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Literature Review: Remediation of Acid Mine Drainage using Alternative Materials in The Mining Industry

Eprilia Simamora[1], Mohammad Nurcholis[2], Aldin Adrian[3]

[1] *Program Magister Teknik Pertambangan, Fakultas Teknologi Mineral*
Universitas Pembangunan Nasional "Veteran" Yogyakarta
St. SWK 104, Condongcatur, Depok, Sleman, Yogyakarta 55283, Indonesia

[1] 212221007@student.upnyk.ac.id

[2,3] *Universitas Pembangunan Nasional "Veteran" Yogyakarta*
St. SWK 104, Condongcatur, Depok, Sleman, Yogyakarta 55283, Indonesia

[2] nurcholis@upnyk.ac.id
[3] aldin.ardian@upnyk.ac.id

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Abstract

This research presents an analysis of literature studies on acid mine drainage management using various innovative methods with alternative materials. Although mining is acknowledged as a major source of energy worldwide, it also pollutes the environment, mostly through Acid Mine Drainage (AMD). Because AMD has a major influence on both human health and the environment, managing it is difficult. Various conventional methods have been developed, but they tend to be expensive and have major side effects. A variety of techniques can be used to effectively manage acid mine drainage and enhance human health and environmental quality. This literature review analyzed several previous studies that examined various approaches to addressing AMD. The findings indicated that the amounts of heavy metals and sulfates in AMD might be decreased by using coal mine waste, organic matter, and artificial wetland systems. However, each approach had advantages and disadvantages and required careful analysis of environmental conditions and the success of the management approach. Further research was needed to develop more effective, economical, and sustainable approaches to AMD management using phytoremediation and bioremediation. Numerous elements should be taken into account, such as the local environmental circumstances, the chemical characteristics of acid mine drainage, and social and economic concerns. Steps to manage AMD included understanding mine site conditions, identifying suitable alternative materials, designing suitable bioreactors, and involving all relevant stakeholders.

Keywords: Acid Mine Drainage, Alternative Materials, Literature Review, Remediation, Wetland System.

Corresponding Author:
Eprilia Simamora
Universitas Pembangunan Nasional "Veteran" Yogyakarta
St. SWK 104, Condongcatur, Depok, Sleman, Yogyakarta 55283, Indonesia
Email: 212221007@student.upnyk.ac.id

I. INTRODUCTION

The mining industry has become a major source of global energy, but mining activities are also often recognized as a major cause of environmental pollution. One major consequence is the creation of acid mine drainage (AMD), which results from the interaction of water and rock and carries various harmful substances that pose risks to both the environment and public health. As noted in the 2013 Outlook for Energy in Indonesia by Badan Pengkajian dan Penerapan Teknologi (BPPT), industrial progress is essential for every nation to foster economic growth, generate employment, and meet basic human needs [3]. This will lead to population growth, enhance industrial development, and raise energy requirements.

Indonesia's industrial sector continues to depend on oil and coal to satisfy its energy demands. Coal is still utilized as a fuel source for Steam Power Plants (SPP). Indonesia ranks among the top countries in coal production. According to the Ministry of Energy and Mineral Resources, in 2018, Indonesia's coal resources were 166 billion tons, with remaining reserves reaching 37 billion tons. According to the Indonesian Mining Association (IMA), in 2014, Indonesia was ranked 3rd in coal exports [7]. As the demand for energy increases, exploration and exploitation of coal mining will continue [17]. As a result, the potential for negative impacts due to mining activities will increase. In Indonesia, coal mining typically employs an open pit mining method, though a few resort to underground mining. Thus, it will influence alterations in the landscape, as well as the chemical, physical, and biological characteristics of soil and water. Overall, it may harm the earth's surface, specifically by creating acid mine drainage.

Acid mine drainage is an environmental issue that arises from activities associated with the mining industry. Acid mine drainage occurs due to the oxidation of rocks that have pyrite (FeS2) and sulfide minerals from other rocks that are exposed to oxygen in water [4]. The natural process of mining sulfide rocks such as pyrite produces sulfuric acid, which can then contaminate surrounding groundwater and rivers. In mining operations, the occurrence of acid mine drainage is inevitable. This is because mining is an activity of removing minerals from rocks to be transported, processed, and utilized so that rock exposure will occur. Acid mine drainage not only damages the local environment but also threatens the sustainability of aquatic ecosystems and soil and disrupts human life that depends on these resources.

Acid mine drainage management is a complex challenge and requires a holistic approach due to its persistent and destructive nature. Conventional methods, such as the use of chemicals to neutralize acid mine drainage, tend to be expensive, have significant side effects on the environment, and are less effective in the long term. Therefore, innovative solutions that are more environmentally friendly and sustainable are needed. Innovative methods using phytoremediation and bioremediation techniques are promising approaches to addressing acid mine drainage problems. This approach uses living organisms, such as plants, bacteria, and natural materials, to naturally decompose or neutralize pollutants. This technique provides several advantages, including lower costs, sustainability, and the ability to improve the environment gradually.

Introducing management with these innovations does present certain challenges. A thorough examination is necessary to grasp the environmental factors, the chemical makeup of acid mine drainage, and the appropriateness of the alternative materials to be used. While the potential of using these systems to improve acid mine drainage quality has been recognized, a comprehensive literature review of studies that have been conducted in various locations and conditions needs to be conducted. An extensive literature review will enhance comprehension of the effectiveness, obstacles, and possible solutions provided by this method to maximize the anticipated outcomes. Building on existing knowledge and identifying further research needs is becoming more important in the effort to maintain environmental sustainability at mining sites.

A. Review of Acid Mine Drainage

Acid mine drainage (AMD) occurs as a result of the oxidation of sulfide minerals when they interact with air and water during mining operations, leading to the production of sulfuric acid that raises the acidity of the water [11]. Sulfide minerals commonly found in mining activities are pyrite with a chemical composition (FeS_2). The typical response that takes place during the creation of acid mine drainage is as follows [14]:

The initial response is the oxidation of sulfide minerals (FeS2) when interact with oxygen and water. In this reaction, ferrous iron (Fe^{2+}) and sulfate are released into the water.

$FeS_{2\,(s)} + 3.5\ O_{2\,(g)} + H_2O_{(\ell)} \rightarrow Fe^{2+}_{(aq)} + 2\ SO_4^{2-}{}_{(aq)} + 4\ H^+_{(aq)}$ (1)

Pyrite + Oxygen + Water → Iron (II)+ Sulfate + Acidity

The second reaction involves the oxidation of ferrous iron to (Fe^{3+}) using oxygen and acidity. $Fe^{2+}_{(aq)} + 0.25\ O_{2\,(g)} + H^+_{(aq)} \rightarrow Fe^{3+}_{(aq)} + 0.25\ H_2O_{(\ell)}$ (2)

Iron (II) + Oxygen + Acidity → Iron (III) + Water

The third reaction is a propagation reaction, taking place as long as pyrite and ferric iron minerals are available. In this reaction, ferric iron will oxidize pyrite and accelerate the oxidation rate.

$FeS_{2\,(s)} + 14\ Fe^{3+}_{(aq)} + 8\ H_2O_{(\ell)} \rightarrow 15\ Fe^{2+}_{(aq)} + 2\ SO_4^{2-}{}_{(aq)} + 16\ H^+_{(aq)}$ (3)

Pyrite + Iron (III) + Water → Iron (II) + Sulfate + Acidity

The fourth reaction is the formation of iron (III) hydroxide precipitates ($Fe(OH)_3$) or "*yellowboy*" in the form of an orange precipitate in water under low pH conditions.

$Fe^{3+}_{(aq)} + 3\ H_2O_{(\ell)} \rightarrow Fe(OH)_{3\,(s)} + 3\ H^+_{(aq)}$ (4)

Iron (III) + Water → Iron Hydroxide + Acidity

When reactions (1) to (4) are combined, a pyrite oxidation reaction is formed that produces acid mine drainage with the products: iron hydroxide, sulfuric acid, and acidity.

$FeS_{2\,(s)} + 3.75\ O_{2\,(g)} + 3.5\ H_2O_{(\ell)} \rightarrow Fe(OH)_{3\,(s)} + 2\ SO_4^{2-}{}_{(aq)} + 4\ H^+_{(aq)}$ (5)

Pyrite + Oxygen + Water → Iron Hydroxide + Sulfuric Acid + Acidity

AMD is one of the sources of water pollution that causes major problems and changes to the environment. When the pH level and metal content in water exceed the tolerable range, it will negatively affect aquatic organisms, damage ecosystems, and pollute the aquatic environment, so adequate treatment methods are needed to overcome these problems [9].

B. Acid Mine Drainage Remediation

The remediation of acid mine drainage is essential for preserving environmental balance by enhancing the quality of mining wastewater through the reduction of its acidity and metal concentration, thereby lessening detrimental effects on the environment and ensuring the conservation of natural resources. This is important for carrying out responsible and sustainable mining activities. Acid mine drainage treatment techniques are divided into two, namely active treatment and passive treatment. The active treatment method is carried out by directly mixing alkaline materials continuously in the field, for example, neutralizing acid mine drainage by manually adding quicklime powder or using an injection pump, aerator, and electricity. The passive treatment method is carried out by allowing acid mine drainage to flow and undergo a natural reaction process, for example, neutralization with natural media in an artificial wetland system (constructed wetland) to improve water quality before being discharged into public channels [10].

II. Research Method

The research stages began based on a literature study summarized from several scientific publications in the form of national and international journals regarding the handling of industrial wastewater based on the use of alternative materials. Reviewed from 2013 to 2024, focusing on handling acid mine drainage. A literature review was a critical process and evaluation of similar studies conducted previously [12]. This research aimed to serve as a guide for recognizing the implementation of alternative materials in the treatment process of acid mine drainage, particularly concerning wastewater from the mining sector. The stages in this study are shown in the flow chart below, as follows:

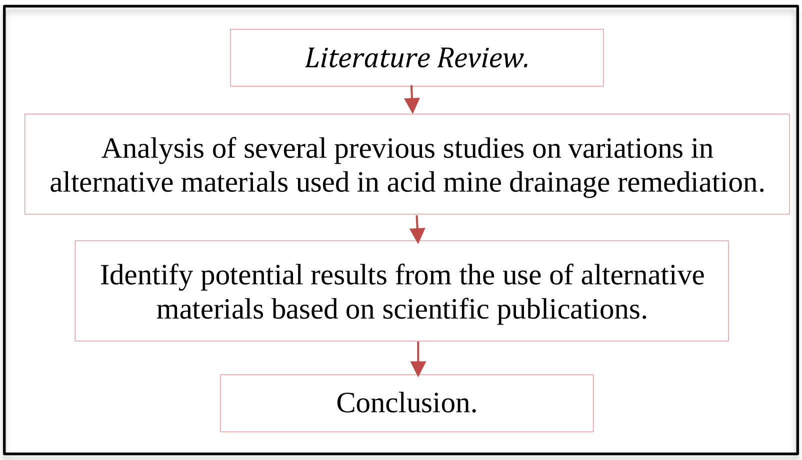

Fig. 1. Research Flow Chart

III. RESULTS AND DISCUSSION

The study of literature encompasses a range of activities, such as gathering library information, reading and documenting, and analyzing research resources. In this study, multiple research compilations were conducted as scientific publications serving as review resources. The previous studies used are:

Table I. THE RESULT OF STUDIES ON AMD TREATMENT USING ALTERNATIVE MATERIALS

Name, Year	Title	Data Collection Methods	Research Methods	Alternative Materials	Research Results
Anisyah Quran Ni, 2022	Overview of Acid Mine Drainage Management Methods Utilizing Sulfate Reducing Bacteria	This study provides a summary of various scientific research focused on the techniques and methods utilized for managing acid mine drainage through the use of Sulfate Reducing Bacteria (SRB). And the purpose of this research is to serve as a reference for the management and enhancement of acid mine drainage quality.	Passive treatment method using natural constructed wetland system	Sulfate Reducing Bacteria (SRB)	The handling of acid mine drainage through a modified reactor with the help of sulfate-reducing bacteria is more effective than using passive treatment because the sulfate removal carried out by sulfate-reducing bacteria is more optimal than the passive method. However, the utilization of reactors requires high costs and more intense maintenance than passive treatment [2].
Fitri Arum Sekarjannah, 2019.	Acid Mine Drainage Management Constructed Wetland System Using Water Hyacinth Plants (*Eichhornia crassipes*) and Addition of Organic Materials	The data were examined utilizing Analysis of Variance (ANOVA) at the 5% significance level. If a notable difference exists, the Duncan Multiple Range Test (DMRT) is conducted at the 5% level.	Passive treatment method using constructed wetland implementing phytoremediation system	Using Water Hyacinth Plants (*Eichhornia crassipes*) and adding organic materials	According to the findings of the study, it can be concluded that: 1). Constructed wetland systems can increase the pH of acidic mine effluent and reduce the solubility of heavy metals like Fe and Mn. 2). The incorporation of organic matter greatly influences the rise in pH. and decreasing dissolved Mn concentration in acid mine drainage remediation but has no significant effect on decreasing Fe concentration in water. Organic matter is also able to absorb heavy metals like Fe and Mn. 3). The optimal arrangement of organic matter for the remediation of acid mine drainage in this research is found in the A3 treatment, specifically compost + wood powder (2:1) with an incubation period of 33 days. 4). Water hyacinth plants (*Eichhornia crassipes*) can absorb heavy metals Fe

Name, Year	Title	Data Collection Methods	Research Methods	Alternative Materials	Research Results
					and Mn within constructed wetland system. The mechanism of action of water hyacinth plant phytoremediation (*Eichhornia crassipes*) is phytoextraction [5].
Yudha Gusti Wibowo, 2021	An Analytical Review of Acid Mine Drainage Remediation	The approach employed in this study is a literature review. The scientific papers (52 articles) referenced in this study were sourced from journals published by (Elsevier, Springer, Nature, and various other reputable international and national journals). The terms employed to search for scientific articles referenced included acid mine drainage, treatment and review of acid mine	Combination Precipitation, Adsorption, Aerobic wetland, Bioremediation methods	Algae, Active charcoal, carbon composite, bacteria, plant and biochar	Environmental pollution resulting from acid mine drainage due to mining activities leads to soil and plant contamination, which can affect human health issues. Multiple attempts have been undertaken to avert the creation of acid mine drainage. Active and passive treatment techniques have been created to decrease contaminant levels in acid mine drainage. The technique involving quicklime remains a viable choice for raising the pH of acid mine drainage through the use of $Ca(OH)_2$. Raising the pH from
		drainage, adsorption, and bioremediation of acid mine drainage.			acidic to neutral conditions is anticipated to lower the concentration of heavy metals in acid mine drainage. Additional techniques that have been created to reduce the contaminating factors of acid mine drainage include adsorption and bioremediation. Multiple studies have created materials capable of decreasing pollutant levels in acid mine drainage. Nonetheless, these techniques are yet to be broadly utilized. Certain studies have indicated that researchers continue to perform trial analyses or experiments at a laboratory level to identify the proper procedures for future use on an industrial scale. It is anticipated that different current techniques can be improved to address the acid mine drainage issue. Additional research aims to create materials that integrate both active and passive techniques to support one another and greatly diminish the harmful aspects of acid mine drainage while avoiding the generation of unrecognized by products [15].
I. N. Jamil, 2013	Bioremediation for Acid Mine Drainage: Organic Solid Waste As Carbon Sources For Sulfate-Reducing Bacteria: A Review	The approach employed in this study is a literature review.	Passive treatment method using biological treatment.	Sulfate Reducing Bacteria (SRB)	Acid Mine Drainage (AMD) leads to environmental contamination, and stopping the occurrence of AMD is a significant solution. Studies indicate that the application of sulfate-reducing bacteria for the bioremediation of AMD has garnered significant interest from numerous researchers. In the past, studies have concentrated on liquid substrates (lactate and ethanol) for sulfidogenic bioreactors. Solid substrate materials could effectively serve as a substrate source to boost the performance of sulfate-reducing bacterial systems.
					This review recognizes that the primary constraint in sulfate reduction by Sulfate Reducing Bacteria (SRB) is the breakdown of complex organic compounds. The total operational

Name, Year	Title	Data Collection Methods	Research Methods	Alternative Materials	Research Results
					expense of a biological treatment facility is a result of system design and site location, benefits derived from metal recovery, choice of substrate, and disposal standart. Identifying appropriate low-cost substrate alternatives like utilizing food waste and organic solid waste may enhance the application of SRB technology. [6].
Rizky Ananda, 2022	pH Neutralization of Acid Mine Drainage Using Open Limestone Channel with Addition of Fly Ash and Silica Sand on Laboratory Scale Testing	The research is classified as experimental research. Experimental research is scientifically reliable research because it is valid and accurate through strict control of outside interference variables to be tested. The focus of this study is acid mine drainage. The pH level of the holding pond is essential for conducting research or studies to determine an effective neutralization technique in managing acid mine drainage.	Passive treatment method using passive open limestone channel with three type combination	Limestone channel approach along with incorporation of fly ash and silica sand	Based on the findings from the AMD, pH neutralization test utilizing the passive open limestone channel approach along with the incorporation of fly ash and silica sand, the subsequent conclusions were reached: 1. In the initial test, designated as combination AA-0, the pH value rose from 3,75 to 7,39. 2. In combination AA-1 or the second test, the pH rose from 3,75 to 7,3. 3. In combination AA-2 or the third examination, the pH value rose from 3,75 to 7,21. Based on the outcomes of three tests conducted with these materials and methods, a final pH value was attained that fell within the AMD quality standards range accepted in Indonesia [1].
Eprilia Simamora, 2024	Literature Study on Coal Acid Mine Drainage Management Using Phytoremediation System	The approach taken in this investigation is a literature review. A literature review includes various tasks connected to gathering literature data, reviewing and annotating texts, and analyzing research materials.	Passive treatment method using implement phyto-remediation system	Reviews on the use of aquatic plants: *Eichhorniacrass ipes*, *Limnocharisflava*, *Neptuniaoleracea*,	The findings show that the use of different types of plants provides a more comprehensive picture. Utilizing a variety of plants or more intricate phytoremediation systems provides a wider comprehension. Evaluation of the ability of plants to absorb Fe and Mn was emphasized.
				Salvinia natans, *Pistia stratiotes*, *Eichornia crassipes*, *Melaleuca cajuputi*, *Nauclea orientalis* and *Vetiveria zizanioides*	The addition of evaluations for other metals or potential pollutants would increase the comprehensiveness of the study. A decrease in plant sorption ability was observed after ten days, but external factors such as temperature, pH, or environmental conditions that influence this decrease were not extensively discussed [13].
Yudha Gusti Wibowo, 2022	Constructed Wetlands for Treatment of Acid Mine Drainage: A Review	A systematic review was performed by gathering literature on wetland usage sourced from Google Scholar. The terms employed for searching the literature included constructed wetlands for acid mine drainage treatment, passive methods for acid mine drainage treatment, and treatment of acid mine drainage.	Economic analysis of Passive treatment method using constructed wetland system, conventional, bioreactor, and bio-cell	*T.latifolia*, *C.malacencis*, and *P.australis*	Constructed wetlands represent an affordable and practical approach to managing Acid Mine Drainage (AMD). Various research has demonstrated that constructed wetlands can decrease metal ions and stabilize low pH levels in mining regions. This occurrence happens due to the presence of microbial communities in plant roots and the surrounding soil. Additionally, heavy metals are diminished because of adsorption processes occurring in the soil. The elevated pH level in the constructed wetland can address the issue of low pH in AMD. Furthermore, adjusting the pH level of AMD can influence the precipitation of metal

Name, Year	Title	Data Collection Methods	Research Methods	Alternative Materials	Research Results
					ions. This paper additionally presents general details, historical context, and an overview of constructed wetlands and AMD. The study additionally describes the effects of AMD on water quality, marine ecosystems, and public health. Current trends in AMD treatment through the use of created artificial wetlands are thoroughly outlined, including composite suggestions for soil design, plant diversity, and the benefits of vegetation as elements of constructed wetlands. In conclusion, the paper outlines possible uses of constructed wetlands in countryside regions and explores future impacts [16].
Yanan Jiao, 2022	A review AMD: Mechanisms of formation, treatment methods, typical engineering cases, and resource recovery.	This method involves the process of turning acidic water into more neutral one by adding substances like limestone to raise its pH level. This method employs a selective precipitation system to remove harmful elements in AMD, thereby decreasing the levels of heavy metals and chemicals.	Microbio-logical methods, constructed wetland methods, adsorption and membrane separation	Sulfate Reducing Bacteria (SRB)	Acid Mine Drainage (AMD) is wastewater from the mining industry that contains high levels of metals and sulfates, creating significant environmental and economic issues for the mining sector and complicating water treatment efforts. Consequently, understanding the mechanisms of AMD development and its related environmental impacts is essential. This paper examines various methods for treating AMD, these treatment methods has advantages and disadvantages when treating AMD. Precipitation is an effective technique for extracting metal from AMD because of its low operational expenses and high efficiency. Nonetheless, it has the drawback of generating substantial amounts of sludge. Furthermore, electrochemical and membrane technologies can be utilized to successfully extract metals; however, the procedure is intricate, operating expenses are elevated, and the implementation of this treatment technology at mining locations is challenging [8].

IV. Results

Several studies have been carried out by different organizations, private firms, and universities on the advancement of biological methods in the mining industry. One of them is the research of Anisyah Alquran Ni (2022), regarding an overview of acid mine drainage management methods using sulfate-reducing bacteria [2]. These findings offer an extensive overview of methods for managing acid mine drainage with the use of sulfate-reducing bacteria. Presents findings that demonstrate the efficiency of modified reactors utilizing sulfate-reducing bacteria to decrease sulfate levels in acid mine drainage. Focuses on active treatment using reactors that require high cost and maintenance. Provides insight into one of the innovative acid mine drainage management methods, albeit with caveats regarding cost and maintenance.

Fitri Arum Sekarjannah (2019), presents findings on the implementation of artificial wetland systems utilizing water hyacinth and incorporating organic matter to lower heavy metal levels in acid mine discharge [5]. Does not provide detailed information on the economic and operational aspects of the proposed system. The potential of using plants and organic matter in acid mine drainage management has been highlighted, although its practical implementation needs further study.

Yudha Gusti Wibowo (2021), shares result a comprehensive review of various acid mine drainage management methods, including active and passive approaches and the application of specific materials in remediation [15]. It does not provide an in-depth analysis of the effectiveness of each of the methods or materials discussed. This review provides a broad understanding of acid mine drainage management options but needs to be accompanied by further research to validate and develop the most effective approaches.

IN. Jamil (2013), provides an extensive analysis of utilizing solid organic waste as a carbon source for sulfate-reducing bacteria in the remediation of acid mine drainage [6]. Does not provide an in-depth evaluation of the potential applications and challenges in applying the bioremediation methods discussed. Highlights the potential use of solid organic waste in bioremediation of acid mine drainage, but further research is needed to assess its implementation and effectiveness.

Rizky Ananda (2022), discussed how to neutralize the pH of acid mine drainage by utilizing open limestone channels along with adding fly ash and silica sand. [1]. The test findings indicated a rise in pH levels from 3,75 to 7,21-7,39, fitting within the acid mine drainage quality standards established in Indonesia. The findings of this research demonstrate that utilizing test materials like fly ash and silica sand in the open limestone channel approach can elevate the pH of acid mine drainage to attain a neutral pH.

Research by Eprilia Simamora (2024), this study conducted a literature review on acid mine drainage management using phytoremediation methods [13]. The findings show that the use of different types of plants provides a broader understanding, but further evaluation of the ability and variety of plants to absorb metal elements is needed. External environmental factors such as temperature and environmental conditions that may affect the outcome of phytoremediation also need to be considered. Including literature on more innovative technologies and approaches in AMD phytoremediation may pave the way for discoveries that can improve the efficiency of the process.

According to research by Yudha Gusti Wibowo (2022), the findings indicate that employing constructed wetlands for AMD treatment effectively decreases metal ions and enhances pH levels in mining regions [16]. The research additionally provides details regarding the history, characteristics, and effects of AMD on water quality, aquatic habitats, and human health. Recent trends in AMD treatment utilizing Constructed Wetlands (CW) are thoroughly detailed, encompassing combined suggestions for soil creation, vegetation diversity, and the benefits of plants as elements of constructed wetlands. The paper describes the potential application of constructed wetlands in rural areas and future considerations.

Yanan Jiao (2022) explained the formation mechanisms and environmental effects of AMD, thoroughly examined the principles and uses of various AMD treatment technologies, and highlighted the limitations encountered in the practical implementation of AMD treatment [8]. In essence, this review will offer valuable insights for directing AMD therapy. Every method has its intricacies, and it is advisable to investigate additional mixed techniques to achieve effective acid mine drainage management. Overall, the evaluation of these materials shows that each study makes a unique contribution to the understanding and practice of acid mine drainage management, but further research is needed to develop more effective, economical, and sustainable approaches.

These studies present various strategies for tackling the issue of AMD, from experimental investigations aimed at neutralizing pH to literature surveys on phytoremediation and bioremediation techniques, the deployment of constructed wetlands, and an extensive review of AMD formation and treatment processes. Utilizing these methods together can aid in effectively managing acid mine drainage and enhancing environmental quality.

When managing acid mine drainage with different innovative techniques and alternative materials, the initial step involves comprehending the particular conditions present at the mine site affected by acid mine drainage. This encompasses the physical, chemical, and biological traits of the water, soil, and adjacent environment. Next, an environmental risk evaluation is conducted to assess the effects of acid mine drainage on nearby ecosystems and public health. This is crucial for developing suitable management strategies. Identify the most suitable management techniques to use for the existing acid mine drainage conditions. This requires research and testing to determine the media materials used such as the selection of plant biomass and organic materials that contain effective ingredients in reducing pollution and restoring the environment.

A suitable bioreactor design is needed to optimize the application of the treatment process through various innovative methods with effective strategies, including the selection of the main media used, the setting of environmental conditions, and regular monitoring of system performance. In carrying out the engineering operation of the treatment system in the field according to the plan that has been designed, it is necessary to pay attention to changes in environmental conditions that may occur. By conducting continuous monitoring of remediation performance, the effectiveness of management can be evaluated periodically. This enables modifications to the strategy if needed, to attain the desired outcomes by engaging all pertinent stakeholders, such as local communities, government, and the mining sector in the implementation and decision-making process. After successfully reducing pollution levels, the next step is to restore and reclaim mined land to restore its ecological function and improve the economic and social value of local communities.

Some potential shortcomings of the studies presented are that the research was conducted on a laboratory scale so the results may not fully reflect field conditions. Other factors that may affect the neutralization process were not considered. The research is based on a literature review, which may result in bias depending on the sources selected. Although it is a systematic review, limited access to certain literature or a tendency to select certain sources may affect the balance of the information. Although this review offers valuable insights, it may not encompass every variation in the use of constructed wetlands for AMD treatment across diverse contexts. The review offers details on AMD treatment methods, but there is a restricted analysis of particular case studies. Since this is a literature review, the originality of the information provided is restricted.

V. Conclusion

From the results of several reviews of literature studies, the following conclusions were obtained:

1. There have been various studies and reviews conducted by various institutions and individuals on acid mine drainage management, with a focus on innovative approaches using alternative materials such as biological processes using organic matter and artificial wetland systems with particular plant species, which could lower heavy metal and sulfate levels in acid mine drainage. Some approaches have their advantages and disadvantages, which require a comprehensive analysis of the contaminated mine situation and have not been fully elaborated in terms of economic and operational aspects**.**
2. The use of passive methods utilizing natural biological materials such as accumulator plants, sulfate-reducing bacteria, and limestone in constructed wetland systems has proven to be superior to active methods that rely on chemical materials for acid mine drainage remediation. This passive approach offers lower operational costs, better ecological sustainability, and minimal environmental impact. Additionally, it leverages natural processes that are stable and capable of supporting holistic ecosystem recovery, making it a more environmentally friendly and sustainable solution for long-term acid mine drainage management.
3. Information on the combination of these methods helps in the management of mine wastewater, to improve environmental quality and benefits to human health. However, there are some potential shortcomings in these studies. Some of these include scale limitations in experimental studies, limitations in considering factors that may affect the treatment process, as well as possible biases in literature reviews, and limited access to certain literature. In addition, systematic reviews of the use of established treatment techniques may not cover all variations in their application across different contexts and lack in-depth analysis of specific case studies.
4. Further research reviews are needed to develop a more effective, economical, and sustainable approach to acid mine drainage management by taking into account various factors in applying each improved treatment technique by environmental aspects, including identification of the chemical properties of acid mine drainage, mine site-specific conditions, environmental risk assessment, successful design of appropriate treatment under these conditions, implementation strategies and regular monitoring of system performance with attention to the involvement of related social aspects.

As for the results of several literature study reviews, the following suggestions were obtained:

1. Conduct further research to develop more effective, economical, and sustainable approaches to treatment techniques. This research should include further testing of different types of alternative materials and the use of advanced techniques in wastewater management construction methods according to the diverse environmental conditions of the mine

2. Before applying appropriate treatment methods and techniques, it is necessary to conduct a comprehensive analysis of the contaminated mine site conditions. This encompasses a thorough comprehension of acid mine drainage, along with the physical, chemical, and biological traits of the water, soil, and adjacent environment.
3. In implementing wastewater treatment systems, it is important to use an integrated approach between scientific research, technology, and practice in the mining industry to achieve success in minimizing the effects of acid mine drainage on ecological systems and health.
4. During the processing process, regular monitoring and evaluation of the performance of the system is required to enable adjustments to the strategy in achieving the desired results.
5. It is important to provide clear and accurate information and involve all stakeholders, including local communities, governments, and the mining industry, in the decision-making process, oversight of sustainable mining practices, and implementation of solutions in acid mine drainage management.
6. Conduct regular monitoring and evaluation of the effectiveness of the methods applied in AMD management to ensure their sustainability and make adjustments if necessary. The restoration and reclamation of mined land to restore its ecological function and enhance the economic and social value of local communities must be monitored to ensure its success.

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