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BIOLEACHING PROCESS BY ORGANISMS IN METAL MINING. REVIEW

Abstract. The problem of soil contamination by heavy metals, acid mine drainage, wastewater dumping sites, the problem of ore shortage, and many more forces people to seek better mining techniques. However, new mining techniques have to be eco-friendly and suit the environmental assessment policy. Bacteria are incredibly versatile organisms with high adaptability, which can live, adapt and thrive particularly everywhere. Sulfide-associated environments harbour diverse bacterial communities capable of metal sulfide oxidation, a process vital for bioleaching and biomining. This review explores the bacterial composition of these environments, focusing on acidophilic bacteria and archaea that drive sulfide mineral dissolution through iron and sulfur oxidation. This paper discusses the oxidation of metal sulfides via two primary pathways, determined by physico-chemical characteristics of minerals. Biofilm formation and extracellular polymeric substances (EPS) significantly influence bioleaching efficiency, while quorum sensing and molecular interactions shape microbial consortia. Understanding these microbial processes is essential for the optimization of biomining, the development of hydrometallurgy, and mitigating the negative effects of ore depletion or metal contamination, such as acid mine drainage.
Keywords: Bacteria, metal sulfides, minerals, remediation, bioleaching, microbial consortia, biotechnology.

Introduction. Microbes have contributed to the formation of water-insoluble sulfides since the early history of life on Earth. The sulfate-reducing bacteria converted metal sulfates into metal sulfides (MS) that have been incorporated into the structure of rocks [1]. Likewise, the increasing abundance of such metal sulfides may be described by the release of toxic mining wastes at the mining sites. Such circumstances force governments to use remediation techniques [2]. Microbial remediation of metal-contaminated sites is more effective since it doesn't require much energy and doesn't produce any toxic gaseous substances. Moreover, the resulting compounds are relatively chemically inert and less likely to react [1]. The bio-processing of metal contamination includes several bioremediation techniques like biosorption by microalgae, bioaccumulation, biomethylation, bio-oxidation or bioreduction, and bioleaching [3]. Bioremediation is the application of microbial systems for cleaning organic or inorganic pollutants by their detoxification, reclamation, or immobilisation [3]. This review is concerned with the mechanisms of bioleaching and their practical importance.

Research methods. Bioleaching is the mobilisation of metal cations in insoluble compounds through a series of chemical reactions [4]. Bioleaching is the principal concept of **biohydrometallurgy**, the biotechnological way of mining [6]. It was found that sulfur-oxidising bacteria that reside within mine acid waters can use insoluble MS in their life cycles and solubilise it. This technique has found its wide use in the extraction of metals from low-grade ores because of its high efficiency, ease of use, and eco-friendly principles [2, 5-6]. The main role of microorganisms in this process is to oxidise metal- and sulfur-containing minerals [5].

Singh & Cameotra (2015) highlight the following advantages of the bioleaching [6]:

1. Low capital requirement
2. The relatively low environmental impact
3. Specificity for substrate
4. Zero discharge
5. Indigenously available species
6. Relatively simple industrial facilities
7. Eco-friendly process
8. Minimal control over the process
9. Relatively convenient conditions, i.e., atmospheric pressure and room temperature
10. Accessibility for all countries since the process doesn't require sophisticated machines

Bacterial Sulfide Oxidation. Bioleaching can be classified into three types based on the chemical reactions that take place: oxidative, acid, and reductive bioleaching. **Oxidative bioleaching** involves the application of microbes that use oxygen as the final electron acceptor during specific reactions. We'll consider only this type of bioleaching since, in the case of sulfides, the acid bioleaching is the same as the oxidative, and there are no reduction reactions [4].

The primary model was proposed in the earliest history of bioleaching to describe the biological dissolution of metal sulfides. Thus, the **direct mechanism** involves the electron transfer between the cell and the reduced substrate. Such organisms possess enzymes that directly oxidise reduced minerals and transfer the electrons to the oxygen. During this method of MS dissolution, the bacterial cell has to be close enough to the substrate [2]. Another method is called the **indirect method**. The ferric ion induces this method of oxidation. Bacteria recycle these ions to maintain the equilibrium between ferric and ferrous ions [2]. The indirect method is divided into two modes: **contact** and **noncontact modes**. Noncontact mode means the reduction of ferrous ions by planktonic bacteria, while the contact method occurs between sedimentary cells and the mineral. However, the cell isn't in contact with the substrate during contact mode, and the cell doesn't oxidize the reduced minerals itself. The oxidation occurs from the reaction between the reduced metal and the ferric ion [2]. The oxidation reaction occurs in the space very close to the surface, where there's a huge concentration of the oxidised ions [3]. Iron plays a vital role, especially its concentration, in the bioleaching process. Cells increase the redox potential locally by concentrating ferric ions in EPS on the surface of the mineral [7]. In this regard, Vera et al. (2022) think that there is no difference between direct and indirect methods. Because bacterial diversity is mainly made up of acidophilic bacteria that don't grow in the absence of ferric ions, ferric ion production has always been observed during cultivation. Thus, both methods include the use of the ferric ions [4]. However, Mishra et al. (2015) consider that there are 3 types of bioleaching: direct or contact, indirect or noncontact, and cooperative [8-9]. Though Vera et al. (2022) describe the differences between direct and indirect methods, Mishra et al. (2015) identify the indirect method as a non-contact method and the direct method as a contact method. On the other hand, Rawlings (2002) describes only the direct and indirect methods, as well as there is no identification of the contact or non-contact modes of the oxidation or the comparison of direct and indirect methods. According to Rawlings (2002), the role of microbiota in the indirect method is collateral, while in the direct method, the microbe induces the direct transfer of electrons [10]. In this regard, we can say that the definitions of Rawlings, 2002 and Mishra et al., 2015 are equal, however, the definition of Vera et al., 2022 is supported by newer research in this area (Figure 1). Thus, no fixed model can describe the bioleaching process, that occurs in the sulfide minerals.

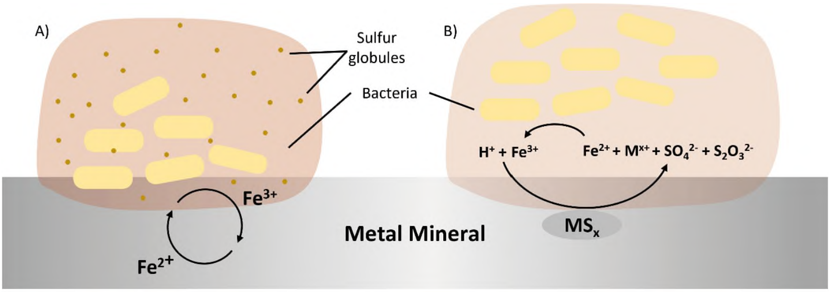

Figure 1 - The general description of direct and indirect methods of mineral dissolution, based on the literature review. A) Describes how bacterial cells directly oxidise (contact mode) reduced metal sulfides to get the energy. EPS has a constant redox potential since bacteria reduce Fe^{2+} to maintain the concentration of Fe^{3+} favourable for the reaction of mineral oxidation. B) On the other hand, we see the indirect method (non-contact mode), that involves the oxidation of mineral by Fe^{3+} from planktonic cells. Based on [4, 8-10]

Metal sulfides differ in their specificity for oxidation. This results from the structure of the mineral. Minerals with lower electrochemical potential are less resistant to the attack by ferric ions. Thus, sphalerite (ZnS) and pyrrhotite (FeS) are easier to solubilize, while molybdenite (MoS_2), with the potential of 700 mV, or enargite, is less likely to be solubilized as fast as the previous minerals [7]. Moreover, the differences in valence resulting from the structure of the sulfides impact the stability of the mineral. Thus, FeS_2 or MoS_2 are made up of 2 sulfur atoms, which create nonbonding orbitals, and these nonbonding orbitals are resistant to the protons. Thus, such minerals are acid-insoluble, and we have to use complex reactions to solubilize them [4]. As a result, 2 different pathways describe the bioleaching of 2 groups of metal sulfides. The **thiosulfate pathway** involves the oxidation of acid-insoluble metal sulfides like FeS_2 to SO_4^{2-} through the thiosulfate intermediate, while the **polysulfide pathway** involves the oxidation of acid-soluble metal sulfides like ZnS through the formation of polysulfides specific for the reaction [4,8-9]. In the polysulfide pathway, the formed sulfuric acid acts as a catalyst by attacking the MS (Figure 2) [9].

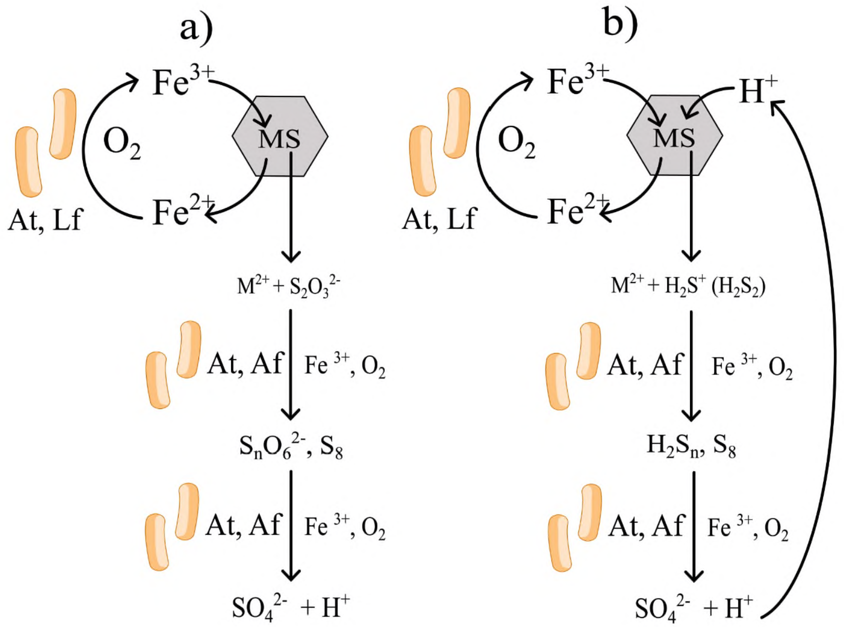

Figure-2. Schematic representation of thiosulfate and polysulfide mechanisms [9]. Degradation is induced by the proton attack and the oxidation process. During the thiosulfate pathway (a), oxidation is very important since the metal sulfide is less susceptible to the proton attack. During the polysulfide mechanism (b), formed sulphuric also induces the degradation of minerals by attacking the bonds between metal and sulfur [2, 8]. Picture based on [4, 8-9]

Bacterial Composition of Sulfide-Associated Environments. The bacterial composition of sulfide-associated environments is a crucial factor in biomining and bio-oxidation, with diverse microorganisms playing key roles in metal extraction, as was described earlier [1]. Dominant bacterial genera include *Acidithiobacillus*, *Leptospirillum*, *Sulfobacillus*,

Acidiferrobacter, and *Ferrimicrobium*, with archaeal representatives such as *Ferroplasma*,

Acidiplasma, and *Sulfolobus* [4]. Microbial communities involved in these processes are primarily composed of **acidophilic, chemolithotrophic iron- and sulfur-oxidizing bacteria**. These bacteria thrive in extreme conditions, using ferrous iron and reduced inorganic sulfur compounds (RISC) as electron donors while tolerating highly acidic environments of pH approximately 1.5- 2.0, and a wide range of temperatures i.e., **mesophiles thrive at 20–35°C, moderate thermophiles at 40–50°C, and extreme thermophiles above 70°C (Table 1)** [1, 7]. This temperature-dependent microbial distribution is particularly relevant in industrial bioleaching, where thermophilic archaea such as *Sulfolobus* sp. and *Ferroplasma* sp. contribute significantly to high-temperature mineral oxidation.

Table 1 - Temperature dependence of microorganisms found on the sulfide minerals. Different species show different optimal temperature ranges, which is very important for their effective application in industrial facilities and mass production. The table was taken from [5].

Acidophilic organism	Type of the bacteria
Iron-oxidising bacteria	
Leptospirillum ferooxidans	Mesophile
L. ferriphilum	Mesophile
L. thermoferrooxidans	Moderate thermophile
Ferrimicrobium acidiphilum	Mesophile
Ferroplasma acidiphilum	Mesophile
Fp. Acidarmanus	Mesophile or Thermotolerant
Sulphur-oxidising bacteria	
Acidithiobacillus ferroxidans	Mesophile
At. caldus	Moderate thermophile
Metallosphaera sp.	Extreme thermophile
Sulfolobus sp.	Extreme thermophile
Iron- and sulphur-oxidising bacteria	
At. ferooxidans	Mesophile
Acidianus sp.	Extreme thermophile
Sulfolobus metallicus	Extreme thermophile
Iron reducers	
Acidiphilum sp.	Mesophile
Iron oxidisers/reducers	
Acidimicrobium ferrooxidans	Moderate thermophile
Iron oxidisers/reducers and sulfur oxidisers	
Sulphobacillus sp.	Mesophiles and moderate thermophiles

The bacterial composition of sulfide-associated environments plays a crucial role in bioleaching and bio-oxidation processes, with distinct microbial consortia adapted to varying temperature and chemical conditions [7]. The primary bacteria involved in these processes include *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*, both key players in iron and sulfur oxidation. However, recent studies indicate that *Leptospirillum* species often dominate iron oxidation in continuous stirred-tank reactors (CSTRs), particularly in the bio-oxidation of arsenopyrite (FeAsS) and copper sulfide concentrates. In bioleaching systems, microbial selection is highly dependent on environmental factors such as pH, temperature, and mineral composition [2, 4]. For example, the addition of ferrous iron to leach solutions can shift microbial dominance from *Leptospirillum* sp. to *Acidithiobacillus ferrooxidans*, highlighting the importance of chemical conditions in shaping microbial populations.

Another key aspect of sulfide-associated microbial communities is the presence of thermophilic and archaeal species, which play a crucial role in high-temperature bioleaching operations. *Acidianus* sp. and *Metallosphaera* sp., along with the iron-oxidizing archaeon *Ferroplasma* sp., have been detected in bioleaching environments with extreme acidity and high metal concentrations. Their presence is particularly significant in chalcopyrite bioleaching, where mesophilic bacteria struggle due to passivation effects. Thermophiles enhance metal recovery and contribute to the stability of bio-oxidation processes by thriving in self-heating heaps and reactors [1, 7]. The shift from mesophilic to thermophilic consortia as temperature rises demonstrates the dynamic nature of these microbial ecosystems, which adapt to environmental conditions to maximize mineral dissolution. Understanding the composition and function of these bacterial communities is essential for optimizing industrial bioleaching processes, reducing environmental impact, and improving metal recovery efficiency.

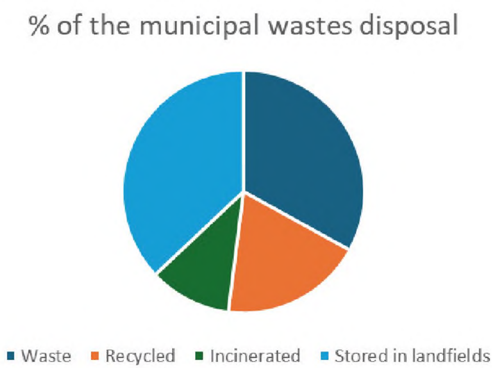

Figure 3 - The percentage of the disposal of municipal wastes.

Application of Bioleaching Nowadays. According to Yeoman et al. (2021) bioleaching is used to extract copper from covellite ore (CuS). The ore is treated with acid for the growth of *A. ferrooxidans.* Bacteria will promote the reaction between CuS and Fe^{3+}, and as a result, Cu^{2+} ions will be formed. Formed Cu^{2+} ions are moved to another tank with scrap metal for the precipitation of Cu^{2+} by iron. This precipitate is used for further concentration stages [11]. Apart from that, many companies use bioleaching pilot plants or experimental copper recovery plants (Table 2). Though the widely used bioleaching mode is **dump leaching,** i.e., the substrate, like rocks, low-grade ores, or other metal garbage, is exposed to microbial attack, there are experimental plants that use techniques like **heap leaching** or **agitated leaching**. Such plants are supplied with special reactors that can maintain cultivation conditions like optimal pH range, rpm, or temperature. The substrate also dictates the microbial composition used for the bioleaching [12-13]. For instance, oxidation reactions within spoil heaps result in higher temperatures, and only thermophilic and mesophilic thermotolerant microbes can inhabit such environments [14]. Thus, they are very rich in acidophilic, thermophilic, and thermotolerant bacteria [13-14]. Waste dumps, on the other hand, are bioleached at lower temperatures by mesophilic bacteria.

Table 2 - Different companies use bioleaching for the recovery of copper, gold, and other metals [12]. Indicated leaching methods are done in special bioreactors with the supplement of nutrients and necessary compounds for the maintenance of certain conditions of cultivation.

Company	Leaching method
Newmont Mining	BIOPRO™ Process - heap leaching of refractory gold ores
Gold Fields, Ltd	BIOX™ Process - agitated tank oxidation of refractory gold ores
BHP Billiton, Ltd.	BioCOP™ Process- agitated tank oxidation and leaching of copper sulfides BioNIC™ Process - agitated tank oxidation and leaching of nickel sulfides BioZINC™ Process - agitated tank oxidation and leaching of zinc sulfides
BacTech Environment	BacTech/Mintek Process - agitated tank oxidation and leaching of copper sulfides
GeoBiotics, Inc.	GEOCOAT™ Process - heap leaching sulfide mineral concentrates

Rendón-Castrillón et al. (2023) suggest that even municipal wastes and solid agricultural debris may be exposed to microbial attack for the remediation of metals. Thus, annually, 12 billion tons of solid waste are produced, and they are very rich in metals, which may be subjected to biological leaching. Bacterial leaching may recover Au, Cu, and Zn, while fungi can recover Ni, V, Al, Mo, Co, Fe, Mn, Ag, Pt, and Pd from those wastes. Researchers recall that agricultural wastes such as crop residues, peanut shells, corn cob ash, rice husk, and cane bagasse are very rich in Ca, Si, Mg, Fe, Al, P, Mg, Zn, and Mn. In 2016, these wastes corresponded to 13% of the lost food supply, while in 2020, it increased to 13.3%. The same issue is seen with municipal wastes, which are annually produced at the level of 2 billion tons (Figure 3) [13]. The bioleaching of such wastes gave high recovery rates of Cd, Zn, Cu, Cr, and Pb [15]. Other substrates that are potentially applicable for metal recovery are industrial wastes. Old and broken TVs, phones, computers, and other e-waste can be reused. Such wastes contain 60 different elements that belong to base metals, critical metals, and platinum group metals [13]. Li-batteries, circuit boards from old phones, and batteries from electric vehicles contain many metals and may be subjected to bioleaching for the recovery of Li, Co, Ni, Mn, and base metals [19-23]. As a result, bioleaching can contribute to the prevention of the environment from heavy metal contamination by the sequestration of those metals from different sources like animal faeces, plant debris, electronic devices, etc.

Currently, there are plenty of places that have industrial bioleaching plants: Río Tinto (Spain), Bagdad, Morenci, Pinto Valley, Sierrita, Morenci in the US, Cerro Colorado, Chuquicamata SBL, Collahuasi, Ivan Zar, Punta del Cobre, Quebrada Blanca, Salvador QM, Sociedad Minera Pudahuel, and Zaldívar in Chile [12]. The abundance of bioleaching plants in Chile is a result of the high dependency of the country on its ore deposits. To mitigate the hazardous impact of traditional mining techniques, Chileans seek eco-friendly methods such as bioleaching. Nowadays, 42% of all copper is produced via environmental biotechnology, and the demand for the development of environmental biotechnology is increasing [16]. Moreover, Sen C. (2015) mentioned that there are at least 10 large-scale bioleaching plants. Some of them are Sao Bento in Brazil, Ashanti and Sansu in Ghana, and Tamboraque in Peru [16]. Such plants utilize acidophilic bacteria for the extraction of uranium from the water-insoluble uranium salts and the extraction of gold from the low-grade ores. Although we described only 2 main pathways, there are other biochemical reactions that can recover metals from their minerals. However, those methods and pathways are specific and used only for specific metals. For instance, HCN-forming bacteria such as *Chromobacterium violaceum* or *Pseudomonas fluorescens* can leach Ni, Au, Pt, and Cu from solid materials like soil or ores, scrap, and other metallic trash [3, 18]. The cyanidation of ores like arsenopyrite (FeAsS) yields gold, however, the ore has to be pre-treated for the reactions to begin. This pre-treatment is done by acidophiles like *A. ferrooxidans*, which solubilize the rock of FeAsS[Au] and free the gold ions. As well, acidophiles can facilitate the recovery of uranium from its ores. They maintain the constant concentrations of Fe^{2+}, Fe^{3+}, as well as SO_4^{2-} that participate in the reactions of the solubilization of insoluble minerals like covellite [11, 21].

Also, the author recalls that bioleaching is mainly used for the production of gold, copper, and uranium, but in the future, bioleaching may be used at the same rate as the traditional leaching techniques, especially for the wastes, bauxite dressing, and bioremediation of contaminated sites [13, 17]. Based on the abovementioned facts, the comparison of traditional metallurgy and bioleaching was conducted with SWOT analysis (Table 3).

Table 3 - SWOT analysis of the differences between bioleaching and traditional methods. Based on the SWOT analysis, we can see that bioleaching is convenient for the extraction of metals from low-grade ores. Even though it operates at normal conditions, it demands the precise control of fluctuations in pH, temperature, and other factors.

	Bioleaching	Traditional methods
S	The main advantage of bioleaching is the use of bacteria, which operate at atmospheric pressure and moderate temperature, i.e., there's no need for a high energy supply, and can operate in low-grade ores. Hence, it's less costly and more eco-friendly [6].	Traditional mining methods, including pyrometallurgy and hydrometallurgy, are well-established and capable of processing large volumes of high-grade ores [3]. These techniques provide faster metal recovery and ensure consistent production, which is crucial for industrial demands.
		Moreover, technological advancements in mechanization and ore separation enhance the efficiency of conventional mining operations.

W	The process is relatively slow compared to traditional mining, often requiring weeks or even months for significant metal recovery. Its efficiency heavily depends on environmental conditions, such as pH, redox potential, and temperature. Furthermore, certain minerals, like molybdenite (MoS_2) and enargite, are more resistant to microbial oxidation due to their high electrochemical potential [2, 4, 7].	Traditional mining has significant environmental drawbacks, including habitat destruction, soil contamination, and the generation of acid mine drainage (AMD) [16-19]. These methods also consume large amounts of energy, contributing to greenhouse gas emissions. Additionally, extracting metals from low-grade ores using conventional techniques is often economically unfeasible.
O	Bioleaching offers promising opportunities for sustainable metal extraction from low-grade ores, mining waste, and electronic scrap. It can also be applied for soil remediation in contaminated mining areas. Recent advancements in genetic engineering may further enhance the efficiency and specificity of bioleaching microorganisms, making the process even more effective [13, 16].	While traditional mining faces environmental challenges, it can benefit from technological innovations aimed at reducing its ecological footprint. Integrating conventional techniques with bioleaching could improve metal recovery while minimizing environmental harm. Moreover, automation and digital monitoring systems can enhance the efficiency and safety of mining operations.
T	The widespread adoption of bioleaching is hindered by process variability and the difficulty of maintaining optimal conditions for microbial activity [2, 4, 7]. Regulatory uncertainties and industry resistance to new technologies further limit its implementation. Additionally, bioleaching is less effective for high-grade ores and projects requiring rapid metal extraction [5].	Traditional mining faces increasing pressure due to stricter environmental regulations, resource depletion, and rising operational costs. Public demand for sustainable practices and the global shift toward greener technologies also challenge the long-term viability of conventional mining approaches [16].

Conclusion. Even though there are no exact mechanisms of sulfide solubilization, this review describes the main mechanisms of bioleaching, such as direct or indirect, contact or non-contact modes. Since there is no fixed idea or model that describes the whole process, which is vital for the industry, further research is needed. Although we described the main 2 types of metal sulfide solubilization and degradation, some other mechanisms that are applied by bacteria were mentioned. Thus, we can recover some metals like Cd, Cu, Ni, or Zn from unusual substrates like fly ash or solid wastes with the help of microbes and fungi [3, 13].

Apart from the mechanisms of bioleaching, some basic environmental factors that affect the growth and effectiveness of bioleaching, such as pH, temperature, redox potential, and mineral composition, were considered. Still, research on the distribution of the bacterial species among minerals is needed, as there are no references on the exact species apart from the *Acidithiobacillus sp.* in this topic, as well as their optimal growth conditions of those organisms.

Nowadays application of bioleaching is also considered. Even though the use of bioleaching is limited by the recovery of copper or gold from low-grade ores, it's thought that in the future it'll be widely used for other industrial processes and will contribute to the remediation of the soil, of low-grade ores, and for the metal scrap.

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МЕТАЛДАР ӨНДІРУДЕГІ ТОПЫРАҚТЫҢ МИКРОБИОЛЕАКЦИЯСЫ. ШОЛУ

Түйіндеме. Топырақтың ауыр металдармен ластануы, қышқылды шахталық дренаж, ағынды сулардың төгіндісі, кен тапшылығы және басқа да мәселелер ғалымдарды тау-кен өндірудің тиімді әдістерін іздеуге мәжбүрлейді. Алайда жаңа тау-кен технологиялары экологиялық тұрғыдан қауіпсіз әрі қоршаған ортаны қорғау саясатына сәйкес болуы керек. Бактериялар – жоғары бейімделгіштігі бар ерекше икемді организмдер, олар кез келген ортада өмір сүріп, бейімделіп, тез дамып кете алады. Құрамында сульфидтер бар орталар металл сульфидтерін тотықтыруға қабілетті әртүрлі бактериялық

қауымдастықтардың тіршілік ету ортасы болып табылады – бұл процесс био сілтілеу және био өндіру үшін маңызды.
Бұл мақалада осы орталардың бактериялық құрамы қарастырылып, темір мен күкіртті тотықтыру арқылы сульфидті минералдарды ерітетін ацидофильді бактериялар мен археилерге назар аударылады. Мақалада метал сульфидтерінің физикалық-химиялық қасиеттеріне байланысты болатын екі негізгі тотығу жолы сипатталады. Биопленкалар мен жасушадан тыс полимерлі заттар (EPS) биошаймалаудың тиімділігіне айтарлықтай әсер етеді, ал кворум-сезіну механизмі мен молекулалық өзара әрекеттестіктер микробтық консорциумдардың қалыптасуын анықтайды. Бұл микробиологиялық процестерді түсіну биокен өндірісін оңтайландыру, гидрометаллургияны дамыту және қышқылды шахталық дренаж сияқты кен тапшылығы немесе металл ластануының теріс әсерлерін азайту үшін өте маңызды.
Түйінді сөздер: Бактерия, металл сульфидтері, минералдар, ремедиация, биошаймалау, микробтық консорциум, биотехнология.

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БИОВЫЩЕЛАЧИВАНИЕ ПОЧВЫ МИКРООРГАНИЗМАМИ ПРИ ДОБЫЧЕ МЕТАЛЛОВ. ОБЗОР

Аннотация. Проблема загрязнения почвы тяжелыми металлами, кислотный шахтный дренаж, сброс сточных вод, нехватка руды и многие другие факторы вынуждают ученых искать более эффективные методы добычи полезных ископаемых. Однако новые горнодобывающие технологии должны быть экологически безопасными и соответствовать политике экологической безопасности. Бактерии — это чрезвычайно универсальные организмы с высокой адаптивностью, способные жить, приспосабливаться и процветать практически в любых условиях. Среды, содержащие сульфиды, являются местом обитания разнообразных бактериальных сообществ, способных к окислению сульфидов металлов — процессу, важному для биовыщелачивания и биодобычи. В данной статье исследуется бактериальный состав таких сред с акцентом на ацидофильных бактерий и археи, которые осуществляют растворение сульфидных минералов путем окисления железа и серы. В статье рассматриваются два основных пути окисления сульфидов металлов, зависящие от физико-химических свойств минералов. Образование биопленок и внеклеточных полимерных веществ (EPS) оказывает значительное влияние на эффективность биовыщелачивания, в то время как механизм кворумсенсинга и молекулярные взаимодействия определяют формирование микробных консорциумов. Понимание этих микробиологических процессов необходимо для оптимизации биодобычи, развития гидрометаллургии и минимизации негативных последствий истощения руд или загрязнения металлами, таких как кислотный шахтный дренаж.

Ключевые слова: Бактерия, сульфиды металлов, минералы, ремедиация, биовыщелачивание, микробный консорциум, биотехнология.

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