quicklime agent	Waste residue produced Pipe scaling Secondary pollution	Low price of raw materials Easy to operate and manage	[9–12]
Quicklime	CaO	90%	$80		Waste residue produced Pipe scaling Secondary pollution Strong reaction with water, difficult to operate	Low price of raw materials	[9–11, 13]
Limestone	$CaCO_3$	60%	$90		Waste residue produced Pipe scaling Secondary pollution	Low price of raw materials	[9–12]
Caustic alkali	$NaOH$	100%	$330		Strong corrosion, difficult to operate High price of raw materials	High neutralization efficiency	[9–12]
Secondary neutralization (neutralized with lime and NaOH)	-	60~90%	-	-	The operation process is complex and needs to be designed according to the water quality	Less waste residue produced High removal rate of metal ions	[9–12, 14, 15]

Table 2 Properties of two slags

Property Chemical composition	Iron slag (%)	Steel slag (%)
CaO	46.3	37.5
MgO	5.9	12.0
SiO_2	35.6	32.5
AL_2O_3	10.3	18.0
S	0.3	1.7
FeO	15.6	17.3
Others	-	-

a lot of sulfate ions in the solution. In order to remove sulfate ions, chemical precipitation is the most common method. Take the treatment of acid mine drainage in the Guixi Smelter of China as an example. Calcium carbonate was added to the wastewater to neutralize the acidity and remove the sulfuric acid. The reaction formula is as follows [23]. Then the solid and liquid of gypsum were separated by a separator. And barium salt and calcium salt were added to form precipitation to separate SO_4^{2-} ion. Although this method was effective, it was not economical enough [24]. In addition, the biological method can also remove excessive SO_4^{2-} ions, but the reaction rate and efficiency are low.

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2 \quad (5)$$

In recent years, based on the advantages of a variety of single sulfate treatment technologies, researchers have also carried out a variety of combination of technologies, such as the combination of chemical precipitation as pretreatment and anaerobic biological treatment technology, which can reduce the discharge of solid waste.

3.2 Sulfidization

The solubility of metal sulfide is usually much lower than that of metal hydroxide, so sulfide can be used to treat acid mine drainage. And sulfur ions can combine with the heavy metal ions to form sulfide precipitation. Generally, common sulfides include CaS, FeS, Na_2S, and H_2S [25].

Table 3 The effect of slag mass concentration on the removal of ions in acid mine drainage

Item	AMD	Iron slag (g/L)		Steel slag (g/L)	
	Ion concentration (mg/L)	2	8	2	8
Cu^{2+}	4.707	4.260	0.653	0.551	0
Pb^{2+}	4.696	1.250	0.433	1.363	0.902
Zn^{2+}	16.95	11.49	4.004	12.92	5.125
Fe^{2+}	760.1	522.4	380.3	594.1	460.5

Xie Guangyan et al. [26] treated acid mine drainage from a lead-zinc mine in the Guangxi province of China by ion flotation, neutralization, precipitation flotation, and sulfide precipitation, respectively. The sulfidization method reached the best treatment effect. And the wastewater treated met the standard of the People's Republic of China (GB 8978-1996). Chen Ming et al. [27] treated the acid mine drainage with sodium hydrosulfide (as sulfide agent), removed heavy metal ions by the neutralization method, and the removal rate of zinc ions reached up to 96.85%.

As for the development of sulfide agent, it was reported that hydrogen sulfide was prepared by sulfide-reducing bacteria after the removal of heavy metal ions. For example, Janyasuthiwong S et al. [28] and Guo L et al. [29] respectively designed the bioreactor, which reduced the operating cost and improved the water quality. The biomass sulfate-reducing bacteria used in the reactor were from Biothane Systems International with a volatile suspended solid (VSS) content of 39.8 g/L on a wet basis. The carrier material for the attachment of biomass was made of low-density polyethylene (PE) particles with a diameter of 3 mm.

A large amount of acid mine drainage containing copper was produced in the Zijin mining industry in China every year. A 10000m^3/day acid mine drainage treatment system was built in 2013, and the sulfidization method was adopted. The process flow diagram is shown in Fig. 2 [30]. Test results of water quality are listed in Table 4. The average recovery rate of iron was 98.96%, and the average recovery rate of copper was 90.41%. According to statistics, the annual net benefit of recoverable copper was nearly \$6 million.

3.3 Constructed Wetland Method

Wetland ecosystem, including natural wetland and constructed wetland, is an effective wastewater treatment technology [31].

Constructed wetland is an ecosystem that uses the interaction of substrate, microorganism, and plant to remove heavy metals in wastewater. Its removal mechanism includes physical precipitation, chemical precipitation, filtration, microbial action, and plant absorption [32].

Zhao Wenrui et al. [33] treated acid mine drainage from the Fankou lead-zinc mine with a *Typha* wetland. The removal rates of Pb, Zn, and Cd in this mine reached 99.0%, 97.3%, and 94.9% respectively. And the wastewater after treatment met the integrated wastewater discharge standard of the People's Republic of China (GB 8978-1996). Yang Chengsheng et al. [26] treated acid mine drainage from a lead-zinc mine in the Guangdong province of China with a *Typha* wetland. The removal rates of Pb, Zn, Cu, and Cd in this mine reached 93.98%, 97.02%, 96.79%, and 96.39% respectively. And the water quality was significantly improved and met the irrigation water quality standard (GB5084-2005). Yang Chengsheng et al. [34] treated acid mine drainage from

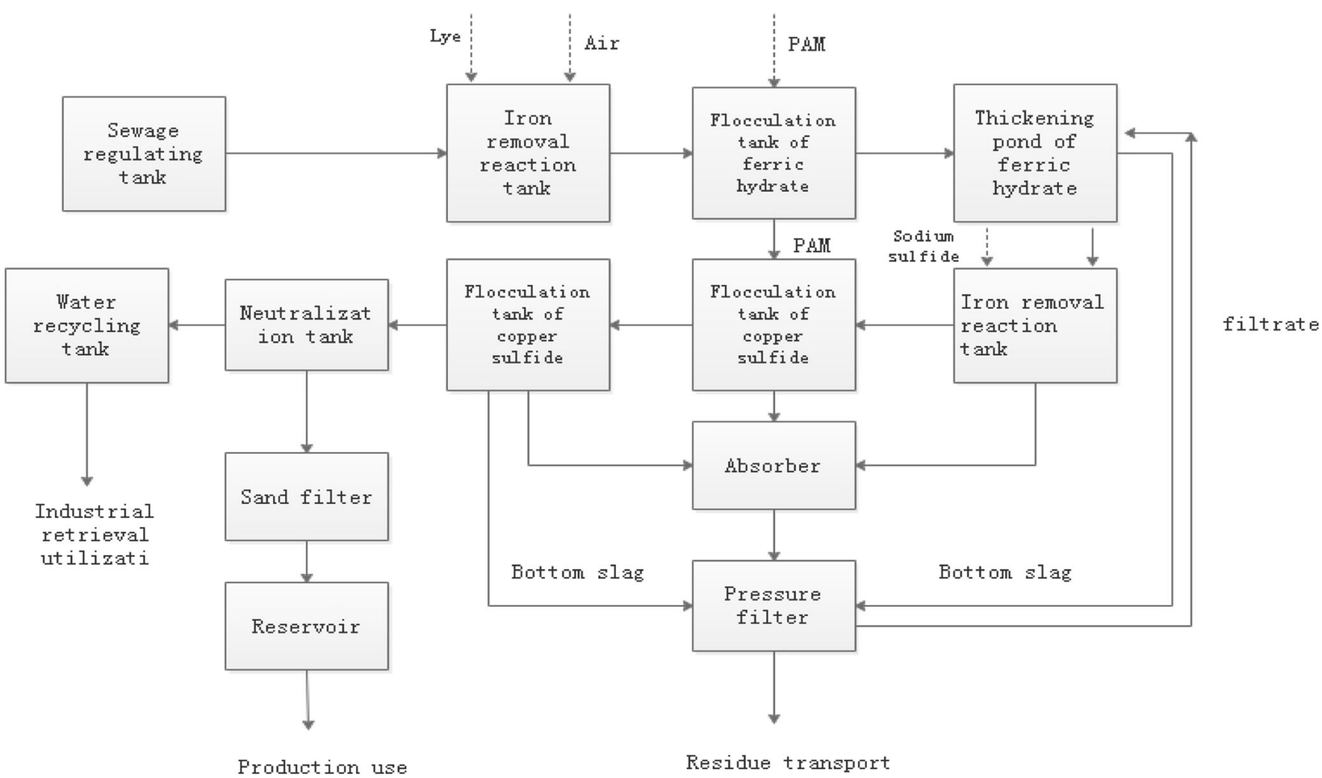

Fig. 2 Process flow diagram

Table 4 Test results of water quality

Item	Stock solution			Effluent from neutralization tank		
Test value	pH	Cu^{2+} (mg/L)	Fe^{3+} (mg/L)	pH	Cu^{2+} (mg/L)	Fe^{3+} (mg/L)
	2.58	324.18	328.58	7.26	0.16	0.18

the other lead-zinc mine in Shaoguan, Guangdong province of China, with a constructed wetland. The removal rates of Pb, Zn, Cu, and Cd reached 92.19%, 93.38%, 97.02%, and 96.39% respectively. Tang Shuyu [35] studied the treatment of acid mine drainage containing iron ions by constructed wetlands in the 1990s. The ion removal rate of iron almost reached 100%, when the pH of the wastewater gradually increased to about 6.

Natural wetlands around the world have been widely reported for their success in removing heavy metals. Table 5 [36] summarizes the situation of natural wetlands, in which the treatment of acid mine drainage by natural wetlands is recorded in detail. According to Table 5, it can be concluded that all kinds of pollutants, including Al, As, Cd, Co, Cu, Fe, Mn, Ni, U, and Zn, can be removed by natural wetlands. And all kinds of plants, climatic conditions, and the other information are described. In addition, metal removing processes are not limited to a specific plant species or climate. The treatment of acid mine drainage with natural wetlands achieves tremendous success.

Munoz R [37] constructed an algae-bacteria-wetland-underwater plant symbiosis system by combining efficient algal ponds and complex constructed wetlands. This system in cooperation with automatic aerated constructed wetlands was used to treat acid mine drainage. The removal rates of Pb, Zn, and Cd in the wastewater after treatment by this collaborative technology reached 95%, 94%, and 99% respectively. Xia Shibin et al. [38] combined the new biofilm reactor with constructed wetlands to treat acid mine drainage. The prefabricated biofilm reactor effectively reduced the pollution load of inlet water, and the subsequent constructed wetland treatment system operated stably.

3.4 Adsorption Method

Adsorption is a method which removes heavy metal ions from the wastewater by the porous adsorption materials. Currently, the commonly used adsorbents include activated carbon, zeolite, chitosan, and bentonite.

Xiao Liping et al. [39] prepared low-cost adsorbents by using bentonite, alkaline auxiliary, and binders to treat acid mine drainage. Bentonite has a special molecular structure and high adsorption capacity. So this adsorbent has a good adsorption effect on heavy metal ions Fe^{2+}, Mn^{2+}, Cu^{2+}, and Zn^{2+}. The molecular structure of bentonite can be seen in Fig. 3 [40].

Dinesh M et al. [41] studied the adsorption effect of lignite on metal ions in acid mine drainage. Lignite had already been used in the treatment of acid mine drainage. Lou Daocheng et al. [42] studied the adsorption effect of modified chitosan on Pb^{2+}, Zn^{2+}, Cd^{2+}, and Ni^{2+}. The removal rates of heavy

Table 5 Natural wetlands shown to treat wastewater

Mine	Location	Dominant plant species	Water quality parameter
Wetlands that only partly improve mine water quality			
Abandoned tin zinc mines	St Hilary Mining District, West Cornwall, UK	*Juncus effusus* *Phragmites australis*	Cu
Carbonate mine	Montana	*Carex rostrata*	Fe, Pb
Coal mines	Eastern USA	*Typha*, *Scirpus* spp.	pH, Al, Fe, Mn
Coal mines	Mpumalanga mining district, South Africa	*Typha* spp.	pH, Al, Fe, Mn
Dunka Mine	MN, USA	*Peat bogs*	Cu, Ni
Mt. Washington Mine	British Columbia, Canada	*Eriophorum angustifolium*	Cu, Al
Natural wetlands at 35 coal mines	PA, USA	Mainly *Typha* spp.	pH, Al, Fe, Mn
Wetlands which improve mine water quality to full environmental compliance			
Mine	Location	Dominant plant Species	Water quality parameter
Cluff Lake, Rabbit Lake	Saskatchewan, Canada	*Carex* species *Sphagnum* moss	U
Hilton Mine	Mt. Isa, Queensland, Australia	Reeds, algae	Fe, Mn, Tl, Zn
Woodcutter's Mine	Darwin, Australia	*Typha* species	Cd, Mn, Pb, Zn
Quirke Mine	Ontario, Canada	*Typha latifolia*	Fe, Ra-226

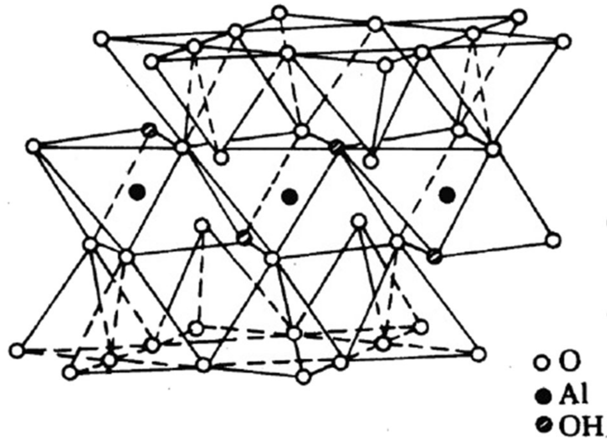

Fig. 3 Molecular structure of bentonite

metal ions after treatment reached 97%. Motsi T et al. [43] adopted natural zeolite to treat acid mine drainage. The adsorption order of natural zeolite on the metal ions was $Fe^{3+} > Zn^{2+} > Cu^{2+} > Mn^{2+}$. Liu Qunfang [44] selected activated carbon of 10~30 mesh to treat acid mine drainage containing radionuclides discharged from a mine. When the pH of the wastewater was between 2.85~7.35, the removal rates of U and Th reached 90%. The summary of common adsorbents is listed in Table 6.

3.5 Microbiological Method

In the natural environment, some microorganisms can absorb the heavy metals into their cells to maintain alive from the external environment and react with sulfate. And some scientific and technical workers have treated acid mine drainage by the microorganisms in various countries. At present, sulfate-reducing bacteria (SRB) treatment of AMD technology has been widely used.

SRB is a general term for the bacteria involved in sulfate reduction metabolic reactions and is widely distributed in seawater, freshwater, and suitable terrestrial environments [46]. Common carbon sources to produce SRB include straw, and corn cob and straw. Sun Jialong et al. [47] used microbial strains as a flocculant to treat acid mine drainage. The removal rate of TI in the wastewater after treatment reached 70.49%. Li Yaxin et al. [48] used some ceramsite and acid fermentation products from the domestic waste to make an anaerobic reactor to treat acid mine drainage. The reduction rate of acid mine drainage after treatment was over 87% at 35 °C.

Xiao Liping et al. [49] treated acid mine drainage with the fermentation product of the sawdust and the chicken manure. The mixture was the carbon source of SRB. The removal rates of Fe^{2+} and Cu^{2+} in acid mine drainage after the reduction of SRB were more than 90%. Su Bingqin et al. [50] treated acid mine drainage with SRB. The acid fermentation products from the sewage treatment plants were the carbon source of SRB. This experiment was carried out in an anaerobic reactor. The removal rates of Fe^{2+}, Mn^{2+}, Ni^{2+}, Zn^{2+}, and Cu^{2+} after treatment all reached 89% under standard conditions.

Some algae also have the ability to treat acid mine drainage, such as *Scenedesmus*, *Cladophora*, *Oscillatoria*, *Anabaena*, and *Phaeodactylum tricornutum*. Algae have the advantages of low cost, no pollution, and sustainability. The summary of the application of several species in AMD bioremediation is listed in Table 7 [51]. The absorption mechanism of a microalgae cell is shown in Fig. 4.

Biomineralization is a process of forming mineral crystals under biological intervention. In biological systems, cells, thalli, and extracellular polymeric substance provide appropriate mineralization sites for mineral growth. So biomineralization can be also used to remove the heavy metal ions in acid mine drainage. Zhou Lixiang et al. [52] attached the acidophilic ferrous oxide to the elastic filler and made it grow on the membrane. When the acid mine drainage flowed through the filler, Fe^{2+} was oxidized to Fe^{3+} and the secondary ore core was formed at the same time. Some heavy metal ions in AMD were removed by in situ adsorption. This research technology provided a new direction for water treatment.

3.6 Ion Exchange Method

The ion exchange method is a process to exchange ions in the exchanger with the ions in the wastewater to remove the harmful ions. At present, the commonly used ion exchanger is ion

Table 6 Summary of adsorption data

Adsorbents	Achieved results	Bulk purchase price in 202 ($/t)	Reusable information	Reference
Bentonite-steel slag composite (mass ratio of 5:5)	Absorption of Cu^{2+} 130.15 mg/g	70	Regenerable Multiple regeneration and reuse	[39]
Modified chitosan	Absorption of Pb^{2+} 127.3 mg/g Absorption of Zn^{2+} 95.56 mg/g Absorption of Cu^{2+} 71.8 mg/g	61	Regenerable	[42]
Zeolite	Absorption of Fe^{3+} 6.41 mg/g Absorption of Zn^{2+} 1.61 mg/g	100	-	[43]
10~30 mesh activated carbon	Removal rates of U and Th 90%	46	-	[44, 45]

Table 7 Summary on the application of several species in AMD bioremediation

Algal species	Remediation role	Growth method	Achieved results
Blue-green algae	Metal adsorption, re-alkalization, nutrient for SRB	Oxidation pond	Removal of Mn 2.59 g/day/m^2
Mixed algal population	Soluble EPS as carbon source for SRB	High-rate algal pond	Up to 57% of sulphates and 52% COD removal
Eunotia exigua and *Pinnularia obscura*	Primary production	Mining Lake	Chlorophylla content 52 ~ 72 mg/m^2
Ulothrix	Metal absorption	AMD, Sar Cheshmeh copper mine	Absorption of Cu 3500 mg/L, As 500 mg
Spirulina sp.	Alkalinity generation and metal precipitation	Bench scale anaerobic digester, primary and secondary treatment	pH rise from 1.8 to 8.18 Reduction of sulphates 89%, Fe 99%, Pb 95%, Zn 93%, Cu 94

exchange resin, including cation exchange resin, amphoteric ion exchange resin, and anion exchange resin.

Zhang XY [53] adopted 732 resin to treat acid mine drainage containing the metal ions Mn^{2+}, Ca^{2+}, and Mg^{2+}. The treatment capacity of Mn^{2+}, Ca^{2+}, and Mg^{2+} was 6.51 mg/g, 0.11 mg/g, and 2.41 mg/g, respectively. Kocaoba S et al. [54] adopted IR120 resin to treat acid mine drainage which contained Cr^{3+}. The removal rate of Cr^{3+} after treatment reached more than 95% when the pH of the wastewater was 5.5; the stirring time was 20 min. Yilmaz et al. [55] adopted IRA743 resin to treat acid mine drainage which contained boron. The removal rate of boron after treatment reached 99.1%. Wang Lei et al. [56] adopted A100, ls-36y, and S984 resins to treat acid mine drainage. The removal rates of Cu^{2+}, Ca^{2+}, and Mg^{2+} reached 85%, 99%, and 99%, respectively. Guimaraes D et al. [57] adopted polystyrene A21 to remove sulfate in acid mine drainage. With the change of operation conditions, the exchange capacity of sulfate was between 8~40 mg/mL. And the recovery rate of sulfate ion reached 100% after the elution by alkali solution. The summary of the application of several resins in AMD treatment is listed in Table 8.

3.7 Membrane Technology

With the progress of membrane technology, acid mine drainage is treated from the source. In recent years, the membrane technology for treating acid mine drainage has received special attention.

Zhong Changming et al. [58] adopted the low-pressure reverse osmosis membrane to treat acid mine drainage. The removal rates of heavy metal ions in this osmosis membrane reached 99% and the concentration of Ni^{2+}, Cu^{2+}, Zn^{2+}, and Pb^{2+} after treatment was less than 0.4 mg/L. The treated acid mine drainage met the discharge standard (GB 8978-1996). Zhu Qiuhua et al. [30] adopted the multistage membrane to treat acid mine drainage containing copper. The removal rate of Cu^{2+} reached 99.8% and the copper can be recovered. Chen Ming et al. [59] adopted the two-stage permeable membrane to treat acid mine drainage of gold and copper mines. The recovery rate of the wastewater was 36.79% and the permeable liquid met the discharge standard. After treatment, the recovery rate of copper was up to 74%.

Membrane technology also can be combined with the adsorption method. Zhang D [60] invented a method to treat acid mine drainage containing cadmium, zinc, molybdenum, and copper. The process flow of this method is shown in Fig. 5.

Source control is to inhibit the production of acid mine drainage by adding chemical reagents and ferric oxide bacteria inhibitors. And source control is an important technology to treat acid mine drainage. At present, membrane technology is mainly used for the source control of acid mine drainage and is a promising technology to treat the wastewater in the future. However, the development of membrane technology is restricted by materials science and other technologies.

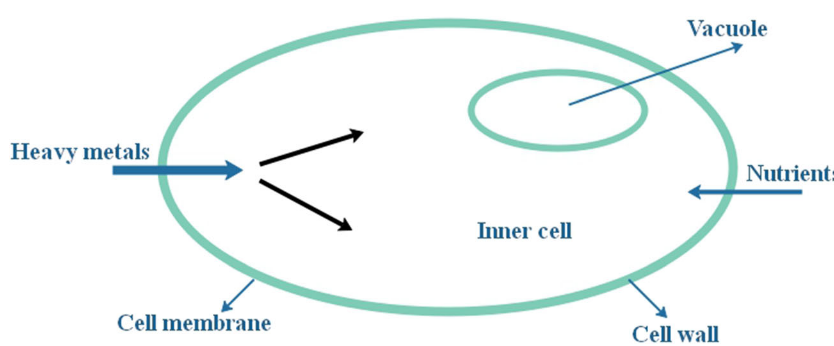

Fig. 4 The absorption mechanism of a microalgae cell

Table 8 Summary on the application of several resins in AMD treatment

Resin	Ionic type	Source	Reusable information	Reference
732 resin	Cationic	Hangzhou Zhenguang Resin Company	Regenerable	[53]
IR120	Strong acidic cation-exchange resin	Rohm and Haas Company	Regeneration after pickling	[54]
IRA743	Weak-base anion exchange resin	Rohm and Haas Company	Regeneration after pickling	[55]
A100	Anionic	-	15% ammonia solution can regenerate it	[56]
A21	Weak-base anion exchange resin	Rohm and Haas Company	Regenerable	[57]

3.8 Microbial Fuel Cell Technology

Microbial fuel cell (MFC) is a device that converts the action of microorganisms into energy and transfers electrons generated by respiration to electrodes [61]. And this technology can be used to treat acid mine drainage (AMD-FC). The mechanism of AMD-FC is to oxidize ferrous ions into iron deposits and effectively separate heavy metal ions from acid mine drainage.

The treatment efficiency of AMD-FC is affected by pH, the iron concentration, and the chemical properties of the solution, and reaches a maximum when pH is 6.3 and the iron concentration is higher than 0.0036 mg/L. At present, the treatment process generates electricity with a maximum power density of 290 MW/m^2 [61].

Compared with the traditional chemical method, microbial fuel cell technology has many advantages, such as comprehensive sources of fuels, less pollution of reaction products, low energy consumption, and producing energy. In addition, it can work under normal temperature and pressure, and it is easy to operate and control.

4 Comparison of Treatment Technology for Acid Mine Drainage

In conclusion, different technologies will lead to different treatment effects of acid mine drainage. The selection of treatment technology depends on the decisive parameters, such as time limit, ground space, cost, environmental conditions, the type of ions in acid mine drainage, and the type of pollutants. The summary and comparison of the above technologies are listed in Table 9.

5 Conclusion and Future Perspectives

In this paper, all the sources, hazards of acid mine drainage, and the treatment technologies for acid mine drainage are reviewed. The effectiveness of each treatment method depends on the economic evaluation and the operation conditions.

Neutralization can quickly neutralize acidic mine drainage and precipitate metal ions effectively. However, this method consumes a lot of chemical agents and produces a large amount of calcium sulfate waste residue, so that the treatment cost increases a lot. Generally, neutralization and oxidation are combined to treat acid mine drainage to improve the treatment effect.

Sulfidization method had been used under the condition of the wide pH range, high removal efficiency, and easy recycling of metals. However, this sulfide sludge could be reoxidized to produce sulfuric acid under the oxidation condition, which decreased the pH value. Hydrogen sulfide gas is easily produced in the process of treatment, which was harmful to the environment and human health. And that would cause the secondary pollution and increase the treatment cost. Moreover, the sulfide agent is expensive, so the sulfidization method should combine with other methods. In a word, the technology of acid mine drainage with sulfide has not been widely used.

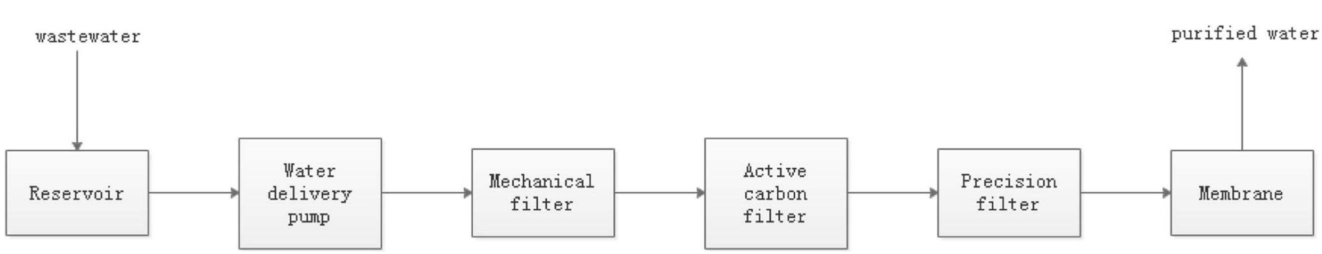

Fig. 5 Process flow diagram

Table 9 Summary and comparison of AMD treatment methods

Method	Principle	Mechanism	Merits	Demerits	References
Neutralization method	The most commonly used method to treat AMD AMD is neutralized by alkali, and the metals are insoluble and easy to be removed after reaction	Neutralizer is added into AMD to raise pH of wastewater and precipitate metal ions	Simple principle Quick and effective method Metal ions precipitate easily Wide range of application	More chemicals are consumed Produce a large amount of calcium sulfate waste residue Easy to cause secondary pollution Lime can not increase the pH value to more than 8, resulting in some metals can not be removed	[9–24]
Sulfidization method	Sulfur ions can combine with heavy metal ions to form sulfide precipitation Neutralize the acidity of AMD	Vulcanized agent transforms metal ions in AMD into metal sulfide precipitation	Applied to a wide-range pH High removal efficiency Metals are easy to recycle	H_2S gas produced Harm the environment and human body Not applicable for large-scale AMD treatment	[25–30]
Constructed wetland method	The treatment effect is affected by the pH value of wetland The method is usually used in combination with pretreatment Natural wetlands need be engineered to biologically produce alkalinity	Treat AMD by adsorption, sedimentation, decomposition, digestion of microorganisms and phytoextraction	Simple technical equipment Cost-effective Long term treatment of AMD	Slow reaction rate Occupy large area Susceptible to pests and diseases High treatment cost in remote areas	[31–38]
Adsorption method	Using the adsorbents which can adsorb metal ions and release oxides and hydroxides	Contaminants in AMD are adsorbed on solid surface, including physical adsorption and chemical adsorption	The types of adsorbents are wide various Materials come from a wide range of sources Strong adsorption capacity	Low treatment efficiency Selectivity to metal ions Sensitive to environmental conditions	[39–45]
Microbiological method	Using animal manure, compost, sawdust, corn cob, straw and so on to produce SRB Using Scenedesmus, Cladophora, Oscillatoria, Anabaena and *Phaeodactylum tricornutum* to remove metal ions in different environment conditions	Biological organism and its metabolites react with metal ions to treat AMD Microalgae can absorb heavy metal ions, and assimilate some small molecular organic matter and other pollutants in AMD	Strong applicability Low investment Environmental friendliness Less pollution	High pH conditions are required High requirements for temperature and other conditions Time-consuming, may cause deterioration of biomass It is difficult to cultivate microalgae on a large scale	[46–52]
Ion exchange method	Selecting ion exchange resin according to the acidity and the ion type in AMD	Ion exchange resins exchange with metal ions to remove contaminants in AMD	Large treatment capacity Heavy metals and water can be recycled	Exchanger is easy to lose efficacy High one-time investment	[53–57]
Membrane technology	Using membrane to treat AMD from the source, and combined with traditional treatment technology according to pollutants	The membrane can adsorb metal ions and degrade organic matter, nitrogen, phosphorus and other pollutants	Simple application method Easy to operate Safe and stable technology Environmental friendliness	Difficult to recover the filtered materials Impossible to separate certain substances Difficulty in large scale application	[30, 58–60]
Microbial fuel cell technology	It is mainly used to treat AMD with high ferrous ion content	Oxidize ferrous ions into iron deposits, and effectively separate heavy metal ions from AMD	A wide range of sources Low energy consumption Production of electric energy Easy to operate and control	Weak treatment capacity Selectivity to ions Slow AMD treatment	[61, 62]

The treatment effect of constructed wetland is affected by the pH value and the environment condition of wetlands. Constructed wetlands have the advantages of simple technical equipment, low investment cost, low operation cost, and no extra energy input. Slow treatment effect and covering a large area are some of the defects. And the limited treatment capacity of acid mine drainage also limits the widespread application of constructed wetland. Although constructed wetlands cover a large area, they usually locate near the mining area with enough lands around them. So this method is an optimal solution to treat acid mine drainage in coal gangue dump. And this method is usually used in combination with pretreatment.

Adsorption method has the advantages of species diversity, multiple sources, low cost, and strong adsorption capacity. The disadvantages of the adsorption method are low treatment efficiency, adsorption selectivity to metal ions, and sensitivity to environmental condition. The influencing factors of this method include temperature, the dosages of absorbent, contact time, the initial concentration of heavy metals, and pH. The key of the adsorption method is the synthesis of the adsorbents. Currently, the adsorption method has been widely used in industrial pollution treatment.

The effect of the microbiological method in AMD treatment is affected by many factors, such as environmental conditions, and the type and generation time of carbon sources. Microbial technology has the advantages of strong environmental adaptability, less investment, environmental friendliness, and less environmental pollution. However, further research and exploration are needed to make it more widely used due to its high requirements for pH, temperature, and other conditions.

The resin used in the ion exchange method has the problems of low initial saturation, poisoning, aging failure, frequent regeneration, and high investment cost. And the ion exchange method is easily disturbed by the pollutants and organic matter and is difficult to treat high concentration wastewater. In addition, the ion exchange method is nonselective to the ions and is sensitive to the pH value. Generally, the ion exchange method can treat acid mine drainage in large quantities. And the ion exchange method can effectively remove the harmful substances and recover the heavy metals. In the future, the research work should focus on effectively reducing the treatment cost of the ion exchange method and increasing the metal recovery rate.

The discharge of acid mine drainage is large and the composition is very complex. So it is of great significance to select an appropriate treatment scheme for acid mine drainage according to the actual situation. It is often not ideal to use a single method to treat acid mine drainage, so the combination of multiple treatment methods is one of the major research directions. Also, economic and efficient treatment technologies for acid mine drainage should be further developed and researched. The application of these technologies reduces the harm to the ecological environment and has become an inevitable trend of the mining industry.

Funding This study was supported by the CNPC Science and Technology Innovation Fund (2017-d-5007-0201), the Liaoning Science and Technology Department Project (20170520344), the Department of Education of Liaoning Province (l2017lfw012), and the Department of Education of Liaoning Province (L2020026).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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