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# A SYSTEMATIC REVIEW ON THE USE OF COVERS FOR ACID MINE DRAINAGE CONTROL

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# A SYSTEMATIC REVIEW ON THE USE OF COVERS FOR ACID MINE DRAINAGE CONTROL

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## RESUMO

Neves, Arthur Couto. **A Systematic Review on the Use Of Covers For Acid Mine Drainage Control**. 2024. 36f. Monografia (MBA em Gestão de Áreas Contaminadas, Desenvolvimento Urbano Sustentável e Revitalização de Brownfields) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2024.

As atividades de mineração têm um impacto significativo na alteração da qualidade das águas subterrâneas e superficiais, levando a desafios ambientais. Uma das principais fontes de contaminação é a Drenagem Ácida de Mina (DAM), que resulta da exposição de sulfetos à água e ao oxigênio, levando a níveis elevados de sulfato ferroso e íons de hidrogênio. Umas das formas de controle para DAM, é a redução da interação dos minerais sulfetados com a água ou o ar e limitar a atividade microbiana, com estratégias como barreiras de oxigênio sendo amplamente adotadas em todo o mundo. Assim, este trabalho tem como objetivo fornecer, por meio de uma revisão sistemática da literatura, uma análise do uso mundial de coberturas para o controle da DAM. Foi constatado que os principais materiais de cobertura utilizados são resíduos alcalinos industriais, especialmente resíduos de fábricas de papel. Além disso, a maioria dos estudos foi elaborada na Europa e na América, com o Canadá e a Suécia sendo as principais origens desses trabalhos. Não apenas resíduos industriais estão sendo usados, mas também resíduos das atividades de mineração; esses materiais de cobertura têm ambas as características de implementações de baixo custo. A maioria dos estudos ainda se concentra em testes de laboratório, o que mostra que mais trabalhos in situ devem ser realizados para validar as proposições publicadas. Por fim, poucos autores relataram avaliações de longo prazo, destacando outra lacuna na literatura sobre estratégias de mitigação da DAM, mostrando a necessidade de avaliações de longo prazo, incluindo a reação da cobertura à variabilidade climática.



**Keywords**: mining contamination, acid mine drainage, prevention techniques.

**ABSTRACT**

Neves, Arthur Couto. **A Systematic Review on the Use Of Covers For Acid Mine Drainage Control**. 2024. 36f. Monografia (MBA em Gestão de Áreas Contaminadas, Desenvolvimento Urbano Sustentável e Revitalização de Brownfields) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2024.

Mining activities have a significant impact on groundwater and surface water quality, leading to environmental challenges. One major source of contamination is the Acid Mine Drainage (AMD), a, results from sulfide exposure to water and oxygen, leading to elevated sulfate, ferrous iron, and hydrogen ion levels. To control AMD, reducing sulfide mineral interaction with water or air and limiting microbial activity is crucial, with strategies like oxygen barriers being widely adopted worldwide. Thus, this paper aims to provide, through a short literature review, an analysis of the worldwide usage of covers for ADM control. It was found that the main cover materials being utilized are industrial alkaline waste, specially wastes from paper mills. Also, most of the studies were elaborated in Europe and America with Canada and Sweden the main origin of these works. Not only industrial wastes are being used but also and wastes from mining activities, these cover materials both have the characteristics of low-cost implementations. Most of the studies still focus on laboratory tests, this shows that more works *in situ* should be performed the validate the propositions published. Finally, few studies reported long term evaluations, this highlighted another gap in the literature on AMD mitigation strategies, showing the need to long-term evaluations including the cover reaction the climate variability.

**Keywords**: mining contamination, acid mine drainage, prevention techniques.

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# 1 INTRODUCTION

Mining activities significantly impact the quality of groundwater and surface waters. The degradation of surface water quality is often caused by chemical discharge into water bodies, alterations in local water regimes, and runoff of rainwater through mined areas, which, as highlighted by Gbedzi *et al.*, (2022), underscore the significant environmental challenges posed by the aforementioned activities.

Studies worldwide, including a review by Worlanyo; Jiangfeng (2021), have documented the release of materials and energy from mining operations. Among the most concerning sources of contamination is Acid Mine Drainage (AMD), recognized for its adverse effects on water quality. It is characterized by low pH levels, high sulfate concentrations, and mobilization of potentially harmful metals, as reported by (DOLD, 2017; VALENTE; LEAL GOMES, 2009).

AMD originates mainly from the exposure of rocks or mining waste constituted by sulfides, like pyrite, to water and oxygen. In the case of pyrite, waste undergoes oxidation when exposed to oxygen and water, resulting in elevated levels of dissolved sulfate, ferrous iron ($Fe^{2+}$), and hydrogen ions ($H^{+}$). A subsequent oxidation of ferrous iron to ferric iron ($Fe^{3+}$) leads to the formation of iron oxyhydroxide precipitates, facilitated by iron bacteria in acidic conditions below pH 2.5, as described by (VALENZUELA-DIAZ *et al*., 2020).

Therefore, water, oxygen, and microorganisms are fundamental for the formation of AMD and a reduced interaction between metal sulfide minerals and water, or air and restriction of microbial activity can reduce AMD. In this context, strategies such as use of bactericides, oxygen barriers (both dry and water covering), organic passivation, silane-based coatings, microencapsulation, and carrier-microencapsulation can be implemented for AMD control (YANG et al., 2023a). Due to its criticality and prominence regarding pollution from mining activities, AMD must be effectively controlled. Thus, those techniques have been widely adopted worldwide. The present study aims to highlight the use of dry or wet coverings as mitigation measures.

# 2 BIBLIOGRAPHIC REVIEW

## 2.1 Mining Operation

In general, mining has four stages: exploration, extraction, processing, and beneficiation (GANDY *et al.*, 2016). The first stage involves the identification and delimitation of material of interest location. Next, the extraction stage involves the removal of this material, which usually can be carried out by two main methods: open-pit or underground mining. The former is usually used for shallow deposits, thus operations begin on the surface. On the other hand, underground mining is adopted when the ore occurs at greater depths, in veins, or in other forms of geological confinement. Despite the distinction of techniques, they can be used in parallel if economic viability is confirmed for this (WIREMAN; STOVER, 2011).

Independent of the method, there is a large generation of waste as the material of economic interest represents a small part of what is extracted in this process. These wastes, include the remaining material that has no economic use, sterile, thus, they are usually disposed of in the soil within the mining plant in locations exposed to climatic events that can carry elements present in their constitution, such as metals and sulfides, to the soil and to groundwater and surface waters (WHITWORTH *et al.*, 2022). Once the ore is extracted, it proceeds to the beneficiation stage. This stage aims at the optimized removal of unwanted compounds from the material extracted from the mining phase.

In mineral process, or beneficiation, physicochemical processes are applied, based on the characteristics of the ore, to carry out this separation leading to a final product with higher concentrations of the substance of interest. Among these mineral treatment processes, the most used are amalgamation, flotation, and leaching (WORLANYO; JIANGFENG, 2021). In this process, another waste is generated, beneficiation tailings, which can generate acid mine drainage, as well as the sterile, when these are composed of sulfides.

## 2.2 Acid Mine Drainage

Acid mine drainage (AMD) is generated, mainly, from the oxidation of pyrite ($FeS_2$) and other sulfide minerals by presence of oxygen and water, and microorganisms

(SULONEN *et al.*, 2021). The AMD can be originated from active or abandoned polysulfide mines, ore and waste rock piles, tailings dams, underground mines, and sulfur-acid soils (MASINDI *et al.*, 2022). Among the mine activities, the primary sources of AMD are mine water from underground mines and open pit mining; wastewater discharged from the flotation process, ore smelting; wastewater and surface runoff formed from atmospheric precipitation; groundwater seepage, tailings pond, and quarry (CHEN *et al.*, 2021).

The oxidation of metal sulfides is a complex process involving various types of reactions, including oxidation-reduction, hydrolysis, ionic complex formation, solution, and precipitation. These reactions lead to the formation of oxidized iron forms, sulfate anions, and strong acidity (CHEN *et al.*, 2021). Factors such as the fineness of sulfide minerals grains, temperature, porosity allowing oxygen penetration, moisture, and the hydrogeological characteristics of the site greatly influence acid production (CHEN *et al.*, 2021). When sulfide minerals, especially pyrite, are exposed to the atmosphere, they rapidly oxidize due to the presence of oxygen, water, and microorganisms (MOODLEY *et al.*, 2018). This synergistic action of water, oxygen, and microorganisms on metal sulfide minerals results in a series of physical, chemical, and biochemical reactions, ultimately leading to the generation of a large volume of acid mine drainage (AMD) (YANG *et al.*, 2023a). The main chemical reactions of this process are shown in Eqs. (1 - 4) (CHEN *et al.*, 2021).

- Process of $FeS_2$ being oxidized to $SO_2^{4-}$ under the action of oxygen and water.

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

- Under sufficient oxygen, $Fe^{2+}$ is oxidized to $Fe^{3+}$ (2)

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

- $Fe^{3+}$ is first oxidized by oxygen, and then transformed into $Fe(OH)_3$ precipitation.

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

- Higher concentration of $Fe^{3+}$ can as an oxidant, accelerating the oxidation of pyrite to produce more $Fe^{2+}$

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

Oxidizing microorganisms promote an important mechanism of metal sulfide minerals oxidation, although these mechanisms are still not clear according to YANG *et al.* (2023a). Still, it is revealed that the influence of the biological process is through an indirect action, classified as either a contact or non-contact action. Contact action refers to microorganisms adhering to the surface of metal sulfide minerals and utilizing extracellular polymer substances (CHEN *et al.*, 2021). Conversely, non-contact action occurs when microorganisms use $Fe^{2+}$ as an electron donor and oxygen as an electron acceptor to continuously oxidize metal sulfide minerals (CHEN *et al.*, 2021).

AMD represents a serious threat for the environment, mainly due to its low pH and the presence of toxic ions (XIN *et al.*, 2021). The acid drainage can also lead to soil erosions, which creates another environmental problem with the sediment carriage to water surfaces, pH decreases in water bodies among others impacts. These alterations in the soil and water matrix will also change the microbial community's development and, consequently, their importance in ecosystem services to maintain the environmental status.

Because of the strong acidity and a large number of toxic ions, the hazards of AMD are very serious, which involve the physical, chemical, biological and ecological. AMD causes a decrease in pH, a loss of nutrients, an increase in metal toxicity, and a decrease in water retention capacity of the soil. That will cause a sharp decline in the content of organic carbon and microbial communities (VARDHAN; KUMAR; PANDA, 2019).

## 2.3 Acid Mine Drainage Prevention

In this context, if ineffectively managed AMD's treatment can be expensive. Even established AMD treatment methods, in general, are shown to be expensive and with low-term success (KEFENI; MSAGATI; MAMBA, 2017). Therefore, prevention is the ideal way when working with AMD (LI *et al.*, 2018). However, the AMD prevention usually is highly challenging.

Since AMD highly depends on the context of sulfide minerals with water and air so microbial activity can be developed, one way to control AMD is to prevent is interaction.

This might inhibit or reduce the pH and toxic ions concentrations of AMD. Hence, according to Chen *et al.*, (2021) methods such bactericide, oxygen barrier (dry and water covering), and surface passivation (such as organic passivation, silane-based coating, microencapsulation, and carrier-microencapsulation technology) can be used to prevent the formation of AMD.

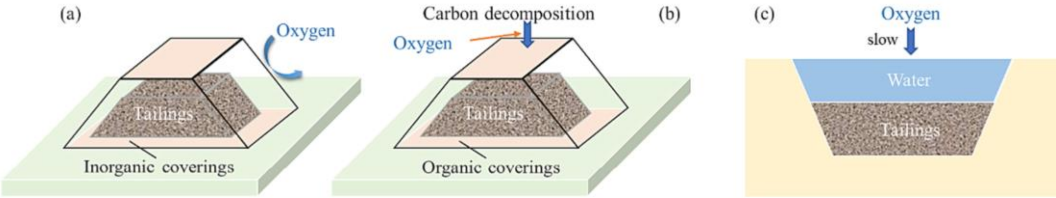


Figure 1: Schematic diagram of oxygen barrier methods (CHEN *et al*., 2021)

A recent search for sustainable development has led to the application of unused industrial waste (or by-products) such as fly ash, green liquor dregs, paper mill sludge, lime mud, among others, as dry covers for the control of AMD (CHEN *et al*., 2021), since they are accessible, low priced, of simple obtaining, and efficient for that purpose (YANG *et al*., 2023).

Among the several methods involved for the use of waste rock for controlling AMD is the inorganic dry covering approach, which employs a range of materials like inorganic minerals, alkaline industrial by-products, and low-sulfur tailings for creating a barrier over sulfide minerals, hindering oxygen or water infiltration. AMD prevention strategies also include soil compaction, dry cover techniques, and use of slag, clay minerals, and mine waste. Dry cover, a prevalent method, employs Non-Acid-Forming (NAF) materials over Potentially Acid-Forming (PAF) ones and is commonly adopted in Indonesian mines due to its efficiency. It aims to minimize oxygen diffusion and water infiltration into waste rock piles, thereby reducing sulfide mineral oxidation. Lime and other alkaline materials (e.g., fly ash and bottom ash) have also been studied because of their potential for preventing AMD generation (CHEN *et al*., 2021).

Organic materials can play a pivotal role in mitigating the formation of acid mine drainage (AMD) by decomposing carbon compounds in low-oxygen environments. Organic coverings commonly employed (e.g., sludge and sawdust) effectively impede tailings oxidation, with a combination of sludge and fly ash showing higher efficacy in inhibiting oxidation. Laboratory tests and field experiments spanning four years have validated the long-term effectiveness of soil-sludge mixtures as oxygen barriers. In addition, the usage of organic covers may lead to a reduction and a dissolution of secondary minerals, potentially reintroducing toxic elements into the environment. Despite concerns over degradation in acidic conditions, organic-based adsorbents show capacity for metal ion uptake for AMD control, as well as high adsorptive capabilities in both batch and column modes and offer potential solutions for AMD mitigation (DARAZ *et al*., 2023; YANG *et al*., 2023).

Water serves as an effective barrier against oxygen due to its slower diffusion rate compared to air, significantly mitigating the formation of AMD. Studies have indicated underground tailings exposed to air yield acidic pore water with elevated concentrations of iron and sulfur, whereas submerged tailings exhibit neutral pore water with reduced concentrations of those elements, showing the effectiveness of water coverage in preventing AMD. However, whereas the water covering method is conceptually simple, its practical application is constrained by geographical and hydrological factors, requiring proximity to lakes or rivers and susceptibility to natural events such as mountain torrents and earthquakes, which may lead to wastewater leakage. Despite its straightforward nature, the approach requires a substantial transportation of sulfide minerals and water to designated storage areas and poses challenges for the water flow control, since the presence of dissolved oxygen in flowing water can induce sulfide mineral oxidation (CHEN *et al*., 2021; YANG *et al*., 2023).

## 3 METHODS

The present study highlights the use of dry or wet coverings as mitigation measures based on a systematic review conducted in prominent databases including Scopus, Science Direct, and Springer Search regarding the usage of techniques for the control of acid mine drainage through the implementation of different types of covering worldwide. Incites Journal Citation Reports (JCR) were consulted for evaluations of the journals' quality on an international scale. For this it was used a tool called StArt 2.3.4.2 to support the paper selection process.

The primary inclusion criterion for articles in this review was their focus on covering techniques (dry or wet) for acid mine drainage control. The search process utilized descriptors ("acid mine drainage" AND "dry cover" OR "wet cover") to filter studies specifically addressing AMD control through covering methods. For the present review it was considered papers published between jan/2009 and nov/2023 (when the data collection ended).

Pre-established inclusion and exclusion criteria were applied and articles solely discussing AMD control techniques, but reporting no results were excluded. Additional data collected included study location, pollutants identified, type of cover adopted, effectiveness of the covering method, and publication year. Once these data was collected, the studies were evaluated by their type of cover usage, material characteristics and local of study.

# 4 RESULTS AND DISSCUSSION

290 studies were obtained from the aforementioned databases. 20 duplicates were spotted and 209 were filtered out during the title evaluation, thus being aligned with the scope of this research. Subsequently, another 22 studies were excluded from the abstract evaluation and, after a full paper reading, 39 were left for consideration (Figure 2).

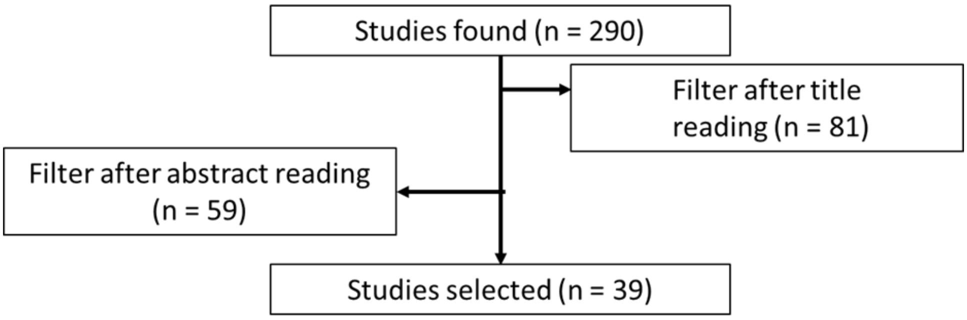


Figure 2: Flowchart delineating the article selection process for review.

152 distinct journals with standout mentions, including Applied Geochemistry with 12 studies, Journal of Environmental Management with nine, and Environmental Earth Sciences, Journal of Geochemical Exploration, and Journal of Hazardous Materials, each with seven, were identified. During the post-selection process, the number of journals narrowed down to 30, with Mine Water and the Environment contributing with six studies to the final selection.

The impact factor of the journals in the final selection ranged from 0.70 (DYNA) to 12.21 (Journal of Cleaner Production), around 50%, were published in journals whose impact exceeded 4.

Among the selected studies, the year with most publications was 2015, with six papers. Figure 3 shows most of them were published between 2017 and 2022.

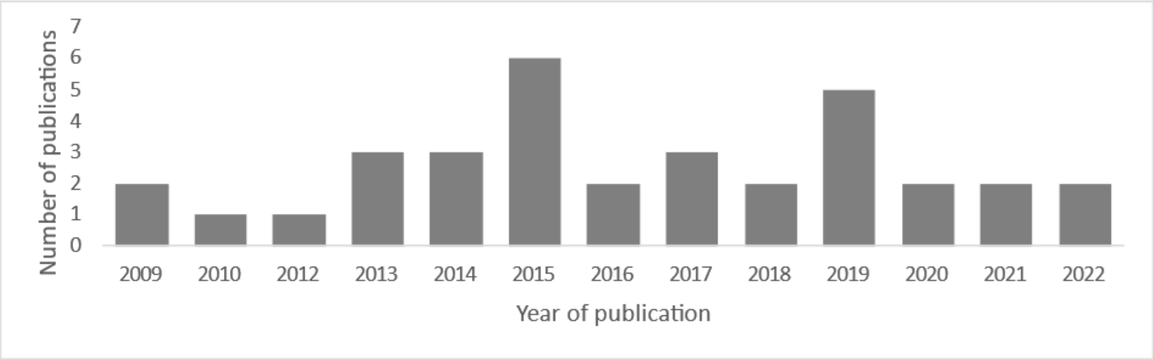


Figure 3: Number of publications by year among the selected studies.

It was found that America and Europe are the continents with the highest number of publications (Figure 4) mainly in function of studies performed in Sweden (14) and Canada (9). The studies revealed a preference for applications of industrial waste or even waste from mines as cover materials due to their availability and low implementation cost.

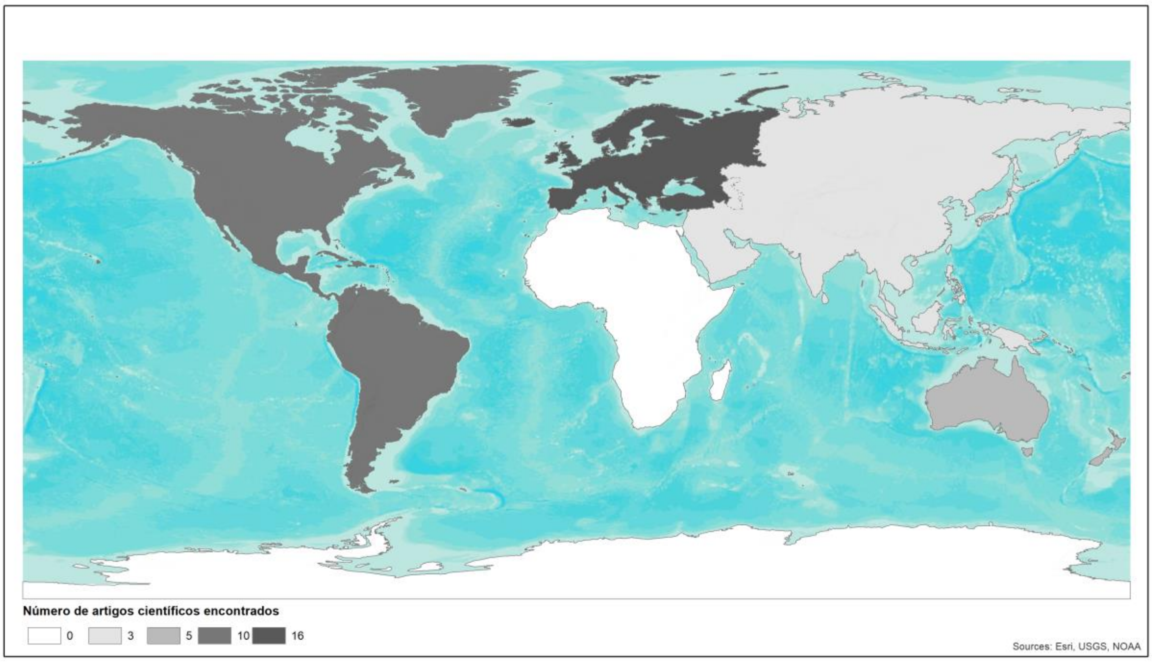


Figure 4: Number of publications per continent among the selected studies

Most selected studies for this study (33) reported the use of dry covers, specifically promoting the reuse of waste from paper industries, followed by the application of rock waste generated during the mine extraction process (Figure 5). A limited amount of papers

(4) on organic and water covers was found (4), which can be attributed to the challenges of management in the application of those covers.

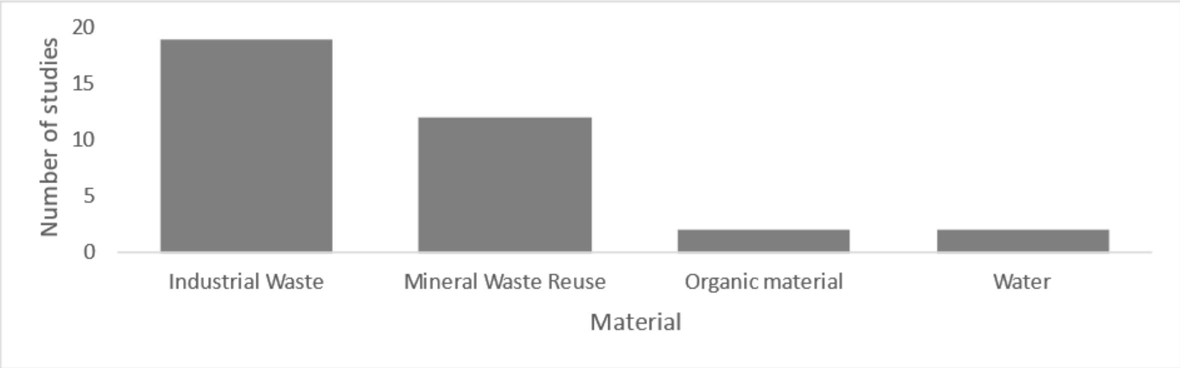


Figure 5: Number of publications per cover material among the selected studies.

Data on type of coverage used, coverage characteristics, development of the study in a laboratory or in situ, description of on-site ore extraction, location and year of study, and primary findings were gathered for each study.

## 4.1 Dry Covers

### *4.1.1 Industrial waste*

Neuschütz and Greger (2010) evaluated the combination of sewage sludge with wood fly as a cover material in a laboratory scale experiment on tailings from a pond site in Sweden. *Phalaris arundinacea L.* was also applied for preventing nutrient leakage from the sewage sludge. The combination reduced the amount of leachate generated, hence, the emission of metals and other nutrients into the soil. The addition of fly ash as a cover material increased the plants biomass and water uptake, decreasing the amount of leakage and the presence of nutrients in the effluent. The authors demonstrated the mix of ash and sludge combined with vegetation can be used in mine tailing treatments only if a sealing layer is employed for preventing root penetration.

Nason, Alakangas, and Öhlander (2013) evaluated the efficiency of sludge as a cover material for sulphatic mine tailings in an eight-year pilot-scale experiment, in Sweden. The material revealed an effective barrier to oxygen, creating physical obstruction and a reactive barrier due to its organic characteristics and preventing oxygen from reaching the tailing underneath the cover. No formation of AMD was observed and the drainage effluent showed lower concentrations of metals, pH, and sulphate compared to a scenario with no use of such a cover system. However, the organic matter content in the sludge is an important factor as a sealing layer – during the study, an 85% reduction in the organic fraction was observed due to aerobic and anaerobic degradation. The proposed cover system is, therefore, recommended for only a short-term application, i.e., a lower than eight years one, since the materials used may lose their characteristics over time.

The use of paper mill sludge and fly ash for AMD control was studied in tailings from a zinc/lead underground mine (LU *et al*., 2013). Soil samples were taken from four *in situ* test areas covered with covered tailings were evaluated after ten years of cover system application. The combination showed effective for preventing the leakage of Arsenic (As), Cadmium (Cd), Copper (Cu), Magnesium (Mg), Manganese (Mn), Lead (Pb), Sulfur (S) and Zinc (Zn) from the tailings, although such immobilized elements might be remobilized under a different chemical condition created by weathering. Moreover, the fly ash fraction for that cover system must be carefully evaluated so that an optimal amount of the material can be used for an efficient control of pollution (LU *et al*., 2013).

Different alkaline wastes from paper mills, fly ash (FA), green liquor dregs (GLD), and lime mud were used in a study performed in Sweden, which evaluated their application as dry covers for waste generated in a copper mill flotation process. The materials showed potential for AMD control due to their high buffering capacity - an increase in pH may lead to immobilization of trace elements in tailings. The cover application was tested in two sites, namely, in oxidized tailings and in non-oxidized ones. GLD and fly ash showed high buffering capacity because of their lime concentration. Overall, the leaching test indicated the feasibility of a short-term use of alkaline residue products as sealing layer materials on tailings. The analysis revealed their low hydraulic conductivity, adequate surface area, high water retention capacity, and maintenance of saturated condition can limit the transport of water and oxygen through the material and prevent it from forming acid waste. In the present study, ash showed a better cover material than GLD due to its higher capacity for immobilization of most trace elements on tailings (JIA *et al*., 2014).

Lu; Alakangas; Wanhainen, (2014) also evaluated the application of industrial waste as cover for ADM control for a mine extraction of Zn, Pb, Cu, Ag, and Au in Sweeden. The authors used paper mill ash and sludge, since their alkaline characteristics can inhibit sulfide oxidation. This cover system with 50 cm of ash on top of sludge evaluated the potential of element mobilization. As discussed by (LU *et al.*, 2013), the fly ash layer length must be carefully evaluated, otherwise it may underperform along the years, as reported in the authors´ new study in 2014. Weathering effects observed on the uppermost 47 cm of fly ash after 10 years´ application were attributed to high pH and the concentration of organic matter after the cover dissolution. Such effects lead to Iron (Fe), Mg, Mn silicates and carbonates and As, Cd, Cu, Fe and Zn sulfides leaching the depletion zone, where the pH was close to 12, and retention deeper down in the tailings, where pH decreased to around 7 - 8. The study showed even cover systems built with adequate material must be carefully designed and tested towards minimizing weathering effects.

Jia *et al.*, (2015) investigated the application of fly ash, green liquor dregs, and lime mud originating from paper mills as a cover system for AMD control. Batch tests analyzed the metal release from tailings, simulating weathering. The materials promoted trace metal immobilization and a decrease in Fe: S ratio. Although GLD showed more effective in increasing pH and As retention in comparison to ash, the authors highlighted the importance of more trials towards the application of those materials for AMD control.

In another study with GLD, fly ash, and sludge, Mäkitalo *et al.*, (2015) evaluated their effectiveness in reducing the flow of water and oxygen into waste generated in a mine from which pyrite, pyrrhotite, sphalerite, chalcopyrite, galena, and covellite were extracted. The authors tried to take advantage of the GLD hydraulic properties, small particle size, and large surface area combined with fly ash and tailings as a cover system that appeared to generate an even better hydraulic conductivity. Different cover combinations were evaluated using GLD + tailings + sludge and GLD + FA + sludge. GLD blended with FA or tailings not only showed low hydraulic conductivity water retention, but also a better water retention capacity when compared to traditional sealing layer such as clayey till. No negative effect on the leaching behavior was observed, possibly indicating a good alternative to sealing layers.

In a different scenario, Jia *et al.*, (2015) analyzed the application of sewage sludge on tailings under flooded anaerobic conditions (application of water covers) investigating the leaching of elements from a flooded system and the leachate of biosolids. Initially, the degradability of the biosolid, i.e., mixture of aerobic and anaerobically digested waste residues generated from slaughterhouse and domestic waste, was followed through the monitoring of methene and carbon dioxide generation. Subsequently, leaching tests revealed a large metal and metalloids reservoir had been established in the biosolids and was stable during the 230 days of testing. Since climate variability can interfere with biosolids efficiency, more studies with long-term monitoring programs are required so that the cover system can be applied in different scenarios.

Mäkitalo *et al.*, (2016) studied the longevity of GLD in laboratory analyzing the stability and effectiveness of different aged materials (3-, 6-, 8-, and 13-year-old ones) in preventing oxygen intake as a cover system. Regarding hydraulic conductivity, one of the main advantages of GLD in AMD control is no significant difference among the aged GLDs. The physical characteristics of fresh and aged GLD are similar; although the water retention capacity declined with age, a high degree of water saturation was maintained. Elements such as sulfur and potassium are expected to leach over time without affecting the material effectiveness. The possible calcite dissolution over the years might alter the GLD properties. However, no indication of such alterations was observed during this research. Studies on the material response to climate variations including dry and wet periods are, therefore, required.

Jia (2017), proposed a new study still evaluating the use of industrial waste for ADM control with wastes from copper mill processing (JIA *et al.*, 2017).Sealing layers were employed as cover materials on a 50-year-old sulfide containing tailings covered with fly ash and GLD for five years. The leaching behaviors were then evaluated in batch tests, which revealed covers led to lower concentrations of trace metals and nutrients present in the leachate effluent, when compared to uncovered tailings. Due to the high pH of the materials, a chemical and mineralogical change in the tailings beneath the covers was identified. A geochemical analysis revealed between GLD and fly ash, the former showed more capable of immobilizing elements.

Jia *et al.*, (2019) evaluated the geotechnical and chemical characteristics of fly ash used for five years as a sealing material on a sulfide-bearing mine. In situ analyses indicated it maintained its water retention capacity over the years, for its degree of water saturation was 90%. Some chemical variations were identified in comparison to a fresh fly ash taken from a paper mill waste and also due to its origin as a raw material (the wood utilized in the paper mill process). Some elements were mobilized in function of weathering effects. The leachate from the cover system maintained its efficiency along the years, as indicated by the limited release of elements from the fly ash, which exceeded the reference limits of inert materials and was far below the limits for hazardous materials. Therefore, fly ash can be used as a sealing material in a long-term perspective.

Sephton, Webb, and Mcknight (2019), employed a mix of fly ash, Portland cement, and acid mine drainage sludge to control AMD. Since such cement can be expensive for AMD control, the authors proposed mixing it with cheaper and more accessible industrial wastes. Portland cement can encapsulate sulfidic materials, reduce AMD rates and permeability, and be used in treatments of acid water due to its alkaline nature. The mixtures, i.e., fly ash from coal combustion and sludge from the neutralization of acid mine drainage with lime, were applied in PAF rocks from a pyrite mine in leaching columns monitored for almost one year. The application showed efficient, since the analyzed leached reduced at least 80% of acidity, metal, and sulfate loads. The cement with lower viscosity penetrated deeply into the waste rocks promoting leachates with higher pH and lower acidity and metal concentrations. The results, combined with the expected longevity of cement, indicated a good mixture of materials for AMD control; however, long-term studies on a larger scale should be performed towards optimizing the application.

Sephton and Webb (2019) investigated the formation of secondary minerals after cement application for AMD neutralization. Leach column tests were performed and the leachates were analyzed through an application of acid solutions (acid mine drainage taken from a pyrite mine) for simulating an AMD scenario. The application of cement was justified by its alkaline characteristics, which initially neutralized the acidity responsible for a prone metals dissolution, reinforcing the potential of the material as a cover layer to AMD control. However, the application of AMD drainage led to the formation of gypsum, ettringite, and thaumasite minerals, which infiltrated the material and created cracks within the cement, resulting in a loss of strength and moisture. Consequently, Portland cement shows greater potential as a passive treatment under unsaturated conditions, since periodic drying facilitates cracking and a deeper penetration of AMD.

Nyström, Kaasalainen, and Alakangas (2019) assessed the leaching of waste rock and lime kiln dust (LKD) for capturing trace elements, thus inhibiting sulfide surfaces and reducing sulfide oxidation in a long-term (109 weeks) basis. LKD was used due to the lack of available potential wastes to be used in AMD control in the vicinity and their unknown alkaline characteristics. A laboratory test evaluated the leachates from sulfide-rich waste rock from a pyrite mine site. The addition of LKD maintained the pH near neutral, thus reducing metal mobilization in more than 99% in comparison to a control experiment in which the concentrations of As, Cu, Pb, and Zn were significantly higher. Therefore, even in low amounts (5 wt.%), LKD shows potential for preventing sulfide oxidation and limiting the mobilization of metals emitted to the solid by the weathering process.

Lu, Leiviskä, and Walder (2021) assessed the impact of applying digested sewage sludge cover over tailings in a deposit area of a nickel mine on the leaching of contaminants. As reported in studies cited in this review, sludge has a high content of organic matter that can serve as both a barrier and an oxygen consumption mechanism for preventing the oxidation of mine waste. The sludge used was comprised of nutrients such as Na, Mg, Al, P, K, and Ca, which facilitates the growth of vegetation. The sludge and tailings taken from a nickel mine were used in a column experiment. Sludge as cover material slowed down oxidation processes underlying tailings and concentration of $SO^{2-}{}_4$, Fe, Mn, Co, Ni, and Zn in the leachate and temperature was considered a key factor in the sludge efficiency, since a better immobilization of elements is achieved above 10°C.

#### *4.1.2 Mineral Waste*

Soares *et al.* (2009) studied AMD control in a pyritic coal beneficiation plant in Brazil, since its waste was acid-generated, and evaluated the three configurations of dry covers using a double capillary barrier with bottom ashes, a dry cover with a single layer of clay, and a dry cover with mixed waste. Initial results indicated the use of compacted clay as a capillary barrier with bottom ash as an alternative cover material is effective in reducing AMD generation. Since the clay layer maintained water saturation as 100%, the underlying layers showed no significant water reduction during or after rainfall events (SOARES *et al*., 2010). The studies also emphasized a need for long periods of experimental testing for evaluations of dry cover performance.

Potentially acid-forming (PAF) rocks and non-acid-forming (NAF) rocks were used in a laboratory test, using a column leach test, in Indonesia, which evaluated AMD control for surface coal mines. The material was selected in function of its low cost, availability, and compatibility with the equipment in coal mines (Shimada *et al*., 2012). The use of PAF and NAF requires their combination produce an inert cover material. Therefore, according to previous studies, a mixture with up to 30% PAF material can provide a neutral leaching environment.

Multiple layer combinations of PAF/NAF ratio showed the performance of a triple layer cover system (NAF/PAF/NAF, in this order) is similar to that of a system with a single layer of NAF. Due to the geochemical equilibrium of the layers, PAF can reduce the need for NAF material and also functions as oxygen-consuming material, thus preventing oxidation reaction (SHIMADA *et al*., 2012).

Aubertin *et al*. (2009) investigated the application of three different materials, namely, a homogeneous waste rock simulating gravelly soil, a silty cover material of variable thicknesses (0.5 or 0.25 meters), and a 6-centimeter upper layer of drainage-runoff material for creating a capillary barrier effects (CCBE) cover system on an inclined site model. CCBE comprises a fine-grained soil layer atop a coarse soil layer that leverages hydraulic property disparities between the layers for avoiding downward water movement at their interface. The coarse-grained material facilitates drainage, significantly decreasing unsaturated hydraulic conductivity. Numerical simulations were performed for analyses of different combinations of layer thicknesses, leading to the conclusion such simulations are crucial for assessments of the response of those covers in inclined conditions. An increase in the cover thickness may enhance its effectiveness up to a certain maximum threshold beyond which the improvement becomes minimal (AUBERTIN *et al*., 2009)

Similarly to Aubertin *et al.* (2009), Kamorina *et al*. (2015) analyzed the application of CCBE on carbonaceous tailings with the use of a mixture of sand, clay, soil amendment with Bluejoint seed, and sheep laurel as a bio-barrier. A cover system consisted of three layers, namely, sand, nonreactive tailings, and sand + gravel. Bluejoints can be used as biobarriers against erosion into CCBE, thus increasing the longevity of the cover system. Moreover, they require low maintenance, since no chemicals are necessary and they can be found at low prices. However, the application of soil amendments may be required for improving the bluejoints herbage yield towards an economically profitable hay crop.

As in Shimada *et al*. (2012) and Matsumoto *et al*. (2015) reinforced the Indonesian challenge towards controlling AMD in coal mine sites due to the lack of NAF rocks. The authors evaluated the viability of using PAF rocks with low potential to be the source of AMD after a laboratory analysis. Those rocks are essentially the PAF ones after the AMD process, thus showing to be alternatives to be used as cover layers for preventing AMD. However, the sulfur form in those rocks must be considered in the material selection for the cover system. Sulfur-bearing rocks, in which most sulfur compounds are readily soluble, can be used as dry covers after a careful evaluation of the potential of acid formation, including a baseline with the use of NAF rocks.

Kalonji, Bussière, and Demers (2017) adopted laboratory tests combined with a numerical prediction to evaluate the effectiveness of CCBE comprised of mine waste rock and desulphurized tailings from a gold–copper and zinc–silver extraction mine. The evaluation involved batch tests monitoring hydrogeological properties of the physical models of CCBE with different proportions of material layers. The numerical modelling enabled foreseeing a low oxygen flux due to the application of the cover material. Therefore, the study demonstrated the possibility of reusing mine wastes as cover materials, since, as observed in both laboratory evaluations and numerical modelling, CCBE can limit oxygen flux. It also highlighted the importance of their characterization prior to the cover system applications and the need for evaluations of their geochemical properties for AMD prevention.

Pabst *et al*. (2018) studied reactive tailings, non-reactive tailings, and till as cover materials for old mine sites with pre-oxidized tailings. The hydrogeological and geochemical properties of the proposed systems were simulated in laboratory tests and comparisons were made in different scenarios of cover material combinations, water saturation, water pressure, and oxygen fluxes. The simulations highlighted the importance of hydraulic properties, material thickness, and water table position for the efficiency of monolayer cover – a deep water table causes the cover to lose saturation. CCBE, built with three cover layers, may be more efficient in restricting oxygen influx, as also claimed by Aubertin *et al*. (2009).

A cover system that uses non-acid generating tailing, desulfurized tailings, NAF waste rocks, and PAF waste rocks was combined to forming a CCBE for an active gold mine Larochelle; Bussière; Pabst (2019). As discussed in the aforementioned studies, in which PAF rocks were used for preventing AMD formation, PAF was also employed as a cover material in the present study due to a limited availability of materials and budget. Placing PAF waste rocks at the bottom of the cover layers can offer economic advantages for companies. During the tests, the cover system saturation was maintained at least 85%, since this characteristic is essential for CCBE. The cover system showed efficiency and pre-oxidized/acid-generating waste rock revealed capable for serving as a capillary break layer without affecting the overall efficiency of the system. Furthermore, the combination of layers reduced PAF contamination and the pH remained near neutral throughout the testing period, resulting in low concentrations of dissolved metals.

A coarse and fine desulphurized tailings cover applied in a non-operational gold mine in Canada was evaluated regarding its response to weather effects (Bashir *et al*., 2020), since local climate is one of the main variables to be considered during the planning of a soil cover application. Based on historical meteorological data, the authors correlated the performance of the cover along the years with the weathering process using numerical models and considering hydraulic properties. Covers with cease material are expected to have water gains for dry and wet years, whereas fine covers maintain water content in wet years and lose water in dry ones. Additionally, fine tailings cover maintains higher saturation compared to coarse cover, resulting in lower oxygen ingress for both historical and future climates. Even in a 30-year scenario, the fine covers showed the oxygen influx was negligible. Therefore, more studies on the impact of weather variations on the efficiency of covers are required.

Abfertiawan *et al*. (2020) investigated the application of NAF and PAF materials in a pyrite and jarosite mine in Sweden. Different thicknesses and NAF/PAF combinations were experimented in laboratory-scale column leaching tests in a 23-week study. The NAF/PAF combination successfully prevented and controlled AMD in coal and mineral mines. Additionally, when NAF was characterized by the presence of carbonate material, AMD prevention was improved by a minimization of oxygen intake and water infiltration even in presence of PAF. Regarding the leachates test, jarosite mineral samples resulted in a better scenario than samples with pyrite. The study reinforced the possibility of using NAF for AMD control, but also suggested even in presence of PAF, the cover system can be an effective pollution controller, enabling a larger application of covers, for NAF is not as available as PAF materials in mining sites with potential AMD generation.

Dublet-Adli *et al*. (2021) proposed AMD control using two types of pre-oxidized tailings, i.e., one with low sulfide content and another with high-sulfide tailings for the design of a CCBE. The cover system was applied in a mine of mainly copper, sulfur, and zinc extraction and a column test evaluated possible chemical, physical, and hydraulic characteristics of the tailings. Both types showed similar results of saturation content and the oxygen concentration indicated tailings with low concentrations of sulfide were not significantly reactive. Low concentrations of oxygen were observed in layers composed of high-sulfide tailings and acid leachate from the CCBE persisted even after 510 days of column testing. Despite some improvement, the oxidation of sulfide minerals appeared to persist in the high sulfide tailings, which is likely attributable to indirect oxidation facilitated by Fe (III) mobilized under low pH conditions. The effectiveness of CCBE with LS tailings was not markedly superior to that of a CCBE with a less efficient moisture retention layer.

Nguyen *et al*. (2022) investigated the rehabilitation of sulfidic Cu-Pb-Zn tailings using a hardpan-based duplex soil system as an un-conventional approach in Australia. A field trial employed the aforementioned system consisting of a substantial hardpan layer (e.g., > 30 cm thick) formed *in situ*, paired with a shallow root zone layer (approximately 50 cm) composed of siliceous, gravelly, and nutrient-poor growth media sourced from an adjacent hillside, which is rich in silicates. Hardpan layers are characterized by their hardened and densely compacted structures, which develop at the capillary fringes as a result of the cementing influence of abundant secondary mineral gels formed during the weathering processes of primary minerals. The hardpan layer proved its dual role as an efficient physical and hydro-geochemical barrier. With a hydraulic discontinuity and hydro-geochemical stabilization in the root zones, it supported the presence of native vegetation for over a decade, even in semi-arid climates, significantly reducing the levels of water-soluble metals and metalloids within the root zones and the plant uptake, despite plant roots extending into the interface of the hardpan horizon.

In a new study, Soares *et al*. (2022) evaluated covers built with soil and bottom ash for preventing AMD again in a coal mine in Brazil and, in a field experiment, proposed monitoring their characteristics and the local whether data. The covers were designed with topsoil, coal ash, clay, mixed tailing (a mixture of coarse tailings and fine coal tailings), and a coarse tailing and the cover systems developed with NAF material showed a significant effluent volume reduction, reaching 99% of the lower volume compared to control experiments. Despite an improved quality with limited element mobilization, the effluent still contained sulfate and manganese concentrations that exceeded regulatory limits. The incorporation of coal ash proved beneficial for water retention, with the cover maintaining up to 85% water content during wetter periods. Seasonal monitoring data revealed fluctuations in effluent quality, with improvements during wet periods for the layer fly ash cover. Overall, the covers successfully reduced effluent volume and enhanced effluent quality, leading to potentially lower costs of leachate treatments.

#### *4.1.3 Organic covers*

Paktunc (2013) delved into controlling Acid Mine Drainage (AMD) in a gold mine in Canada using biosolids cover to manage arsenic (As) stability in tailings. The arsenic content in the tailings varied between 0.15 and 0.36 wt% and was distributed among goethite, pyrite, and arsenopyrite. Observations revealed secondary oxidation by-products in exposed tailings and a lower section of biosolids-covered tailings, indicating goethite dissolution. In tailings with below 0.085 mg/L leachate arsenic concentrations, As species remained stable when exposed. However, biosolids-covered tailings exhibited increased As concentrations in leachate near the cover and rising iron concentrations towards the top. The study sheds light on mineral behavior, alterations in arsenic speciation, and mobility under reducing conditions facilitated by organic covers. It also advances assessments of long-term stability of arsenical minerals in tailings and offers valuable insights for environmental protection strategies.

Beauchemin *et al.*, (2018) evaluated the bio-geochemical stability of 4-to-5-year tailings from a Cu-Ni pyrrhotite mine site after the application of a 50 cm-thick or a 1 m-thick biosolid cover planted with energy crops. In a field experiment, the analysis involved different scenarios with the use of a thin cover, a thick one, and a control with no vegetation or cover. The organic cover induced alterations in redox conditions, pH levels, carbon content, and humidity, resulting in a partial dissolution of jarosite and gypsum beneath the cover, whereas goethite appeared to remain stable. The organic cover impeded oxygen penetration into the tailings, thereby preventing AMD. Furthermore, the covers partially neutralized pH, decreased water-soluble metal and sulfate concentrations in surface oxidized tailings, and facilitated rapid improvements in fertility, carbon cycling, and ecological functions (BEAUCHEMIN *et al.*, 2018)

#### *4.1.4 Water Cover*

Jackson and Parbhakar-Fox (2016) evaluated the use of a water cover in a tailing dam as a wet coverage to control AMD in an iron extraction area in Tasmania. Since the tailing dam construction followed the local natural gradient, the authors could investigate the tailings geochemistry in different depths. The southern and northern extents of the dam showed AMD potential due to the low pH in those areas and signs of oxidation on tailings present in the sub-areal zone of the dam. A visible correlation was observed in the sub-aqueous zone of the wet cover, between depth and tailing oxidation, where up to 2.5 m depth an AMD reduction could be identified. A dominantly carbonaceous-rich sediment capping layer to the end was evident in an estimated 10m depth. Nevertheless, water covers showed a good measure for geothenical stable facilities, and the authors suggested new methods for breaking source pathway receptor chains should be evaluated.

Luo *et al*. (2018) used a water cover containing proline solution and deionized water in a laboratory test with coal mine waste. Coal gangue was subjected to that solution for 540 days while a control test was prepared. The control experiment showed oxidation and poor-quality leachate (low pH and high concentration of trace metals), whereas the solution showed significant improvements, for the concentration of elements was not high and decreased the acidophilic sulfur-oxidizing bacteria also leading to near neutral pH. The study demonstrated a proline solution can be used for pollution control in coal gangue dumps.

## 5 CONCLUSION

The literature review conducted detected several studies on AMD control techniques, but also a limited number of publications on AMD management with the use of covers in Canada and Sweden, thus highlighting a gap in the literature on AMD mitigation strategies worldwide. A preference for dry cover was identified, indicating its effectiveness in AMD control and prevention. However, the limited number of studies on other types of covers can be associated with variations in terminology for water cover. A growing interest in alternative low-cost cover materials has reflected a shift towards sustainable and economically viable AMD control methods. Therefore, future studies must consider the local availability of cover materials, for their effectiveness is closely associated with the waste producing AMD and the specific geological and environmental conditions of the site.

The efficacy of AMD control measures, including cover systems, must be tested in laboratory-scale experiments prior to their field applications for ensuring optimum results. Another gap in the literature refers to the lack of long-term monitoring reports, which are essential for assessments of the performance of those techniques over time. Therefore, studies must consider and report local weather variations and their influence on cover efficiency towards comprehensive insights into the dynamic nature of AMD management strategies. Overall, analyses of such factors will contribute to the development of robust and adaptive approaches for mitigating AMD and safeguarding environmental health in mining-affected areas.

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