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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. The oxidative dissolution of sulphide minerals causes AMD, 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.

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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, some metal mining effluents contain high levels of harmful compounds, such as cyanides and heavy metals, which have major human health and environmental consequences (Akçıl & Koldas, 2006). 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 (Fashola et al., 2016). Acid Mine Drainage developed from the sulfide minerals in the ground during mining operations (Alakangas et al., 2013). Most sulfide minerals would oxidize and create acid, metal ions, and sulfate when exposed to water and oxygen, which would then leach into groundwater as well as surface water (Lei et al., 2023). 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 (Gadd, 2010). 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 (Raab and Feildmann, 2003).

FORMATION OF ACID MINE DRAINAGE (AMD)

Leach water from open pits, tailings pits, waste rock dumps, abandoned mines and underground deposits are the main sources of AMD, 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 (Yuan et al., 2022). AMD discharges contain low pH, high specific conductivity, high concentrations of iron, aluminium, and manganese contents, and low toxic heavy metal concentrations (Akçıl & Koldas, 2006).

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Pyrite (FeS2) 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 (H2SO4) and dissolved ferric ions (Fe3+) are produced when pyrite weathers, increasing pyrite disintegration and hastening the release of hazardous metals from surrounding minerals (Ouyang et al., 2015). The oxidation of pyrite (or sulphide) into dissolved iron, sulphate, and hydrogen is the first and most significant reaction (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 (Akçıl & Koldas, 2006).

$$4FeS_2 + 15O_2 + 14H_2O \longrightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \qquad \text{Eq. (1)}$$

$$Fe^{2+} + 1/4O_2 + H^+ \longrightarrow Fe^{3+} + 1/2H_2O \qquad \text{Eq. (2)}$$

If the pH is low, (Eq. (2)) won't happen until it reaches 8.5. The conversion of ferrous to ferric 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 equation (2) reaches pH values between 2.3 and 3.5, lowering the pH and leaving little Fe^{3+} in solution (Simate & Ndlovu, 2014).

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/cm3 (Ali and Khan, 2016). threat to ecosystems, agricultural land, and human health, because of its high acidity and non-biodegradable heavy metal (HM) contamination in living things and food chains (Munyai et al., 2021).

AMD contains heavy metals that have been 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/cm3 (Ali and Khan, 2016). 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 and chronic diseases in the lungs, liver, haematological system, nervous system, and reproductive organs (Zhang, 2022).

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 (Simate & Ndlovu, 2014).

Table 1. Effects of heavy metal exposure on humans (Monachese et al., 2012).

Heavy Metal	Effect
Arsenic	Bronchitis, dermatitis, poisoning
Cadmium	Renal dysfunction, lung disease, lung cancer, increased blood pressure, kidney damage
Chromium	nervous system damage, fatigue, irritability
Copper	Anemia, liver and kidney damage
Lead	Lower IQ, liver, kidney, and gastrointestinal damage
Manganese	damage to the nervous central system
Mercury	Damage to the nervous system, protoplasm poisoning, tremors, gingivitis
Uranium	neuropathy, developmental impairments, lower IQ, hypertension, and cancers of the skin, lungs, bladder, and kidney
Zinc	Nervous membrane damage

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Table 2. Effects of heavy metal exposure on plants (Gardea-Torresdey et al., 2005).

Heavy Metal	Effect
Nickel	Reduces seed germination, dry mass accumulation, protein production, chlorophylls and enzymes; increases free amino acids
Cadmium	Decreases seed germination, lipid content, and plant growth; induces phytochelatins production
Chromium	Decreases enzyme activity and plant growth; produces membrane damage, chlorosis and root damage
Copper	Inhibits photosynthesis, plant growth and reproductive process; decreases thylakoid surface area
Lead	Reduces chlorophyll production and plant growth; increases superoxide dismutase
Mercury	Decreases photosynthetic activity, water uptake and antioxidant enzymes; accumulates phenol and proline
Zinc	Reduces Ni toxicity and seed germination; increases plant growth and ATP/chlorophyll ratio

BIOREMEDIATION

Heavy metal contaminants and native microorganisms interact intricately in environmental ecosystems. These organisms have evolved unique resistance mechanisms that allow them to survive and, in a few instances, remove/reduce heavy metal contaminant concentrations in their environments (Monachese et al., 2012). The process by which microorganisms interact with heavy metal contaminations to reduce/remove the contamination is known as bioremediation (Pratush *et al*., 2018). Typically, these techniques include the absorption or adsorption of harmful metal ions, which lessens the associated negative effects on the ecosystem (Njoku *et al*., 2020). Microbes alter the ionic state of heavy metals, which affects their solubility, bioavailability, and mobility in both soil and aquatic environments (Ayangbenro and Babalola, 2017). Heavy metal mobilization or immobilization facilitates microbial remediation, which is subsequently followed by oxidation-reduction, chelation, metallic complex modification, and biomethylation (Pratush *et al*., 2018).

MECHANISMS OF MICROBES' RESISTANCE TO HEAVY METALS

Microbes employ mechanisms such as biosorption, bioaccumulation, biotransformation, and bioleaching to survive in a metal-polluted environment (Lin and Lin, 2005).

Bioaccumulation And Biosorption

Both bioaccumulation and biosorption are mechanisms by which microbes bind to heavy metals and contaminants in the environment and concentrate them (Joutey *et al.,* 2015). Microorganisms use their cellular structure to collect heavy metal ions, which they subsequently sorb onto the binding sites in the cell wall in a process known as biosorption (Malik, 2004).

This mechanism of passive absorption doesn't rely on the metabolic cycle. Adsorption and absorption onto the cell surface of microorganisms are two typical techniques for the bioremediation of heavy metals. Adsorption is distinct from absorption in that it entails the dissolution or penetration of a fluid (the absorbate) by a liquid or solid (the absorbent) (Jovancicevic *et al.*, 1986). While absorption affects the entire volume of the material, adsorption only occurs on the surface of the substance.

Bioleaching

Bioleaching is carried out by a diverse spectrum of microbes, the most notable of which are acidophiles. Acidophiles are chemolithotrophs that oxidize Fe^{2+} to Fe^{3+} and/or reduce sulfur to sulfuric acid and thrive in low pH environments, particularly those with a pH of 2.0 or below. Sulfuric acid

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generates ferric ions and protons, which dissolve metal oxides from gold (Srichandan *et al*., 2014), facilitating metal extraction by separating metals in the solid phase from the more water-soluble phase. Heavy metal may be extracted and recovered via bioleaching, which employs microorganisms as reduction agents (Wang and Zhao, 2009).

Biotransformation

Biotransformation is a process that alters the structural properties of a chemical molecule, resulting in the development of more polar molecules (Pervaiz *et al*., 2013). 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 (Pande *et al*.,2022).

MICROBIAL METALS INTERACTION

Metals can be solubilized and/or precipitated by microbial activity via metabolic activities, changes in pH or redox conditions, 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 (Konhauser, 2009).

Microbial Metabolism

To comprehend microbe-metal interactions, we must first comprehend how microbes metabolize. Microbes, like all living organisms, require energy to develop and reproduce. There are two basic ways to generate energy: "phototrophy" from light and "chemotrophy" from the oxidation of inorganic or organic molecules (Pepper & Gentry, 2015). Light-sensitive pigments found in phototrophs such as algae and some bacteria absorb energy from sunlight and create electrons from water (oxygenic) or Fe^{2+} (anoxygenic) (Konhauser, 2009). Microbial metal reduction is a process that can change metals and metalloids found in mine waste by acting as electron acceptors. It is fairly typical for bacteria to be able to utilize multiple metabolic pathways to function under various environmental conditions, such as switching from aerobic respiration to nitrate reduction in the subtoxic zone (facultative anaerobes), H_2 oxidizing bacteria switching to a heterotrophic metabolism when organic compounds are available (facultative chemolithoautotrophs), or fermenting organic matter when terminal electron acceptors are scarce (Konhauser, 2009; Pepper & Gentry, 2015).

Nitrogen, phosphorus, iron, and sulfur are vital nutrients for microbes, and the biogeochemical cycle of these elements is necessary for all life on Earth. The limited amounts of these vital nutrients can restrict microbial activity in a gold mine environment (Newsome *et al*., 2021). While certain bacteria and archaea are capable of fixing nitrogen from the air, other microorganisms need it in the form of ammonium, nitrate, or organic nitrogen. The majority of microorganisms need soluble inorganic orthophosphate, which is produced by phosphatase enzymes from organic phosphate molecules. Through a negative influence on microbial activity, heavy metal pollution can alter how well soil functions. Microbial enzymes, which 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, along with microbial biomass and diversity, basal and substrate respiration rates, etc. (Alkorta *et al*., 2003).

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Table 3. Microbe-mediated remediation and resistance mechanism of heavy metals (Pande *et al.*,2022).

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 Cd2+	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	

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. (Monachese et al., 2012). 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.

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