ENVIRONMENTAL ASPECTS OF BIOHYDROMETALLURGY

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Аннотация. В статье рассматриваются экологические аспекты биогидрометаллургии как современного и перспективного направления переработки минерального сырья. Проанализированы основные преимущества биотехнологических методов по сравнению с традиционными металлургическими процессами, включая снижение энергопотребления и уменьшение негативного воздействия на окружающую среду. Особое внимание уделено возможным экологическим рискам и мерам по обеспечению экологической безопасности. Показана роль биогидрометаллургии в развитии экологически устойчивых промышленных технологий.

Ключевые слова: биогидрометаллургия, экологические аспекты, биовыщелачивание, микроорганизмы, охрана окружающей среды, устойчивое развитие.

Annotatsiya. Mazkur maqolada mineral xomashyoni qayta ishlashning zamonaviy va istiqbolli yoʻnalishi boʻlgan biogidrometallurgiyaning ekologik jihatlari koʻrib chiqilgan. An’anaviy metallurgiya jarayonlari bilan solishtirganda biotexnologik usullarning energiya sarfini kamaytirish va atrof-muhitga salbiy ta’sirni pasaytirish kabi afzalliklari tahlil qilingan. Shuningdek, mumkin boʻlgan ekologik xavflar va ekologik xavfsizlikni ta’minlash choralari yoritilgan. Biogidrometallurgiyaning ekologik barqaror sanoat texnologiyalarini rivojlantirishdagi ahamiyati koʻrsatib berilgan.

Kalit soʻzlar: biogidrometallurgiya, ekologik jihatlar, biovyshchelachivanie (biovyshchlash), mikroorganizmlar, atrof-muhitni muhofaza qilish, barqaror rivojlanish.

Abstract. The article examines the environmental aspects of biohydrometallurgy as a modern and promising approach to mineral raw material processing. The main advantages of biotechnological methods compared to traditional metallurgical processes are analyzed, including reduced energy consumption and lower environmental impact. Special attention is given to potential environmental risks and measures to ensure environmental safety. The role of biohydrometallurgy in the development of environmentally sustainable industrial technologies is highlighted.

Keywords**:** biohydrometallurgy, environmental aspects, bioleaching, microorganisms, environmental protection, sustainable development.

Introduction. In recent years, increasing environmental concerns have intensified the search for environmentally friendly technologies in the mining and metallurgical industries. Traditional metallurgical methods are often associated with high energy consumption, significant greenhouse gas emissions, and the generation of large amounts of industrial waste, which negatively affect the environment. Biohydrometallurgy represents an alternative approach to metal extraction that utilizes the metabolic activity of microorganisms. This technology enables the processing of low-grade ores and industrial wastes while reducing the need for high temperatures and aggressive chemical reagents. As a result, biohydrometallurgical processes are considered more environmentally sustainable compared to conventional metallurgical techniques. Despite its environmental advantages, biohydrometallurgy may also pose certain ecological risks, such as the formation of acidic effluents and the potential impact on surrounding ecosystems. Therefore, a comprehensive assessment of both the benefits and limitations of this technology is necessary to ensure its safe and effective application. The aim of this article is to analyze the environmental aspects of biohydrometallurgy, including its ecological advantages, potential risks, and measures for minimizing negative environmental impacts

Basics of Biohydrometallurgy. Biohydrometallurgy is the science of obtaining metals using microorganisms. It is a modern field in the chemical industry. A vast number of bacteria can oxidize inorganic substrates (mineral ores) and obtain energy in the process. Using such methods, iron, zinc, and other non-ferrous metals can be extracted from ores. Biogeotechnological methods allow obtaining additional amounts of non-ferrous metals by utilizing the "tailings" of beneficiation plants, sludges, and metallurgical waste, as well as processing so-called off-balance ores, extracting metals from seawater and effluents. The application of biological methods intensifies the processes of mineral raw material extraction, reduces their cost, while eliminating the need for labor-intensive mining technologies; it also allows for process automation.

Principles of biological methods for aerobic and anaerobic waste processing.

The biological purification method is based on the ability of microorganisms to use various compounds found in wastewater as growth substrates. The advantages of this method lie in the ability to remove a wide range of organic and inorganic substances from effluents, the simplicity of equipment design and process flow, and relatively low operating costs.

Two types of processes are used for biological wastewater treatment:

1. Aerobic, in which microorganisms use oxygen to oxidize substances;
2. Anaerobic, in which microorganisms have no access to either free dissolved oxygen or preferred electron acceptors such as nitrate ions.

Anaerobic wastewater treatment processes. The bioreactors used for these purposes – septic tanks and methanogenic tanks – are sedimentation tanks in which the settled sludge undergoes anaerobic degradation. Septic tanks are usually operated at a temperature of 30–35 °C. Septic tanks are used in rural sewage systems and in cities for small-scale sewage systems. Pathogenic microbes and helminth eggs remain in the digested sludge, so it cannot be used as fertilizer. A methanogenic tank is a device for the anaerobic fermentation of liquid organic waste with the production of methane. Sludge and activated sludge enter the methanogenic tank from above through a pipe. To accelerate the fermentation process, the methanogenic tank is heated and its contents are mixed. Heating is carried out by a water or steam radiator. In the absence of oxygen, organic substances (fats, proteins, etc.) form fatty acids, from which methane and carbon dioxide are produced during further fermentation.

Aerobic wastewater treatment processes. In aerobic treatment processes, part of the organic substances oxidized by microorganisms is used in biosynthesis processes, while the rest is converted into harmless products – H2O, CO2, NO2, etc.

Aerobic biological treatment consists of two stages:

1. mineralization – oxidation of carbon-containing organic matter,
2. nitrification.

When there are practically no organic substances left in the treated wastewater, the second stage of treatment begins – nitrification. During this process, nitrogen-containing substances in the wastewater are oxidized to nitrites and then to nitrates. A complex biological association participates in biological treatment processes, consisting not only of bacteria but also including unicellular organisms – aquatic fungi, protozoa, microscopic animals, and others. This biological association forms in the biological treatment process as activated sludge or biofilm. Activated sludge consists of brown-yellow flakes sized 3–150 μm, suspended in water, and formed by colonies of microorganisms, including bacteria. The latter form mucous capsules – zoogloea. Biofilm is a mucous coating of the filtering layer material of treatment facilities by living microorganisms, with a thickness of 1–3 mm. Biological wastewater treatment is carried out in various types of facilities – biofilters and aeration tanks. Aeration tank - a reservoir (most often rectangular in cross-section) through which wastewater mixed with activated sludge flows, where biochemical treatment of the wastewater takes place. Air introduced by aerators mixes the wastewater with the activated sludge and saturates it with oxygen necessary for the bacteria's vital activity.

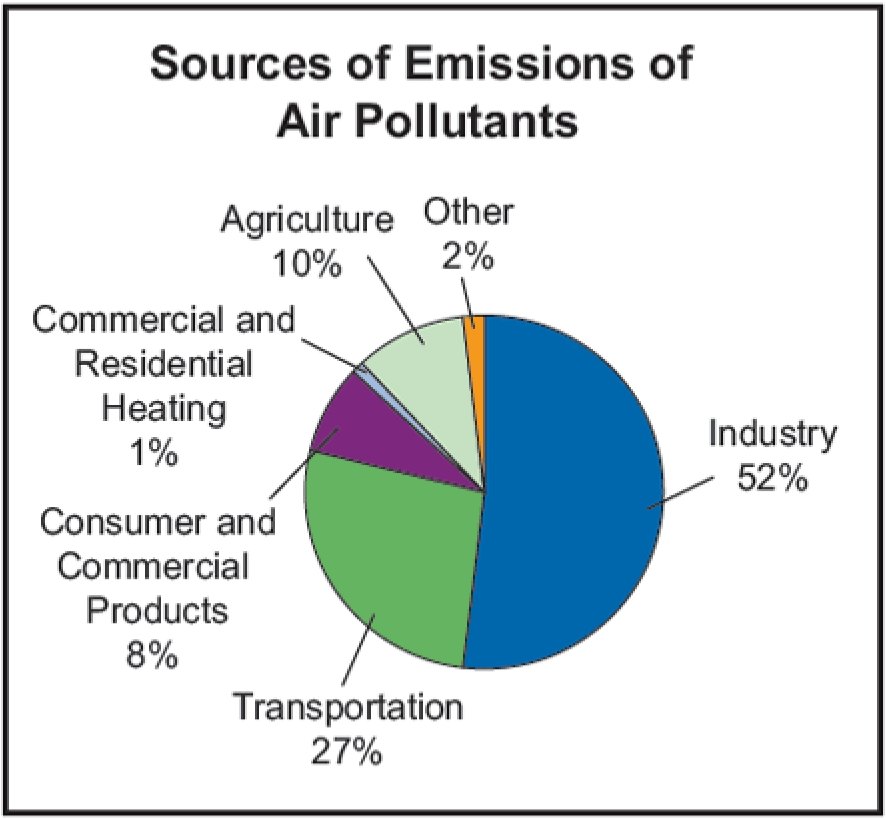
Applications of biotechnological methods for the purification of gas-air emissions and degradation of xenobiotics. Biological methods for cleaning gas-air emissions have been applied relatively recently and so far on a limited scale. Biological methods of air purification are based on the ability of microorganisms to break down a wide range of substances and compounds into the final products CO2 and H2O under aerobic conditions. Microorganisms utilize ammonia, oxidize sulfur dioxide, hydrogen sulfide, and dimethyl sulfoxide. The resulting sulfates are utilized by other microbial species. There is evidence of effective oxidation of carbon monoxide, one of the most dangerous air pollutants, by aerobic carboxidobacteria.

Three types of installations are used for biological air purification: biofilters, bioscrubbers, and bioreactors with a washed layer.

1. Biofilters. The main element of a biofilter for air purification is the filtering layer, which adsorbs toxic substances from the air. These substances then diffuse in dissolved form to microbial cells, are incorporated into them, and undergo degradation. Natural materials such as compost, peat, etc., are used as carriers for the filtering layer. The air to be purified is supplied by a fan into the system, passes through the filtering layer in any direction, either from bottom to top or vice versa. At the same time, the air must pass evenly through the entire mass of the filtering layer. Therefore, the layer must be homogeneous and have a certain degree of moisture.
2. Bioscrubbers. Compared to biofilters, bioscrubbers occupy less space as they are towers several meters high. Operating costs when using bioscrubbers are higher because the bio-purification process of water requires significant expenses. The use of bioscrubbers is effective when there are highly soluble toxic substances in the air. The productivity of bioscrubbers is significantly higher compared to biofilters, while the purification efficiency is also high.
3. Bioreactors with a washed layer. The most promising for air purification are bioreactors with a washed layer. These installations, practically not inferior in the degree of purification, are characterized by a higher specific productivity (several thousand cubic meters of purified air per hour). Such compact installations are very effective for air purification in intensive livestock enterprises. A bioreactor with a washed layer differs from a conventional biofilter only in that the biofilm formed on the surface of the synthetic packing cannot provide

microorganisms with the required nutrients, so they must be supplied with water, which constantly circulates through the reactor in either co-current or counter-current flow relative to the gas flow. At the same time, excess biomass is removed from the surface of the packing, which prevents clogging and increases the service life.

Main reasons of air pollution:



Methods and Apparatuses for Cleaning Exhaust Gases. According to the nature of harmful impurities, methods for cleaning gases from aerosols and from gaseous and vaporous impurities are distinguished. All gas cleaning methods are primarily determined by the physicochemical properties of the impurities, their aggregate state, dispersity, chemical composition, and others. The variety of harmful impurities in industrial gas emissions leads to a wide range of cleaning methods, reactors, and chemical reagents used.

A brief description of some gas cleaning methods._Methods of cleaning, based on their main principle, can be divided into mechanical cleaning, electrostatic cleaning, and cleaning using acoustic and ultrasonic coagulation._Mechanical gas cleaning includes dry and wet methods. Dry methods include:

1) gravitational settling;
2) inertial and centrifugal dust collection;
3) filtration.

Gravitational settling is based on the sedimentation of suspended particles under the influence of gravity when dusty gas moves at a low velocity without changing the flow direction. The process is carried out in settling gas ducts and dust-settling chambers. To reduce the height of particle settling in the settling chambers, many horizontal shelves are installed at a distance of 40–100 mm, breaking the gas flow into flat streams. The degree of air purification in dust-settling chambers does not exceed 50–60%. The method is suitable only for preliminary, coarse gas cleaning. Inertial settling is based on the tendency of suspended particles to maintain their original direction of motion when the gas flow direction changes. Among inertial devices, louver dust collectors with a large number of slots (louvers) are most commonly used. Gases are dusted as they pass through the slots and change their direction of motion. Dust particles with d < 20 μm are not captured in louver devices. The degree of purification, depending on particle dispersion, ranges from 20-70%. The inertial method can only be used for coarse gas cleaning. Besides low efficiency, a disadvantage of this method is the rapid wear or clogging of the slots. Centrifugal gas cleaning methods are based on the action of centrifugal force generated when the gas flow being cleaned rotates inside the cleaning apparatus or when parts of the apparatus itself rotate. Various types of cyclones are used as centrifugal dust cleaning devices: battery cyclones, rotating dust collectors (rotoclones), and others. The degree of dust removal depends on particle size. For high-capacity cyclones, particularly battery cyclones, the cleaning efficiency is about 90% for particles with a diameter d > 30 μm. For particles with d = 30 μm, the cleaning efficiency decreases to 80%, and for d = 5 μm, it is less than 40%. Cyclones are widely used for coarse and medium gas cleaning from aerosols. Filtration is based on passing the gas to be cleaned through various filtering fabrics (cotton, wool, chemical fibers, fiberglass, etc.) or other filtering materials (ceramics, metal ceramics, porous plastic partitions, etc.). Filtration is a very common method for fine gas cleaning. Its advantages are relatively low equipment cost (except for metal ceramic filters) and high fine cleaning efficiency. The disadvantages of filtration are high hydraulic resistance and rapid clogging of the filtering material with dust.

Wet gas cleaning from aerosols is based on washing the gas with a liquid (usually water) with the most developed possible surface contact between the liquid and aerosol particles and the most intensive possible mixing of the cleaned gas with the liquid. This universal method of gas cleaning from dust, smoke, and fog particles of any size is the most common technique for the final stage of mechanical cleaning, especially for gases that need to be cooled. Wet cleaning devices include packed and centrifugal scrubbers, Venturi scrubbers, spray scrubbers, tray scrubbers, and bubbling-foam scrubbers. Electrostatic gas cleaning serves as a universal means suitable for any aerosols, including acid mists, and for particles of any size. The method is based on ionization and charging of aerosol particles as the gas passes through a high-voltage electric field created by corona electrodes. Particle deposition occurs on grounded collecting electrodes. The degree of aerosol removal is over 90%, reaching up to 99.9%. The drawback of this method is the high cost of construction and maintenance of cleaning installations and significant energy consumption to create the electric field. Acoustic and ultrasonic coagulation, as well as preliminary electrification, are still rarely used in industry and are mainly in the development stage. They are based on the enlargement of aerosol particles, which facilitates their capture by traditional methods. *Devices for cleaning technological emissions into the atmosphere from aerosols:* dry dust collectors (cyclones); wet dust collectors (scrubbers); filters; electrostatic precipitators.

1. Dry dust collectors (cyclones). Dry dust collectors are designed for coarse mechanical cleaning from large and heavy dust. The principle of operation is the settling of particles under the action of centrifugal force and gravity. Various types of cyclones are widely used: single, grouped, battery. The dust-gas flow is introduced into the cyclone through the inlet pipe 2, twists, and makes a rotational-translational movement along the body 1. Dust particles are thrown against the wall of the body by centrifugal forces and then collected by gravity into the

dust bunker 4, from where they are periodically removed. The gas, freed from dust, turns 180º and exits the cyclone through pipe 3.

2. Wet Dust Collectors (Scrubbers). Wet dust collectors are characterized by high efficiency in cleaning fine dust particles up to 2 microns in size. They operate on the principle of depositing dust particles onto the surface of droplets under the influence of inertia forces or Brownian motion. The dust-laden gas flow is directed through pipe 1 onto the liquid surface 2, where the largest dust particles settle. Then the gas rises against the flow of liquid droplets supplied through nozzles, where cleaning from fine dust particles occurs.

3. Filters. Designed for fine gas purification by depositing dust particles (up to 0.05 microns) on the surface of porous filtering partitions. According to the type of filtering media, there are fabric filters (fabric, felt, sponge rubber) and granular filters. The choice of filtering material is determined by purification requirements and operating conditions: degree of purification, temperature, gas aggressiveness, humidity, quantity and size of dust, etc.

4. Electrostatic Precipitators. Electrostatic precipitators are an effective method for cleaning suspended dust particles (0.01 μm) and oil mist. The operating principle is based on ionization and the deposition of particles in an electric field. Ionization of the dust-gas flow occurs at the surface of the corona electrode. Acquiring a negative charge, dust particles move toward the collecting electrode, which has a charge opposite to that of the corona electrode. As dust particles accumulate on the electrodes, they fall under the force of gravity into a dust collector or are removed by shaking.

Environmental Risks and Limitations. Despite its environmental advantages, biohydrometallurgy is associated with several potential environmental risks that require careful consideration and management. One of the major environmental concerns is the use of chemical reagents in auxiliary processes such as flotation, which is often applied prior to or alongside biohydrometallurgical treatment. During flotation, various chemical reagents are used, including collectors, frothers, activators, depressants, and pH modifiers. These substances are designed to enhance mineral separation efficiency; however, their release into the environment may lead to contamination of water bodies and soil. Improper handling or disposal of flotation reagents can negatively affect aquatic ecosystems and pose risks to living organisms due to their toxicity and persistence in the environment. Another significant environmental issue is related to iron removal during the bioprocessing of copper slags and other metallurgical wastes. In biohydrometallurgical systems, large amounts of iron are often dissolved into solution along with target metals. The subsequent removal of iron requires a series of chemical and physical processes, including oxidation, neutralization, and precipitation. These processes are frequently conducted at elevated temperatures and involve additional chemical inputs, which can increase energy consumption and generate secondary waste products. If not properly managed, iron-rich precipitates and process effluents may contribute to environmental pollution and complicate waste disposal. Therefore, while biohydrometallurgy is generally considered a more environmentally friendly alternative to conventional metallurgical methods, the associated chemical treatments and by-product management processes highlight the need for effective environmental control measures. The development of improved reagent management strategies and optimized iron removal techniques is essential to minimize the ecological impact of biohydrometallurgical operations.

Environmental Advantages of Biohydrometallurgy. Biohydrometallurgy is widely regarded as an environmentally safe and sustainable approach to metal extraction, particularly in the processing of electronic waste. The growing accumulation of electronic waste poses a serious environmental challenge due to the presence of toxic components and valuable metals. Biohydrometallurgical methods offer an effective solution by enabling metal recovery under mild operating conditions while minimizing environmental harm. One of the key advantages of biohydrometallurgy is its low level of environmental pollution. Unlike conventional pyrometallurgical processes, which require high temperatures and result in significant emissions of greenhouse gases and toxic compounds, biohydrometallurgical processes operate at ambient or moderately elevated temperatures. In comparison with traditional hydrometallurgical methods, biohydrometallurgy also reduces the consumption of aggressive chemical reagents, thereby decreasing the generation of hazardous liquid and solid wastes.

Another important advantage is the reduction of environmental impact during electronic waste recycling. Electronic waste contains hazardous substances that can contaminate soil and water if improperly disposed of. The extraction of metals from such waste using biohydrometallurgical techniques not only mitigates its negative environmental effects but also allows valuable metals to be recovered and reused in industrial applications. This contributes to resource conservation, waste reduction, and the development of a circular economy.

Comparison with Traditional Metallurgical Methods. Biohydrometallurgy has several advantages over traditional metallurgical processes such as smelting and conventional hydrometallurgy. Traditional methods are often costly and inefficient when processing low-grade ores or industrial wastes due to high energy requirements and limited metal recovery efficiency. As a result, significant amounts of valuable metals may remain unrecovered and be discarded as waste. In contrast, biohydrometallurgical processes are capable of extracting metals present in low concentrations within ores, tailings, and waste materials. By utilizing the metabolic activity of microorganisms, this approach allows metals that are inaccessible to conventional technologies to be recovered under milder operating conditions. This significantly improves resource utilization by unlocking the full potential of mineral deposits that might otherwise be overlooked or stored in unused waste piles and tailings. Consequently, biohydrometallurgy reduces the need for additional mining operations, lowers waste generation, and contributes to more sustainable and environmentally responsible metal production.

Future of Biohydrometallurgy. The future of biohydrometallurgy is closely linked to the growing demand for sustainable and environmentally friendly technologies in the mining and metallurgical industries. As high-grade mineral resources become increasingly depleted, the importance of efficient processing of low-grade ores, industrial wastes, and mine tailings continues to rise. One of the key directions for future development is the improvement of microbial efficiency through advanced biotechnological approaches. Ongoing research focuses on optimizing microbial consortia, enhancing process control, and improving tolerance to extreme environmental conditions. These advancements are expected to increase metal recovery rates and reduce processing time. Another promising area is the expansion of biohydrometallurgical applications in electronic waste recycling. With the rapid growth of electronic devices, biohydrometallurgy offers a sustainable solution for recovering valuable metals while minimizing environmental pollution and supporting circular economy principles.

In addition, the integration of biohydrometallurgy with other green technologies, such as renewable energy systems and closed-loop water management, is expected to further reduce the environmental footprint of metal extraction processes.

Overall, biohydrometallurgy has strong potential to become a key component of future sustainable metallurgical practices.

Conclusion. In this article, the environmental aspects of biohydrometallurgy were analyzed, including its advantages, potential environmental risks, and future prospects. Biohydrometallurgy was shown to be an environmentally friendly alternative to conventional metallurgical methods due to its lower energy consumption, reduced emissions, and ability to recover metals from low-grade ores and waste materials. Despite certain environmental challenges related to reagent use and by-product management, proper process control and environmental safety measures can significantly minimize negative impacts. Overall, biohydrometallurgy represents a promising approach for sustainable metal extraction and plays an important role in the development of environmentally responsible industrial technologies.

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