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Environmental and Ecological Impacts of Acid Mine Drainage, Using Microbes to Mitigate Its Effects

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***Abstract*—Acid Mine Drainage (AMD) contamination is the primary environmental issue in industrial areas and where geological mining occurs. AMD is caused by oxidative dissolution of sulphide minerals, natural ecosystems depend on microbial diversity and functioning at their best. This review presents the long-term effects of AMD water such as pollution from Heavy Metals (HM) on humans and plants, and the solution to the problem of heavy metal pollution by microbes metal interactions.**

***Keywords*—Acid Mine Drainage (AMD), remediation, heavy metals, microbe, environmental effects**

I. INTRODUCTION

Mining for some minerals, such as gold, copper, and nickel, is related to acid drainage issues, which can harm streams and biodiversity in the long run. Furthermore, toxic substances like cyanides and heavy metals can be found in high concentrations in some metal mining effluents, which have major human health and environmental consequences [1]. The acidity of surrounding soils caused by Acid Mine Drainage (AMD) from abandoned gold mines has an impact on the mobility of heavy metals and the variety of soil microbes [2]. AMD is caused by oxidative dissolution of sulphide minerals in the ground during mining operations [3]. When exposed to water and oxygen, most sulphide minerals oxidise and produce acid, metal ions, and sulphate, which would then leach into groundwater as well as surface water [4]. In recent years, researchers have focused a lot of emphasis on microbes and their metabolism in AMD. Microbes interact with metals and minerals, in both natural and artificial settings, changing their physical and chemical states. Metals and minerals can also have an impact on the growth, activity, and survival of microbes [5]. By dissolving the metal ions in natural materials like coal and gold, microbes can transform heavy metals including cadmium (Cd), lead (Pb), copper (Cu), mercury (Hg), nickel (Ni), uranium (U), and zinc (Zn) into soluble species.

However, they are also capable of working in the reverse direction, causing insoluble species like magnetite to develop as a result of their metabolic activities. Microbes can metabolize heavy metals into soluble or volatile organometallic compounds, such as trimethylarsine or dimethylarsinic acid. It is just as crucial to consider how these biologically produced metal compounds, biologically mobilized metals, or biologically precipitated metals affect how metals are distributed in the environment as it is to consider how the pure physicochemical interactions take place [6].

II. FORMATION OF ACID MINE DRAINAGE (AMD)

The primary sources of AMD are leaching water from open pits, tailings pits, waste rock dumps, abandoned mines, and underground deposits, which is one of the major pollutants having an adverse effect on the environment. Wastewater released during ore flotation and smelting is another major source of AMD [7]. Low pH, high specific conductivity, high iron, aluminium, and manganese concentrations, and low toxic heavy metal concentrations are all present in AMD discharges.

Pyrite (FeS_2) is a common metal sulfide mineral in tailings and an important mineral raw material. When exposed to liquid water and oxygen, pyrite can weather quickly. Sulfuric acid (H_2SO_4) and dissolved ferric ions (Fe^{3+}) are produced when pyrite weathers, increasing pyrite disintegration and hastening the release of hazardous metals from surrounding minerals [8]. The first and most important reaction is the oxidation of pyrite (or sulphide) into dissolved iron, sulphate, and hydrogen (Eq. (1)); however, the rate of pyrite oxidation and the subsequent acid production is dependent on solid phase compositional variables, microbial activity, and the availability of oxygen and water.

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \quad (1)$$

$$Fe(ii) + 1/4O_2 + H^+ \rightarrow Fe(iii) + 1/2H_2O \quad (2)$$

If the pH is low, (Eq. (2)) won't happen until it reaches 8.5. The conversion of ferrous to ferric ion at pH values below 5 under abiotic conditions is slow, hence in general, under many conditions, (Eq. (2)) is the rate-limiting step in pyrite oxidation. $Fe(OH)_3$ (and to a lesser extent, jarosite, $H_3OFe_3(SO_4)_2(OH)_6$) can precipitate when ferric iron formed in Eq. (2) reaches pH values between 2.3 and 3.5, lowering the pH and leaving little Fe^{3+} (Fe(iii)) in solution [9].

III. EFFECTS OF ACID MINE DRAINAGE (AMD)

AMD contains heavy metals that have dissolved. Heavy metals are naturally occurring metals with an atomic number larger than 20 and molecular weights greater than 53. They also have a higher density than 6 g/cm^3 [10].

Heavy metals can continue to be a threat to ecosystems, agricultural land, and human health, because of their high acidity and non-biodegradable Heavy Metal (HM) contamination in living things and food chains [11].

Heavy metals can continue to be present in the natural ecosystem for a long period, they can build up at different stages of the biological chain, which can lead to both acute

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and chronic diseases in the lungs, liver, haematological system, nervous system, and reproductive organs [12]. Table 1 shows the effect of heavy metal exposure on humans. Heavy metal concentrations in plant tissues can affect the growth of plants in a variety of ways, when plants are exposed to heavy metals, they undergo oxidative stress, which damages their cells and disturbs their ionic balance, altering their morphology and physiology. Some of the effects of heavy metals on plants are shown in Table 2.

Table 1. Effects of heavy metal exposure on humans [13]

Heavy Metal	**Effect**
Arsenic	Bronchitis, dermatitis, poisoning
Cadmium	Lung damage, lung cancer, high blood pressure, renal dysfunction, and kidney damage
Chromium	Irritability, tiredness, and damage to the nervous system
Copper	Damage to the kidneys, liver, and anaemia
Lead	Damage to the liver, kidneys, and gastrointestinal tract; lower IQ
Manganese	Damage to the nervous system
Mercury	tremors, gingivitis, protoplasm poisoning, and nervous system damage
Uranium	neuropathy, developmental impairments, lower IQ, hypertension, and cancers of the skin, lungs, bladder, and kidney
Zinc	Nervous membrane damage

Table 2. Effects of heavy metal exposure on plants [14]

Heavy Metal	**Effect**
Nickel	Increases free amino acids and decreases enzymes, chlorophylls, protein synthesis, dry mass accumulation, and seed germination
Cadmium	Decreases plant growth, lipid content, and seed germination while increasing the production of phytochelatins
Chromium	Causes membrane damage, chlorosis, and root damage; reduces enzyme activity and plant growth
Copper	Inhibits the process of photosynthesis, plant growth, and reproduction; reduces the surface area of thylakoids
Lead	Decreases the synthesis of chlorophyll and plant growth while increasing superoxide dismutase
Mercury	Reduces water absorption, antioxidant enzyme activity, and photosynthetic activity; builds up proline and phenol
Zinc	Enhances plant growth and the ATP/chlorophyll ratio while reducing Ni toxicity and seed germination.

IV. BIOREMEDIATION

Heavy metal contaminants and native microorganisms interact intricately in environmental ecosystems. These organisms are able to survive because they have developed special resistance mechanisms and, in a few instances, remove/reduce heavy metal contaminant concentrations in their environments. The process by which microorganisms interact with heavy metal contaminations to reduce/remove the contamination is known as bioremediation [15]. Typically, these techniques include the absorption or adsorption of harmful metal ions, which lessens the associated negative effects on the ecosystem [16]. The Ionic state of heavy metals are altered by microbes, which affects their solubility, bioavailability, and mobility in both soil and aquatic ecosystems [17]. Heavy metal mobilization or immobilization facilitates microbial remediation, which is subsequently followed by oxidation-reduction, chelation, metallic complex modification, and biomethylation.

V. MECHANISMS OF MICROBES' RESISTANCE TO HEAVY METALS

To survive in an environment contaminated with metals, microbes use processes like biosorption, bioaccumulation, biotransformation, and bioleaching [18].

A. *Bioaccumulation and Biosorption*

Microbes bind to heavy metals and other contaminants in the environment through the processes of bioaccumulation and biosorption, which concentrate the contaminants [19]. Heavy metal ions are gathered by microorganisms via their cellular structure, and then they undergo a process called biosorption whereby they sorb onto the binding sites in the cell wall [20].

This mechanism of passive absorption doesn't rely on the metabolic cycle. There are two common methods used in the bioremediation of heavy metals: adsorption and absorption onto the cell surface of microbes. When a fluid (the absorbate) dissolves or penetrates a liquid or solid (the absorbent), it is referred to as adsorption [21], Adsorption only takes place on the material's surface, whereas absorption affects the entire volume of the substance.

B. *Bioleaching*

Bioleaching is carried out by a diverse spectrum of microbes, the most notable of which are acidophiles. Acidophiles are low pH organisms, especially those with a pH of 2.0 or lower. They are chemolithotrophs that oxidise Fe^{2+} to Fe^{3+} and/or reduce sulphur to sulfuric acid. Metal oxides dissolve when sulfuric acid produces protons and ferric ions [22], facilitating metal extraction through the removal of more water-soluble metals from the solid phase. Heavy metals can be extracted and recovered through a process called bioleaching, which uses microorganisms as reduction agents [23].

C. *Biotransformation*

Biotransformation is a process that alters the structural properties of a chemical molecule, resulting in the development of more polar molecules. In other words, the interaction of metal and microbes changes heavy metals and organic chemicals into a less hazardous state. The evolution of this process in microbes allows them to adapt to environmental changes. Microbial transformations can occur via the synthesis of new carbon bonds, isomerization, the addition of functional groups, oxidation, reduction, condensation, hydrolysis, methylation, and demethylation [24].

VI. MICROBIAL METALS INTERACTION

Metals can be solubilized and/or precipitated by microbial activity via metabolic activities, alterations in redox or pH levels, secretion of chelating chemicals, and/or passive sorption. Microbes can employ these activities to obtain energy, or they can spend energy and become part of metal absorption or resistance mechanisms. Microbially precipitated metals are sometimes referred to as biominerals, and the process of production is referred to as biomineralization [25].

A. *Microbial Metabolism*

To comprehend microbe-metal interactions, we must first comprehend how microbes metabolize. Like all other living things, microbes need energy to grow and proliferate. There are two basic ways to generate energy: “Chemotrophy” results from the oxidation of inorganic or organic molecules, while “phototrophy” is caused by light [26]. Phototrophic organisms, including algae and certain bacteria, possess pigments that are sensitive to light. These pigments absorb solar radiation and convert water (oxygenic) or Fe^{2+} (anoxygenic) into electrons. Through its ability to act as an electron acceptors, microbial metal reduction is able to change metals and metalloids present in mine waste. Multifunctionality is a common trait among bacteria, allowing them to operate in a variety of environments. Examples of this include facultative anaerobes, which switch from aerobic respiration to nitrate reduction in the subtoxic zone, H_2 oxidising bacteria that switch to a heterotrophic metabolism when organic compounds are available, and facultative chemolithoautotrophs, which ferment organic matter when terminal electron acceptors are scarce.

Nitrogen, phosphorus, iron, and sulfur are vital nutrients for microbes, the biogeochemical cycle of these elements is essential to all forms of life on Earth. In a mining environment, the scarcity of these essential nutrients may limit microbial activity [27]. Some microbes require nitrogen in the form of ammonium, nitrate, or organic nitrogen, whereas certain bacteria and archaea can fix nitrogen from the air. Soluble inorganic orthophosphate is needed by the majority of microbes and is generated from organic phosphate molecules by phosphatase enzymes. Through a negative influence on microbial activity, heavy metal pollution can alter how well soil functions. Table 3 shows microbes mediated remediation and resistance mechanism of heavy metals. Together with microbial biomass and diversity, basal and substrate respiration rates, etc., microbial enzymes that mediate nutrient cycling in soils (e.g., dehydrogenases for C cycling, ureases for N cycling, phosphatases for P cycling, sulfatases for S cycling, etc.) are used as indicators for soil health [28].

Table 3. Microbe-mediated remediation and resistance mechanism of heavy metals [24]

Microbial group	**Heavy metals contamination**	**Microorganism**	**Microbial/Resistance mechanism**
BACTERIAL	Cadmium	Pseudomonas aeruginosa	Biosorption
	Lead	Bacillus subtilis X3	Bioimmobilization
	Cadmium and lead	Pseudomonas aeruginosa and Bacillus cereus	Bioaugmentation
	Cadmium	Cupriavidus sp. strain Cd^{2+}	Bioprecipitation
	Nickel	Bacillus sp. KL1	Biosorption
	Copper, cadmium, and zinc	Desulfovibrio desulfuricans	Extracellular sequestration
	Cadmium and zinc	Synechococcus sp.	Intracellular sequestration
	Mercury, cadmium, and zinc	Escherichia coli	Active export
	Mercury	Bacillus firmus	Enzymatic detoxification
AlGAE	Cadmium, zinc, lead, and nickel	Asparagopsis armata	Biosorption
	Lead, nickel, and cadmium	Cystoseira barbata	
	Lead, nickel, cadmium, and zinc	Codium vermilara	
FUNGI	Copper, lead	Aspergillus niger	
	Lead	Botrytis cinereal	
	Silver	Pleurotus platypus	

VII. CONCLUSION

The issue of metal contamination in the environment and human diet will always exist and continue to have an adverse effect on human health. Although many developed nations have made some efforts to monitor and lessen the issue, heavy metal leaks are an inevitable byproduct of industrial activity, so the problem still exists. The bioremediation techniques for AMD treatment have been discussed in this review. The design and optimization of reliable methods to enhance bioremediation processes will be aided by future studies on AMD-impacted microbiomes that integrate meta-omics and process engineering.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to the intellectual discussion underlying this paper, literature exploration, writing, reviews, and editing, and accept equal responsibility for the content and analyses. Both authors had approved the final version.

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