Major Project

REMEDIATION OF ACID ROCK DRAINAGE: CURRENT PREVENTION AND MITIGATION METHODS

LWS 548 Major Project

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EXECUTIVE SUMMARY

Acid Rock Drainage (ARD) is recognized as a major environmental issue globally, especially for hard rock sulfide mining. Among negative impacts of ARD are threats to ecosystem health, destruction of habitats, deterioration of aquatic ecosystems, risk of groundwater contamination and public health concerns.

The traditional and most used treatment involves neutralization by adding lime or limestone. However, this traditional treatment has significant environmental impacts and very short long-term performance. Besides, ARD varies significantly between mine sites, thereby other remediation strategies may provide better results than the active neutralization method.

This paper presents a review of the various techniques available and assesses biological and abiotic remediation methods currently used worldwide. The goal is to provide alternative sustainable remedies other than active neutralization with lime/limestone, contribute to ecological restoration, a recommended next step to mitigation strategies, and support site-specific decision-making processes in mine sites impacted by ARD.

The assessment was grounded on a systematic literature review to critically compare current ARD prevention and mitigation techniques. The techniques were divided into two major categories: Prevention and Treatment. Treatment was further divided into Biological and Abiotic methods, which were compared considering specific factors, including: mine site conditions, metals concentration, area, type of design, long-term efficiency, environmental impacts and costs.

Based on the literature reviewed, this study compiled a summarized table of comparison, which provides a simplified and general view of the various remediation methods, as an initial guide for future detailed research. Prevention methods and both Active and Passive Biological treatments were found to have lower environmental impacts. For future research, next steps would be: to include other emerging strategies in the comparison, especially the integration of different approaches and the use of industrial by-products, and to evaluate the potential of each technique to support site-specific ecological restoration actions.

Insights from the comparison of available remediation methods, based on key factors such as costs, effectiveness and environmental impacts, may help site-specific decision-making process and inform local communities, the reclamation practitioner and environmental engineers on more sustainable remediation strategies available.

1. INTRODUCTION

Acid Rock Drainage (ARD) is recognized as a major environmental issue globally, especially for hard rock sulfide mining (Zhou et al., 2019; Park et al., 2018). The acid wastewater generated by mineral dissolution poses a serious threat to contamination of underground and surface water at considerable distances from the mining area, and even centuries after mine closure (Kollias et al., 2021; Rambabu et al., 2020). This is considered "second only to global warming and ozone depletion" as major ecological risks by the USA Environmental Protection Agency (US-EPA) (Moodley et al., 2018). Among negative impacts of ARD are threats to soil structure, destruction of habitats, deterioration of aquatic ecosystems, risk of groundwater contamination and public health concerns (Moodley et al., 2018; Karagüzel et al., 2020).

The generated acid drainage dissolves the metals present in the mine waste minerals, increases its mobility, and transport through the water cycle, as illustrated in Figure 1 (Ugya et al., 2018). The resulting wastewater has high concentration of dissolved iron salts and often free sulfuric acid (Rambabu et al., 2020). This leaching of acid continues until the sulfides are leached out, a very slow process, taking up to hundreds of years or more (Ugya et al., 2018). Therefore, long-term remediation of mine waste presents a huge challenge for both the scientific community and also the mining industry (Jia et al., 2015).

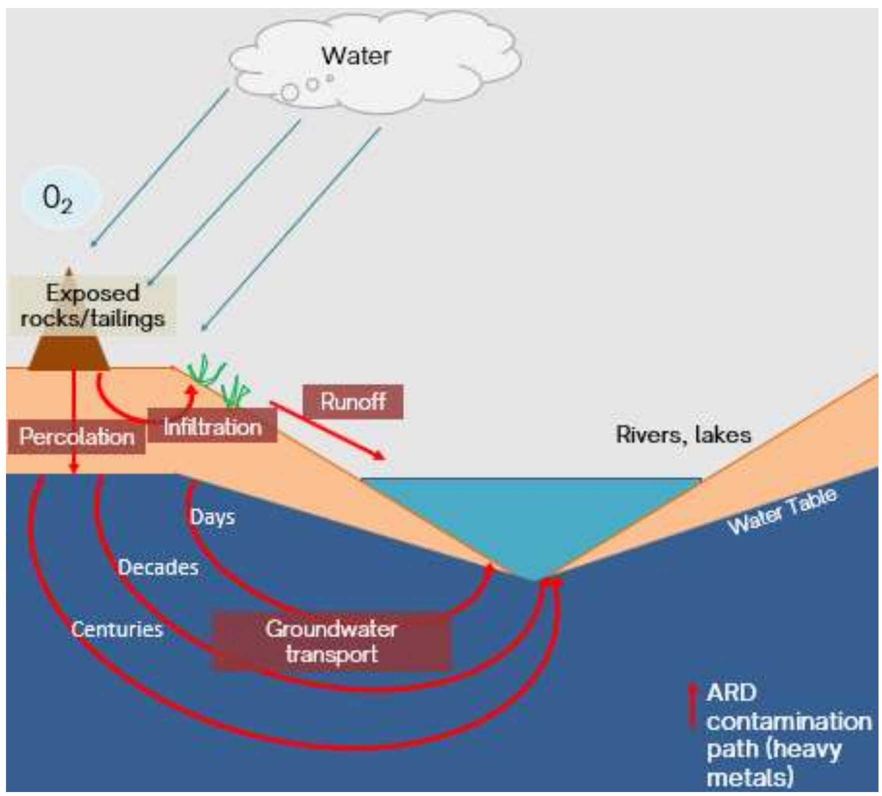

Figure 1. Diagram of a simplified ARD contamination path. Tailings are processed rock or soil left over from mining activity (MAC, n.d.). The infiltration of precipitation, or irrigation, consists of water entering into the soil pores, while in the percolation water enters groundwater storage (Pokorný & Rejšková, 2008). Runoff is liquid water leaving the region (Dingman, 2015). Groundwater contamination paths may take centuries after the contamination event to reach rivers and lakes (Muralikrishna & Manickam, 2017).

The main cause of Acid Rock Drainage is the oxidation of sulfide minerals such as pyrite (FeS_2), the most abundant sulfide mineral worldwide (Fan et al., 2017). The exposure to oxygen, water, and microorganisms may lead to complex physical, chemical and biological reactions (Zhou et al., 2019). Although this process occurs naturally, mining activities, highway construction and other large-scale excavations may accelerate the process (Simate & Ndlovu, 2014; Turingan et al., 2020). Thus, these activities and notably mine waste rock and tailings exposed to air and water react and produce ARD (Figure 2), thereby generating low pH wastewater with high concentrations of sulfate, iron and dissolved metals (Hakkou et al., 2009).

There are several methods of ARD remediation presented and discussed in the literature. The neutralization treatment of ARD by the continuous addition of alkaline substrates is the most widely used (Moodley et al., 2018; Kefeni et al., 2017). Limestone (CaCO3) is one of the most used products for neutralization worldwide, as it is usually readily available in the local surrounding of mining sites and is cheaper than other materials if commercially produced (Kapil & Bhattacharyya, 2017; Ouakibi et al., 2013). However, this traditional method usually results in new waste streams that require further treatment or must be disposed as hazardous neutralization sludge (Simate & Ndlovu, 2014). Besides, limestone weathers more quickly than the sulfides and, unless limestone is added continuously, ARD may continue for 100's of years, and thus, need for a continuous supply of chemicals and energy (Roy Chowdhury et al. 2015). In consequence, this does not present an efficient remedy in the long-term (Zhou et al., 2019).

The addition of limestone for ARD chemical neutralization presents significant challenges regarding cost-efficiency and sustainability for longer periods of time (Tabelin et al., 2019). In order to address this, researchers are currently interested in looking for low-cost and more sustainable ARD prevention and treatment methods. Emerging technologies include the use of bioremediation processes, the recovery or reuse of resources, integrated approaches, and also the active neutralization method by using alternative materials, such as natural minerals and industrial by-products (Kefeni et al., 2017). This paper presents a critical review of current techniques available and compares them to support site-specific decision-making processes.

The study objectives are:

- Provide a systematic review of the literature on current prevention methods and biological and abiotic treatments for ARD.

- Compare the various techniques suggested in the literature, based on efficiency and environmental impacts, and summarize key findings in accessible language for the general public.
- Inform researchers, environmental engineers, reclamation practitioners and local communities on more sustainable remedies in the longer term, and support site-specific decision-making processes in mine sites impacted by ARD.

2. METHODS

The methodology of this research was grounded on a systematic literature review, and the analysis of relevant case studies to critically compare current ARD prevention and treatment techniques. The treatments were divided into biological and abiotic methods. Biological methods were basically focused on bioremediation in the majority of the literature reviewed. Prevention and treatment methods were compared considering specific factors: mine site conditions, metals concentration, area, type of design, long-term efficiency, environmental impacts and costs.

3. LITERATURE REVIEW

3.1 ARD formation

A thorough understanding of ARD formation processes is essential to predict the production of acidic conditions over time, and also to properly analyze available remediation techniques (Moodley et al., 2018). Once sulfide minerals are exposed to oxygen and water, the chemical process of pyrite occurs by four main reactions, Eq 1-4 (Zhou et al., 2019; Tong et al., 2021):

i. Pyrite (FeS_2) produces sulfuric acid (H_2SO_4) and ferrous sulfate ($FeSO_4$) under the action of oxygen:

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

ii. Ferrous ions (Fe^{2+}) are oxidized to ferric irons (Fe^{3+}) in the presence of free oxygen or sulfur-oxidizing bacteria (naming *Thiobacillus thiooxidans*, *Thiobacillus ferooxidans*, as they use the produced energy for their metabolism) (RoyChowdhury et al. 2015):

   $Fe^{2+} + 1/4O_2 + H^+ \rightarrow Fe^{3+} + 1/2H_2O$, (2)

iii. Hydrolysis or oxidation of pyrite by ferric ions:
$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$. (3)

iv. Precipitation of iron-hydroxide (contribute to lowering the pH):
$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+$, (4)

Oxidation as given by Equation 3 is much faster than by Equation 1, thus the oxidation by ferric ions is the predominant reason for the generation of acidic wastes (Tong et al., 2021). As a result, the pH system drops drastically while the mobility of toxic metals increases significantly (RoyChowdhury et al. 2015). Based on these reactions, numerous remediation strategies have been proposed, often acting on oxygen availability, pH neutralization, environmental conditions for bacteria growth, sulfide minerals exposure, among others (RoyChowdhury et al. 2015; Sahoo et al., 2013).

ARD may occur in both metal (mainly gold, copper, and nickel) and coal mines, commonly associated with iron sulfides (Akcil & Koldas, 2006; Blodau, 2006). Additionally, for both metal and coal mining areas pyrite is the predominant form, and thus, waste rocks and tailings containing sulfides are a major source of ARD (Acharya & Kharel, 2020; Blodau, 2006). In ores, other metal sulfides may also occur in appreciable quantities, such as sphalerite (ZnS), galena (PbS), chalkopyrite ($CuFeS_2$), and arsenopyrite (FeAsS) (Blodau, 2006). In coal, sulfur may occur in organic sulfur, pyritic sulfur, or sulfate sulfur forms (Acharya & Kharel, 2020). Pyrite contents are often higher in ore mining areas and may reach 85% (weight) in mine tailings (Blodau, 2006). Thus, in many cases and depending on the host-rock geology, metal mining generates more acidic wastewaters and with higher metal content than coal mines, demanding more robust remediation strategies (Martínez et al., 2019).

3.2 ARD prevention and treatment:

In general, ARD remediation technologies can be classified into two major categories: prevention and treatment. While treatment techniques aim to mitigate impacts of produced ARD by treating the resulting acid drainage, prevention methods are directed towards controlling the formation of ARD, preferable to limit pyrite oxidation at source (Zhou et al., 2019; RoyChowdhury et al. 2015).

Additionally, there are two main categories for ARD treatment, namely active treatment and passive treatment (Rambabu et al., 2020). Active methods usually include the addition of alkaline substrates to neutralize the acidic drainage (Li et al., 2018). Passive systems rely on natural physical, chemical and biological processes, by creating reducing conditions and using alkaline organic substances (Trumm, 2010; Naidu et al., 2019). Recently those methods have been reclassified into biological treatment and abiotic treatment, each one with sub-categories of active and passive systems (Rambabu et al., 2020), as summarized in Figure 2.

One important distinction to make is between the concepts of biological methods and ecological methods. Biological treatments are mainly focused on bioremediation technologies. Ecological methods would be a recommended next step to remediation techniques, aiming to recover local ecosystems' health and cultural values. The various ARD prevention and treatment approaches are discussed in the following sections.

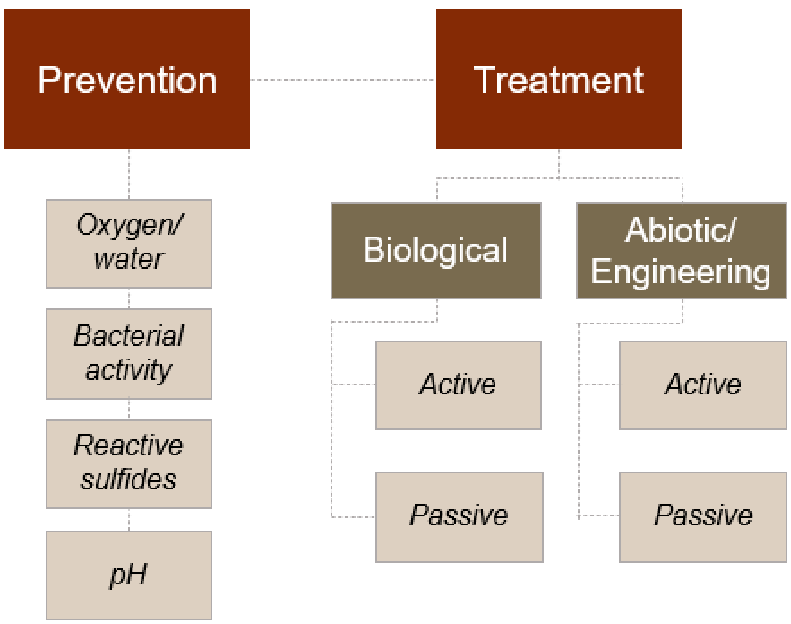

Figure 2: Classification of ARD remediation methods considered in this study.

3.2.1 Prevention

Prevention of ARD formation is often considered the most sustainable management strategy. However, efficient prevention is notably difficult to implement, especially in the longer term (Kefeni et al., 2017; Naidu et al., 2019; Viadero et al., 2020). As mentioned before, there are essential elements to the generation of ARD: oxygen, water, sulfur-oxidizing bacteria, and exposed sulfides. Hence, prevention of ARD should try to exclude or limit one of those (Pozo-Antonio et al., 2014). Prevention approaches listed in Table 1 are divided into: control of oxygen and water, control of bacterial activity, control of reactive sulfides and control of pH.

Table 1: Summary of advantages and disadvantages of prevention methods.

Control	Method	Mechanism	Advantages	Disadvantages	References
Oxygen/ water	- Surface and groundwater interception	Waterproof channels, pipes and slope changes used to reduce water supply to acid-generating waste piles.	Easy to apply, cheap and works well in conjunction with other methods.	Requires accurate hydrological and hydrogeological studies prior to installation.	Pozo-Antonio et al., 2014; RoyChowdhury et al. 2015
	- Water cover	Flooding underground mines or tailings storage to prevent air infiltration.	Efficient to stabilize tailings and relatively less expensive for larger-scale mine sites.	Requires sufficient water, not applicable to arid regions or with acute wet/dry seasons.	RoyChowdhury et al. 2015; Sahoo et al., 2013; Simate & Ndlovu, 2014; Li et al., 2018; Park et al., 2018
	- Dry cover	Covering the waste with soil or rock to prevent water and air penetration.	Efficient to stabilize mining waste, possibility to combine materials, and applicable to most situations.	Rarely prevent ARD entirely due to hydraulic conductivity and water saturation, and shows indirect effects on landscapes caused by excavations.	Pozo-Antonio et al., 2014; Moodley et al., 2018
	- Backfilling	Refilling an underground with the mine waste rock.	Reduces the volume of waste rock to be treated and also helps to stabilize the mining site.	Likely infiltration of oxygen, expensive and site-specific, waste rock needs to be pre-treated.	Moodley et al., 2018; Kefeni et al., 2017
Bacterial activity	- Inhibition/ bactericides	Reduce bacterial activity or exterminate bacteria in the mine wastes by adding bactericides.	Efficient at quickly inhibiting the growth of microorganisms.	Only short-term effects, requiring repetitive addition, and some bactericides are toxic to aquatic organisms.	Park et al., 2018; RoyChowdhury et al. 2015

Reactive sulfides	- Desulfurization	Separation of sulfide-rich minerals from low sulfur-bearing tailings.	Possibility to recover sulfide minerals from mine waste.	The tailings with low sulfur may also generate acidic wastewaters.	Sahoo et al., 2013
	- Passivation/ encapsulation	Application of a thin coating on sulfide minerals surfaces to prevent water and oxygen infiltration.	Possibility to use natural materials, like Natural Organic Matter.	Unstable at lower pHs, few studies available to compare different coatings efficiencies, unclear long-term stability.	Park et al., 2018; Moodley et al., 2018
	- Biological Source Treatment	Forming a biological coating of sulfate-reducing bacteria on the surface of sulfide minerals.	Works well at lower pH, is relatively cheap, and easily applied.	Long-term stability is not understood, needs extensive modelling.	Moodley et al., 2018
pH	- Application of chemicals	Addition of alkaline substrates in the tailings to increase the pH and precipitate metals.	There are some accessible and relatively cheap alkaline chemicals available, reduces acid release.	Loss of efficiency within a few years due to coating, and requires large amounts of chemicals.	Pozo-Antonio et al., 2014
	- Co-disposal and blending	Co-disposal or blending of tailings with acid-consuming materials.	Possibility to use natural rocks and industrial wastes.	Requires a correct calculation of the balance between acid potential and neutralization potential, together with a homogeneous mixing to be truly effective.	Park et al., 2018; RoyChowdhury et al. 2015

3.2.2 Treatment

Currently, the most used strategy to remediate ARD is active and passive treatment systems. Since prevention methods are more difficult to implement, treatment technologies present a more practical option (Naidu et al., 2019). In addition, if prevention techniques are not planned at the early stages of mining activity, a suitable mitigation technique is immediately required (Park et al., 2018). Mitigation methods listed in the next sections were divided into abiotic treatment and biological treatment, each with various passive and active systems.

Abiotic treatment

Abiotic treatment techniques generally involve chemical treatment, energy-demanding processes, or engineered structures (Simate & Ndlovu, 2014). The abiotic treatments listed in Table 2 are divided into active and passive systems.

Table 2: Summary of advantages and disadvantages of abiotic treatments.

System	Method	Mechanism	Advantages	Disadvantages	References
Active	**- Chemical neutralization plants (traditional and most used method)**	**Active neutralization using alkaline substrates (mostly lime and limestone) to increase pH and precipitate metals.**	**Easily modified/ versatile, quick neutralization.**	**Temporary/ short-term results, needs a continuous supply of chemicals and produces a large volume of sludge.**	Park et al., 2018; Moodley et al., 2018
	- Ion exchange	The process is to exchange ions in the exchanger with the ions in the wastewater to remove the harmful ions.	Possibility to recycle heavy metals and water, large treatment capacity, high efficiency.	High initial investment, easily disturbed and loses efficacy over time.	Tong et al., 2021
	- Reverse osmosis	Use of membranes that let water pass through but retain dissolved or suspended solids.	Easy to operate, efficiency is high, possibility to retain salts and metals.	Expensive, prone to membrane fouling over time, waste stream usually requires further treatment.	Naidu et al., 2019; Rambabu et al., 2020; Simate & Ndlovu, 2014; Kefeni et al., 2017

	- Membrane technology	Using membranes to treat ARD. The membrane can absorb ions and degrade pollutants.	Easy to operate, versatile. Low energy and chemicals consumption.	Difficult to implement on larger scales, filtered materials are difficult to recover.	Rodríguez-Galán et al.,2019; Tong et al., 2021
	-Electrochemical process	Negatively polarizing the tailings interface to minimize oxygen reactivity.	Relatively lower costs, possibility to recover metals and generate electricity.	Mechanism is still unclear; more field studies are necessary to prove long-term effectiveness.	Sahoo et al., 2013; Rodríguez-Galán et al.,2019
	- Adsorption process	Use adsorbent materials to adsorb metals.	Easy to operate, low volume of sludge, doesn't require chemicals.	Low efficiency, doesn't treat suspended solids, some adsorbents are expensive and have a limited lifespan.	Tong et al., 2021; Moodley et al., 2018
Passive	- Anoxic limestone drains	Wide underground systems filled with limestone ($CaCO_3$) and with anoxic conditions (no free oxygen).	Little space, relatively cheap, efficient in the short term.	Conditions difficult to maintain, clogging reduces efficiency over time, not good for high metal concentrations.	Moodley et al., 2018; RoyChowdhury et al. 2015
	- Dispersed alkaline substrate (DAS)	Wood chips mixed with fine particles of limestone ($CaCO_3$).	Increased limestone reactivity and reduced clogging. Good results for highly acidic waters.	Relatively new, requires further research about long-term efficiency.	Martínez et al., 2019; Rakotonimaro et al., 2016

The traditional abiotic active neutralization method highlighted in bold in Table 2 is the most adopted, worldwide. However, this traditional treatment results in significant environmental impacts (Zhou et al., 2019). Active addition of limestone creates abundant and unstable wastes (Simate & Ndlovu, 2014). Also, the dissolution of limestone ($CaCo_3$) results in a potential source of CO_2 to the environment (Mathiba & Awuah-Offei, 2016). Additionally, limestone has a faster dissolution rate than sulfide minerals, and thus, an ineffective long-term performance due to armoring by heavy metals present in ARD. The heavy metals coat limestone mineral surface and decrease neutralization capacity (Moodley et al., 2018). Many alternative methods have been recently researched aiming to overcome some of those limitations (Viadero et al., 2020; Moodley et al., 2018).

Biological treatment

Biological treatments, also known as bioremediation, are considered promising options to treat ARD. They rely on natural biochemical processes, microbial activity and reactive organic materials to stabilize, accumulate or remove contaminants (Rambabu et al., 2020; Schwarz et al., 2020; RoyChowdhury et al., 2015). The biological treatments listed in Table 3 are divided into active and passive systems.

Table 3: Summary of advantages and disadvantages of biological treatments.

System	Method	Mechanism	Advantages	Disadvantages	References
Active	- Sulfate-reducing bioreactors	Bioreactors are vessels designed to provide an effective environment for enzymes or whole cells to transform biochemicals into products. The ones to treat ARD involve sulfate-reducing bacteria. The ARD passes vertically through a thick organic layer and limestone bed and is discharged through the drainage system.	Predictable performance, high metal removal ability, small area required.	Dependent on complex biochemical processes, sensitive to pH and temperature changes, requires repetitive addition of organic materials and shows limited lifetime.	Erickson, 2011; Moodley et al., 2018; RoyChowdhury et al. 2015
Passive	- Compost reactors, Constructed wetlands	Constructed wetlands are based on interactions between substrates, microorganisms, and	Low maintenance, relatively low cost, good for land and habitat rehabilitation.	Large area, long residence time, restricted to low acidic conditions, not adaptable to changes in water quality, can accumulate toxic metals.	Tong et al., 2021; Naidu et al., 2019; Rambabu et al., 2020

		plants to remove heavy metals in wastewater.			
	- Successive Alkalinity Producing Systems (SAPS)	Basic elements: organic wetting layer (to prevent air infiltration and support bacterial growth), limestone layer, and a drainage system - must also include a flushing system.	Small area required, efficient for high concentrations of Fe, but low Al.	Requires ongoing maintenance, is highly dependent on geochemical conditions, requires site-specific design, and is not adaptable to load changes.	Naidu et al., 2019; Rambabu et al., 2020; Trumm, 2010
	- Permeable reactive barriers (PRB)	Barriers that react with chemicals of concern and allows water to flow; underground trenches filled with permeable reactive materials.	Relatively low cost, small area, doesn't require waste disposal systems.	Requires extensive modelling, limited to less than 20 m below the ground, prone to clogging, long-term performance unknown.	Moodley et al., 2018; Rambabu et al., 2020
	-Phytoremediation	Use of plants for the treatment or removal of contaminants from soil and surface/groundwater, directly on site.	Non-intrusive, relatively lower costs, aesthetically pleasing and socially accepted, stabilizes soil, increases organic matter and soil moisture.	Depth limited to the root zone, applicable only to low to medium contamination, slower process, requires more field studies for optimization.	RoyChowdhury et al. 2015; Karaca et al., 2018
	- Algal based bioremediation	Using algae strains to accumulate select metals and increase the pH.	Relatively lower costs, high efficiency for metal and sulfate removal.	Very sensitive to pH, temperature and oxygen concentration variations.	Rambabu et al., 2020

3.3 Comparison and discussion

The prediction and selection of ARD remediation strategy should be site-specific and take local environmental conditions into consideration (Simate & Ndlovu, 2014). The resulting ARD composition is highly dependent on local factors such as mineral weathering susceptibility, mineral composition, climate, topography, soil biota among others. Those factors have significant impacts on the level of acidity generated, the evolution of ARD with time and the wastewater flow through the water cycle (Rambabu et al., 2020).

In order to assess remediation techniques efficiencies at different site conditions, Table 4 summarizes key characteristics for the major ARD remediation methods, which include: prevention, abiotic active and passive treatments, and biological active and passive treatments. In brief, mine sites with more serious cases of acid water pollution require more robust treatment and corrective techniques, while more benign drainages may not even need remediation measures (Lapakko, 2002; Pozo-Antonio et al., 2014). Methods which demand less energy are preferable for closed mines, while active systems with high energy and chemicals demand are preferable for operating mines (Trumm, 2010). Additionally, post-closure mines usually show more stable chemistry and flow rates, which favors passive systems (Trumm, 2010).

Table 4: Summarized comparison between mine site conditions, metals concentration, area, type of design, long-term efficiency, environmental impacts and costs regarding major remediation methods (the general conditions were based on the majority of technologies, exceptions may apply).

Method	Site operation	Acidity/Metal concentration	Area required	Design	Long term efficiency	Environmental impacts	Total Costs	References
Prevention	**Post-closure** (requires less energy and maintenance)	**Low** (rarely prevent highly acidic wastewaters completely)	**Small to Large** (depends on the specific method)	**Site-specific** (very sensitive to changes in environmental conditions)	**Low** (requires extensive modelling and renovation over time)	**Low** (depends on materials used)	**Low** (depends on renovation and initial investment)	RoyChowdhury et al. 2015; Sahoo et al., 2013; Pozo-Antonio et al., 2014; Moodley et al., 2018
Abiotic Active	**Operating** (demands more energy)	**High** (usually with the possibility of recovering metals)	**Small** (usually chemical plants)	**Versatile** (by simply changing the chemical or dosage)	**Low** (requires continuous supply of chemicals, less efficient over time)	**High** (depends on the chemicals used and produced sludge)	**High** (depends on the chemicals and initial investment)	Park et al., 2018; Moodley et al., 2018; Simate & Ndlovu, 2014
Abiotic Passive	**Post-closure** (requires less energy)	**Low** (depends on the specific method, more recent techniques can treat high concentrations)	**Large** (depends on the specific method)	**Site-specific** (very sensitive to changes in environmental conditions)	**Low** (prone to clogging, requires renovation over time)	**High** (depends on the chemicals used and produced sludge/less sludge than the active method)	**Low** (depends on renovation and initial investment)	Moodley et al., 2018; RoyChowdhury et al. 2015; Martínez et al., 2019; Trumm, 2010; Kefeni et al., 2017
Biological Active	**Operating** (demands more energy)	**High** (usually with the possibility of recovering metals)	**Small** (usually bioreactors)	**Versatile** (by changing bioreactors parameters/allows differential removal of metals)	**Low** (long-term performance not understood)	**Low** (based on natural processes, less environmental pollution)	**High** (depends on initial investment)	Moodley et al., 2018; Rambabu et al., 2020; RoyChowdhury et al. 2015; Tong et al., 2021

(cont.) Method	Site operation	Acidity/Metal concentration	Area required	Design	Long term efficiency	Environmental impacts	Total Costs	References
Biological Passive	**Post-closure** (requires less energy)	**Low** (depends on the specific method)	**Large** (depends on the specific method)	**Site-specific** (very sensitive to changes in environmental conditions)	**Low** (prone to clogging, requires renovation over time)	**Low** (based on natural processes, less environmental pollution)	**Low** (depends on renovation and initial investment)	Rambabu et al., 2020; Naidu et al., 2019; Tong et al., 2021

Table 4 presents a brief comparison between major remediation methods but it is important to acknowledge that ARD is a complex process and exceptions may apply depending on specific technologies and local conditions. This table provides a simplified and general view of the studied methods, as an initial guide for more detailed research. In brief, a better understanding of each method's requirements together with a profound knowledge of site-specific environmental conditions are key to select appropriate remediation strategies (Simate & Ndlovu, 2014).

Biological treatments are currently considered promising for ARD control since they rely on natural processes and are often more environmentally friendly. Prevention methods and Passive treatments are generally better suited for less acidic wastewaters, demand less energy and chemicals, and produce less sludge. However, they are often based on slower processes and require more site-specific field studies for optimization. Active treatments are usually most efficient for highly acidic wastewaters, show faster results with immediate implementation and are versatile. On the other hand, they require a continuous supply of chemicals and energy and produce high volumes of hazardous sludge.

Sludge production and disposal from ARD traditional active treatment are extremely challenging, thus much emphasis is now being directed towards exploring greener remediation methods (Naidu et al., 2019; Simate & Ndlovu, 2014). According to Table 4, Prevention methods and both Active and Passive Biological treatments show lower environmental impacts, as highlighted in green in the Table. Notably, biological passive treatment has emerged as one of the most promising alternatives to active neutralization with limestone recently (Kefeni et al., 2017). Emerging techniques such as Successive Alkalinity Producing Systems and Algal Based Bioremediation show promising results for highly acidic wastewaters with lower environmental impacts at the same time (Rambabu et al., 2020; Trumm 2010).

According to the literature reviewed, each method shows different trade-offs depending on site conditions. The one exception is the long-term efficiency. This was described as a challenge for all methods analyzed in this study, and some of the causes are briefly listed below for Prevention, Abiotic and Biological treatments:

- Prevention methods lose efficiency over time. The sealing layers of dry covers suffer chemical and microbial degradation over time, bactericides need to be added repetitively, and different wet and dry cover systems eventually permit air and water infiltration (Pozo-Antonio et al., 2014; Moodley et al., 2018; RoyChowdhury et al. 2015)

- Abiotic active systems require a continuous supply of chemicals and energy, alkaline materials such as limestone are prone to coating and lose efficiency with time, and membranes inevitably suffer fouling. Abiotic passive systems are prone to clogging over time (Park et al., 2018; Moodley et al., 2018; Simate & Ndlovu, 2014).
- Biological active methods have limited lifespan, are sensitive to changes in temperature during winters, and their long-term efficiency is still not totally understood. Biological passive systems eventually need renovation and are complex environments, requiring extensive modelling and more long-term research (Moodley et al., 2018; RoyChowdhury et al. 2015; Rambabu et al., 2020; Naidu et al., 2019).

3.4 Ecological Restoration

Technologies listed in Table 4 aim to compensate for the environmental damages caused by the exposure of sulfide minerals and subsequent generation of acid wastewaters. The recommended next step would be ecological restoration actions. Ecological restoration is based on processes to assist the recovery of a degraded area, regarding ecosystem health, integrity and sustainability. Currently, restoration goals also include the legislation, cultural values and socioeconomic context. These are crucial to enhance the support from the local community and to develop more realistic and efficient projects in the longer term (Aradottir & Hagen, 2013).

3.5 Remediation approach

Based on the information gathered, a simplified and recommended approach to remediate areas impacted by ARD follows:

1. **First, understanding ARD at the site.**
   Pre-analyze local conditions to determine mineral chemical composition, acid-producing potential and weathering rates through appropriate geochemical analyses, static tests and kinetic tests (Lapakko, 2002; Zhou et al., 2019).
2. **Second, minimizing ARD sources.**
   During planning and mining operations adopt some recycling technologies to minimize

tailings and mining residues. These may help to reduce the impact of toxic chemicals from the tailings (Kefeni et al., 2017).

3. **Next, understanding remediation options and developing an action-plan before the full-scale installation of remediation technologies.**
   A thorough understanding of the remediation options which are efficient at site conditions and show lower environmental impacts is key to the decision-making process. On-site small-scale tests to review risks of failure and to plan for different acidity levels are also recommended (Trumm, 2010). In addition to opting for greener remediation methods, there are other emerging strategies aiming to increase sustainability in ARD control, such as the recycling of valuable materials or the use of industrial by-products and naturally available minerals. These have been reported in detail by previous studies (Kefeni et al., 2017; Moodley et al., 2018; RoyChowdhury et al., 2019; Viadero et al., 2020).
4. **Finally, integrating the remediation plan with ecological restoration actions.** These actions aim for the long-term recovery of ecosystems' services and values and are dependent on clear goals and continuous monitoring. This should be based on specific local conditions and the input of the local community (Aradottir & Hagen, 2013; Douglas, 2002).

4 CONCLUSIONS

There are several methods of ARD remediation presented and discussed in the literature, each showing different trade-offs depending on site conditions. Thus, a critical analysis of available ARD remediation methods is necessary in order to select the most appropriate strategy for a specific site. Based on the literature reviewed, this study produced a summarized table of comparison, which provides a simplified and general view of the various ARD remediation methods currently used, as an initial guide for more detailed research.

Active neutralization is still adopted in a generalized manner but this method shows significant environmental impacts and is not the most efficient for every situation. As a result, researchers are currently interested in looking for low-cost and more sustainable ARD prevention and treatment methods. From the literature reviewed, Prevention methods and both Active and Passive Biological treatments show lower environmental impacts than active neutralization. Also, there are other strategies to increase the sustainability of ARD control, such as minimizing mine wastes, recovering valuable metals, and using by-products from other industries.

Despite great research efforts regarding ARD clean-up, ARD remediation is still a challenge, especially for the longer term. Insights from the comparison of available remediation methods presented in this paper, which is based on key factors such as costs, effectiveness and environmental impacts may help site-specific decision-making process and inform local communities and environmental engineers on more sustainable remediation strategies available.

5 RECOMMENDATIONS

- The prediction and selection of ARD remediation strategy should be site-specific and take local environmental conditions into consideration. Prior to adopting a specific method, mineral chemical composition, acid-producing potential and weathering rates should be properly measured. Then, a critical analysis of available ARD remediation methods is necessary in order to select the most appropriate strategy for the site.
- This study is a simplified guide for further and more detailed research considering specific site conditions. The main goal was to review various methods currently adopted worldwide and summarize the key requirements for each. The summary provided is based on general conditions for most of the technologies currently used. However, ARD is a complex process and exceptions may apply depending on specific technologies and local conditions.
- The goal of this study was to provide information in support of further research on ARD remediation. The next step would be to include emerging mitigation strategies in the analysis, especially the integration of different methods and the use of naturally available minerals or industrial by-products. Another important next step would be to evaluate the potential of each technique to support site-specific ecological restoration actions.

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