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Sustainable development, i.e. environmental, technological and economic aspects in mineral engineering

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Abstract:

The chapter presents examples of innovative approaches to developing sustainable mineral engineering. Global and Polish initiatives related to the energy transition of the mining industry are given. Completed projects related to the green branch of mineral mining are discussed. Reference was made to the issue of mining waste management. The importance of these activities in environmental, technological and economic aspect is highlighted.

Keywords: sustainability, mineral engineering, green energy, green technologies, flotation tailings

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1. Introduction

In recent years, a significant change in the dynamics of growth in global mineral mining has been observed. For example, in the 2000s, total global mineral mining amounted to about 60 billion tons, currently it reaches about 100 billion tons [1]. Specificity of the mining industry, i.e. management of non-renewable raw materials, degradation of the Earth's surface and generation of large amount of waste, means that it is perceived as one of the significant negative impacts on the natural environment [2, 3, 4, 5]. Therefore, this industry is one of those that awaits the most difficult challenges in the context of implementing the assumptions of sustainable development. The same concerns the KGHM Polska Miedź S.A., where the development of the company is based on the following five keystones: flexibility, efficiency, ecology, safety and sustainable development, e-industry and energy [6].

The global mining industry is responsible for about 6.2% of the world's energy consumption, the largest part of which (30%) is used in grinding processes [7]. With this in mind, one of the main directions set by mining companies in relation to sustainable development is to have their own sources of green energy [8, 9]. Striving to implement the strategy in this area also gives measurable economic, environmental and technological effects, allowing for the reduction of operating costs, improvement of energy security, access to green financing or development of innovative solutions.

To implement the assumptions of their sustainable development strategies, mining companies also develop and implement green technologies in the field of new methods of ore mining and processing. The potentially green technologies, most of which are at the development stage, are bio hydrometallurgical methods. A more promising direction combining aspects of processing and mining are in-situ bioleaching methods. Another application of bioleaching may be the recovery of elements from difficult-to-enrich sulfide polymetallic ores and their semi-finished products. Flotation tailings are the most problematic product of minerals beneficiation in terms of meeting the requirements of sustainable development. They usually make a stream of >90% of the ore directed to beneficiation, hence the possibilities of their full management are limited, and due to the low content of elements, their further processing often becomes economically unjustified. Lack of possibilities of waste management can be compensated by using this material as a construction material for Mining Waste Disposal Facilities, thus reducing the need to use other materials [10].

The above chapter aims to present the most important directions of development of the mining industry, which the mining companies are currently looking for as part of satisfying the assumptions of the sustainable development.

2. Green energy for the mining industry

The mineral mining industry, as a main source of metals, plays an important role in the energy transformation. Metals such as aluminum, cobalt, copper, lithium and nickel are important raw materials for manufacturing the batteries or photovoltaic panels. A significant share of these raw materials is obtained in the mining processes [11]. The production of these essential materials consumes a lot of energy, which is currently obtained mainly from non-renewable sources. Due to its high energy intensity and energy strategy, the mineral mining industry is also involved in green energy projects (Table 1).

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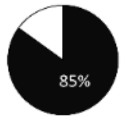
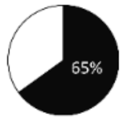
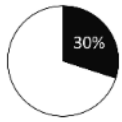
Table 1. Global examples of photovoltaic projects at mining industry plants

Reference	Plant	Country	Power [MW]	Covering the demand of the plant for electric energy [%]
[12]	Gabriela Mistral copper mine	Chile	35	
[13]	Gudai-Darii iron ore mine	Australia	34	
[14]	Evander w Mpumalanga gold mine	South Africa	10	
[15]	DeGrussa copper and gold mine	Australia	10	
[16]	KGHM Zanam	Poland	3,4	

35 MW Pampa Elwira project is an example of a photovoltaic installation providing electricity to a mining plant. One of the largest solar installations in the world is located in the Atacama Desert. It provides 54,000 MWh of thermal energy to the Chilean Gabriela Mistal copper mine owned by Codelco. The project replaces 85% of fossil fuels used in the process, reducing the combustion of diesel oil and reducing CO2 emissions by almost 15 thousand tons per year [12]. Using the oppressive hot climate of the area where the mine and processing plant are located, economic and environmental issues have been perfectly reconciled.

Another example of a solar power plant providing energy to a mine and processing plant is the photovoltaic installation operating for the Gudai-Daria iron ore mine in the Pilbara region in Australia. In 2021, a 34 MW photovoltaic farm was installed, consisting of approximately 10,000 solar panels. It was estimated that the solar power plant would cover 65% of the mine's average electricity demand, and even its whole demand during peak electricity generation periods. Additionally, installed together with a new lithium-ion battery energy storage system, the solar power plant reduces annual carbon dioxide emission by approximately 90,000 tons compared to conventional methods of generating energy from gas [13].

One of the KGHM Polska Miedź S.A. strategies is to reduce greenhouse gas emissions in the field of energy management and the use of renewable energy sources for its own plants [6] is the photovoltaic project at the KGHM Zanam plant in Legnica, Poland. The panels cover approximately half of the electricity required by the plant [16]. Currently, the Capital Group is planning further photovoltaic projects. At the beginning of 2024, a permit was issued for the construction of a photovoltaic farm for the Głogów Copper Smelter with a total installed power of 7.5 MW. Green energy from the sun is a strategic goal of KGHM Polska Miedź S.A. The energy transformation plans for 2030 assume at least 50% coverage of electricity from own sources, including renewable energy. This also allows for increasing energy independence and reducing the operating costs of the plants of KGHM [6]. A unique plant on a global scale with the most effective technological solutions related to energy acquisition is the Sierra Gorda copper mine. The Sierra Gorda mine, co-owned by KGHM Polska Miedź, is located in Chile in the Atacama Desert at an altitude of approximately 1,700 m above sea level. It manages a copper-molybdenum deposit, including both sulfide and oxide copper ores. The amount of energy needed to power the plant reaches 1,300 GWh per year. From January 2023, the Chilean mine will generate 100% of its electricity from renewable energy sources, such as solar, wind and hydropower installations. Using 100% of green energy eliminates approximately 1 million tons of CO2 emissions per year. This meets one of the main goals of the plant's development strategy, which is to minimize any potential negative impacts on the community and the environment [17].

The global economic crisis, the Russian invasion on Ukraine, which resulted in a dynamic increase in electricity prices (Fig. 1), increased the importance of renewable energy sources. Despite the increase in the prices of photovoltaic modules, energy from the sun on a utility scale is the least expensive option for newly generated electricity in the vast majority of countries around the world [18]. Approach of companies from the mineral industry includes plans to expand current designs of installations generating electricity from renewable sources and research on the technology, location and size of future potential possibilities to reduce carbon dioxide emission.

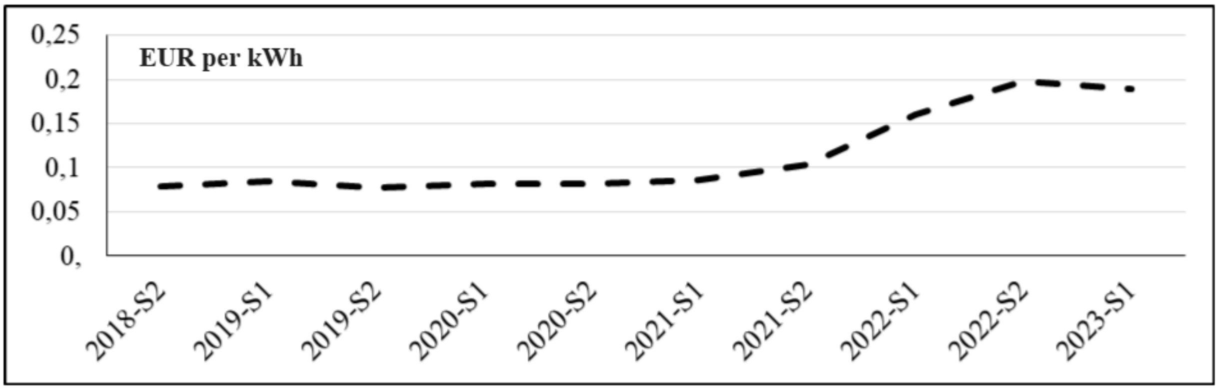


Fig. 1. Increase in electricity prices in 2018-2023 [19]

3. Green technologies in the mining industry

In the face of growing environmental challenges in the mineral industry, where mining and processing of raw materials are essential for industrial development, the green technology initiatives are becoming crucial [20]. The mineral industry must address the requirements of sustainable management of natural resources while maintaining operational efficiency and market competitiveness [20]. Green technologies cover a range of innovative solutions designed to minimize negative impacts on the environment, including not only renewable energy sources such as solar, wind, hydrothermal or geothermal energy, but also innovations in energy efficiency, waste management, and recycling [21]. Their common goal is to reduce greenhouse gas emissions, minimize pollution and manage resources sustainably. Environmental regulatory requirements and social expectations are becoming increasingly stringent, putting pressure on the industry to transform. Despite the obvious advantages, this process faces many obstacles, including the initial costs associated with the implementation of state-of-the-art technologies, the need for qualified staff to manage these technologies, and issues related to their availability [21]. The future of mineral engineering will certainly depend on the further implementation and development of green technologies. This approach is reflected in projects such as Bioshale and Biomore, which combine advanced technology with the needs of the environment and economy [22].

The Bioshale project, co-financed by the European Commission, was initiated with the aim of developing breakthrough biotechnologies enabling the exploitation of ores containing valuable metals, such as copper (Cu), nickel (Ni), zinc (Zn) and other metals used in high-tech technologies, including noble metals such as silver (Ag) or platinum (Pt). It was crucial to take into account the challenges posed by the high content of organic matter and carbonates, which make the recovery of metals by conventional methods difficult [23].

The project, realized from October 2004 to December 2007, included research work on deposits in Talvivaara (Finland), not explored so far, deposits of Lubin (Poland) and Mansfeld (Germany), where extraction had ended and waste heaps remained. In the BIOSHALE project research work focused on limitations and possibilities of extracting the black shales. Attention was paid to testing and optimization of bioleaching processes for the extraction of metals from black shales, where recovery up to 98% copper from shale ore was possible in the bioleaching process, with use of microorganisms to extract elements, mainly metals from lean ores due to the natural ability of microorganisms to use inorganic compounds as a source of energy, while acidifying the environment, which makes many substances, including metals, soluble and easier to recover from ores. Equally impressive is the result of up to 92% silver recovery (PLINT process) [23]. The operations covered a wide spectrum of activities, from selection for strains of microorganisms with high biological activity, through laboratory experiments aimed at determining the optimal process conditions, to pilot tests and tests on an industrial scale. In the bioleaching process, even ores with low metal concentrations, which would traditionally be difficult and uneconomical to extract, can become a valuable source of raw material, which highlights the potential of this technique in comparison to traditional methods. Studies have copper cathodeslme shown that it is possible to increase the efficiency of metal recovery, which is a significant step forward in the development of ecological technologies for bioprocessing of black shale ores [24]. The diagram of the technology based on the Bioshale project concept is shown in Fig. 2 in a simplified way, demonstrating the key aspects and processes used in this method [25].

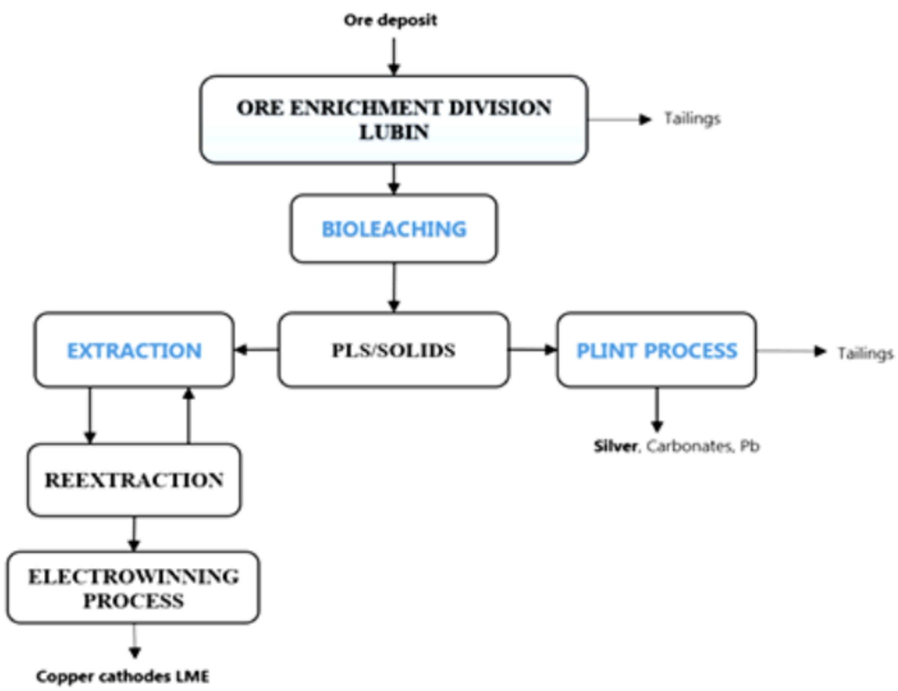


Fig. 2. Simplified diagram of Bioshale technology [25]

Another project, BIOMOre, initiated in 2015, introduces a new concept of metal extraction from deep ore deposits using biotechnology. BIOMOre was an initiative funded by the EU Horizon 2020 program, which aimed to develop a novel technology for metal extraction from deep ore deposits using biotechnology, including bioleaching. The three-year project brought together 23 partners from nine different countries, including five universities. The main role of microorganisms in this process was to generate Fe3+ ions in bioreactors placed on the surface and inject the solution into an injection well directly into the deep ore deposits. The leaching solution moves through natural flow paths in the deposit, which can be expanded by hydraulic fracturing. The metal-enriched solution (leachate) is then brought back to the surface through an extraction well [26].

Throughout the process, special attention was paid to waste minimization and designing the systems in a way that allows for their stability without environmental hazards. Within the BIOMOre project, numerous laboratory-scale and in situ tests were carried out to understand and optimize the process. Various parameters were verified, such as pressure and temperature on microorganisms and the kinetics of copper recovery. Specific experiments on deactivation and decontamination were also carried out to develop recommendations for eliminating the bacteria from deep underground ore deposits. The diagram below (Fig. 3) shows the concept of the surface and underground parts of the process. It is a visualization of the BIOMOre project concept, which aims to extract metals from deep ore deposits using biotechnology [26].

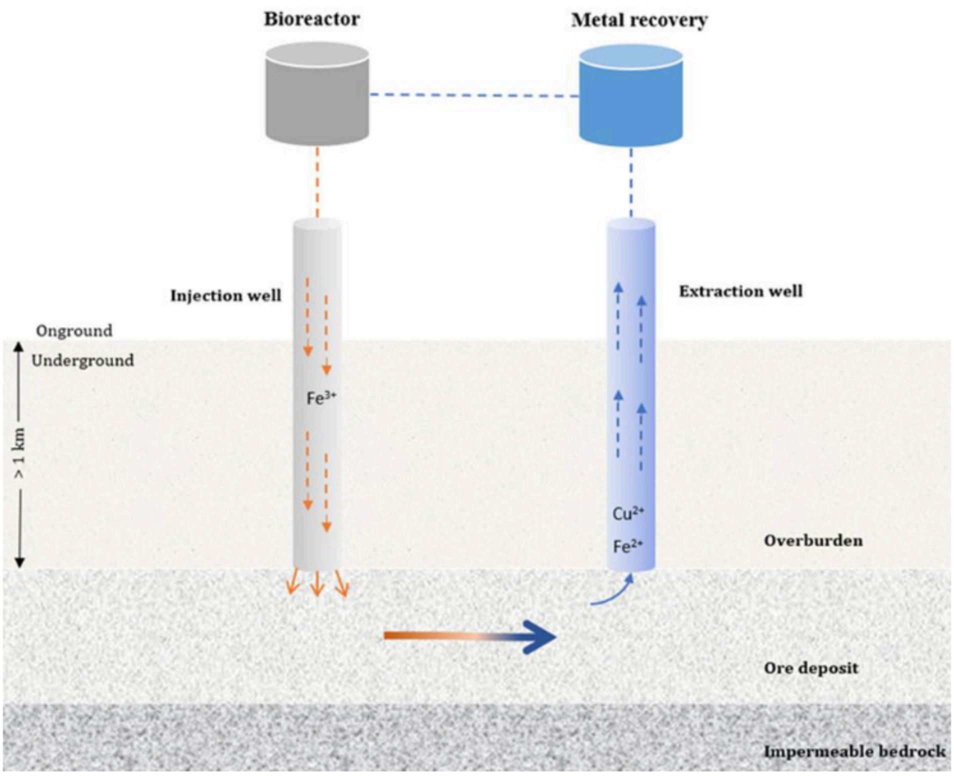


Fig. 3. Schematic diagram of the visualization of the BIOMOre project concept [26]

Both projects demonstrate the significant potential of biotechnology in the mining industry, offering alternative or complementary methods to traditional technologies. Through their activities, these initiatives contribute to the development of sustainable exploitation of mineral resources while offering new perspectives for resource exploitation with less negative impact on the environment.

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Implementation and results of projects such as Bioshale and BIOMOre underline the key role of green technologies in the mineral industry, demonstrating that advanced biotechnologies can not only reduce the impact of mining processes on the environment, but also open up new economic opportunities for the mining sector. They also emphasize the need for continuous research work and development in the field of green technologies, which is crucial to achieving sustainable development in the mineral industry and, more broadly, in the global economy.

The bioleaching process has been implemented in various locations around the world in the mining industry, with some outstanding examples being the Udukona deposit located in Russia and the Talviaara deposit located in Finland.

The Udukona deposit, the largest copper deposit in Russia and the third largest in the world, has reserves of 26.7 million tons of copper [27]. The Udokan project uses advanced technology for processing oxidized, sulfide-oxidized and low-grade mixed ores. This technology includes stages such as stack bioleaching, combining pyro- and hydrometallurgical methods for ore processing [28]. Another important and most famous example is the Talvivaara deposit, where the bioleaching process was also implemented for processing polymetallic ores under extreme conditions of the North. The Talvivaara deposit became the first large-scale commercial operation of nickel sulfide stack leaching. This process included, among other things, crushing, screening and conditioning of the ore before leaching [29]. The first bioleaching lasts 13-14 months, after which the leached ore is transferred and re-stacked on the second-stage stacks. In the metal recovery process, metals are precipitated from the bioleach solution. Construction of the plant began in spring 2007 and the first metal sulfides were produced at the plant in October 2008. The development of the bioleaching process continued on an industrial scale, focusing on improving the permeability and aeration of the stack. Development of the bioleaching process at Talvivaara, starting with a pilot plant in 2005, contributed to improving the permeability and aeration of the stack, which in turn improved the leaching results. Despite initial challenges, the stack bioleaching process at Talvivaara has achieved its goals, becoming an example of successful extraction of metals from low-grade ores [29].

These examples demonstrate the application of bioleaching not only for more efficient extraction of metals from low-grade ores, but also as part of activities towards a more sustainable and environmentally friendly mining industry. These technologies are particularly relevant in the context of limited natural resources and increasing environmental awareness.

4. Tailings from flotation beneficiation of non-ferrous metal ores in the sustainable development strategy

The mining industry, as part of its core business, generates waste that falls into the category of non-renewable waste from industry (industrial waste) [30]. In the case of plants dealing with beneficiation of non-ferrous metal ores, flotation tailings are the main generated waste during production [31]. In the world literature, we can find examples of concepts for their management, with few actual implementations [32]. This is a significant stream of wastes in Poland, where industrial wastes are generated at the amount of 115 million Mg annually, they constitute the largest component representing 25.7% [33] (Fig. 4). Waste end flotation product in the processing plants of KGHM Polska Miedź S.A. makes over 99.5% of the waste stream from flotation beneficiation of non-ferrous metal ores.

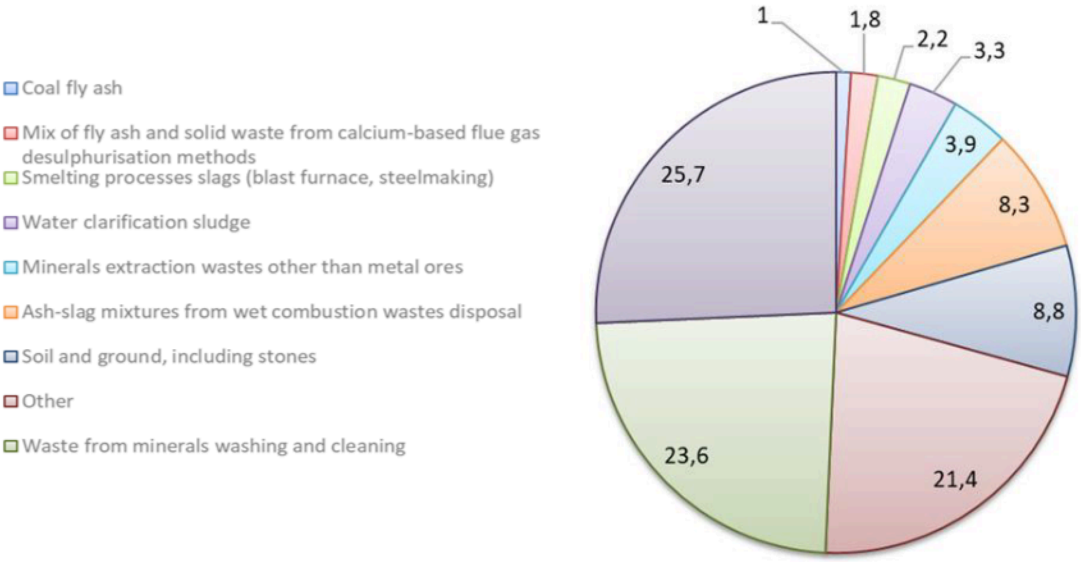

Fig. 4. Structure of generated wastes by their types in 2022

Such a high share of mining waste in the structure of industrial waste means that the sustainable development of the copper industry must refer to the aspect of their management in a sustainable manner. Currently, all waste is used to build and seal the Żelazny Most tailings storage facility. This reduces the need to use other materials for the facility over structure. Since the launch of operation, other possible forms of flotation waste management have been sought in a way that brings measurable effects for the natural environment and the company's financial results. One of the directions considered as part of striving for the above is the use of mining waste for the production of materials for construction purposes [10]. The possibility of using waste for these purposes is the subject of one of the projects implemented in the consortium of KGHM Cuprum sp. z o.o. Research and Development Center, Łukasiewicz Research Network - Institute of Ceramics and Building Materials and Metraco Sp. z o.o. The project is intended to manage 1 million Mg of flotation waste from current production per year. Other projects focusing on using this material for production of autoclaved concrete, aggregate for road construction, mineral fertilizers, or hydraulic backfill have realized for years [34, 35, 36]. Unfortunately, in most cases, the limitations that affect the possibility of implementing these solutions are the following:

- significant number of wastes to be managed,
- market absorption,
- meeting the quality requirements for commercial products,
- high investment cost,
- environmental and social restrictions.

Further recovery of minerals not extracted at the stage of beneficiation processes is another form of using the wastes [37]. In the non-ferrous metals industry, there are only few examples of using the technology for re-recovery of elements from flotation tailings. This is due to the specific properties of the minerals contained in this material as well as their grain size, which make their recovery in the beneficiation process difficult [38]. Tests in this area focused mainly on the recovery of copper and silver, due to their increased concentration in wastes, especially at the inactive Gilów and Wartowice OUOW facilities [39, 40]. Production of the elements concentrate from these wastes with their increased content could be realized by the hydrometallurgical methods. While the solutions at the technical and technological level requires efficiency of the process, they encounter problems related to the management of post-process waste, which in some cases may be classified as hazardous. However, taking into account the nature of these processes, this gives rise to problems resulting from environmental and social conditions [41]. This approach allows for the classification of OUOW as an anthropogenic deposit, which currently does not function in Polish legislation.

5. Conclusion

Projects involving renewable energy, bioengineering technologies, and waste management bring mining companies closer to the sustainable development goals defined by their strategies. One of the most recognizable examples of green energy production is the KGHM Polska Miedź S.A. Sierra Gorda Chilean mine, where 100% of energy consumption is supplied by renewable energy sources. The company also aims to supply 50% of its Poland-based operations with solar energy.

Biotechnologies for element recovery have been successfully implemented on an industrial scale in Finland and Russia. However, such solutions are not widely adopted globally due to high initial costs, their cutting-edge stage of development, and technological limitations. Nevertheless, companies continue to invest in biotechnology development because of its potential to reduce greenhouse gas emissions, minimize pollution, and promote sustainable resource management. One of the most intriguing projects is BIOMORE, which presented a new concept of metal extraction from deep ore deposits using biotechnology. The proposed technology, which is still under development, would allow metals to be extracted directly from deposits without the need for mine infrastructure construction, thus eliminating many of the negative aspects associated with traditional mining.

To further minimize the environmental impact of mining activities, companies are exploring new approaches for tailings utilization. This stream constitutes the majority of ore processed in flotation-based mining activities. A reduction in the volume of this waste stream might be achieved by using it as a material for the production of autoclaved concrete, aggregate for road construction, mineral fertilizers, or hydraulic backfill. One such technology, developed for carbonate tailings by KGHM Polska Miedź S.A., has a capacity of 1 million tons per year and was created during the FLOT-BUD project. This technology is still being refined and improved.

The completed projects are a strong contribution to future ideas and solutions for an increasingly sustainable mineral economy. Finding a balance between the environment, technology and economy is important in implementation of a given technology.

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