Science and Technology Indonesia
e-ISSN:2580-4391 *p*-ISSN:2580-4405
Vol. 8, No. 3, July 2023

Review Paper

Emerging Strategies for Mitigating Acid Mine Drainage Formation and Environmental Impacts: A Comprehensive Review of Recent Advances

Yudha Gusti Wibowo[1,6]*, Muhammad Fauzul Imron[2]*, Setyo Budi Kurniawan[3], Bimastyaji Surya Ramadan[4], Tarmizi Taher[5,6], Alvian Hayu Sudibya[7], Hutwan Syarifuddin[8], Khairurrijal Khairurrijal[6,9,10]

[1]*Department of Mining Engineering, Faculty of Technology and Industry, Institut Teknologi Sumatera, Lampung, 35365, Indonesia*
[2]*Study Program of Environmental Engineering, Department of Biology, Faculty of Science and Technology, Universitas Airlangga, Kampus C UNAIR, Jalan Mulyorejo, Surabaya, 60115, Indonesia*
[3]*Laboratory of Algal Biotechnology, Centre Algatech, Institute of Microbiology of the Czech Academy of Sciences, Opatovický mlýn, Novohradská 237, 379 81 Třeboň, Czech Republic*
[4]*Department of Environmental Engineering, Universitas Diponegoro, Semarang, 50275, Indonesia*
[5]*Department of Environmental Engineering, Institut Teknologi Sumatera, Lampung, 35365, Indonesia*
[6]*Reseach and Innovation Centre of Advanced Materials, Institut Teknologi Sumatera, Lampung, 35365, Indonesia*
[7]*Department of Oil and Gas Engineering, Institut Teknologi Sumatera, Lampung, 35365, Indonesia*
[8]*Postgraduate Program of Environmental Science, Universitas Jambi, Jambi, 36361, Indonesia*
[9]*Department of Physics, Institut Teknologi Sumatera, Lampung, 35365, Indonesia*
[10]*Department of Physics, Institut Teknologi Bandung, Bandung, 4013, Indonesia*
***Corresponding authors**: yudha.wibowo@ta.itera.ac.id; fauzul.01@gmail.com

Abstract
Acid mine drainage (AMD) is a significant threat to the environment due to its high acidity and metal ion content. To effectively eliminate pollutants from AMD, various approaches are necessary. This review aims to provide a comprehensive understanding of recent advances in AMD mitigation. While treatment technologies have developed to eliminate AMD, they often produce sludge as a by-product and require expensive maintenance. As a cost-effective alternative, the recovery of AMD resources can reduce toxicity and promote reuse of heavy metals and rare earth elements. This review also analyzes the challenges and prospects of AMD mitigation implementation, including current mitigation conditions and knowledge gaps. Researchers can benefit from this review by gaining insight into research progress in this area, identifying strengths and weaknesses of current AMD mitigation applications, and exploring future research directions.

Keywords
Acid Mine Drainage, Wastewater Treatments, Adsorption, Bioremediation, Constructed Wetlands, Electrochemical, Membrane Technology

Received: , Accepted:
https://doi.org/10.26554/sti.2023.8.3.344-352

1. INTRODUCTION

Acid mine drainage (AMD) has become an environmental problem in several countries with mining areas (Lee et al., 2022a). AMD is formed when oxygenating water contact with sulfur-containing material to form an acid solution (Shen et al., 2022; Zhang et al., 2022). The solution will have a very low pH (< 3) and can dissolve heavy metals when in contact with materials containing heavy metals (Chen et al., 2021a; Xin et al., 2021). In general, AMD is formed from ex-mining lands, like coal and metal mining, which is a long-term threat because of its formation for decades from the mining land if no prevention of AMD formation is carried out (Borden et al., 2022). Some research reported that AMD contains dissolved metals such as iron, aluminium, zinc, copper, and other metals (Brar et al., 2022; Shi et al., 2022; Zhang et al., 2022). Therefore, AMD entering the environment can cause pollution to water bodies and soil, and also it can have adverse effects on living organisms (Abfertiawan et al., 2020).

AMD's pollution of surface water, groundwater, and soil is mostly caused by non-active mining areas that are not adequately reclaimed (Li et al., 2014). This effect is that materials containing sulfur and heavy metals will always generate AMD. Therefore, some researchers have encouraged to look for cost-effective and environmentally friendly methods to prevent the formation of AMD (Bai et al., 2021; Demers et al., 2017). Based on previous studies, oxygen barrier (dry and water cover) (Matsumoto et al., 2016; Moncur et al., 2015) and surface passivation techniques can be applied to prevent AMD formation (Zeng et al., 2013). In general, the dry cover method is often used to prevent the formation of AMD (Lu et al., 2013). The principle of this technique is an oxygen barrier where rocks having the potential to produce acidity will be covered with non-acidity materials (Abfertiawan et al., 2020). Some materials that can be used as cover are organic soil (Demers et al., 2017), fly ash (Win et al., 2020), green liquor dregs (Mäkitalo et al., 2014), and others. Besides that, the surface passivation technique can reduce the pyrite oxidation rate to 50–95% (Qian et al., 2017; Zeng et al., 2013). However, if the mitigation process is not good, the AMD formation will still occur. In practice, the process of preventing AMD formation is very challenging (Chen et al., 2021a).

Generated AMD must be treated before it is discharged into the environment. In general, the choice of AMD processing technology will differ depending on the source, composition, pH, environment, and cost (Park et al., 2019). Many researchers have proposed several technologies categorized into active and passive treatment techniques (Bai et al., 2021; Vasquez et al., 2022). Examples of passive techniques are bioremediation, constructed wetlands, phytoremediation (Wibowo et al., 2023a; Wibowo et al., 2022b) and bioreactors (Ka-ot and Joshi, 2022; Thomas et al., 2022; Wang et al., 2021a), while the active techniques include neutralization, precipitation, adsorption, electrochemical treatment, and membrane technology (Angai et al., 2022; Bao et al., 2022; Lee et al., 2022b). Both techniques have advantages and disadvantages (Ighalo et al., 2022). For the advantage, the active technique has high efficiency while the passive technique does not require much cost (Park et al., 2019). While for the disadvantage, AMD treatment is very costly for active techniques and requires an extended period for passive techniques, respectively (Kefeni et al., 2017). Although the treatment has high efficiency in the active technique, it generates a by-product in the form of sludge concentrated in heavy metals (Hu et al., 2022). Therefore, it is necessary to carry out other treatments on the by-products.

Based on the limitation of the treatment technique, recovering resources from AMD could be another option that can be used to reduce AMD toxicity (Hermassi et al., 2022). Some researchers reported that AMD contains various heavy metals that can be recovered by several methods (Barthen et al., 2022; Chen et al., 2022; Li and Zhang, 2022). Therefore, micro-flotation, precipitation, ion exchange, adsorption, and membrane distillation can be applied to recover AMD (Bai et al., 2021; Brar et al., 2022; José and Ladeira, 2021; Qiu et al., 2021). Hermassi et al. (2022) reported that common metals of Fe, Al, Mn, Ca, Mg, Cd, and Pb can be recovered from AMD by phosphate precipitation and ion exchange. Besides, Menzel et al. (2021) also reported that a total of 100% copper recovery from AMD could be achieved by integrating sulfide precipitation and microfiltration. Based on that, compared to the treatment technique, the AMD recovery technique can be a promising option for increasing the value of AMD resources (López et al., 2018).

The purpose of this review is to provide more understanding of recent advances in the prevention of AMD formation and AMD mitigation with their limitation. Although many review papers have discussed it, this review will help researchers see the knowledge gap as a direction for future research, understand research progress in this area and analyze the strengths and weaknesses of current AMD mitigation applications. Therefore, this review paper summarizes AMD related to the source, microbial community, biogeochemical process, and impact of AMD on the environment. In addition, several AMD formation prevention technologies are also described. Recent treatment technology for mitigation is also presented in this review paper. In addition, recovery of AMD resources is also discussed, along with the methods used based on previous research. Therefore, challenges and prospects in AMD mitigation implementation are also discussed to evaluate the current mitigation conditions.

2. METHOD

This review employed a systematic literature review approach, combined with content analysis, to establish a comprehensive and holistic understanding of the treatment methods for age-related macular degeneration (AMD). Additionally, a mapping of recently published papers focusing on AMD treatment was conducted using the Scopus database. The keyword "acid mine drainage treatment" was utilized, resulting in the identification and analysis of 3,141 relevant documents. To visualize and map potential topics for the review, VOSViewer software version 1.6.19 was employed as a powerful tool.

3. RESULTS AND DISCUSSION

3.1 Research Overview

A systematic literature review approach, combined with content analysis, offers a robust methodology for conducting in-depth research and generating comprehensive insights. By combining these two methods, researchers can gather, analyze, and synthesize a wide range of relevant information from multiple sources, providing a comprehensive understanding of a particular topic. A systematic literature review involves a meticulous and structured search strategy to identify and retrieve relevant studies from various databases, ensuring a comprehensive coverage of the existing literature. This approach minimizes biases and ensures transparency by following predefined criteria and guidelines for study selection. By systematically examining a broad range of literature, researchers can identify patterns, trends, and knowledge gaps, enhancing the credibility and reliability of the findings.

Content analysis, on the other hand, involves a detailed examination and interpretation of the collected data. It allows researchers to identify and extract key themes, concepts, and information from the selected studies. By employing coding schemes and categorization techniques, content analysis enables researchers to analyze the textual or visual content of the literature, providing a deeper understanding of the subject matter. Combining systematic literature review with content analysis enhances the rigor and comprehensiveness of the research process. It enables researchers to identify commonalities, differences, and emerging themes across multiple studies, facilitating the synthesis of diverse perspectives and evidence. This approach helps to identify research gaps, theoretical frameworks, and areas for further investigation.

Moreover, the integration of content analysis within a systematic literature review enables researchers to go beyond a simple summary of the literature. It allows for a more nuanced analysis of the content, such as identifying conceptual frameworks, theoretical perspectives, methodological approaches, and practical implications. By extracting and analyzing relevant information, researchers can provide deeper insights into the research topic, identify trends, and propose future directions for research and practice. However, it is important to acknowledge the limitations of this approach. The quality and availability of the literature can impact the findings, and the interpretation of data during content analysis can be subjective to some extent. Therefore, it is crucial for researchers to clearly articulate their methodology, criteria for study selection, and data analysis techniques to enhance the transparency and replicability of their work.

Figure 1 provides a visualization of the total number of documents retrieved from the Scopus database related to the keyword "acid mine drainage treatment." The data reveals an upward trend in the number of published papers since 2013, indicating a growing concern for the environmental degradation caused by acid mine drainage. Notably, the peak number of published papers was observed in 2016, surpassing 200 papers. It is worth highlighting that even in May 2023, there have over 100 papers published, surpassing the total number of documents published until December 2022. This observation aligns with previous studies that have reported an increasing awareness of the environmental issues associated with acid mine drainage. The continuous publication of research papers in this field suggests an ongoing interest in addressing and mitigating the problems caused by AMD.

Figure 2 shows the most contribution of authors according to 3,141 documents by Scopus database. It explains that the authors that published most papers in AMD treatment come from China. This is related with the condition that China is the country that has abundant resources of mining (coal, and minerals). China is renowned for its abundant reserves of various minerals and natural resources. The country's geological wealth encompasses a wide range of valuable resources, including coal, iron ore, rare earth elements, copper, gold, and more. These abundant mine resources in China have played a significant role in driving the country's economic growth, industrial development, and global trade. One of the key resources found in abundance in China is coal. China has the world's largest coal reserves, and it has a dominant player in the global coal industry for many years. Coal has a vital energy source for China, fueling its rapid industrialization and providing electricity for its growing population. However, China's reliance on coal has also led to significant environmental challenges, such as air pollution, greenhouse gas emissions and AMD. The acidic mine water produced as a result of coal mining activities in China often contains high concentrations of various pollutants, including heavy metals such as iron, manganese, and aluminum. These pollutants pose significant risks to both human health and the environment. Acidic water with elevated metal concentrations can contaminate rivers, lakes, and groundwater, leading to the destruction of aquatic ecosystems and impacting the availability of clean water for various uses.

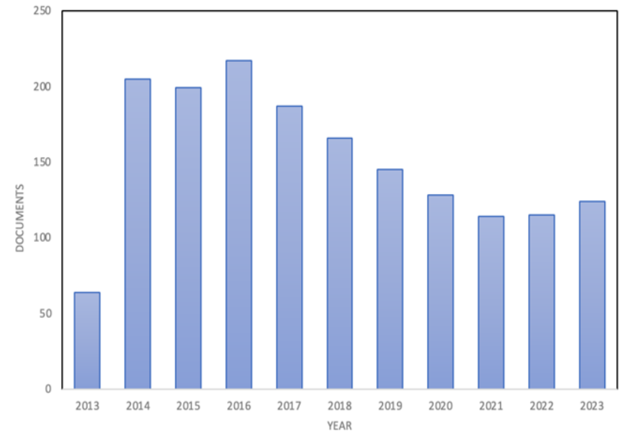

Figure 1. Documents from Scopus Database

Figure 3 presents the prominent keywords used in the context of AMD treatment. The primary keyword utilized is "acid mine drainage," which represents the central concept. Another notable keyword is "adsorption," which signifies one of the potential treatment methods for addressing AMD-related issues. Adsorption has emerged as a promising approach in tackling the challenges posed by AMD. Furthermore, the figure displays several other keywords such as phytoremediation, biomass, algae, nanoparticle, bioremediation, constructed wetlands, and membrane. These keywords indicate the diverse range of treatment options being explored for AMD. However, it is noteworthy that "adsorption" stands out as the most popular keyword, possibly due to its limited application at an industrial scale. Consequently, researchers are driven to investigate the optimal materials, contact time, and dosage of adsorbents to effectively address the complexities associated with AMD. By identifying and analyzing these keywords, researchers gain insights into the prevailing trends and areas of focus within the field of AMD treatment. This information aids in directing future research endeavors and optimizing the development of effective and efficient treatment methods for AMD.

3.2 Acid Mine Drainage

3.2.1 Overview of AMD

AMD is wastewater in coal mining activities. Characteristics of AMD in mining areas are low pH (<6) and high heavy metals (Zhao et al., 2012). AMD is classified into five types

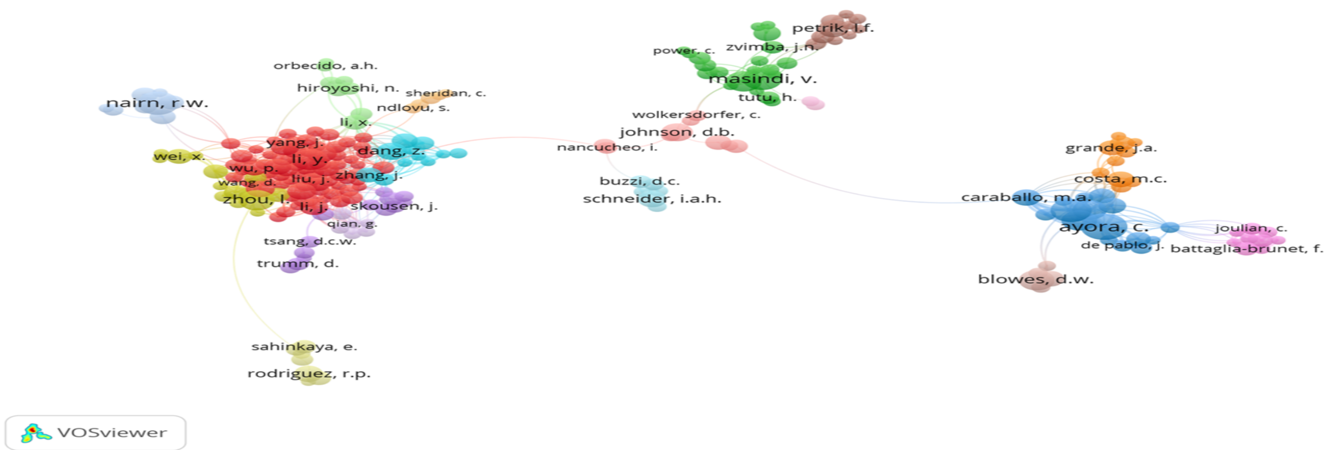

Figure 2. Most Contribution of Published Paper by Authors Name

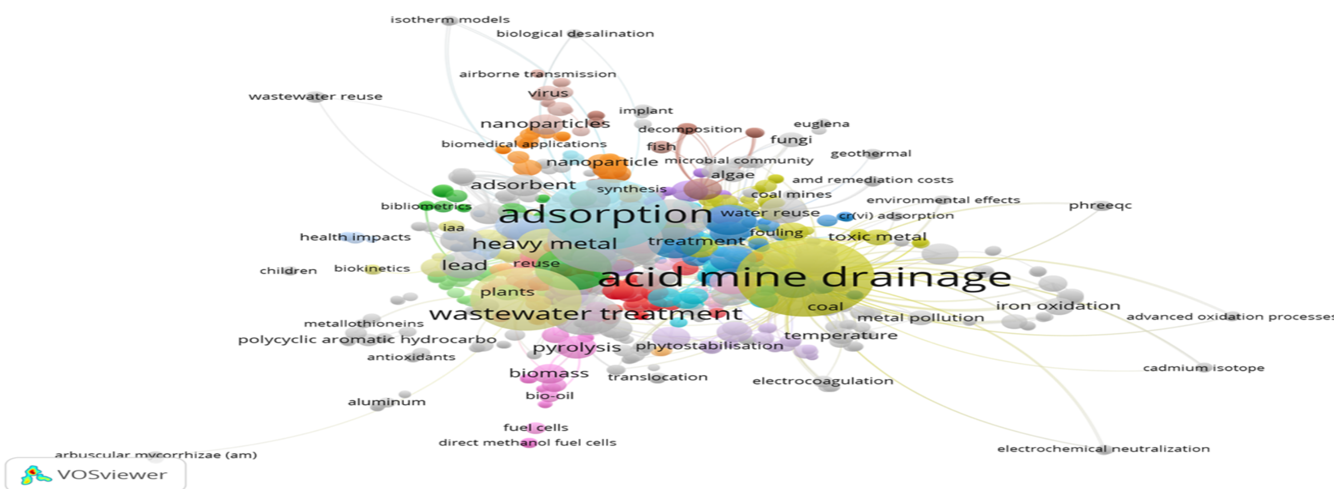

Figure 3. Keywords of Related Published Papers

according to chemical reactions and compounds (Acharya and Kharel, 2020). The first type of AMD is AMD with a pH of less than 4.5 and high metal ions such as Mn, Al, and Fe. The first AMD type also contains high levels of acidity and oxygen. A recent study reported that the first type of AMD was found in Jambi Province, Indonesia. This study shows that AMD in Jambi Province contains high Al, Mn, Fe and Ca contaminations (Wibowo et al., 2020). The second type of AMD is wastewater from mining areas that have a high concentration of Fe and Mn, this type also has a low oxygen level (even in several cases, it does not have oxygen), and the AMD is alkaline (pH>6). AMD type two is a type of AMD often found in small-scale coal mines. Under oxidizing conditions, AMD type two will turn into type one AMD. The decrease in pH of AMD causes this condition. The decrease in pH in AMD will cause the mobilization of metals in the water to be very fast, and this condition is one of the factors that cause the high content of heavy metals in AMD. The third type of AMD is indicated by the presence of Fe and Mn at low to moderate concentrations with low to no oxygen content and relatively good acidity (pH >6). The third type of AMD is characterized by the alkalinity being more significant than the acidity value. Type three AMD is also known as alkaline mine drainage. Under oxidizing conditions, AMD type III will form acid from the hydrolysis of the salt, and the precipitation reaction will be neutralized by alkaline compounds found in nature. AMD type four is a change from AMD type one, neutralized but still has high suspended particles. Changes in AMD type four usually occur after adding calcium carbonate or other materials that can produce $Ca(OH)_2$. Even though there has an increase in pH, AMD still contains heavy and light metals harmful to humans. A recent study informed that the deposition of heavy metals through precipitation could only occur in Fe and Mn metals, while other metal ions cannot be precipitated at neutral pH (source). The last type is AMD type one which has successfully neutralized and contains high Ca and Mg, one of the efforts to prevent the formation of AMD type five is to place AMD in a location with low alkalinity.

All types of AMD are formed due to the contact between air, sulfide minerals (FeS/pyrite) and air. Pyrite rocks commonly found in mining areas and closely related to the formation of AMD include pyrite (FeS), marcasite (FeS_2), pyrrhotite (FexSx), galena (PbS), chalcocite (Cu_2S), chalcopyrite ($CuFeS_2$), arsenopyrite (FeAsS), molybdenite (MoS_2), covellite (CuS) and sphalerite (ZnS) (Mkandawire, 2020). Land clearing in open mining areas will oxid iron sulfide to ferrous iron and sulfur and contain a low pH, and the Eq reaction can describe this condition.

$$FeS_2 + \frac{7}{2}O_2 + H_2O \leftrightarrows Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

Ferrous iron (Equation 1) is then oxidized to be ferric iron (Fe^{3+}). The reaction to changing ferrous iron to ferric can be seen in Equation 2.

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \leftrightarrows Fe^{3+} + \frac{1}{2}O_2 \quad (2)$$

If hydrolysis occurs in AMD at Equation 2 will form the reaction in Equation 3.

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

Reaction to Equation 3 can turn into a reaction in Equation 4 if acidity is formed, breaking down FeS_2 to produce more Fe^{2+}, sulfate, and acidity (H^+). If there is a slowdown in each reaction, there is a possibility that the formation of AMD will slow down. Then if there is a reaction that stops at one of the Equation, the formation of AMD will also stop.

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

Lack of water or oxygen in each reaction of the formation of AMD will inhibit the oxidation of sulfide minerals. This condition can cause the formation of AMD to slow down or stop. Sulfide minerals such as pyrite are generally found in the subsurface under the water layer. This location usually does not contain oxygen, so AMD does not form. Land clearing carried out for mining purposes causes pyrite below the surface of the water to oxidize because it meets oxygen to form AMD. In stable (undisturbed) conditions, the sulfide minerals below the surface are confined to massive rocks. Although there is potential for oxidation in controlled conditions, natural conditions can neutralize the AMD. This condition is due to the minimal amount of oxygen below the surface. Thus, the surrounding rock can dilute and neutralize the volume of AMD formed. The primary mechanism of pyrite oxidation in the environment can be seen in the image below.

In addition, sulfur is a mineral that can cause the formation of AMD. Sulfur is also found in coal, contaminating water and air. Sulfur found in coal or other rocks associated with coal is in the form of organic sulfur, pyrite, or sulfate. Sulfur in mining environments is usually found in the form of sulfate in small amounts in coal or other rocks containing pyrite. Sulfur in the form of sulfate is produced from the oxidation process of sulfide minerals such as jarosite ($KFe_3(SO_4)_2(OH)_6$) which is readily soluble to produce acidic solutions in the environment. Sulfur or sulfide is a sulfur mineral that is commonly found in coal. The iron disulfide is one of coal's most common sulfide minerals (FeS_2). Pyrite, one of the factors causing AMD, is divided into six types: primary massive, primary euhedral pyrite, plant replacement pyrite, mossy pitted pyrite, secondary cleat coast, and framboidal pyrite. Pyrite and sulfur, which are factors forming AMD, are reported to have a directly proportional amount below the soil surface.

Another factor that is also reported to affect the formation of acid mine drainage is the activity of bacteria. The bacteria most reported to be associated with iron oxide (Fe^{2+}) and metal sulfide were *T. ferrooxidans* and *T. thiooxidans*. A study reported that *T. ferrooxidans* and *T. thiooxidans* could oxidize elemental sulfur and sulfide to sulfuric acid. ($S° + 1.5\ O_2 + H_2O \rightarrow H_2SO_4$ and $S^{2-} + 2O_2 + 2H^+ \rightarrow H_2SO_4$). The mechanism of pyrite oxidation involving bacteria is divided into two types: direct metabolic reaction where bacteria will make direct contact with pyrite rock and indirect metabolic reaction mechanism where bacteria and pyrite rock do not require direct physical contact. In indirect metabolism, bacteria will oxidize Fe^{2+} to Fe^{3+}.

3.2.2 Microbial Community in AMD

The microbial community in AMD plays a crucial role in the biogeochemical processes occurring in these environments. AMD is characterized by its high acidity and elevated concentrations of heavy metals, which create extreme conditions that are challenging for most organisms to survive. However, certain acidophilic microorganisms have adapted to thrive in these harsh environments and contribute to the overall microbial community dynamics. One of the primary groups of microorganisms found in AMD is acidophilic bacteria. These bacteria have evolved mechanisms to tolerate and utilize the high levels of acidity present in these environments. They possess various acid resistance mechanisms, such as proton pumps and pH regulation systems, which allow them to maintain intracellular pH and survive under extreme acidic conditions. Acidophilic bacteria are involved in several important processes, including the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which is a key step in the generation of AMD. Through this process,

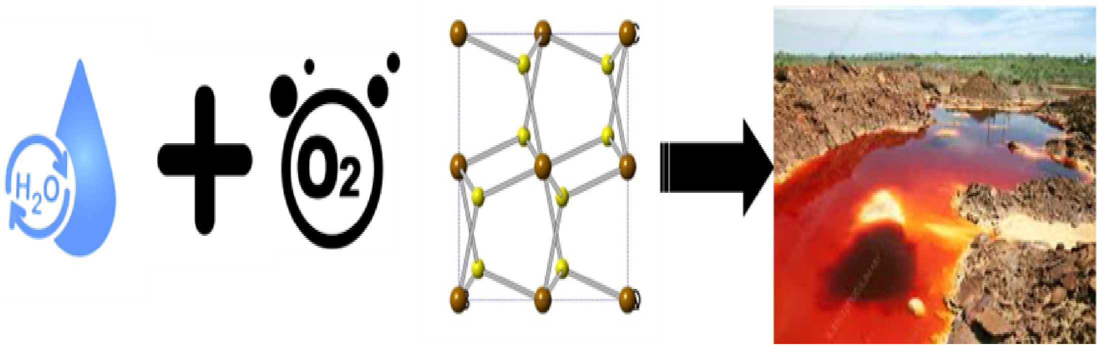

Figure 4. Mechanism of Pyrite Oxidation

they contribute to the release of metals from sulfide minerals and the subsequent contamination of water bodies.

Additionally, acidophilic bacteria play a vital role in sulfur cycling within AMD ecosystems. They are capable of oxidizing reduced sulfur compounds, such as sulfides and elemental sulfur, to generate sulfate ions. This oxidation process not only contributes to the overall acidity of the drainage but also provides a source of energy for these bacteria. Furthermore, some acidophilic bacteria are involved in the reduction of sulfate, which can lead to the production of hydrogen sulfide (H_2S) and contribute to the formation of acid mine drainage. Archaea also contribute to the microbial community in AMD, although they are less well-studied compared to bacteria. Acidophilic archaea belonging to the phylum Euryarchaeota, such as Ferroplasma and Acidiplasma, have identified in AMD environments. These archaea are capable of oxidizing iron and sulfur compounds, similar to acidophilic bacteria. Their presence in AMD indicates their ability to withstand extreme acidity and contribute to the biogeochemical processes occurring in these environments.

In addition to bacteria and archaea, fungi have also detected in AMD ecosystems. While their role in AMD is not as well-understood as that of bacteria and archaea, they are known to contribute to organic matter decomposition and nutrient cycling. Fungal species such as Aspergillus and Penicillium have identified in AMD environments, and their ability to tolerate acidic conditions suggests their potential involvement in the breakdown of organic matter and the overall functioning of the microbial community. The microbial community in AMD is not only important for the biogeochemical processes occurring within these environments but also holds potential for biotechnological applications. Certain acidophilic microorganisms have studied for their ability to recover valuable metals from AMD through a process known as bioleaching. These microorganisms can selectively leach metals from solid ores, offering an environmentally friendly alternative to traditional mining methods.

Some of the microbes involved in the formation of AMD are *Acidithiobacillus ferrooxidans* bacteria. These bacteria are microorganisms that are responsible for the formation of Fe^{2+} in AMD. The presence of *Acidithiobacillus ferrooxidans* bacteria will accelerate the rate of Fe^{2+} oxidation up to six times faster. A study reported more fully that the bacteria active in the formation of AMD were Q-proteobacteria, specifically *Acidithiobacillus spp*. (formerly *T. ferrooxidans*, *Thiobacillus caldus*) and Thiobacillus spp. In addition, the Norwegian mine has found the presence of the bacterium *Thiomonas sp.* (strains Ynys1 and Ynys3 and an isolate designated NO-16 (Johnson et al., 2001). In addition to Norway, six species of heterotrophic K-proteobacteria of the genus *Acidiphilum* were in pure culture. *Acidiphilum cryptum* (strain JF-5) has isolated from a lake near a mining area in Germany. Baker and Banfield (2003) has reported in their research that there are many bacteria involved in the formation of AMD, besides that, these bacteria are also the cause of the low pH value in AMD in various mining areas in the world. One AMD that has a pH lower than 1.0 has found in several mines in mountainous areas. Several group names are proposed to classify the bacteria involved in forming AMD, including thermoplasma, Eplasma, Dplasma, CPlasma, Bplasma, Aplasma and Ferroplasma.

Archaea and Eucarya are the two most commonly reported bacterial lineages found in the formation of AMD. *Thermoplasmatales* and *Sulfolobales* are the two types of bacterial species in the archaea group most commonly found in AMD. *Sulfolobales* and *Metallosphaera prunae* were also found in AMD environments, while the bacteria *Sulfolobales* genera, *Acidianus* and *Sulfolobus* were only found in acidic geothermal environments (Baker and Banfield, 2003). Many studies have reported the presence of bacteria in the Eucarya group found in AMD. Ciliates belong to *Cinetochilium* genus, and an amoeba related to *Vahlkampça sp*. Within the lineage *Heterolobosea*, and three gallates (*Eutreptial spp.*), *Vahlkampca sp.* has also isolated and found in iron mines in mountainous areas. Bacteria belonging to the aforementioned Eukaryotic category were also found in the Rio Tinto River, Spain, at pH 2 (Amaral Zettler et al., 2002).

3.2.3 Impact of AMD on the Environment

The impact of acid mine drainage (AMD) on the environment is significant and widespread, affecting various ecosystems and natural resources. AMD is formed when water interacts with sulfide minerals exposed during mining activities, resulting in the release of acidic water containing high concentrations of heavy metals and other contaminants. This acidic and metal-laden drainage poses numerous environmental challenges that can have long-lasting effects. One of the primary concerns related to AMD is the contamination of water bodies. As AMD discharges into streams, rivers, and groundwater sources, it alters the water chemistry, making it highly acidic and toxic to aquatic life. The acidic conditions reduce the pH of the water, negatively impacting the survival and reproduction of aquatic organisms. The elevated levels of heavy metals, such as iron, aluminum, and manganese, released from sulfide minerals can accumulate in water bodies, posing a risk to fish, invertebrates, and other aquatic organisms. These metal contaminants can impair the health and reproductive capabilities of aquatic species, disrupt food chains, and lead to the loss of biodiversity in affected ecosystems.

The effects of AMD are not limited to water bodies. When acidic mine water comes into contact with soils, it can cause soil acidification and lead to the depletion of essential nutrients. Acidic conditions in the soil hinder the growth of plants and can result in reduced crop yields and the loss of vegetation cover. The impacts of AMD on terrestrial ecosystems are particularly concerning as they can disrupt the balance of natural habitats, leading to habitat degradation and fragmentation. Moreover, AMD can have far-reaching consequences for human communities. Contaminated water sources resulting from AMD can jeopardize the availability of clean drinking water, posing risks to human health. Heavy metals and other contaminants present in AMD can accumulate in the food chain, potentially reaching humans through the consumption of contaminated crops and aquatic organisms. This exposure to toxic substances can have detrimental effects on human health, leading to various illnesses and disorders. Another important consideration is the economic impact of AMD. The contamination of water sources hampers their usability for industrial, agricultural, and recreational purposes, thereby affecting local economies that rely on these resources. The negative perception associated with AMD-affected areas can also deter potential investments and tourism, further impacting local economies and employment opportunities.

AMD is surface water that has decreased in quality due to the oxidation process of sulfide and oxygen minerals. A recent study even reported that AMD does not only have a destructive impact on surface water. AMD is reported to have polluted karst aquifers in Guizhou Province, China with the discovery of Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, F^-, and Fe contents (Ren et al., 2021). In addition, water and soil pollution have also reported in Guangdong Province, China (Liao et al., 2016). Pollution on surface water is caused by surface water in contact with sulfide minerals exposed due to the mining process. Groundwater pollution is caused by acid mine drainage infiltrating the soil until it reaches the aquifer. This condition will be hazardous if it occurs for a long time. Contaminated groundwater can long-term impact communities around mining areas that use groundwater to meet their daily needs.

Groundwater pollution does not only occur in China. A recent study reported groundwater pollution in the Osarizawa Mine area, Akita Prefecture, Japan. Although mining activities have stopped since the 1970s, the impact on groundwater quality degradation is still happening (Nishimoto et al., 2021). Using contaminated groundwater for bathing and drinking will cause various health problems. Heavy metal contamination caused by AMD will impact the supply chain. AMD will impact agricultural products produced in the region, which will harm human health. A study reported that long-term consuming foods and beverages containing heavy metals would cause cancer, poisoning, skin disease and death (Tolvanen et al., 2019; Kim et al., 2007). The impact of heavy metal accumulation is not only found in crops consumed by humans. Accumulation of heavy metals (Fe and Mn) has also found in endemic plants *Lavandula stoechas subsp*. *Luisieri* in Portugal and the Southwest of Spain, in 2017, several endemic plants such as *Lavandula stoechas subsp. luisieri*, *Origanum vulgare subsp. virens*, and *Calaminetha nepeta subsp. nepeta* (Sabina et al., 2019).

Heavy metals contained in AMD can contaminate the soil through the infiltration process. Besides that, heavy metal contamination in the soil will also cause heavy metals to be absorbed by plant roots, causing the plant to be contaminated. Heavy metals adsorbed on plant roots will be distributed through the xylem and phloem to the plant body parts. In addition, AMD is also reported to have caused water quality pollution, Stream Sediments and Periphytic Diatom Communities in the Surrounding Streams of the Aljustrel Mining Area in Portugal (Luís et al., 2009). Several species contents were found, such as Al, As, Ca, Cd, Cu, Fe, K, Mn, Na, Ni, Pb, S, Sb and Zn, in the stream area, while the surface water was found to be contaminated with As, Cu, Cd, Fe, Pb, Zn with variations in a concentration above the environmental quality standard (Luís et al., 2009).

Addressing the environmental impact of AMD requires comprehensive and sustainable mitigation strategies. Efforts are focused on preventing or minimizing the generation of AMD through improved mining practices, waste management, and the implementation of appropriate environmental regulations. Treatment technologies are also employed to mitigate the effects of existing AMD discharges, including neutralization processes, sedimentation ponds, and constructed wetlands that facilitate the removal of heavy metals and reduce acidity. Reclamation and restoration efforts are crucial for rehabilitating AMD-impacted areas. Restoring affected ecosystems involves the remediation of water bodies, soil amelioration, and the reintroduction of suitable vegetation. These restoration projects aim to recover biodiversity, improve water quality, and promote the recovery of ecosystem functions. Furthermore, public awareness and education campaigns are essential for promoting responsible mining practices and fostering a greater understanding of the environmental impacts of AMD. Collaboration between government agencies, mining companies, and local communities is vital to effectively manage and mitigate the impact of AMD on the environment.

3.3 Recent Advances in AMD Treatment

3.3.1 Adsorption

Adsorption has identified as a highly effective method for reducing pollutant parameters in AMD (Wibowo et al., 2022c; Wibowo et al., 2022a), and recent studies have sought to explore novel adsorbent materials for this purpose. One such material is shrimp shell waste Nunez-Gomez et al., 2019. This approach is unique and has novel value since previous studies have primarily focused on coconut shells as an adsorbent. The study found that shrimp shell waste was highly effective in reducing Fe levels, with a reduction of up to 99% at pH 7 and a 97% decrease at pH 4 (Nunez-Gomez et al., 2019). However, the decrease in Fe content in acidic conditions (pH 4) was less effective due to heavy metal mobilization occurring quickly under acidic conditions. On the other hand, there was a precipitation process on Fe metal in neutral conditions, leading to an optimal decrease.

AMD treatment methods are not limited to the use of waste materials. In fact, research has shown that bentonite modified with Fe_3O_4-chitosan can effectively neutralize AMD. This nanocomposite has found to significantly reduce the amount of Cr(IV) in AMD, despite the fact that this heavy metal is rarely found in AMD in natural conditions and has different characteristics than Fe. Chemical kinetics studies have revealed that the optimal dose for adding bentonite-chitosan to AMD is 60 mg, with an impressive adsorption capacity of 24 mg/g (Feng et al., 2019).

The process of reducing heavy metals and other pollutant parameters in AMD occurs through the agglomeration of dissolved substances, such as heavy metals, BOD, COD, TSS, and TDS, onto the surface of the adsorbent (Gopalakrishnan et al., 2018). The adsorption of pollutant material into the pores of the adsorbent is driven by cohesive forces, hydrostatic forces, and hydrogen bonding forces that act on the entire surface of the adsorbent molecule (Hou et al., 2019). Various attempts have made to develop the materials used in the adsorption process. A recent study reported that adsorbents could be made with a simple technology that utilizes slow pyrolysis. The new material reported to have succeeded in reducing the heavy metal content while increasing the pH of AMD is a combination of biochar derived from coconut shell and clamshell produced simply by using a modified reactor (Wibowo et al., 2022a). The results of the study reported that biochar-clamshell was not only able to absorb heavy metals but also succeeded in reducing the content of Al, Ca, and Mg. Another recent study reported that biochar was made from other abundant materials such as coal and peat (Budihardjo et al., 2021). In addition, these materials are also reported to be successfully combined in various phases (solid-solid, solid-liquid and solid-colloid combination) (Wibowo et al., 2022a). The common materials that use in adsorption process could be seen in Table 1.

The adsorption process between AMD and the adsorbent occurs in physical and chemical adsorption types (Al-Ghouti and Da'ana, 2020; Wang and Guo, 2020). The physical adsorption process occurs when the intermolecular forces are more significant than the attractive intermolecular forces or the relatively weak attractive forces between the adsorbate and the adsorbent surface (Van der Waals Force) (Qu et al., 2018). The Van Der Waals force occurs because of the contact between AMD as a fluid and the adsorbent as a solid material. The second adsorption process that may occur between AMD and the adsorbent occurs due to the exchange or sharing of electrons between the adsorbate molecule and the adsorbent surface so that a chemical reaction occurs (Ahmadijokani et al., 2021). If heavy metal sorption in AMD occurs under chemical reaction conditions, the bonds that occur will be stronger than chemical reactions. In detail, the different types of adsorptions can be distinguished based on Table 2.

3.3.2 Bioremediation

The passive bioreactor is the most commonly used bioremediation technique in treating AMD. Passive bioreactors use various materials such as compost, manure, organic waste and alkaline agents (Rambabu et al., 2020), in which an anaerobic environment is created due to the fermentation of these components. These conditions favour the biological reduction of sulfate and metal precipitation (Robinson-Lora and Brennan, 2011). Combining omics, bioreactors, and microbiome engineering will provide more significant potential for AMD bioremediation processes. Aspects of vegetation can influence the bioremediation process. This process has two constructed wetlands (CW) techniques that are often used, namely unplanted constructed wetlands (CCW) and planted constructed wetlands (PCW). Many studies have reported the positive influence of wetland plants on increasing the pH of metal-rich wastewater, possibly due to the release of organic acids and exudates from plant roots (Dean et al., 2013). Both provide a significant difference in metal removal in AMD.

During the initial CW operation, AMD handling contributed to an increase in pH due to the formation of organic acids (such as humic acid, formic acid and oxalic acid), carbonate ions from microbial oxidation of organic media as well as dissolution of surface-bound hydroxyl ions from the surfaces of bamboo chips and manure (Jiang and Li, 2020). However, during the process, alkalinity is produced through sulfate reduction. Towards the end of the study, there was a decrease in effluent pH below the higher HLR. Judging from the dissolved COD, PCW effluent samples were consistently higher than CCW.

PCW showed a reduction in sulfate of (85-30%), while CCW gave a more significant reduction of (92-42%). It was further observed that the sulfate concentration in PCW effluent was always higher than CCW. This situation might indicate the formation of a micro-aerobic zone due to the release of oxygen near the vegetation roots, and the higher redox potential may suppress microbial-assisted sulfate reduction in PCW (Aguinaga et al., 2019). The alkali formation process is directly related to sulfate reduction and the production of bicarbonate

Table 1. Commonly Materials in Adsorption Method

Material	Description	References
Activated Carbon	Highly porous carbon material with a large surface area and strong adsorption capacity.	(El Qada et al., 2006; Foo and Hameed, 2011; Ji et al., 2009; Kadirvelu et al., 2004; Mariana et al., 2021)
Zeolites	Crystalline aluminosilicates with uniform pore structures, suitable for adsorbing heavy metals in AMD	(Erdem et al., 2004; Hong et al., 2019; Motsi et al., 2009; Rios et al., 2008; Wingenfelder et al., 2005)
Biochar	Carbon-rich material produced from biomass pyrolysis, known for its adsorption properties and potential for contaminant removal	(Chen et al., 2021b; Deepa et al., 2019; Fazal et al., 2020; Lyu et al., 2020; Wibowo et al., 2023b)
Clay Minerals	Naturally occurring minerals such as kaolinite, bentonite, and montmorillonite, capable of adsorbing various contaminants.	(Borthakur et al., 2021; Ghorbel-Abid and Trabelsi-Ayadi, 2015; Han et al., 2019; Manohar et al., 2006; Rao and Kashifuddin, 2016; Yu et al., 2013)
Fly Ash	Residue generated from coal combustion, often used as an adsorbent due to its high silica and alumina content.	(Gitari et al., 2006; Keller et al., 2020; Kumar and Pakshirajan, 2021; Orakwue et al., 2016; Sahoo et al., 2013)
Iron Oxides	Materials like iron hydroxides and iron oxides, known for their high affinity for heavy metals and other contaminants	(Muedi et al., 2021; Sibrell and Tucker, 2012; Verplanck et al., 2004; Yang et al., 2015)
Modified Silica Gel	Silica gel modified with functional groups to enhance its adsorption capacity and selectivity for specific contaminants	(Koohestani et al., 2018; Wang et al., 2023; Wilfong et al., 2022)
Carbon Nanotubes	Cylindrical carbon structures with high aspect ratios, offering large surface areas and excellent adsorption capabilities	(Gugushe et al., 2019; Jerez et al., 2014; Ramokgopa et al., 2021; Rodríguez et al., 2020)
Chitosan	Biopolymer derived from chitin, exhibiting adsorption properties for heavy metals and other contaminants in AMD	(Feng et al., 2019; Igberase et al., 2018; Machodi and Daramola, 2020; Machodi and Daramola, 2019; Ramasamy et al., 2018)
Algal Biomass	Living or non-living biomass derived from algae, utilized for the removal of metals and nutrients in AMD	(Bwapwa et al., 2017; Du et al., 2022; Martínez-Macias et al., 2019; Rose et al., 1998)
Lignocellulosic Materials	Biomass materials derived from plant cell walls, such as sawdust and rice husks, capable of adsorbing heavy metals	(Burman et al., 2019; Han et al., 2005; Han et al., 2019; Magowo et al., 2023; Muhammad et al., 2017; Shin et al., 2004)
Polymers	Synthetic materials with diverse structures and functional groups, offering customizable adsorption properties for AMD treatment	(Dlamini et al., 2019)

Material	Description	References
Hydroxyapatite	Calcium phosphate-based material with high affinity for metal contaminants in AMD	(Agha Beygli et al., 2019; Li et al., 2021; Oliva et al., 2012; Street, 2016)
Bentonite	Clay mineral with excellent adsorption capacity, commonly used in combination with other adsorbents for AMD treatment	(Hussain and Ali, 2021; Kubilay et al., 2007; Liu and Zhou, 2010; Thakur et al., 2021; Zhan et al., 2019)
Mesoporous Silica	Silica materials with well-defined mesopores, providing high surface areas and enhanced adsorption capabilities	(Falayi et al., 2019; Lachowicz et al., 2019; Ramasamy et al., 2018)
Graphene Oxide	Two-dimensional carbon-based material with exceptional adsorption properties for various contaminants in AMD	(Dong et al., 2015; Etale et al., 2021; Rahimi and Mohaghegh, 2017)
Manganese Oxides	Manganese-based materials that exhibit strong adsorption affinity for heavy metals and other pollutants in AMD	(Outram et al., 2018)
Walnut Shell	Natural adsorbent derived from walnut shells, offering potential for the removal of heavy metals from AMD	(Chang et al., 2022; Gheju and Balcu, 2021; Li et al., 2019; Moreno-Barbosa et al., 2013)

Table 2. Different Physical and Chemical Reactions in Adsorption

Chemical Sorption	Physical Sorption
Large adsorption enthalpy (usually between 40-400 kJ/mol)	Small adsorption enthalpy (usually less than 20 kJ/mol)
Adsorption occurs in the monolayer	Multilayer adsorption occurs
It can occur at high temperatures	Occurs at temperatures below the boiling point of the adsorbate
The adsorption process occurs when the system has an activation energy	It does not involve the activation of energy

ions. These conditions are favourable because they are necessary for the growth and function of sulfate-reducing bacteria (SBR) (Dev et al., 2016). The biological assimilation of sulfur into plants is also known to contribute to the overall sulfate removal efficiency in CWs (Wu et al., 2013).

This method is proven to be able to remove Fe (99–77%), Zn (98–90%), Co (96–92%), Ni (89–96%) and Cr (99–95%). Statistical analysis showed a significant difference ($p<0.05$) between the overall metal removal efficiency of CCW and PCW, except for Al, Mn and Cr. Mn stripping can be caused by the release of weakly adsorbed Mn^{2+} ions, and the simultaneous release of Mn without undergoing treatment because the precipitation of manganese in the (oxy-)hydroxide form requires pH>9. Under anaerobic/anoxic conditions, Mn^{2+} remains in a reduced soluble state and is thus very difficult to remove (Mohan and Chander, 2001; (Neculita and Rosa, 2019)). The addition of 0.05 M EDTA showed a fairly high extraction efficiency of Fe, Zn and Cr metals. The addition of EDTA showed the recovery of precious metals through precipitation (30–98%). The bioremediation process could by providing using several methods like described on Table 3.

3.3.3 Constructed Wetlands

Acid mine drainage (AMD) is an emerging environmental issue that is difficult to avoid in most mining activities (Oberholzer et al., 2022). AMD is formed when sulfide minerals in the soil are exposed to a rich oxygen atmosphere so that they undergo an oxidation process and then react with water, air, and biotic components. This result causes an increase in the concentration of SO_4^{2-} ions in the environment, especially the aquatic environment (Tong et al., 2021). Since sulfates are strong acids, their presence makes water acidic, dissolves and leaches dangerous heavy metals into the environment.

The primary source of AMD is active activities or abandoned mining sites, which use open-pit or underground mining systems. In addition, AMD can also source from tailing dumps, ore stockpiles, pit lakes, and sludge ponds (Pat-Espadas et al., 2018). Since AMD will harm the environment, it must be

Table 3. Description of Bioremediation Method on AMD Treatment

Treatment Method	Description
Passive Treatment	Utilizes natural processes to treat acid mine drainage. Involves constructing wetlands, ponds, or other systems. Relies on microbial activity to neutralize acidity. Enhances biological reactions for metal precipitation. Requires long-term monitoring and maintenance.
Active Treatment	Involves adding microbial cultures or nutrients. Accelerates the natural degradation of pollutants. Utilizes sulfate-reducing bacteria or iron-oxidizing bacteria to reduce metal concentrations. Requires continuous monitoring and management.
Constructed Wetlands	Uses specially designed wetland systems. Promotes the growth of microorganisms and plants. Removes metals through adsorption and precipitation. Effective for treating low-to-moderate acidic drainage.
Bioprecipitation	Utilizes microorganisms to precipitate metals. Stimulates the growth of metal-resistant bacteria. Reduces metal concentrations through biomineralization.
Bioleaching	Involves using microorganisms to extract metals. Enhances the solubilization and recovery of metals. Uses acidophilic bacteria or fungi in the process.
Bioventing	Relies on introducing air or oxygen into contaminated soil or groundwater. Promotes the growth of aerobic bacteria for degradation. Reduces the concentration of pollutants over time.
Microbial Fuel Cells	Harnesses the metabolic activity of microorganisms. Converts organic matter into electrical energy. Can be used to treat acid mine drainage and generate electricity simultaneously.

treated to avoid severe environmental damage. This section describes AMD treatments employing the constructed wetland treatment system (CWTS), which discusses the commonly used design parameters (flow configuration and plant species used).

CWTS is one of the wastewater treatment methods that prioritize an ecological approach. This method offers a wastewater treatment solution that is more environmentally friendly, safe, and at a relatively more affordable cost (Wu et al., 2019). CW is an artificial wetland designed as closely as possible to a natural wetland to remove contaminants and improve water quality by optimizing physical, chemical, and biological processes in integrated conditions.

Besides being widely used in domestic wastewater treatment, CWTS has also widely applied in processing AMD produced by various mining activities. In AMD treatment, the CWTS is categorized as a passive treatment method combining several processes, including biogeochemical, geochemical, and physical (Singh and Chakraborty, 2021). This method involves interactions between substrates, microorganisms, and plants to remove heavy metals contained in AMD. Several types of removal mechanisms are possible, including filtration, adsorption, plant absorption, physical precipitation, chemical precipitation, and the action of microorganisms (Tong et al., 2021). Although it uses fewer chemicals or modern technologies, which can save operational costs, this method requires a relatively long processing time than other waste treatment methods.

In general, CWTS can be classified into two categories; (1) based on the water flow regime (surface flow and sub-surface flow), and (2) based on the type of plant or vegetation grown.

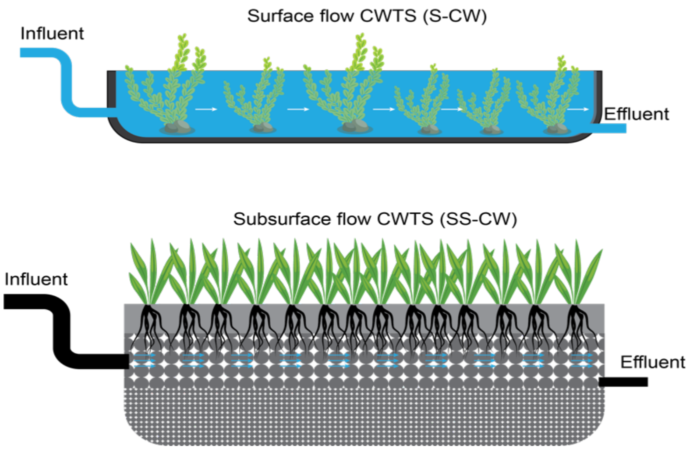

Figure 5. Schematic Layout of Surface Flow and Subsurface Flow CW

CWTS with surface flow type (S-CW) is generally a shallow basin where the treated wastewater is directly contacted with the atmosphere and growing vegetation (Figure 5). CWTS with the surface flow can be grouped based on the type of macrophyte grown, such as emergent, submerged, floating leaved plant, and free-floating macrophyte. CWTS with the subsurface type (SS-CW) is generally a sealed basin where the treated wastewater is placed 0.3–0.9 meters below the ground surface and is channeled through sand or gravel (Figure 5). On the surface of the SS-CW, plants whose roots will reach the wastewater are grown. This type of CWTS can be classified based on the flow type, namely horizontal and vertical.

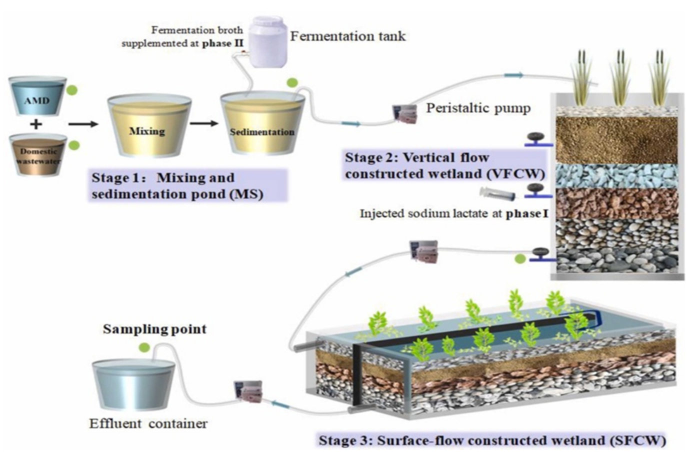

Figure 6. Schematic Diagram of Hybrid CWST (Wang et al., 2021b)

Based on their removal performance, each type of CWTS exhibited different efficiency and selectivity against specific contaminants. Many reports have stated that SS-CW produces higher metal removal than S-CW for certain metals such as Al, Mn, Ni, and Zn. As for Fe, using both methods produces the same efficiency (Pat-Espadas et al., 2018). Therefore, these methods can also be combined to produce a hybrid system with several configurations to improve the removal performance. For instance, Wang et al. have designed a CWTS involving SS-CW followed by S-CW for treating AMD in a lab-scale application (Figure 6). They reported that the designed hybrid CWTS exhibited high removal efficiencies, 89.4% for Mn, and 99% for Fe, Zn, Cd, and Cu. Several research results using CWTS to treat AMD using the S-CW, SS-CW, and hybrid methods can be seen in Table 4.

In addition to the flow type, the selection of plants or vegetation also significantly impacts the contaminant removal performance of a CWTS. Zubair et al. (2020) have conducted a series of studies to investigate the ability of Typha angustifolia to remove Fe using the S-CW method. They reported that this plant could remove up to 70.88% Fe. In another study, Nguyen et al. studied the effect of using cattails in pilot-scale AMD treatment using the S-CW method. The results indicated that using these plants could significantly reduce the metals in AMD. The presence of cattail in CWTS reduced the metal content of Cd, Zn, Cu, and As, respectively, by 83.8%, 84.6%, 57.1%, and 45.4% (Zubair et al., 2020). Several other plant species tested for AMD treatment under the CWTS method can be seen in Table 5.

3.3.4 Electrochemical Treatment

Electrochemical treatment has emerged as a promising method for the treatment of AMD, offering an efficient and environmentally friendly approach to mitigate the impacts of this widespread issue. Electrochemical treatment utilizes electrochemical reactions to remove contaminants from AMD, targeting both acidity and heavy metal content. This discussion will explore the principles, benefits, and challenges associated with electrochemical treatment for AMD. At its core, electrochemical treatment involves the application of an electric current to facilitate chemical reactions that drive the removal or transformation of contaminants. In the context of AMD, electrochemical treatment typically involves two key processes: electrocoagulation and electrooxidation.

Electrocoagulation is primarily employed to address the high metal concentrations in AMD. During this process, metal ions present in the acidic water are attracted to oppositely charged electrodes, forming coagulated particles. These particles can then be separated from the treated water through sedimentation or filtration. Electrocoagulation offers advantages such as rapid metal removal, high efficiency, and the ability to handle a wide range of metal contaminants. Electrooxidation, on the other hand, focuses on reducing the acidity of AMD and promoting the oxidation of sulfide minerals. This process occurs at the anode, where oxygen evolution takes place, resulting in the generation of hydroxide ions that neutralize acidity. Simultaneously, the oxidation of sulfide minerals leads to the formation of sulfate ions, reducing the sulfide content in the AMD. Electrooxidation offers benefits such as pH adjustment, reduction of sulfide concentrations, and the potential for simultaneous removal of heavy metals.

Table 4. Type of CWTS and its Metal Removal Efficiency in AMD Treatment

CWTS	Removal Efficiency	References
SS-CWST	99.7% (Cr), 97.8% (Ni), 93.7% (Co), 91.6% (Fe)	(Singh and Chakraborty, 2020)
S-CWST	70.88% (Fe)	(Zubair et al., 2020)
SS-CWST	99–77% (Fe), 98–90% (Zn), 96–92% (Co), 89–96% (Ni) and 99–95% (Cr)	(Singh and Chakraborty, 2021)
Hybrid (S-CWST + SS-CWSR)	89.4% (Mn), 99% (Fe, Zn, Cd, and Cu)	(Wang et al., 2021a)

Table 5. Plants used in AMD Treatment Through CWTS

Plant	CWTS type	Metal Removal	References
Typha angustifolia	S-CW	70.88% (Fe)	(Zubair et al., 2020)
Typha latifolia	S-CW	54.13% (Se)	(Etteieb et al., 2021)
Phragmites australis	SS-CW	>96% (As and Fe) >94% (Pb)	(Lizama-Allende et al., 2021)
Iris pseudoacorus	SS-CW	> 98% (Cu), > 95% (Cd), 91% (Cr) and > 91% (Zn)	(Chen et al., 2021b)

One of the key advantages of electrochemical treatment for AMD is its versatility and adaptability to varying water chemistry and contaminant compositions. The electrochemical system can be customized and optimized based on the specific characteristics of the AMD, allowing for effective treatment regardless of the site-specific conditions. Additionally, electrochemical treatment can be combined with other processes, such as precipitation or membrane filtration, to further enhance the overall treatment efficiency. Another significant advantage of electrochemical treatment is its potential for resource recovery. The removed heavy metals can be recovered from the electrode surfaces, offering the possibility of recycling and reusing these valuable resources. This aspect aligns with the principles of circular economy and sustainable resource management, making electrochemical treatment an attractive option for AMD treatment.

However, electrochemical treatment for AMD is not without challenges. The high energy requirements and operational costs associated with electrochemical systems can be significant barriers to implementation, especially in large-scale applications. Additionally, the electrode materials used in the treatment process may be susceptible to degradation and fouling over time, requiring regular maintenance and replacement. The optimization of operating parameters, such as current density, pH control, and electrode configuration, also requires careful consideration to achieve optimal treatment efficiency.

Electrochemical methods are reported to prevent AMD formation by protecting the cathode of the ore body (Bejan and Bunce, 2015). In addition to preventing the formation of AMD, electrochemical methods can also be used to reduce pollutant parameters in AMD. A recent study reported that the combination of electrochemical/CaO methods increased the pH of AMD from 2.7 to 6.71. Besides that, the combination of electrochemical/CaO methods also reduced the content of sulfate, Hg, Pb, V, Cr, Mn, Fe, Zn, Co, Ni and Cu became very small (between 0.001-0.074) (Radić et al., 2014).

The process of reducing heavy metal levels in AMD is influenced by the strong current flowing at the anode and cathode. The electrochemical process of AMD processing follows Ohm's law associated with Faraday's law I which states that the mass of the substance formed at each electrode is proportional to the strength of the electric current flowing in the electrolysis. A study confirmed this result for 10-60 mA that a bigger current could better reduce pollutants from AMD (Bunce et al., 2001). This condition informs that the greater the current flowing at the cathode and anode, the greater its ability to reduce heavy metal content in AMD. The electrochemical process in AMD processing occurs when the anode (Al electrode) is oxidized to Al^{3+}, the anode (C electrode) undergoes Cl^- oxidation to Cl_2, and AMD is reduced to OH- resulting in heavy metal degradation, coagulation and an increase in AMD pH. The process of reducing the pollutant content in AMD using the electrochemical method can be seen in Figure 7.

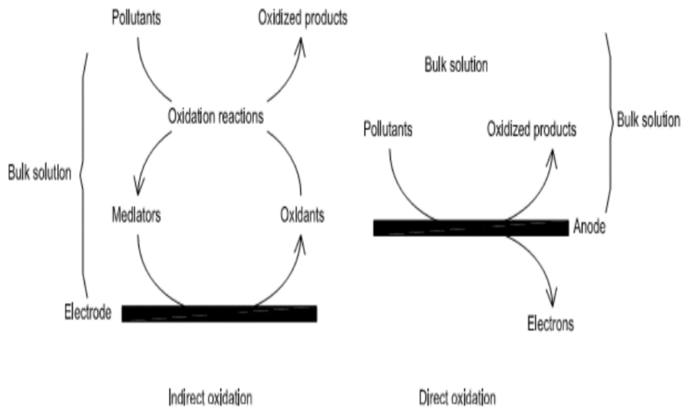

Figure 7. Electrochemical Oxidation in Pollutant Removal (Li et al., 2010)

Another effort that can be made to increase the use of electrochemical to reduce pollutant parameters in AMD is to combine it with other methods. A recent study reported a combination of microbial/electrochemical methods. This method is made using three modified reactors to be able to utilize electrochemical and microbial electrochemical for AMD treatment. The study's results reported that combining these methods could reduce pollutant parameters up to >80%. Although this method succeeded in reducing pollutant parameters in AMD, the pH condition in AMD was unstable. This condition was caused by the accumulation of Cl^- (Brewster et al., 2018). The others electrochemical method for AMD treatment can be seen in Table 6.

3.3.5 Membrane Technology

Membrane technology is a promising approach for treating AMD, which is a major environmental problem in mining areas. The high acidity and heavy metal content of AMD pose significant challenges for traditional treatment methods. However, membrane technology offers a sustainable solution for AMD treatment by selectively filtering out pollutants and recovering valuable resources. The use of semi-permeable membranes in filtration methods such as reverse osmosis (RO) and nanofiltration (NF) has shown to effectively remove dissolved metals from AMD, resulting in highly purified water that meets environmental discharge standards (Agboola, 2019).

Membrane technology has several advantages over traditional AMD treatment methods. Firstly, it is a low-waste and energy-efficient approach that produces minimal waste compared to other methods that generate large volumes of sludge. Secondly, it enables the recovery and reuse of valuable metals and minerals present in the AMD solution, contributing to a circular economy approach to resource management. Thirdly, membrane technology can be adapted to treat a variety of AMD sources, including low-pH, high-salinity, and complex waste streams, making it a versatile and flexible solution for AMD treatment.

Research on membrane technology for AMD treatment is ongoing, with a focus on optimizing the performance and durability of membranes, reducing costs, and developing scalable and practical systems (Houchins et al., 2012). Advances in membrane materials, design, and operation have improved the efficiency and effectiveness of membrane technology for AMD treatment. Moreover, research on the recovery and reuse of valuable metals and minerals from AMD is also progressing, with efforts focused on developing cost-effective and environmentally friendly recovery methods. Membrane technology offers an important opportunity for the sustainable management of AMD, and ongoing research and development will continue to advance its effectiveness and feasibility.

The membrane distillation process is often used to treat groundwater polluted by acid mine drainage and wastewater (Asif et al., 2021). MD can remove metals and organic compounds up to 98-100% (Asif et al., 2021; Kesieme and Aral, 2015). Incorporating persulfate increases the process of removing micropollutants by 20% and reduces accumulation (Silva et al., 2018). The content of iron oxide during the process can increase the occurrence of scaling. This hypothesis is proven through the characterization of the fouling layer (Asif et al., 2021). Distillation membranes often recover copper contained in AMD. A synthetic adsorbent was used, namely mesoporous silica material SBA-15. The material was prepared hydrothermally and modified by Mn loading and amine grafting. Modified SBA-15 can selectively adsorb Cu from AMD solution with pH adjusted to 5.2 (Ryu et al., 2020). Direct contact membrane distillation (DCMD) can recover water contaminated with AMD with a high purity of 80%. Concentrated AMD solution can increase the adsorption capacity of Cu used by DCMD. The process of clarifying copper deposits also often uses a filtration membrane. Sulfide precipitation combined with membrane microfiltration can recover copper up to 100%. Each AMD requires a different flux value, approximately more than 0.1 L/m^2s. Membrane microfiltration can be combined with the gravity method to get better results (Menzel et al., 2021).

4. COMPARISON OF SEVERAL METHODS FOR TREATING AMD

Adsorption is a widely used method for treating AMD due to its high removal efficiency for heavy metals and pollutants. It has the advantage of using readily available adsorbent materials, making it easily accessible for implementation. The operation of adsorption is relatively simple with low energy requirements, and it can be integrated into existing treatment systems. However, adsorbents may require regeneration or proper disposal to prevent secondary contamination. The performance of adsorption can be influenced by factors such as pH, temperature, and the type of adsorbent used. Additionally, adsorbents have limited capacity and need periodic replacement or replenishment.

Table 6. Electrochemical Method for Treating AMD

Electrochemical Method	Description	Abilities	References
Electrocoagulation	Uses electric current to coagulate and remove contaminants from AMD.	Precipitates contaminants, removes suspended solids, and improves water quality.	(Foudhaili et al., 2020; Foudhaili et al., 2019; Nariyan et al., 2018; Oncel et al., 2013; Stylianou et al., 2022)
Electrooxidation	Applies electric current to oxidize and degrade organic and inorganic pollutants.	Efficiently removes organic compounds, destroys pathogens, and reduces contaminant levels.	(Sun et al., 2015b; Sun et al., 2013; Tu et al., 2017; Zhai et al., 2013; Evangelou and Zhang, 1995)
Electro-Fenton	Generates oxidizing agents using electricity and Fe^{2+} catalysts for contaminant breakdown.	Effective for degrading organic pollutants and promoting oxidation reactions in AMD.	(Chai et al., 2020; Huang et al., 2020; Sun et al., 2015a; Sun et al., 2018; Zhai et al., 2019)
Electrodialysis	Applies electric field to selectively transport ions through ion-exchange membranes.	Concentrates and separates target ions, allowing for the removal of specific contaminants.	(Juve et al., 2022; Buzzi et al., 2013; Liu et al., 2022b; Martí-Calatayud et al., 2014)

Bioremediation offers a cost-effective and environmentally friendly solution for AMD treatment. Microorganisms can convert metals into less toxic forms through bioreduction or bioaccumulation processes, while plants can uptake and accumulate metals in their biomass via phytoremediation. Bioremediation is suitable for long-term, sustainable treatment. However, it may have limitations in treating certain contaminants or in cases of extreme pH or high metal concentrations. The treatment efficiency of bioremediation can also be affected by environmental factors, such as temperature and nutrient availability. Furthermore, bioremediation may require a longer treatment time compared to other methods.

Constructed wetlands provide a sustainable and passive treatment option for AMD. Wetland vegetation, soil, and microorganisms work together to absorb and transform contaminants, while the wetland media filters and retains pollutants. Constructed wetlands are effective in removing metals, neutralizing acidity, and improving water quality. However, their implementation requires sufficient space and long-term maintenance to sustain their treatment performance.

Electrochemical technologies involve the application of an electric current to treat AMD. Methods such as electrocoagulation, electrooxidation, and electro-Fenton can remove contaminants through precipitation, oxidation, and the generation of reactive species. Electrochemical methods offer high treatment efficiencies and can selectively target specific contaminants. However, they may require energy input and specialized equipment for operation, making them relatively expensive compared to other methods.

Membrane technologies, such as electrodialysis and membrane electrolysis, utilize selective membranes to separate and concentrate contaminants from AMD. They are effective in desalination and targeted contaminant removal. However, membrane technologies may be limited by fouling, requiring proper pre-treatment and maintenance to sustain their performance. Thus, the selection of a treatment method for AMD depends on various factors, including the specific contaminants present, site conditions, treatment goals, and cost considerations. A combination of different techniques or the integration of multiple treatment steps may be necessary to achieve desired water quality standards while minimizing environmental impacts and costs.

5. RESOURCE RECOVERY OPPORTUNITIES FROM AMD

AMD is one toxic wastewater due to its low pH and high content of various heavy metal ions (Ighalo et al., 2022). Treatment of AMD mainly focuses on increasing the pH and reducing the concentration of dissolved metal ions (Hu et al., 2022). Most AMD treatments involved neutralization and precipitation processes (de Moraes and Ladeira, 2021). The precipitation resulted in the sludge containing a solid form of the precipitated metals (Ighalo et al., 2022). Precipitated metals have the opportunity to be recovered and further utilized. Not only by precipitation, simultaneous metal recovery and algae-lipid production were also reported by Brar et al. (2022), which involve the high metal tolerance algae strain of *Chlorella vulgaris* for the treatment of AMD. Recent developments in the resource recovery opportunities from AMD are tabulated in Table 7.

Table 7. Recent Advances in Resource Recovery Opportunities from AMD

Method	Recovered resource	Summary	Reference
Micro-flotation	Pyrite	• Utilization of AMD increased the pyrite floatation by 64% • The addition of AMD improves the adsorption of dixanthogen which promotes the pyrite floatation	(Bai et al., 2021)
Biosorption and bioaccumulation using algae	Iron, aluminium, mangan, and biodiesel	• NaOH addition significantly reduces the concentration of heavy metals in AMD • *C. vulgaris* was able to produce 0.35 g lipid/g biomass when cultivated using AMD at pH 8 • Converted algae biomass into biodiesel met the international specification	(Brar et al., 2022)
Phosphate precipitation and ion exchange	Rare earth elements	• Common metals of Fe, Al, Mn, Ca, Mg, Cd, and Pb can be simultaneously recovered with the rare earth elements • pH and total phosphate played an essential role in the recovery • $PrPO_4$(s) and $CePO_4$(s) were detected using XRD	(Hermassi et al., 2022)
Selective precipitation	Iron	• H_2O_2 induced the stabilization of Fe^{2+} to Fe^{3+} • Iron was recovered using OH selective precipitation • Economic analysis showed that the used method is 14 cents cheaper per m^3	(Hu et al., 2022)
Ion exchange	Rare earth elements	• Fractionation of rare earth elements reaches up to 85% with LEWATIT MDS 200H resin • Longer residence time promoted fractionation • Elution with 0.02 M EDTA promoted the separation of aluminium and calcium from rare earth elements	(José and Ladeira, 2021)
Fluidized bed bioreactor	Copper, lead, cadmium, zinc, nickel, and iron	• Biological sulfate reduction facilitated the metal removal from AMD • More than 95% of metal removal and around 50% of recovery were achieved • Lower recovery was achieved in influent pH of 3 compared to a pH 7	(Kumar and Pakshirajan, 2021)

Method	Recovered resource	Summary	Reference
Clay adsorption	Rare earth elements and yttrium	• Acid desorption was used to reclaim the sorbed elements • Recovered rare earth elements reached 3.37 kg/d after precipitation	(Liu et al., 2022a)
Sulfide precipitation and membrane filtration	Copper	• A total of 100% copper recovery can be achieved by integrating sulfide precipitation and microfiltration • The final turbidity of the AMD was less than 2 NTU	(Menzel et al., 2021)
Precipitation	Rare earth elements and uranium	• Adding Fe into the AMD induced the rare earth elements to recover via Fe-Al precipitation • Adding Fe to neutral pH reduced the efficiency of rare earth elements and uranium precipitation	(de Moraes and Ladeira, 2021)
Polymer inclusion membrane	Copper	• The hydrophobic modification was used to enhance the selectivity and stability of the membrane • The 2-aminomethylpyridine showed the highest increase in membrane selectivity for copper ion and stability	(Qiu et al., 2021)
Membrane distillation	Iron	• A combination of direct contact membrane distillation and photocatalysis was used to recover iron from AMD • The utilization of Fenton catalyst recovered iron-oxalate	(Yang et al., 2015)

Referring to Table 7, iron, copper, and rare earth elements are the most mentioned resource to be recovered from the AMD treatment. Fifty to 100% recovery efficiency can be obtained for various metals (Kumar and Pakshirajan, 2021; Menzel et al., 2021). Several technologies involved in recovering metals from AMD mainly focused on selective precipitation by adjusting the wastewater pH (Hu et al., 2022; de Moraes and Ladeira, 2021). Besides the selective precipitation by adjusting pH, sulfide and phosphate precipitation were also mentioned to recover the soluble metals in AMD (Hermassi et al., 2022; Menzel et al., 2021). The separation of metals needs to be conducted when precipitation is used as the recovery method. If adsorption or ion exchange methods were used, elution or desorption are needed to recover the desired metal from the adsorbent or resin. Recent advances also reported using AMD as a growth medium for algae after neutralization. Algae species of *C. vulgaris* were used by Brar et al. (2022) as they can withstand high metal exposure and simultaneously perform biosorption and bioaccumulation to reduce the metal concentration in AMD. The algae biomass produced after metal desorption can be processed further into biodiesel, which opens new opportunities in greener technology (Kurniawan et al., 2021).

6. CHALLENGES AND PROSPECTS

AMD is generated by rocks and tailings of the mineral processing activity. The oxidation of some typical minerals induces the formation of AMD. Therefore, the AMD leachable from minerals oxidation under the influence of soluble salts or metal oxides are not entirely understandable (Tabelin et al., 2020). Despite the focus on the formation of AMD, the chosen technology for AMD treatment is also necessary to mitigate the environmental impact of AMD formation. Managing AMD containing high metal concentrations is compulsory to prevent ground and surface water contamination. As mentioned in the previous subsection, some technologies may have a good treatment efficiency but need higher maintenance and investment costs (Vital et al., 2018). Since the nature of AMD is acidic, precipitation is always done by adding standard alkali solutions such as lime, sodium carbonate, and sodium hydroxide as pre-treatment. Therefore, waste material from tailings was reported to be used as AMD neutralization. The treated AMD can achieve pH around 6.5–8.5, satisfying for removing metals. However, the feasibility and environmental footprint of the material should be considered in the future study as it was comparable with common alkali materials (Kaur et al., 2018). The two-step ferrite-formation process, which was introduced by Igarashi et al. (2020), may give some advantages compared to the conventional neutralization process using lime. However, the process depends on the concentration of silicate (Si). When the Si concentration is higher than 4 ppm, ferrite formation is limited. More studies regarding the effective control of Si concentration are needed to get a higher ferrite formation (Igarashi et al., 2020). Other considerations that should be determined to remove the pollutants from AMD are post-treatments of neutralization such as electrocoagulation, chemical coagulation, adsorption and ion exchange (Nariyan et al., 2018).

Membrane separation technology is an advanced AMD treatment that is still limited to be found in the literature. Fouling becomes the most significant disadvantage of the applicability of this technology. Therefore, effective pre-treatment should be applied to achieve higher efficiency through the membrane. Consequently, the optimum operating condition of the membrane system should be studied further (Pino et al., 2018). Another advanced membrane separation, forward osmosis (FO), considered a novel and advanced membrane process, is still not applicable in a broader range of AMD. However, this technology is the potential for further process development (Vital et al., 2018). Integrating technology such as chemical precipitation and EC improved efficiency and reduced weaknesses. However, the potential use of this integrated system needs to be explored deeply since the potential of by-product generation may harm the environment (Nariyan et al., 2018). Another potential integration system using submerged membrane distillation and zeolite sorption system is also introduced in the literature. This integrated technology was favourable for removing many heavy metals in AMD. However, a lower removal rate may have resulted from a higher pollutant concentration. Thus, testing the applicability of this technology in long-term experiments is needed to be an alternative solution for treating AMD (Ryu et al., 2019). Biomining technologies are also another emerging technology that researchers should consider. The system's limitation is the instability consortia to treat wastewater with lower pH effectively. Bioaugmentation of acidophilic consortia is still needed to reduce the chemical and physical treatment dependencies, resulting in a higher cost and complex installation (Quatrini and Johnson, 2018).

7. CONCLUSION

Mining activities have reported as activities that cause a decrease in the quality of surface water and groundwater. The decrease in pH and the increase in heavy metals in the water around the mining area are caused by the oxidation process or contact between air, water and sulfide minerals. The role of bacteria is also reported to be very significant in forming AMD. Some bacteria can even increase the formation of AMD up to 6 times. AMD is a hazardous waste that can cause environmental and human health problems. Various studies have reported that AMD has contaminated the soil, causing plants to be exposed to heavy metals. Even some endemic plants in Portugal and Spain were reported to be contaminated with heavy metals from AMD. Besides being harmful to the environment, heavy metal contamination found in AMD has also reported to have caused various diseases in humans and caused death.

AMD is divided into five types due to differences in the characteristics of the constituent rocks. Various attempts have made to reduce pollutant parameters in AMD. The formation of AMD is different in each place. Adsorption is one method that is widely reported to be successful in reducing heavy metal levels in AMD. The adsorption process occurs because of the contact between the adsorbent and AMD. There are two types of adsorption processes, namely physical and chemical adsorption. Physical adsorption is an adsorption process that occurs on the surface of the adsorbent, has small enthalpy energy (less than 20 kJ), and multilayer adsorption occurs at temperatures below the boiling point of the adsorbate, does not involve activation energy and chemical adsorption which has prominent characteristics. Adsorption enthalpy (usually between 40-400 kJ/mol), adsorption occurs in the monolayer, can occur at high temperatures, and the adsorption process occurs when the system has activation energy.

CW is one of the most straightforward and easy-to-apply methods to reduce heavy metal content and increase pH in AMD. This method utilizes the microbial community and phytoremediation processes from plants that can absorb heavy metals through their roots. In addition, the relatively alkaline CW conditions can increase the pH so that some heavy metals can be precipitated. Another method that can be used is the electrokinetic method. This method utilizes the current flowing at the anode and cathode so that it can absorb heavy metals in AMD. Its success is influenced by several factors, such as the operating condition and the distance between the anode and cathode. The last method that can be used is the membrane method. Unfortunately, this method is not economical because it requires an enormous cost to make the material. Thus, this paper successfully provides more understanding of recent advances in the prevention of AMD formation and AMD mitigation with their limitation.

REFERENCES

Abfertiawan, M. S., Y. Palinggi, M. Handajani, K. Pranoto, and A. Atmaja (2020). Evaluation of Non-Acid-Forming Material Layering for the Prevention of Acid Mine Drainage of Pyrite and Jarosite. *Heliyon*, **6**(11); e05590

Acharya, B. S. and G. Kharel (2020). Acid Mine Drainage from Coal Mining in the United States–An Overview. *Journal of Hydrology*, **588**; 125061

Agboola, O. (2019). The Role of Membrane Technology in

Acid Mine Water Treatment: A Review. *Korean Journal of Chemical Engineering*, **36**; 1389–1400

Agha Beygli, R., N. Mohaghegh, and E. Rahimi (2019). Metal Ion Adsorption from Wastewater by g-C 3 N 4 Modified with Hydroxyapatite: A Case Study from Sarcheshmeh Acid Mine Drainage. *Research on Chemical Intermediates*, **45**; 2255–2268

Aguinaga, O. E., J. F. Wakelin, K. N. White, A. P. Dean, and J. K. Pittman (2019). The Association of Microbial Activity with Fe, S and Trace Element Distribution in Sediment Cores within a Natural Wetland Polluted by Acid Mine Drainage. *Chemosphere*, **231**; 432–441

Ahmadijokani, F., S. Tajahmadi, A. Bahi, H. Molavi, M. Rezakazemi, F. Ko, T. M. Aminabhavi, and M. Arjmand (2021). Ethylenediamine-Functionalized Zr-Based MOF for Efficient Removal of Heavy Metal Ions from Water. *Chemosphere*, **264**; 128466

Al-Ghouti, M. A. and D. A. Da'ana (2020). Guidelines for the Use and Interpretation of Adsorption Isotherm Models: A Review. *Journal of Hazardous Materials*, **393**; 122383

Amaral Zettler, L. A., F. Gómez, E. Zettler, B. G. Keenan, R. Amils, and M. L. Sogin (2002). Eukaryotic Diversity in Spain's River of Fire. *Nature*, **417**(6885); 137–137

Angai, J. U., C. J. Ptacek, E. Pakostova, J. G. Bain, B. R. Verbuyst, and D. W. Blowes (2022). Removal of Arsenic and Metals from Groundwater Impacted by Mine Waste Using Zero-Valent Iron and Organic Carbon: Laboratory Column Experiments. *Journal of Hazardous Materials*, **424**; 127295

Asif, M. B., W. E. Price, Z. Fida, A. Tufail, T. Ren, and F. I. Hai (2021). Acid Mine Drainage and Sewage Impacted Groundwater Treatment by Membrane Distillation: Organic Micropollutant and Metal Removal and Membrane Fouling. *Journal of Environmental Management*, **291**; 112708

Bai, S., Y. Bi, J. Li, P. Yu, Z. Ding, C. Lv, and S. Wen (2021). Innovative Utilization of Acid Mine Drainage (AMD): A Promising Activator for Pyrite Flotation Once Depressed in a High Alkali Solution (HAS)–Gearing Towards a Cleaner Production Concept of Copper Sulfide Ore. *Minerals Engineering*, **170**; 106997

Baker, B. J. and J. F. Banfield (2003). Microbial Communities in Acid Mine Drainage. *FEMS Microbiology Ecology*, **44**(2); 139–152

Bao, Y., J. Lai, Y. Wang, Z. Fang, Y. Su, D. S. Alessi, N. S. Bolan, X. Wu, Y. Zhang, and X. Jiang (2022). Effect of Fulvic Acid Co-Precipitation on Biosynthesis of Fe(III) Hydroxysulfate and its Adsorption of Lead. *Environmental Pollution*, **295**; 118669

Barthen, R., M. L. Sulonen, S. Peräniemi, R. Jain, and A.-M. Lakaniemi (2022). Removal and Recovery of Metal Ions from Acidic Multi-Metal Mine Water using Waste Digested Activated Sludge as Biosorbent. *Hydrometallurgy*, **207**; 105770

Bejan, D. and N. J. Bunce (2015). Acid Mine Drainage: Electrochemical Approaches to Prevention and Remediation of Acidity and Toxic Metals. *Journal of Applied Electrochemistry*, **45**; 1239–1254

Borden, R. K., P. L. Brown, and S. Sturgess (2022). Geochemical and Hydrological Evolution of Mine Impacted Waters at the Argyle Diamond Mine, Western Australia. *Applied Geochemistry*, **139**; 105253

Borthakur, P., M. Aryafard, Z. Zara, Ř. David, B. Minofar, M. R. Das, and M. Vithanage (2021). Computational and Experimental Assessment of pH and Specific Ions on the Solute Solvent Interactions Clay-Biochar Composites Towards Tetracycline Adsorption: Implications on Wastewater Treatment. *Journal of Environmental Management*, **283**; 111989

Brar, K. K., S. Etteieb, S. Magdouli, L. Calugaru, and S. K. Brar (2022). Novel Approach for the Management of Acid Mine Drainage (AMD) for the Recovery of Heavy Metals Along with Lipid Production by *Chlorella vulgaris*. *Journal of Environmental Management*, **308**; 114507

Brewster, E. T., G. Pozo, D. J. Batstone, S. Freguia, and P. Ledezma (2018). A Modelling Approach to Assess the Long-Term Stability of a Novel Microbial/Electrochemical System for the Treatment of Acid Mine Drainage. *RSC Advances*, **8**(33); 18682–18689

Budihardjo, M. A., Y. G. Wibowo, B. S. Ramadan, M. A. Serunting, and E. Yohana (2021). Mercury Removal using Modified Activated Carbon of Peat Soil and Coal in Simulated Landfill Leachate. *Environmental Technology & Innovation*, **24**; 102022

Bunce, N. J., M. Chartrand, and P. Keech (2001). Electrochemical Treatment of Acidic Aqueous Ferrous Sulfate and Copper Sulfate as Models for Acid Mine Drainage. *Water Research*, **35**(18); 4410–4416

Burman, N. W., C. M. Sheridan, and K. G. Harding (2019). Lignocellulosic Bioethanol Production from Grasses Pre-Treated with Acid Mine Drainage: Modeling and Comparison of SHF and SSF. *Bioresource Technology Reports*, **7**; 100299

Buzzi, D. C., L. S. Viegas, M. A. S. Rodrigues, A. M. Bernardes, and J. A. S. Tenório (2013). Water Recovery from Acid Mine Drainage by Electrodialysis. *Minerals Engineering*, **40**; 82–89

Bwapwa, J., A. Jaiyeola, and R. Chetty (2017). Bioremediation of Acid Mine Drainage using Algae Strains: A Review. *South African Journal of Chemical Engineering*, **24**; 62–70

Chai, Y., P. Qin, J. Zhang, T. Li, Z. Dai, and Z. Wu (2020). Simultaneous Removal of Fe(II) and Mn(II) from Acid Mine Wastewater by Electro-Fenton Process. *Process Safety and Environmental Protection*, **143**; 76–90

Chang, J., S. Deng, X. Li, Y. Li, J. Chen, and C. Duan (2022). Effective Treatment of Acid Mine Drainage by Constructed Wetland Column: Coupling Walnut Shell and its Biochar Product as the Substrates. *Journal of Water Process Engineering*, **49**; 103116

Chen, G., Y. Ye, N. Yao, N. Hu, J. Zhang, and Y. Huang (2021a). A Critical Review of Prevention, Treatment, Reuse, and Resource Recovery from Acid Mine Drainage. *Journal of Cleaner Production*, **329**; 129666

Chen, J., S. Deng, W. Jia, X. Li, and J. Chang (2021b). Removal of Multiple Heavy Metals from Mining-Impacted Water by Biochar-Filled Constructed Wetlands: Adsorption and Biotic Removal Routes. *Bioresource Technology*, **331**; 125061

Chen, Y., J. Long, S. Chen, Y. Xie, Z. Xu, Z. Ning, G. Zhang, T. Xiao, M. Yu, and Y. Ke (2022). Multi-Step Purification of Electrolytic Manganese Residue Leachate using Hydroxide Sedimentation, Struvite Precipitation, Chlorination and Coagulation: Advanced Removal of Manganese, Ammonium, and Phosphate. *Science of the Total Environment*, **805**; 150237

de Moraes, M. L. B. and A. C. Q. Ladeira (2021). The Role of Iron in the Rare Earth Elements and Uranium Scavenging by Fe–Al-Precipitates in Acid Mine Drainage. *Chemosphere*, **277**; 130131

Dean, A. P., S. Lynch, P. Rowland, B. D. Toft, J. K. Pittman, and K. N. White (2013). Natural Wetlands Are Efficient at Providing Long-Term Metal Remediation of Freshwater Systems Polluted by Acid Mine Drainage. *Environmental science & technology*, **47**(21); 12029–12036

Deepa, A., P. Prakash, and B. K. Mishra (2019). Performance of Biochar-Based Filtration Bed for the Removal of Cr(VI) from Pre-Treated Synthetic Tannery Wastewater. *Environmental Technology*, **42**; 257–269

Demers, I., M. Mbonimpa, M. Benzaazoua, M. Bouda, S. Awoh, S. Lortie, and M. Gagnon (2017). Use of Acid Mine Drainage Treatment Sludge by Combination with a Natural Soil as an Oxygen Barrier Cover for Mine Waste Reclamation: Laboratory Column Tests and Intermediate Scale Field Tests. *Minerals Engineering*, **107**; 43–52

Dev, S., S. Roy, and J. Bhattacharya (2016). Understanding the Performance of Sulfate Reducing Bacteria Based Packed Bed Reactor by Growth Kinetics Study and Microbial Profiling. *Journal of Environmental Management*, **177**; 101–110

Dlamini, C. L., L.-A. De Kock, K. K. Kefeni, B. B. Mamba, and T. A. M. Msagati (2019). Polymeric Ion Exchanger Supported Ferric Oxide Nanoparticles as Adsorbents for Toxic Metal Ions from Aqueous Solutions and Acid Mine Drainage. *Journal of Environmental Health Science and Engineering*, **17**; 719–730

Dong, S., X. Dou, D. Mohan, C. U. Pittman Jr, and J. Luo (2015). Synthesis of Graphene Oxide/Schwertmannite Nanocomposites and Their Application in Sb(V) Adsorption from Water. *Chemical Engineering Journal*, **270**; 205–214

Du, T., A. Bogush, O. Mašek, S. Purton, and L. C. Campos (2022). Algae, Biochar and Bacteria for Acid Mine Drainage (AMD) Remediation: A Review. *Chemosphere*; 135284

El Qada, E. N., S. J. Allen, and G. M. Walker (2006). Adsorption of Methylene Blue Onto Activated Carbon Produced from Steam Activated Bituminous Coal: A Study of Equilibrium Adsorption Isotherm. *Chemical Engineering Journal*, **124**(1-3); 103–110

Erdem, E., N. Karapinar, and R. Donat (2004). The Removal of Heavy Metal Cations by Natural Zeolites. *Journal of Colloid and Interface Science*, **280**(2); 309–314

Etale, A., D. Nhlane, and H. Richards (2021). Graphene Oxide Nanosheets for Treatment of Mine-Drainage Contaminated Water: The Effect of Phosphate Functionalisation on U(VI) Removal. *Materials Today: Proceedings*, **38**; 647–651

Etteieb, S., M. Zolfaghari, S. Magdouli, K. K. Brar, and S. K. Brar (2021). Performance of Constructed Wetland for Selenium, Nutrient and Heavy Metals Removal from Mine Effluents. *Chemosphere*, **281**; 130921

Evangelou, V. P. and Y. Zhang (1995). A Review: Pyrite Oxidation Mechanisms and Acid Mine Drainage Prevention. *Critical Reviews in Environmental Science and Technology*, **25**(2); 141–199

Falayi, T., F. Ntuli, and F. N. Okonta (2019). Desilication of Calcined Pulverised Fly Ash and Use of Silicate Solution to Prepare a Mesoporous Silica Adsorbent for Heavy Metals in Acid Mine Drainage. *International Journal of Environmental Technology and Management*, **22**(2-3); 155–176

Fazal, T., A. Razzaq, F. Javed, A. Hafeez, N. Rashid, U. S. Amjad, M. S. U. Rehman, A. Faisal, and F. Rehman (2020). Integrating Adsorption and Photocatalysis: A Cost Effective Strategy for Textile Wastewater Treatment using Hybrid Biochar-TiO_2 Composite. *Journal of Hazardous Materials*, **390**; 121623

Feng, G., J. Ma, X. Zhang, Q. Zhang, Y. Xiao, Q. Ma, and S. Wang (2019). Magnetic Natural Composite Fe_3O_4-Chitosan@ Bentonite for Removal of Heavy Metals from Acid Mine Drainage. *Journal of Colloid and Interface Science*, **538**; 132–141

Foo, K. Y. and B. H. Hameed (2011). The Environmental Applications of Activated Carbon/Zeolite Composite Materials. *Advances in Colloid and Interface Science*, **162**(1-2); 22–28

Foudhaili, T., O. Lefebvre, L. Coudert, and C. M. Neculita (2020). Sulfate Removal from Mine Drainage by Electrocoagulation as a Stand-Alone Treatment or Polishing Step. *Minerals Engineering*, **152**; 106337

Foudhaili, T., T. V. Rakotonimaro, C. M. Neculita, L. Coudert, and O. Lefebvre (2019). Comparative Efficiency of Microbial Fuel Cells and Electrocoagulation for the Treatment of Iron-Rich Acid Mine Drainage. *Journal of Environmental Chemical Engineering*, **7**(3); 103149

Gheju, M. and I. Balcu (2021). Sequential Abatement of FeII and CrVI Water Pollution by Use of Walnut Shell-Based Adsorbents. *Processes*, **9**(2); 218

Ghorbel-Abid, I. and M. Trabelsi-Ayadi (2015). Competitive Adsorption of Heavy Metals on Local Landfill Clay. *Arabian Journal of Chemistry*, **8**(1); 25–31

Gitari, M., L. Petrik, O. Etchebers, D. Key, E. Iwuoha, and C. Okujeni (2006). Treatment of Acid Mine Drainage with Fly Ash: Removal of Major Contaminants and Trace Elements. *Journal of Environmental Science and Health Part A*, **41**(8); 1729–1747

Gopalakrishnan, I., R. Sugaraj Samuel, and K. Sridharan (2018). Nanomaterials-Based Adsorbents for Water and Wastewater Treatments. *Emerging Trends of Nanotechnology* *in Environment and Sustainability: A Review-Based Approach*; 89–98

Gugushe, A. S., A. Nqombolo, and P. N. Nomngongo (2019). Application of Response Surface Methodology and Desirability Function in the Optimization of Adsorptive Remediation of Arsenic from Acid Mine Drainage using Magnetic Nanocomposite: Equilibrium Studies and Application to Real Samples. *Molecules*, **24**(9); 1792

Han, H., M. K. Rafiq, T. Zhou, R. Xu, O. Mašek, and X. Li (2019). A Critical Review of Clay-Based Composites with Enhanced Adsorption Performance for Metal and Organic Pollutants. *Journal of Hazardous Materials*, **369**; 780–796

Han, J. S., S.-H. Min, and Y.-K. Kim (2005). Removal of Phosphorus using AMD-Treated Lignocellulosic Material. *Forest Products Journal*, **55**(11); 48–53

Hermassi, M., M. Granados, C. Valderrama, C. Ayora, and J. L. Cortina (2022). Recovery of Rare Earth Elements from Acidic Mine Waters: An Unknown Secondary Resource. *Science of the Total Environment*, **810**; 152258

Hong, M., L. Yu, Y. Wang, J. Zhang, Z. Chen, L. Dong, Q. Zan, and R. Li (2019). Heavy Metal Adsorption with Zeolites: The Role of Hierarchical Pore Architecture. *Chemical Engineering Journal*, **359**; 363–372

Hou, D., J. Yu, and P. Wang (2019). Molecular Dynamics Modeling of the Structure, Dynamics, Energetics and Mechanical Properties of Cement-Polymer Nanocomposite. *Composites Part B: Engineering*, **162**; 433–444

Houchins, C., G. J. Kleen, J. S. Spendelow, J. Kopasz, D. Peterson, N. L. Garland, D. L. Ho, J. Marcinkoski, K. E. Martin, and R. Tyler (2012). US DOE Progress Towards Developing Low-Cost, High Performance, Durable Polymer Electrolyte Membranes for Fuel Cell Applications. *Membranes*, **2**(4); 855–878

Hu, X., H. Yang, K. Tan, S. Hou, J. Cai, X. Yuan, Q. Lan, J. Cao, and S. Yan (2022). Treatment and Recovery of Iron from Acid Mine Drainage: A Pilot-Scale Study. *Journal of Environmental Chemical Engineering*, **10**(1); 106974

Huang, A., D. Zhi, H. Tang, L. Jiang, S. Luo, and Y. Zhou (2020). Effect of Fe^{2+}, Mn^{2+} Catalysts on the Performance of Electro-Fenton Degradation of Antibiotic Ciprofloxacin, and Expanding the Utilizing of Acid Mine Drainage. *Science of the Total Environment*, **720**; 137560

Hussain, S. T. and S. A. K. Ali (2021). Removal of Heavy Metal by Ion Exchange using Bentonite Clay. *Journal of Ecological Engineering*, **22**(1); 104–111

Igarashi, T., P. S. Herrera, H. Uchiyama, H. Miyamae, N. Iyatomi, K. Hashimoto, and C. B. Tabelin (2020). The two-Step Neutralization Ferrite-Formation Process for Sustainable Acid Mine Drainage Treatment: Removal of Copper, Zinc and Arsenic, and the Influence of Coexisting Ions on Ferritization. *Science of the Total Environment*, **715**; 136877

Igberase, E., P. Osifo, and A. Ofomaja (2018). Mathematical Modelling of Pb^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Cr^{6+} and Cd^{2+} Ions Adsorption from a Synthetic Acid Mine Drainage Onto Chitosan Derivative in a Packed Bed Column. *Environmental Technology*, **39**(24); 3203–3220

Ighalo, J. O., S. B. Kurniawan, K. O. Iwuozor, C. O. Aniagor, O. J. Ajala, S. N. Oba, F. U. Iwuchukwu, S. Ahmadi, and C. A. Igwegbe (2022). A Review of Treatment Technologies for the Mitigation of the Toxic Environmental Effects of Acid Mine Drainage (AMD). *Process Safety and Environmental Protection*, **157**; 37–58

Jerez, J., A. C. Isaguirre, C. Bazán, L. D. Martinez, and S. Cerutti (2014). Determination of Scandium in Acid Mine Drainage by ICP-OES with Flow Injection On-Line Preconcentration using Oxidized Multiwalled Carbon Nanotubes. *Talanta*, **124**; 89–94

Ji, L., W. Chen, L. Duan, and D. Zhu (2009). Mechanisms for Strong Adsorption of Tetracycline to Carbon Nanotubes: A Comparative Study using Activated Carbon and Graphite as Adsorbents. *Environmental Science & Technology*, **43**(7); 2322–2327

Jiang, G. and X. Li (2020). *A New Paradigm for Environmental Chemistry and Toxicology*. Springer

Johnson, D. B., S. Rolfe, K. B. Hallberg, and E. Iversen (2001). Isolation and Phylogenetic Characterization of Acidophilic Microorganisms Indigenous to Acidic Drainage Waters at an Abandoned Norwegian Copper Mine. *Environmental Microbiology*, **3**(10); 630–637

José, L. B. and A. C. Q. Ladeira (2021). Recovery and Separation of Rare Earth Elements from an Acid Mine Drainage-Like Solution using a Strong Acid Resin. *Journal of Water Process Engineering*, **41**; 102052

Juve, J.-M. A., F. M. S. Christensen, Y. Wang, and Z. Wei (2022). Electrodialysis for Metal Removal and Recovery: A Review. *Chemical Engineering Journal*, **435**; 134857

Ka-ot, A. L. and S. R. Joshi (2022). Application of Acid and Heavy Metal Resistant Bacteria from Rat-Hole Coal Mines in Bioremediation Strategy. *Journal of Basic Microbiology*, **62**(3-4); 480–488

Kadirvelu, K., M. Kavipriya, C. Karthika, N. Vennilamani, and S. Pattabhi (2004). Mercury(II) Adsorption by Activated Carbon Made from Sago Waste. *Carbon*, **42**(4); 745–752

Kaur, G., S. J. Couperthwaite, B. W. Hatton-Jones, and G. J. Millar (2018). Alternative Neutralisation Materials for Acid Mine Drainage Treatment. *Journal of Water Process Engineering*, **22**; 46–58

Kefeni, K. K., T. A. Msagati, and B. B. Mamba (2017). Acid Mine Drainage: Prevention, Treatment Options, and Resource Recovery: A Review. *Journal of Cleaner Production*, **151**; 475–493

Keller, V., S. Stopić, B. Xakalashe, Y. Ma, S. Ndlovu, B. Mwewa, G. S. Simate, and B. Friedrich (2020). Effectiveness of Fly Ash and Red Mud as Strategies for Sustainable Acid Mine Drainage Management. *Minerals*, **10**(8); 707

Kesieme, U. K. and H. Aral (2015). Application of Membrane Distillation and Solvent Extraction for Water and Acid Recovery from Acidic Mining Waste and Process Solutions. *Journal of Environmental Chemical Engineering*, **3**(3); 2050–2056

Kim, J. Y., B. T. Lee, K. H. Shin, K. Y. Lee, K. W. Kim, K. G. An, Y. S. Park, J. Y. Kim, and Y. H. Kwon (2007). Ecological Health Assessment and Remediation of the Stream Impacted by Acid Mine Drainage of the Gwangyang Mine Area. *Environmental Monitoring and Assessment*, **129**; 79–85

Koohestani, B., A. K. Darban, E. Darezereshki, P. Mokhtari, E. Yilmaz, and E. Yilmaz (2018). The Influence of Sodium and Sulfate Ions on Total Solidification and Encapsulation Potential of Iron-Rich Acid Mine Drainage in Silica Gel. *Journal of Environmental Chemical Engineering*, **6**(2); 3520–3527

Kubilay, Ş., R. Gürkan, A. Savran, and T. Şahan (2007). Removal of Cu(II), Zn(II) and Co(II) Ions from Aqueous Solutions by Adsorption Onto Natural Bentonite. *Adsorption*, **13**; 41–51

Kumar, M. and K. Pakshirajan (2021). Continuous Removal and Recovery of Metals from Wastewater using Inverse Fluidized Bed Sulfidogenic Bioreactor. *Journal of Cleaner Production*, **284**; 124769

Kurniawan, S. B., S. R. S. Abdullah, M. F. Imron, A. Ahmad, N. S. Mohd Said, N. F. Mohd Rahim, M. Mohammad Alnawajha, H. Abu Hasan, A. R. Othman, and I. F. Purwanti (2021). Potential of Valuable Materials Recovery from Aquaculture Wastewater: An Introduction to Resource Reclamation. *Aquaculture Research*, **52**(7); 2954–2962

Lachowicz, J. I., G. R. Delpiano, D. Zanda, M. Piludu, E. Sanjust, M. Monduzzi, and A. Salis (2019). Adsorption of Cu^{2+} and Zn^{2+} on SBA-15 Mesoporous Silica Functionalized with Triethylenetetramine Chelating Agent. *Journal of Environmental Chemical Engineering*, **7**(4); 103205

Lee, G., J. Han, M. Jang, and M. Kim (2022a). Long-Term Treatment of Acid Mine Drainage by Alkali Diffusion Ceramic Reactor: Simultaneous Metal Removal Mechanisms. *Chemosphere*, **298**; 134186

Lee, Y., Y. Ren, M. Cui, Y. Zhou, O. Kwon, J. Ko, and J. Khim (2022b). Arsenic Adsorption Study in Acid Mine Drainage using Fixed Bed Column by Novel Beaded Adsorbent. *Chemosphere*, **291**; 132894

Li, Q. and W. Zhang (2022). Process Development for Recovering Critical Elements from Acid Mine Drainage. *Resources, Conservation and Recycling*, **180**; 106214

Li, R., Y. Liu, G. Lan, H. Qiu, B. Xu, Q. Xu, N. Sun, and L. Zhang (2021). Pb(II) Adsorption Characteristics of Magnetic GO-Hydroxyapatite and the Contribution of GO to Enhance its Acid Resistance. *Journal of Environmental Chemical Engineering*, **9**(4); 105310

Li, W., Q. Zhou, and T. Hua (2010). Removal of Organic Matter from Landfill Leachate by Advanced Oxidation Processes: A Review. *International Journal of Chemical Engineering*, **2010**

Li, Y., M. Yue, J. Ye, T. Xu, and Y. Liu (2019). Walnut Shell Powder Can Limit Acid Mine Drainage Formation by Shaping the Bacterial Community Structure. *Current Microbiology*, **76**; 1199–1206

Li, Z., Z. Ma, T. J. van der Kuijp, Z. Yuan, and L. Huang (2014). A Review of Soil Heavy Metal Pollution from Mines in China: Pollution and Health Risk Assessment. *Science of the Total Environment*, **468**; 843–853

Liao, J., Z. Wen, X. Ru, J. Chen, H. Wu, and C. Wei (2016). Distribution and Migration of Heavy Metals in Soil and Crops Affected by Acid Mine Drainage: Public Health Implications in Guangdong Province, China. *Ecotoxicology and Environmental Safety*, **124**; 460–469

Liu, H., H. Guo, O. Pourret, Z. Wang, M. Liu, W. Zhang, Z. Li, B. Gao, Z. Sun, and P. Laine (2022a). Geochemical Signatures of Rare Earth Elements and Yttrium Exploited by Acid Solution Mining Around an Ion-Adsorption Type Deposit: Role of Source Control and Potential for Recovery. *Science of the Total Environment*, **804**; 150241

Liu, W., Y. Zhao, X. Hu, X. Li, M. Zhang, Z. Geng, Q. Wang, W. Cheng, and Y. Dong (2022b). A Combined Electrodialysis and Coal Dust Suppression System for Acid Mine Drainage Treatment and High Mechanical Hydrogel Dust Suppressant Generation. *Water Cycle*, **3**; 126–132

Liu, Z. R. and S. Q. Zhou (2010). Adsorption of Copper and Nickel on Na-Bentonite. *Process Safety and Environmental Protection*, **88**(1); 62–66

Lizama-Allende, K., J. Ayala, I. Jaque, and P. Echeverría (2021). The Removal of Arsenic and Metals from Highly Acidic Water in Horizontal Subsurface Flow Constructed Wetlands with Alternative Supporting Media. *Journal of Hazardous Materials*, **408**; 124832

López, J., M. Reig, O. Gibert, E. Torres, C. Ayora, and J.-L. Cortina (2018). Application of Nanofiltration for Acidic Waters Containing Rare Earth Elements: Influence of Transition Elements, Acidity and Membrane Stability. *Desalination*, **430**; 33–44

Lu, J., L. Alakangas, Y. Jia, and J. Gotthardsson (2013). Evaluation of the Application of Dry Covers Over Carbonate-Rich Sulphide Tailings. *Journal of Hazardous Materials*, **244**; 180–194

Luís, A., P. Teixeira, S. Almeida, L. Ector, J. Matos, and E. Ferreira da Silva (2009). Impact of Acid Mine Drainage (AMD) on Water Quality, Stream Sediments and Periphytic Diatom Communities in the Surrounding Streams of Aljustrel Mining Area (Portugal). *Water, Air, and Soil Pollution*, **200**; 147–167

Lyu, H., J. Tang, M. Cui, B. Gao, and B. Shen (2020). Biochar/Iron (BC/Fe) Composites for Soil and Groundwater Remediation: Synthesis, Applications, and Mechanisms. *Chemosphere*, **246**; 125609

Machodi, M. J. and M. O. Daramola (2019). Synthesis and Performance Evaluation of PES/Chitosan Membranes Coated with Polyamide for Acid Mine Drainage Treatment. *Scientific Reports*, **9**(1); 1–14

Machodi, M. J. and M. O. Daramola (2020). Synthesis of PES and PES/Chitosan Membranes for Synthetic Acid Mine Drainage Treatment. *Water SA*, **46**(1); 114–122

Magowo, E., C. Sheridan, and K. Rumbold (2023). Fermentable Sugars as Bioprocessing Feedstocks from Lignocellulosic Biomass Pretreated with Acid Mine Drainage. In

Advances in Lignocellulosic Biofuel Production Systems. Elsevier, pages 161–178

Mäkitalo, M., C. Maurice, Y. Jia, and B. Öhlander (2014). Characterization of Green Liquor Dregs, Potentially Useful for Prevention of the Formation of Acid Rock Drainage. *Minerals*, **4**(2); 330–344

Manohar, D., B. Noeline, and T. Anirudhan (2006). Adsorption Performance of Al-Pillared Bentonite Clay for the Removal of Cobalt(II) from Aqueous Phase. *Applied Clay Science*, **31**(3-4); 194–206

Mariana, M., A. K. HPS, E. Mistar, E. B. Yahya, T. Alfatah, M. Danish, and M. Amayreh (2021). Recent Advances in Activated Carbon Modification Techniques for Enhanced Heavy Metal Adsorption. *Journal of Water Process Engineering*, **43**; 102221

Martí-Calatayud, M. C., D. C. Buzzi, M. García-Gabaldón, E. Ortega, A. Bernardes, J. A. S. Tenório, and V. Pérez-Herranz (2014). Sulfuric Acid Recovery from Acid Mine Drainage by Means of Electrodialysis. *Desalination*, **343**; 120–127

Martínez-Macias, M. d. R., M. A. Correa Murrieta, Y. Villegas Peralta, G. E. Dévora Isiordia, J. Álvarez Sánchez, J. Saldivar Cabrales, and R. G. Sánchez Duarte (2019). Uptake of Copper from Acid Mine Drainage by the Microalgae Nannochloropsis Oculata. *Environmental Science and Pollution Research*, **26**; 6311–6318

Matsumoto, S., H. Shimada, T. Sasaoka, G. J. Kusuma, and R. S. Gautama (2016). Construction of Dry Cover System for Prevention of Acid Mine Drainage at Mine Waste Dump in Open Cast Coal Mines, Indonesia. *Journal of Environmental Protection*, **7**(02); 160

Menzel, K., L. Barros, A. Garcia, R. Ruby Figueroa, and H. Estay (2021). Metal Sulfide Precipitation Coupled with Membrane Filtration Process for Recovering Copper from Acid Mine Drainage. *Separation and Purification Technology*, **270**; 118721

Mkandawire, M. (2020). Opportunities and Challenges of Re-Mining Mine Water for Resources. *Recovery of Byproducts from Acid Mine Drainage Treatment*; 315–350

Mohan, D. and S. Chander (2001). Single Component and Multi-Component Adsorption of Metal Ions by Activated Carbons. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **177**(2-3); 183–196

Moncur, M. C., C. J. Ptacek, M. B. Lindsay, D. W. Blowes, and J. L. Jambor (2015). Long-Term Mineralogical and Geochemical Evolution of Sulfide Mine Tailings Under a Shallow Water Cover. *Applied Geochemistry*, **57**; 178–193

Moreno-Barbosa, J. J., C. López-Velandia, A. d. P. Maldonado, L. Giraldo, and J. C. Moreno-Piraján (2013). Removal of Lead(II) and Zinc(II) Ions from Aqueous Solutions by Adsorption Onto Activated Carbon Synthesized from Watermelon Shell and Walnut Shell. *Adsorption*, **19**; 675–685

Motsi, T., N. Rowson, and M. Simmons (2009). Adsorption of Heavy Metals from Acid Mine Drainage by Natural Zeolite. *International Journal of Mineral Processing*, **92**(1-2); 42–48

Muedi, K. L., H. G. Brink, V. Masindi, and J. Maree (2021). Effective Removal of Arsenate from Wastewater using Aluminium Enriched Ferric Oxide-Hydroxide Recovered from Authentic Acid Mine Drainage. *Journal of Hazardous Materials*, **414**; 125491

Muhammad, S. N., F. M. Kusin, M. S. Md Zahar, F. Mohamat Yusuff, and N. Halimoon (2017). Passive Bioremediation Technology Incorporating Lignocellulosic Spent Mushroom Compost and Limestone for Metal-and Sulfate-Rich Acid Mine Drainage. *Environmental Technology*, **38**(16); 2003–2012

Nariyan, E., C. Wolkersdorfer, and M. Sillanpää (2018). Sulfate Removal from Acid Mine Water from the Deepest Active European Mine by Precipitation and Various Electrocoagulation Configurations. *Journal of Environmental Management*, **227**; 162–171

Neculita, C. M. and E. Rosa (2019). A Review of the Implications and Challenges of Manganese Removal from Mine Drainage. *Chemosphere*, **214**; 491–510

Nishimoto, N., Y. Yamamoto, S. Yamagata, T. Igarashi, and S. Tomiyama (2021). Acid Mine Drainage Sources and Impact on Groundwater at the Osarizawa Mine, Japan. *Minerals*, **11**(9); 998

Nunez-Gomez, D., C. Rodrigues, F. R. Lapolli, and M. A. Lobo-Recio (2019). Adsorption of Heavy Metals from Coal Acid Mine Drainage by Shrimp Shell Waste: Isotherm and Continuous-Flow Studies. *Journal of Environmental Chemical Engineering*, **7**(1); 102787

Oberholzer, M. M., P. J. Oberholster, L. L. Ndlela, A. M. Botha, and J. C. Truter (2022). Assessing Alternative Supporting Organic Materials for the Enhancement of Water Reuse in Subsurface Constructed Wetlands Receiving Acid Mine Drainage. *Recycling*, **7**(3); 41

Oliva, J., J. Cama, J. Cortina, C. Ayora, and J. De Pablo (2012). Biogenic Hydroxyapatite (Apatite II™) Dissolution Kinetics and Metal Removal from Acid Mine Drainage. *Journal of Hazardous Materials*, **213**; 7–18

Oncel, M., A. Muhcu, E. Demirbas, and M. Kobya (2013). A Comparative Study of Chemical Precipitation and Electrocoagulation for Treatment of Coal Acid Drainage Wastewater. *Journal of Environmental Chemical Engineering*, **1**(4); 989–995

Orakwue, E. O., V. Asokbunyarat, E. R. Rene, P. N. Lens, and A. Annachhatre (2016). Adsorption of Iron(II) from Acid Mine Drainage Contaminated Groundwater using Coal Fly Ash, Coal Bottom Ash, and Bentonite Clay. *Water, Air, & Soil Pollution*, **227**; 1–12

Outram, J. G., S. J. Couperthwaite, and G. J. Millar (2018). Enhanced Removal of High Mn(II) and Minor Heavy Metals from Acid Mine Drainage using Tunnelled Manganese Oxides. *Journal of Environmental Chemical Engineering*, **6**(2); 3249–3261

Park, I., C. B. Tabelin, S. Jeon, X. Li, K. Seno, M. Ito, and N. Hiroyoshi (2019). A Review of Recent Strategies for Acid Mine Drainage Prevention and Mine Tailings Recycling. *Chemosphere*, **219**; 588–606

Pat-Espadas, A. M., R. Loredo Portales, L. E. Amabilis-Sosa, G. Gómez, and G. Vidal (2018). Review of Constructed Wetlands for Acid Mine Drainage Treatment. *Water*, **10**(11); 1685

Pino, L., C. Vargas, A. Schwarz, and R. Borquez (2018). Influence of Operating Conditions on the Removal of Metals and Sulfate from Copper Acid Mine Drainage by Nanofiltration. *Chemical Engineering Journal*, **345**; 114–125

Qian, G., R. C. Schumann, J. Li, M. D. Short, R. Fan, Y. Li, N. Kawashima, Y. Zhou, R. S. C. Smart, and A. R. Gerson (2017). Strategies for Reduced Acid and Metalliferous Drainage by Pyrite Surface Passivation. *Minerals*, **7**(3); 42

Qiu, X.-j., T. Jia, T. Jun, H.-p. Hu, X.-b. Ji, and J.-g. Hu (2021). Selective Recovery of Cu(II) Through Polymer Inclusion Membranes Mediated with 2-Aminomethylpyridine Derivatives. *Transactions of Nonferrous Metals Society of China*, **31**(11); 3591–3601

Qu, Z., F. Sun, X. Liu, J. Gao, Z. Qie, and G. Zhao (2018). The Effect of Nitrogen-Containing Functional Groups on SO_2 Adsorption on Carbon Surface: Enhanced Physical Adsorption Interactions. *Surface Science*, **677**; 78–82

Quatrini, R. and D. B. Johnson (2018). Microbiomes in Extremely Acidic Environments: Functionalities and Interactions that Allow Survival and Growth of Prokaryotes at Low pH. *Current Opinion in Microbiology*, **43**; 139–147

Radić, S., V. Vujčić, Ž. Cvetković, P. Cvjetko, and V. Oreščanin (2014). The Efficiency of Combined CaO/Electrochemical Treatment in Removal of Acid Mine Drainage Induced Toxicity and Genotoxicity. *Science of the Total Environment*, **466**; 84–89

Rahimi, E. and N. Mohaghegh (2017). New Hybrid Nanocomposite of Copper Terephthalate MOF-Graphene Oxide: Synthesis, Characterization and Application as Adsorbents for Toxic Metal Ion Removal from Sungun Acid Mine Drainage. *Environmental Science and Pollution Research*, **24**; 22353–22360

Ramasamy, D. L., V. Puhakka, S. Iftekhar, A. Wojtuś, E. Repo, S. B. Hammouda, E. Iakovleva, and M. Sillanpää (2018). N- and O-Ligand Doped Mesoporous Silica-Chitosan Hybrid Beads for the Efficient, Sustainable and Selective Recovery of Rare Earth Elements (REE) from Acid Mmine Drainage (AMD): Understanding the Significance of Physical Modification and Conditioning of the Polymer. *Journal of Hazardous Materials*, **348**; 84–91

Rambabu, K., F. Banat, Q. M. Pham, S. H. Ho, N. Q. Ren, and P. L. Show (2020). Biological Remediation of Acid Mine Drainage: Review of Past Trends and Current Outlook. *Environmental Science and Ecotechnology*, **2**; 100024

Ramokgopa, S. K., K. Sikhwivhilu, R. M. Moutloali, and K. Moothi (2021). Process Optimisation Through Response Surface Methodology for Treatment of Acid Mine Drainage using Carbon Nanotubes-Infused thin Film Nanocomposite Membranes. *Physics and Chemistry of the Earth, Parts A/B/C*, **124**; 103008

Rao, R. A. K. and M. Kashifuddin (2016). Adsorption Studies of Cd(II) on Ball Clay: Comparison with Other Natural Clays. *Arabian Journal of Chemistry*, **9**; S1233–S1241

Ren, K., J. Zeng, J. Liang, D. Yuan, Y. Jiao, C. Peng, and X. Pan (2021). Impacts of Acid Mine Drainage on Karst Aquifers: Evidence from Hydrogeochemistry, Stable Sulfur and Oxygen Isotopes. *Science of the Total Environment*, **761**; 143223

Rios, C. A., C. D. Williams, and C. L. Roberts (2008). Removal of Heavy Metals from Acid Mine Drainage (AMD) using Coal Fly Ash, Natural Clinker and Synthetic Zeolites. *Journal of Hazardous Materials*, **156**(1-3); 23–35

Robinson-Lora, M. A. and R. A. Brennan (2011). Anaerobic Precipitation of Manganese and Co-Existing Metals in Mine Impacted Water Treated with Crab Shell-Associated Minerals. *Applied Geochemistry*, **26**(5); 853–862

Rodríguez, C., C. Tapia, E. Leiva-Aravena, and E. Leiva (2020). Graphene Oxide–ZnO Nanocomposites for Removal of Aluminum and Copper Ions from Acid Mine Drainage Wastewater. *International Journal of Environmental Research and Public Health*, **17**(18); 6911

Rose, P., G. Boshoff, R. Van Hille, L. Wallace, K. Dunn, and J. Duncan (1998). An Integrated Algal Sulphate Reducing High Rate Ponding Process for the Treatment of Acid Mine Drainage Wastewaters. *Biodegradation*, **9**; 247–257

Ryu, S., G. Naidu, M. A. H. Johir, Y. Choi, S. Jeong, and S. Vigneswaran (2019). Acid Mine Drainage Treatment by Integrated Submerged Membrane Distillation–Sorption System. *Chemosphere*, **218**; 955–965

Ryu, S., G. Naidu, H. Moon, and S. Vigneswaran (2020). Selective Copper Recovery by Membrane Distillation and Adsorption System from Synthetic Acid Mine Drainage. *Chemosphere*, **260**; 127528

Sabina, R.-O., E. S. Santos, and M. M. Abreu (2019). Accumulation of Mn and Fe in Aromatic Plant Species from the Abandoned Rosalgar Mine and Their Potential Risk to Human Health. *Applied Geochemistry*, **104**; 42–50

Sahoo, P., S. Tripathy, M. Panigrahi, and S. M. Equeenuddin (2013). Evaluation of the Use of an Alkali Modified Fly Ash as a Potential Adsorbent for the Removal of Metals from Acid Mine Drainage. *Applied Water Science*, **3**; 567–576

Shen, C., G. Zhang, K. Li, and C. Yang (2022). A Pathway of the Generation of Acid Mine Drainage and Release of Arsenic in the Bioleaching of Orpiment. *Chemosphere*, **298**; 134287

Shi, M., X. Min, C. Tian, T. Hao, S. Zhu, Y. Ge, Q. Wang, X. Yan, and Z. Lin (2022). Mechanisms of Pb(II) Coprecipitation with Natrojarosite and its Behavior During Acid Dissolution. *Journal of Environmental Sciences*, **122**; 128–137

Shin, E., J. Han, and S. Min (2004). Removal of Phosphorus from Water using Lignocellulosic Material Modified with Iron Species from Acid Mine Drainage. *Environmental Technology*, **25**(2); 185–191

Sibrell, P. and T. Tucker (2012). Fixed Bed Sorption of Phosphorus from Wastewater using Iron Oxide-Based Media Derived from Acid Mine Drainage. *Water, Air, & Soil Pollu-*

tion, **223**; 5105–5117

Silva, T. L., S. Morales-Torres, C. M. Esteves, A. R. Ribeiro, O. C. Nunes, J. L. Figueiredo, and A. M. Silva (2018). Desalination and Removal of Organic Micropollutants and Microorganisms by Membrane Distillation. *Desalination*, **437**; 121–132

Singh, S. and S. Chakraborty (2020). Performance of Organic Substrate Amended Constructed Wetland Treating Acid Mine Drainage (AMD) of North-Eastern India. *Journal of Hazardous Materials*, **397**; 122719

Singh, S. and S. Chakraborty (2021). Bioremediation of Acid Mine Drainage in Constructed Wetlands: Aspect of Vegetation (*Typha latifolia*), Loading Rate and Metal Recovery. *Minerals Engineering*, **171**; 107083

Street, F. (2016). Removal of Fe, Zn and Mn Ions from Acidic Mine Drainage using Hydroxyapatite. *Journal of Environmental Protection and Ecology*, **17**(4); 1472–1480

Stylianou, M., E. Montel, A. Zissimos, I. Christoforou, K. Dermentzis, and A. Agapiou (2022). Removal of Toxic Metals and Anions from Acid Mine Drainage (AMD) by Electrocoagulation: The Case of North Mathiatis Open Cast Mine. *Sustainable Chemistry and Pharmacy*, **29**; 100737

Sun, M., X.-R. Ru, and L.-F. Zhai (2015a). In-Situ Fabrication of Supported Iron Oxides from Synthetic Acid Mine Drainage: High Catalytic Activities and Good Stabilities Towards Electro-Fenton Reaction. *Applied Catalysis B: Environmental*, **165**; 103–110

Sun, M., W. Song, L. F. Zhai, X. R. Ru, and Y. Z. Cui (2013). Elucidating Electro-Oxidation Kinetics of Fe(II) in the Anode of Air–Cathode Fuel Cells from an Fe(II) Speciation Perspective. *Chemical Engineering Journal*, **228**; 781–789

Sun, M., N. N. Wu, L. F. Zhai, and X. R. Ru (2015b). Manipulate an Air–Cathode Fuel Cell Toward Recovering Highly Active Heterogeneous Electro-Fenton Catalyst from the Fe(II) in Acid Mine Drainage. *Minerals Engineering*, **84**; 1–7

Sun, Y. M., L. F. Zhai, M. F. Duan, and M. Sun (2018). In Situ Fabrication of Electro-Fenton Catalyst from Fe^{2+} in Acid Mine Drainage: Influence of Coexisting Metal Cations. *ACS Sustainable Chemistry & Engineering*, **6**(11); 14154–14161

Tabelin, C. B., R. D. Corpuz, T. Igarashi, M. Villacorte-Tabelin, R. D. Alorro, K. Yoo, S. Raval, M. Ito, and N. Hiroyoshi (2020). Acid Mine Drainage Formation and Arsenic Mobility Under Strongly Acidic Conditions: Importance of Soluble Phases, Iron Oxyhydroxides/Oxides and Nature of Oxidation Layer on Pyrite. *Journal of Hazardous Materials*, **399**; 122844

Thakur, A. K., R. Kumar, P. Chaudhari, and R. Shankar (2021). Removal of Heavy Metals using Bentonite Clay and Inorganic Coagulants. *Removal of Emerging Contaminants Through Microbial Processes*; 47–69

Thomas, G., C. Sheridan, and P. E. Holm (2022). A Critical Review of Phytoremediation for Acid Mine Drainage-Impacted Environments. *Science of the Total Environment*, **811**; 152230

Tolvanen, A., P. Eilu, A. Juutinen, K. Kangas, M. Kivinen, M. Markovaara-Koivisto, A. Naskali, V. Salokannel, S. Tuulentie, and J. Similä (2019). Mining in the Arctic Environment–A Review from Ecological, Socioeconomic and Legal Perspectives. *Journal of Environmental Management*, **233**; 832–844

Tong, L., R. Fan, S. Yang, and C. Li (2021). Development and Status of the Treatment Technology for Acid Mine Drainage. *Mining, Metallurgy & Exploration*, **38**; 315–327

Tu, Z., J. Wan, C. Guo, C. Fan, T. Zhang, G. Lu, J. R. Reinfelder, and Z. Dang (2017). Electrochemical Oxidation of Pyrite in pH 2 Electrolyte. *Electrochimica Acta*, **239**; 25–35

Vasquez, Y., C. M. Neculita, G. Caicedo, J. Cubillos, J. Franco, M. Vásquez, A. Hernández, and F. Roldan (2022). Passive Multi-Unit Field-Pilot for Acid Mine Drainage Remediation: Performance and Environmental Assessment of Post-Treatment Solid Waste. *Chemosphere*, **291**; 133051

Verplanck, P. L., D. K. Nordstrom, H. E. Taylor, and B. A. Kimball (2004). Rare Earth Element Partitioning Between Hydrous Ferric Oxides and Acid Mine Water During Iron Oxidation. *Applied Geochemistry*, **19**(8); 1339–1354

Vital, B., J. Bartacek, J. Ortega-Bravo, and D. Jeison (2018). Treatment of Acid Mine Drainage by Forward Osmosis: Heavy Metal Rejection and Reverse Flux of Draw Solution Constituents. *Chemical Engineering Journal*, **332**; 85–91

Wang, H., M. Zhang, J. Xue, Q. Lv, J. Yang, and X. Han (2021a). Performance and Microbial Response in a Multi-Stage Constructed Wetland Microcosm Co-Treating Acid Mine Drainage and Domestic Wwastewater. *Journal of Environmental Chemical Engineering*, **9**(6); 106786

Wang, J. and X. Guo (2020). Adsorption Isotherm Models: Classification, Physical Meaning, Application and Solving Method. *Chemosphere*, **258**; 127279

Wang, Y., Y. He, A. Gong, L. Qiu, M. Zhang, M. Traore, X. Zhan, Y. Li, Y. Bai, and Y. Liu (2023). Selective Recovery of Rare Earth Metals from Acid Mine Drainage by Pyrrolidinediglycolamide Silica Column. *Journal of Environmental Chemical Engineering*; 110091

Wang, Y., J. Wang, Z. Li, H. Wang, X. He, and C. Wang (2021b). A Novel Method Based on Membrane Distillation for Treating Acid Mine Drainage: Recovery of Water and Utilization of Iron. *Chemosphere*, **279**; 130605

Wibowo, Y., D. Muhammad, M. Naswir, and B. Muljadi (2020). Low-Cost Modified Reactor to Produce Biochar and Clamshell as Alternative Materials from Acid Mine Drainage Problem Solving. In *IOP Conference Series: Earth and Environmental Science*, volume 483. IOP Publishing, page 012031

Wibowo, Y. G., M. Naswir, and B. S. Ramadan (2022a). Performance of a Novel Biochar-Clamshell Composite for Real Acid Mine Drainage Treatment. *Bioresource Technology Reports*, **17**; 100993

Wibowo, Y. G., A. T. Nugraha, and A. Rohman (2023a). Phytoremediation of Several Wastewater Sources using *Pistia stratiotes* and *Eichhornia crassipes* in Indonesia. *Environmental Nanotechnology, Monitoring & Management*; 100781

Wibowo, Y. G., B. S. Ramadan, S. Sudibyo, H. Safitri,

A. Rohman, and H. Syarifuddin (2023b). Efficient Remediation of Acid Mine Drainage Through Sustainable and Economical Biochar-CaO Composite derived from solid waste. *Environment, Development and Sustainability*; 1–24

Wibowo, Y. G., H. Safitri, I. B. I. Malik, and S. Priyanto (2022b). Alternative Low-Cost Treatment for Real Acid Mine Drainage: Performance, Bioaccumulation, Translocation, Economic, Post-Harvest, and Bibliometric Analyses. *Sustainability*, **14**(22); 15404

Wibowo, Y. G., H. Safitri, and B. S. Ramadan (2022c). Adsorption Test using Ultra-Fine Materials on Heavy Metals Removal. *Bioresource Technology Reports*, **19**; 101149

Wilfong, W. C., T. Ji, Y. Duan, F. Shi, Q. Wang, and M. L. Gray (2022). Critical Review of Functionalized Silica Sorbent Strategies for Selective Extraction of Rare Earth Elements from Acid Mine Drainage. *Journal of Hazardous Materials*, **424**; 127625

Win, T. S., S. Dwiki, S. Mastumoto, and G. J. Kusuma (2020). Application of Fly Ash and Organic Material as Dry Cover System in Prevention of Acid Mine Drainage Generation. *Journal of Geoscience and Environment Protection*, **8**(5); 56–64

Wingenfelder, U., B. Nowack, G. Furrer, and R. Schulin (2005). Adsorption of Pb and Cd by Amine-Modified Zeolite. *Water Research*, **39**(14); 3287–3297

Wu, S., P. Kuschk, A. Wiessner, J. Müller, R. A. Saad, and R. Dong (2013). Sulphur Transformations in Constructed Wetlands for Wastewater Treatment: A Review. *Ecological Engineering*, **52**; 278–289

Wu, S., J. Vymazal, and H. Brix (2019). Critical Review: Biogeochemical Networking of Iron in Constructed Wetlands for Wastewater Treatment. *Environmental Science & Technology*, **53**(14); 7930–7944

Xin, R., J. F. Banda, C. Hao, H. Dong, L. Pei, D. Guo, P. Wei, Z. Du, Y. Zhang, and H. Dong (2021). Contrasting Seasonal Variations of Geochemistry and Microbial Community in Two Adjacent Acid Mine Drainage Lakes in Anhui Province, China. *Environmental Pollution*, **268**; 115826

Yang, J. S., M. J. Kwon, Y. T. Park, and J. Choi (2015). Adsorption of Arsenic from Aqueous Solutions by Iron Oxide Coated Sand Fabricated with Acid Mine Drainage. *Separation Science and Technology*, **50**(2); 267–275

Yu, W. H., N. Li, D. S. Tong, C. H. Zhou, C. X. C. Lin, and C. Y. Xu (2013). Adsorption of Proteins and Nucleic Acids on Clay Minerals and Their Interactions: A Review. *Applied Clay Science*, **80**; 443–452

Zeng, S., J. Li, R. Schumann, and R. Smart (2013). Effect of pH and Dissolved Silicate on the Formation of Surface Passivation Layers for Reducing Pyrite Oxidation. *Computational Water, Energy, and Environmental Engineering*, **2**(02); 50

Zhai, L.-F., Y.-M. Sun, H.-Y. Guo, and M. Sun (2019). Surface Modification of Graphite Support as an Effective Strategy to Enhance the Electro-Fenton Activity of Fe_3O_4/Graphite Composites In Situ Fabricated from Acid Mine Drainage using an Air-Cathode Fuel Cell. *ACS Sustainable Chemistry & Engineering*, **7**(9); 8367–8374

Zhai, L.-F., Z.-H. Tong, M. Sun, W. Song, S. Jin, and H. Harada (2013). Enhanced Electricity Generation from Electrochemical Oxidation of FeII in an Air–Cathode Fuel Cell Amended with Chelating Anions. *Industrial & Engineering Chemistry Research*, **52**(6); 2234–2240

Zhan, X., L. Xiao, and B. Liang (2019). Removal of Pb II) from Acid Mine Drainage with Bentonite-Steel Slag Composite Particles. *Sustainability*, **11**(16); 4476

Zhang, D., R. Cao, Y. Song, Y. Wang, P. Zhang, Y. Wang, F. Xiao, S. Wang, and Y. Jia (2022). Molecular Structures of Dissolved and Colloidal AsV–FeIII Complexes and Their Roles in the Mobilization of AsV Under Strongly Acidic Conditions. *Journal of Hazardous Materials*, **430**; 128266

Zhao, H., B. Xia, J. Qin, and J. Zhang (2012). Hydrogeochemical and Mineralogical Characteristics Related to Heavy Metal Attenuation in a Stream Polluted by Acid Mine Drainage: A Case Study in Dabaoshan Mine, China. *Journal of Environmental Sciences*, **24**(6); 979–989

Zubair, A., N. Abdullah, R. Ibrahim, and A. Rachma (2020). Effectivity of Constructed Wetland using *Typha angustifolia* in Analyzing the Decrease of Heavy Metal (Fe) in Acid Mine Drainage. In *IOP Conference Series: Earth and Environmental Science*, volume 419. IOP Publishing, page 012160

