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Harnessing Microorganisms for Biomining: Unveiling the Power of Microbial Mining

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ABSTRACT
Biomining, an emerging technology, utilizes biological substances to extract valuable metals from their ores. The term microbial mining is particularly used to describe the use of microorganisms in the extraction of metals. The mining industry is growing rapidly as metal demand increases, leading to the discovery of new, profitable, and cheap mining processes. Crucial mining industries highly demanded, and have extensive usage in daily life, attract researchers to use microorganisms for this approach. This review article aimed to provide comprehensive and updated knowledge about microbial mining that covered its different aspects. various databases like Google Scholars, Science Directs, and Scopus etc., were searched for the relevant terms and the related literature was downloaded, analyzed, and screened for literature. The fact that microorganisms are present everywhere and are already in use in different applications leads to the concept of microbial mining. In the soil, microbes have different effects on soil topology and have different interactions with metals, as some elements are crucial for their growth too. Different microorganisms, i.e., *Acidithiobacillus ferrooxidans*, are studied for their mining potential, and currently, a good number of microbes are used in this industry. The peculiar properties of these microbes include their growth at low pH and high temperatures and their ability to not alter the composition of the metals. Microbial mining has both pros and cons; it is environmentally friendly, economically cheap, and easy to approach, but it is a complex process and has low productivity. Understanding and adopting microbial mining will attract industrialists around the globe and thus not only aid the country's economy but can also help with climate change.

KEYWORDS
Microorganisms, bacteria, biomining, bioleaching, metals

INTRODUCTION

Microorganisms have ubiquitous distribution and are found in every environment, varying in numbers and types, constituting approximately 159,000 species. These include bacteria, fungi, protozoa, algae, mites, and viruses[1]. Microorganisms have been used by human beings for centuries, particularly in activities like baking and brewing, but it has been in the last 150 years when measures have been taken to fully utilize their capabilities. Modern genetic engineering techniques are likely to further broaden their range of

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potential usage. Since the beginning of life on earth, microorganisms have played a role in both the formation and breakdown of minerals in the crust of the earth. In ancient Roman times, and perhaps before that, the ability of some bacteria to break down a range of mineral deposits was known[2,3]. Without being aware that microorganisms were involved, these early miners exploited microbial activities to extract copper from their ore. Although some forms of microorganism-assisted metal recovery have been used for centuries, the mineral biotechnology sector has gained rapid growth in recent years, and a range of factors are contributing[2, 4-6]. The use of microorganisms in cyanide destruction was also developed in the previous century and commercialized for the gold mining industry, indicating the potential use of microorganisms in the mining process[7].

Although there are some particular groups of bacteria that have developed a distinct mode of existence and have helped humans over the past 2000 years, scientists have recently recognized the potential revolutionary horizons and aspects of these bacteria in metallic minerals[3]. Mining industries are increasingly aware of the possibilities of microbiological methods for extracting precious metals from their low-grade ore and the handling of acidic and metal-rich wastewaters. In the soil, these microbes have their community in a balanced way, and any disturbance can cause unequal distributions. Due to the mining process, the soil topology is changing, which leads to disturbance in the associated microbial community[8]. The presence of metals like silver, aluminum, cadmium, gold, lead, and mercury can create resistance to soil microorganisms, particularly when these are present in higher concentrations[9]. Microorganisms contribute significantly to the clean environment approaches not only they are using in the mining industries but can also help in the reduction of waste and its management in a friendly way[10,11]. The majority of metal ores exist naturally in the form of metal sulfide, which requires different mechanical and roasting steps to extract these metals from their ores, and these processes are not considered environmentally friendly. Air pollution, like the emission of Sulphur gas, is produced in this process. Likewise, the mining industry in general aids the country's economy but also creates different public health problems[12]. Luckily, uncountable microorganisms present that help in this process, as their usage is environmentally friendly and economically valuable[3,13].

In the current socio-economic scenario of the world, rapid climate change is asking for affordable and environmentally friendly processes that cover both sides[14]. Keeping in mind this concept and the promising potential of microorganisms in different known processes, the researcher tried to intricate the association between them, and hence the concept of microbial mining was developed. So far, valuable work has been done in identifying the suitable microbes, the mechanisms of action, the metals that are extracted, and the allied things associated with microbial mining. But, to the best of our knowledge, there is a gap in the current literature that shows the different aspects of biomining and microbial mining in a single document. Moreover, the present literature focuses more on bioleaching and its associated processes, and limited data is available that clearly describes the microbial mining potential. Hence, this review article was aimed to aid the existing literature in the following ways: It provides recent and updated knowledge of biomining while more emphasizing bacterial mining; it gives the known mechanisms and their values understandably; It covers the present-day gap in the biomining literature and gives an insight into how this industry is useful in different aspects; It provides both pros and cons to bacterial mining and gives practical solutions to the current global environmental issues.

MATERIALS AND METHODS

The literature for this article was performed by searching different terms like mining, microbial mining, biological mining, mining and bacteria, mining and microbes, metal-microbes interaction, etc., on different websites. The relevant literature from different sources was downloaded, screened, and critically analyzed for the subject materials. The focus was kept on the mining potential of microorganisms.

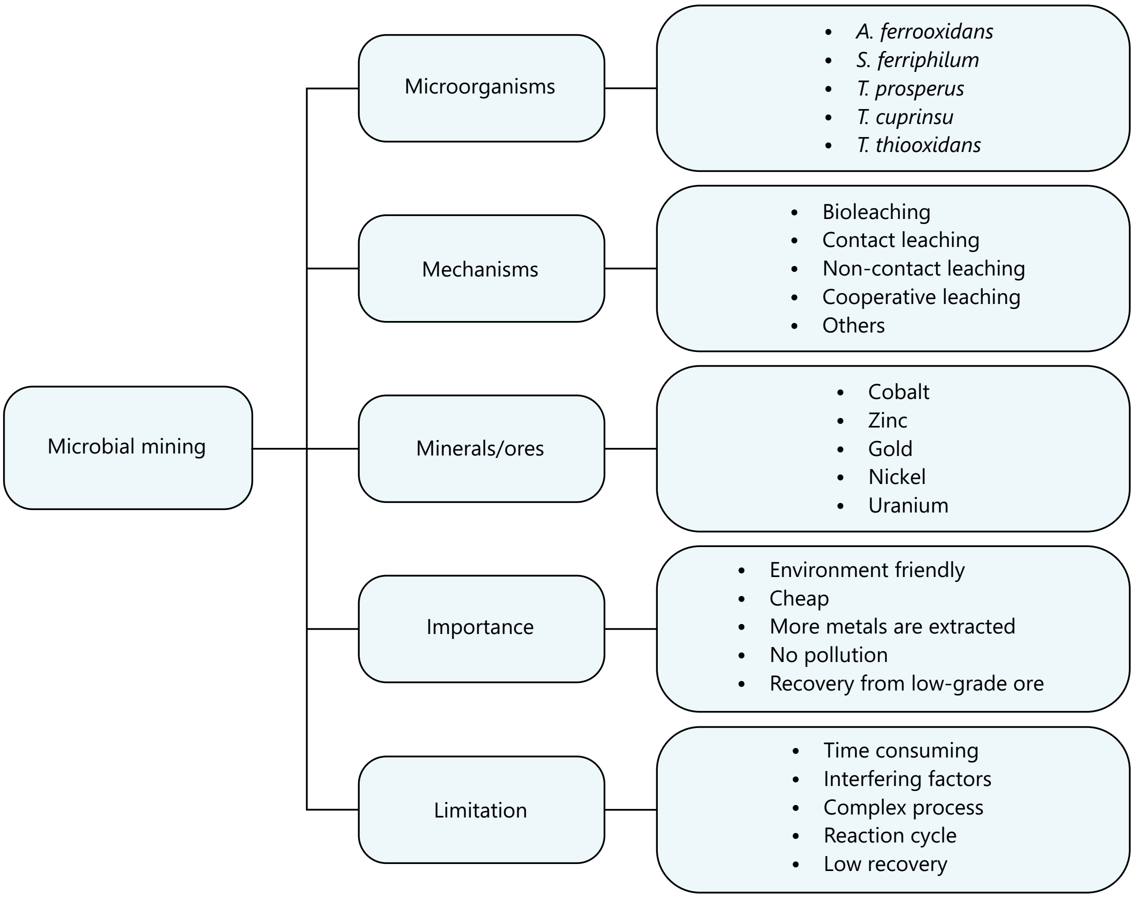

Fig. 1: Microbial mining showing its different aspects

Concept and development of microbial mining: Historically, it is known that mineral-microbial interaction gives a characteristic sign to rocks like morphology, composition, surface topology, and the presence of organic substances. This can lead to the co-evaluation of earth, minerals, and microbes[15]. The term microbial mining refers to the field of study where microorganisms are employed to extract metals from their ores[10,13,16]. The general term biomining is exclusively used to describe the extraction and recovery of metals from their ores that rely on biological environments, predominantly on microorganisms[17-19]. Biomining technology is currently used in different parts of the globe, where it competes with other hydrometallurgy and chemical processes[13]. Among the sea of microorganisms, *Thiobacillus ferrooxidans*, which gets its energy by oxidizing Sulphur, sulfides, and ferrous iron, is considered the most extensively studied and used group of microorganisms[20]. It is also documented that microorganisms with moderate thermophilic capacity have a great potential for microbial mining[13]. Using biomining technology, an estimated 15% of copper, 5% of gold, and lower amounts of other metals (including nickel and zinc) are being produced globally[16,19]. The recovery of metals from processed and waste streams is another use of targeted bio mineralization at some current and abandoned mine sites[16]. The spectrum of microbial mining, i.e., microorganisms using, mechanisms following, ore extracting, and the associated pros and cons are illustrated in Fig. 1. To extract and concentrate metals from their ores, there will be alternative methods that compete with the existing bio-extractive techniques. Different techniques, like pressure leaching, are more modern but non-biological methods. Pyro-metallurgical processes (ore roasting and smelting) have been improved through millennia and frequently represent significant investments by mining corporations[21]. The primary challenges of biomining are the time-consuming process of extracting metal at an economic level, as well as concerns about the reliability and robustness of the biological process involved[22]. The common consensus is that biomining, on the other hand, is a considerably more eco-friendly method since it requires very low temperatures (and hence uses less energy) and leaves behind fewer carbon emissions[15]. The latter claim is supported as the majority of microbes that are involved in mineral oxidation processes are autotrophs (i.e., fix carbon dioxide like green plants), in contrast to smelting processes that produce significant amounts of CO_2[23]. It is shown that indigenous microbes are widely used in biomining because they show good adaptability and a higher leaching rate[21]. The metal-microbe interaction in mining can also affect biomining, as some metals are required for the growth of bacteria[24]. The different microorganisms that are used in microbial mining and their descriptions are summarized in Table 1.

Technology advancements in biomining: The first recognized biomining operation was established in the first 20 years after the identification of bacterial species that were shown to catalyze pyrite and other base metals containing sulphide minerals in acidic liquors[16,29,31]. In the 1960s, the new biotechnological aspect, i.e., extracting copper from waste rock dumps, was developed by the Kennecott Copper Corporation in Mexico[18,32,33]. In the 1970s, *in situ* mining was widely employed to recover uranium from worked-out deep mines in Canada. Bioleaching technology, besides the mining process, is also applied in other different applications. For instance, this technology is used in waste water treatment, industrial effluents, petroleum refining and purification, bioremediation of heavy metals, etc.[10,22,34].

Table 1: Different types of microorganisms used in the biomining/microbial mining process

Microorganisms	Description	References
Acidithiobacillus ferrooxidans	Isolated in 1947, that oxidize the metal sulfide to metal ions. They required ferrous iron as an electron donor	Bosecker[3], Jerez[4], Ye[13] and Gao *et al.*[21]
Leptospirillum ferriphilum	It is involved in the oxidation of Fe (III) to Fe (II) and works better at low pH. It is unable to oxidize sulfur or its compounds while showing more sensitivity to copper	Bosecker[3], Ye[13] and Rawlings[25]
Thiobacillus	It is the most active genus in biomining	Bosecker[3] and Rawlings[25] Seifelnassr and Abouzeid[26]
Acidianus, *Metallosphaera*, and *Sulfolobus*	These genera have a high copper extraction rate	Ye[13] and Rawlings[25]
Thiobacillus thiooxidans	After its isolation in 1922, it became famous for the rapid oxidation of elemental sulfur	Bosecker[3], Rawlings[25] and Seifelnassr and Abouzeid[26]
Thiobacillus prosperus	It is a halotolerant metal-mobilizing bacteria	Bosecker[3] and Abashina and Vainshtein[27]
Thiobacillus cuprinus	It is a facultative chemolithoautotrophic bacteria that oxidizes metal sulfides	Bosecker[3]
Thiobacillus-like bacteria	It is a thermophilic bacteria that uses ferrous iron as a source of energy	Bosecker[3]
Acidianus brierleyi	It is chemolithoautotrophic, facultative aerobic, and highly acidophilic and grows on ferrous iron, elemental sulfur, and metal sulfides	Rawlings[2], Abashina and Vainshtein[27] and Everts[28]
Sulfolobus	Their members are aerobic, facultatively chemolithotrophic bacteria that oxidize ferrous iron, elemental sulfur, and sulfide minerals	Rawlings[2], Bosecker[3] and Rawlings and Johnson[17]
Bacillus	Members of this genus show effectiveness in metal solubilization	Bosecker[3]
Thiobacillus acidophilus and *Thiobacillus oranoporus*	These are mesophilic and rod-shaped bacteria that oxidize elemental sulfur for their growth. They grow well with an optimum pH of 2.5 to 3.0	Seifelnassr and Abouzeid[26] and Suzuki[29]
Pseudomonas putida/ *Aspergillus flavus*	These are the strains that ensure an increase in iron content of about 3% after 10 days of leaching	Seifelnassr and Abouzeid[26], and Krebs *et al.*[30]
Aspergillus niger	It is particularly effective in the leaching of Pb	Krebs *et al.*[30]
Acidithiobacillus caldus	It oxidizes the reduced sulfur compounds but inert to ferric iron and shows good growth at low pH	Rawlings[2]
Acidianus infernus	It grows best at 90°C and requires an optimum pH of 2.0	Rawlings[2]

Table 2: Different mining industries using microbes in their extraction process

Mining industry	Process/mechanism	References
Copper production	Microorganisms can increase the overall efficiency by 20%. Around 20-25% of the world's total copper is produced using bioleaching	Bosecker[3], Ye[13], Gao *et al.*[21], Rawlings[25] and Brierley and Brierley[36]
Extraction of gold	It is not directly obtained by biomining, as it is not oxidized when present in its metallic form. It is obtained via bio-oxidation, which is a cheap and easy process	Fashola *et al.*[12], Ye[13], Gao[21] and Seifelnassr and Abouzeid[26]
Nickel, cobalt, and zinc	Extraction of these metals is performed via bioleaching when the framework conditions exclude conventional processes	Ye[13], Seifelnassr and Abouzeid[26], Suzuki[29] and Brierley and Brierley[36]
Uranium	Uranium is extracted by in-situ bioleaching, in which the insoluble UO_2 is oxidized to water-soluble uranyl ions $(UO_2)^{2+}$ with the help of microorganisms	Bosecker[3], Ye[13], Rawlings[25] and Kenarova *et al.*[37]
Silicate, carbonate, and oxide ores	Biotechnological processing on an industrial scale does not exist yet, but heterotrophic bacteria and fungi could be used	Bosecker[3] and Ye[13]

Currently, biomining technology is also improving in terms of bioleaching microorganisms, like the identification and characterization of newly identified microbes, etc.[35]. The other approaches followed in the booming advancement include biomining of waste products, as this technology has an affective capacity to recycle and solubilize the waste; bioleaching at low redox value; the conventional bioleaching process gives a low percentage of the extracted metals; hence, this problem is solved by providing low temperature and less positive redox potential; mineral dissolution with bio reductive substances, this method is developed to extract the target metals from oxidized ores deposits and operate under anoxic conditions[16]. Table 2 summarizes different mining industries and their respective ore production.

Bioleaching: A component of microbial mining is called bioleaching. Nowadays, among the existing mining methods, bioleaching has gained significance. It is the conversion of insoluble valuable metals into their soluble form with the help of microorganisms[13,38]. Bioleaching is an environmentally friendly process that helps in the extraction of costly metals[22,29,39]. It is known that bacteria and fungi were used for the bioleaching process with different mechanisms. For instance, chemolithotrophic bacteria are used to extract low-grade Ni. The cumulative value of bioleaching with bacteria has more value than other processes[39]. The different bioleaching processes and their mechanisms are previously documented by Sand *et al.*[20], while the direct and indirect bioleaching of cobalt from its ore has been documented recently[39]. The presence of unwanted mineral components in the ores through their interaction with microbes is known as biobeneficiation[26]. Basically, the bioleaching process was developed for the extraction of valuable metals (i.e., gold) once the first patent was published in the late 1950s[3,25,27].

Generally, in the bioleaching process, the microorganisms oxidize the metal sulfide oxidation products and give protons and Fe (III), which create a pH gradient and allow the Fe ions to go into the solution[13]. It is also known that all metal sulfide and their oxidation do not proceed in the same mechanism but can follow different intermediate compounds[25]. The bacterial leaching occurs in acidic conditions (pH 1.5-3.0) in which most of the metal ions remain in solution[3,16,21,25]. Both autotrophic and heterotrophic microorganisms are used in the bioleaching process, but this method is mostly used for autotrophic microorganisms, as they have a higher cost and require more organic substances[3,13]. The bioleaching process can help to meet the global demand for these important metals[38]. Multiple factors contribute to the bioleaching processes that were summarized earlier by Bosecker[3] and recently by Gao *et al.*[21] and Sani and Haris[22]. The summary of these factors is illustrated in Fig. 2.

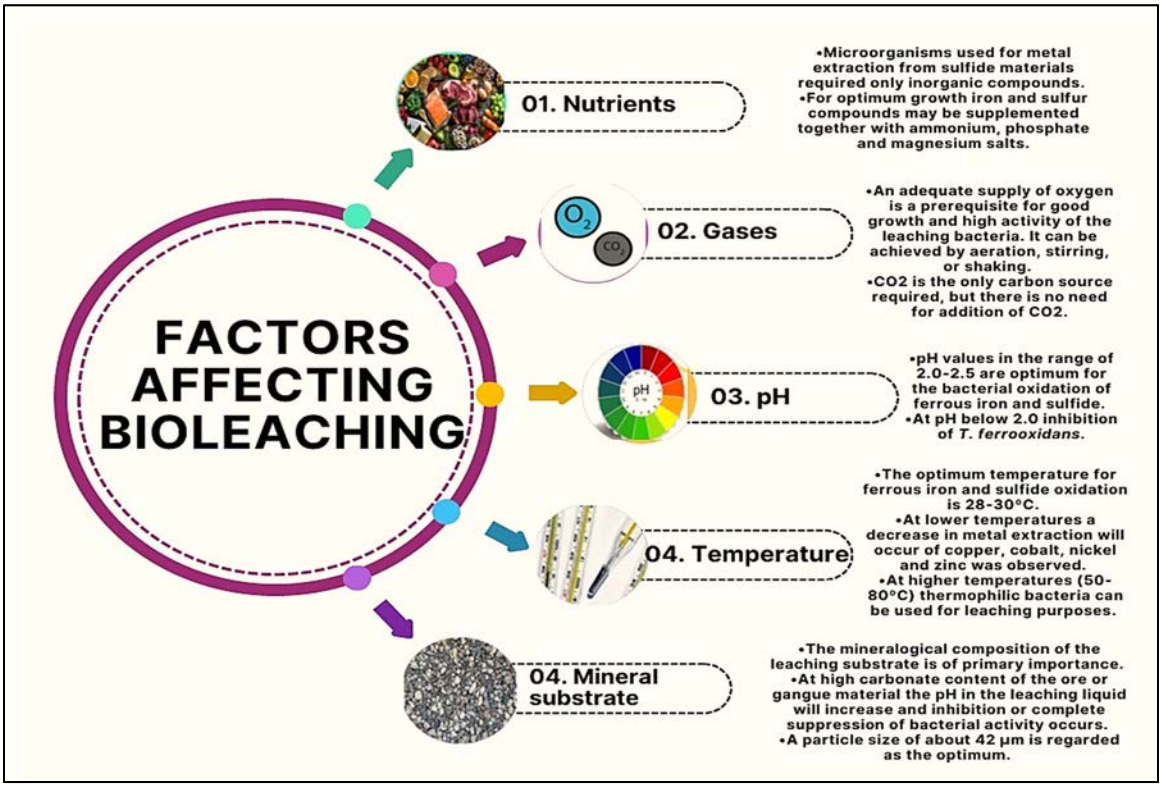

Fig. 2: Different factors that affect the process of bioleaching

Biological leaching mechanism: The processes of direct and indirect action are both applied in bioleaching. In direct action, microorganisms directly act on the ore, while in the indirect process, bacteria produce chemicals like acids or ions that help to extract metal from their ore[22]. The direct and indirect methods are used together in the mining industry to efficiently extract metals. Recently, contact leaching and non-contact leaching are used instead of direct and indirect bioleaching, which describe the bioleaching process by attaching or planktonic cells[22]. Cooperative leaching is used to indicate the dissolution of collides using planktonic cells[13,25]. Extracellular polymeric substances (EPS) are the mediators and contact substances that help in the attachment of microbes to the mineral surfaces. When the microbes are attached to the surface, they stimulate the EPS, which has a chemical nature and thus enhances their production up to 100 times[13]. The conceptual mechanism of action is shown in Fig. 3.

Direct bioleaching: During direct bioleaching, the oxidation-sensitive minerals are directly attacked by microorganisms using different enzymes[13]. For example, in direct bioleaching, the ferrous ions are oxidized to ferric ions by bacteria like *Thiobacillus ferrooxidans*, which move the electrons from iron to oxygen, and thus a more soluble form of iron is obtained from the iron ore pyrite (FeS_2). Similarly, sulphur is extracted from iron ore pyrite by *Thiobacillus thiooxidans* in the form of sulphate, which is also more soluble[3].

Indirect bioleaching: In the indirect approach of mineral bioleaching, bacteria produce potent oxidizing agents that react with metals and remove them from their ores[3,13]. Upon the oxidation of iron and sulphur bacteria produce oxidizing agents (ferric ions) and sulphuric acid, respectively. During this process, an acidic environment is necessary, which is provided by the ongoing oxidation of different metals[40,41].

Bioleaching-related microbes: The most suitable and applicable bacteria for bioleaching are those that are naturally involved in growing up in the rocks. The biomining microorganisms shared a common characteristic. For instance, these microbes are chemolithoautotrophic and use reduced inorganic substances as sources of electron donors. The optimum pH for these bacteria is 1.5-2.0 and use electron

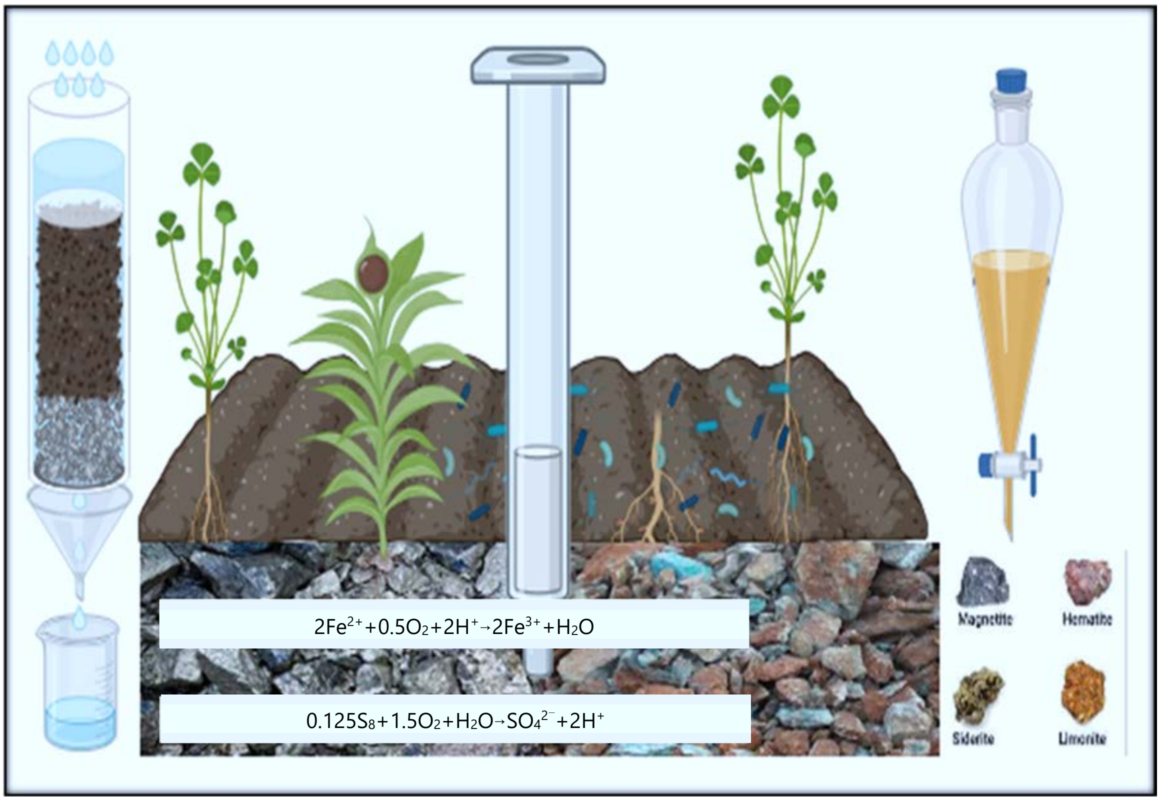

Fig. 3: Process of microbial mining

Different types of ores are present in the earth, both in combined and isolated form. These ores are extracted via direct and indirect bioleaching. The microorganisms present in the earth's crust can help with their oxidation, mostly oxidized sulfur compounds

acceptors instead of oxygen[41]. These microorganisms also fix CO_2[2]. The bacteria *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans* are the most frequently used for bioleaching. *Thiobacillus ferrooxidans* is a Gram-negative, motile, and non-spore-forming rod-shaped bacteria[3], which gets its energy for growth or development by oxidizing the sulphur or iron in ore. These bacteria convert sulphides, thiosulphates, and sulphur to sulphate and oxidize ferrous ions to ferric ions. Similar roles are also performed by *Thiobacillus thiooxidans*, which primarily grows on rocks or sulfur-containing ores. Other bacteria involved in the bioleaching of copper and molybdenum from ores like chalcopyrite and molybdenite include *Sulfolobus acidocaldarius* and *Sulfolobus brierleyi*.

These are acidophilic and thermophilic bacteria that mostly thrive in hot springs. *Leptospirillium ferrooxidans* and *Thiobacillus organoparpus* are the two other bacteria that combine to extract iron and copper from pyrite and chalcopyrite[3]. These different kinds of microorganisms and their classification are shown in Fig. 4. It is also possible to use some bacteria, such as *Pseudomonas aeruginosa*, to extract high-value metals like uranium from low-quality uranium ore that contains 0.2% of the elemental uranium. In less than 10 seconds, this microbe extracts 100 mg of uranium from a 1 L solution. *Rhizopusarrhizus* is another bacterium that may extract uranium from low grade uranium ores.

Pros and cons of bioleaching: The bioleaching process has both positive and negative aspects. Extraction from low-grade ores, which is economically feasible, environmentally friendly, and the isolation of costly metals in good quantities, etc., has few positive potentials for bioleaching. Likewise, time consumption, quality compromised, chance of contamination, leaching efficiency, etc., reflect their negative aspects[21].

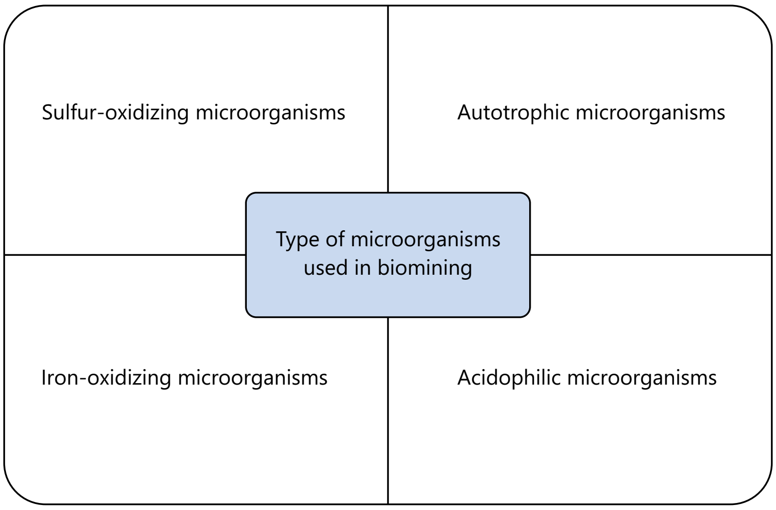

Fig. 4: Different types of microorganisms used in biomining

Potential effects of microbiology on mining: On the surface, it would appear that studying and using microbiology had very little in common with mining for metal ore and coal. But in the last few decades, microbial-based biotechnologies have been developed, and they have a significant impact on the worldwide mining sector, particularly in the area of processing of copper and gold ore.

The mining industry can be affected by microbial interventions in a variety of ways, including:

- Providing an alternative method for processing waste materials, mineral concentrates, and ores produced from previous, less effective mining operations. Biomining is frequently regarded as being more environmentally friendly than traditional methods of obtaining metals, such as pyro metallurgy
- Providing new efficient ways to extract and recycle metals from processed water and waste streams
- Providing different ways to process toxic waste waters, such as acid mine drainage, using more environmentally friendly techniques (such as passive remediation systems rather than chemical treatment)

Current processes for biomining: For microbial-assisted metal recovery on a commercial scale, there are primarily two different types of processes: Stirred tank and irrigation-type processes. In the process of irrigation techniques, crushed ore or concentrates that have been placed in columns or dumps are exposed to leaching solutions[2,42]. Additionally, there are many examples of irrigating an ore deposit in place, that is, without bringing the ore to the surface. Continuously operating, highly aerated stirred tank reactors are used in stirred tank-type processes. Both types of fermentation processes have the feature of not being sterile, and no attempt is made to keep the inoculum sterile, unlike the majority of other commercial fermentation processes. Because the extremely acidophilic microorganisms produce an environment that is unsuitable for the growth of other organisms, and hence sterility is not required[2].

Irrigation-type processes: Copper is the metal that bioleaching recovers in most cases. It is challenging to get accurate information on the overall amount of copper ore processed by microbially aided methods. However, it was started in 1999 that the copper-heap bioleaching units constructed since 1990s and still in use processed more than tons of ore annually[2,16,36,42]. For the extraction of copper from chalcopyrite, the technique used is the advanced form of the above mentioned technique, while all commercial procedures for copper recovery use the dump, heap, or *in situ* irrigation type.

Dump leaching, which began in the late 1960s, is one of the most well-known dump leaching facilities situated at the Kennecott Copper mine in Utah[5,42]. Almost four billion tons of low-grade copper ore waste are being stored in this dump. The Chuquicamata division of Codelco's Bala Ley facility in Chile is an advanced plant and stores less material. In the heap leaching technique, large heaps of ore are arranged, and then microorganisms are strewn over the leach pile. The obtained solution is collected and processed through a processing step, which helps to recover even more metals[16].

Stirred tank processes: The efficiency and capacity of mineral biooxidation are improved by using highly aerated, stirred-tank bioreactors[18]. These reactors can only be used with high-value ores and concentrates since they are expensive to build and maintain[17]. Typically, the bioreactors are set up in a sequence and operated in a continuous-flow mode, with feed to the first tank and overflowing into the next tank until the biooxidation of the minerals is complete[43]. This process spans 3-5 days to complete across all reactor phases[2,18].

Pros and cons of microbial mining: Biomining, or microbial mining, is a growing industry and covers different areas with potential applications. Being economically cheap and environmentally friendly, the method is adopted in many parts of the globe. Among the several factors that led to the development of technology are the high demand for metals, enthusiasm to work with challenges, as many ores are challenging to extract, the high eco-friendly of nature, the high cost of previously available methods, the higher demand for labor in conventional methods, and other technological issues that are associated with them. Microbial mining is an economically effective method as there is no cost of smelting and refining, extraction from low-grade ores, and avoiding the cost of acids used[18].

Besides the aforementioned advantages of biomining, there are still associated challenges. Among the technical challenges, purity is most important as the extracted metal has some impurities from other metals[18]. On the commercial side, the challenges include that mostly biomining is applied by the companies, and they can extract their own mineral reservoirs, which have no greater benefits for the nation[18]. The spectrum aspects of microbial mining, i.e. process, benefits, risks, and future, are illustrated in Fig. 5.

Practical path to advance the biomining technologies; factors to be considered: Biomining got the researchers' attention, and currently, worldwide research, both at the academic and applied levels, is ongoing. The university researchers are digging into the fundamentals of the technologies and developing new and applied methods to improve all aspects of the technologies. As mentioned earlier, most biomining is conducted by private companies for their resources, which get more benefits, but for local consumers, these are still costly. The lack of collaboration between academia and industry leads to the complete usage of biomining technologies. How to use this technology for the bitterness of whole nations is summarized in a few practical steps and processes summarized in Fig. 6.

Probiotics in biomining: The field of probiotics is growing fast. These are the live microorganisms, which, when administered in adequate amounts, confer a health benefit on the host[44]. These are considered friendly microbes and have a broad spectrum of benefits. Currently, seven genera are recommended to have probiotic strains. There is a selection criterion that is followed for a strain to be used as a probiotics[44]. These criteria include tolerance, aggregation, production of antimicrobial substances, and synthesis of vitamins[45]. These microbes are also tested for their potential, like heat and temperature stress, shelf-life, and at different storage conditions for their possible biotechnological applications.

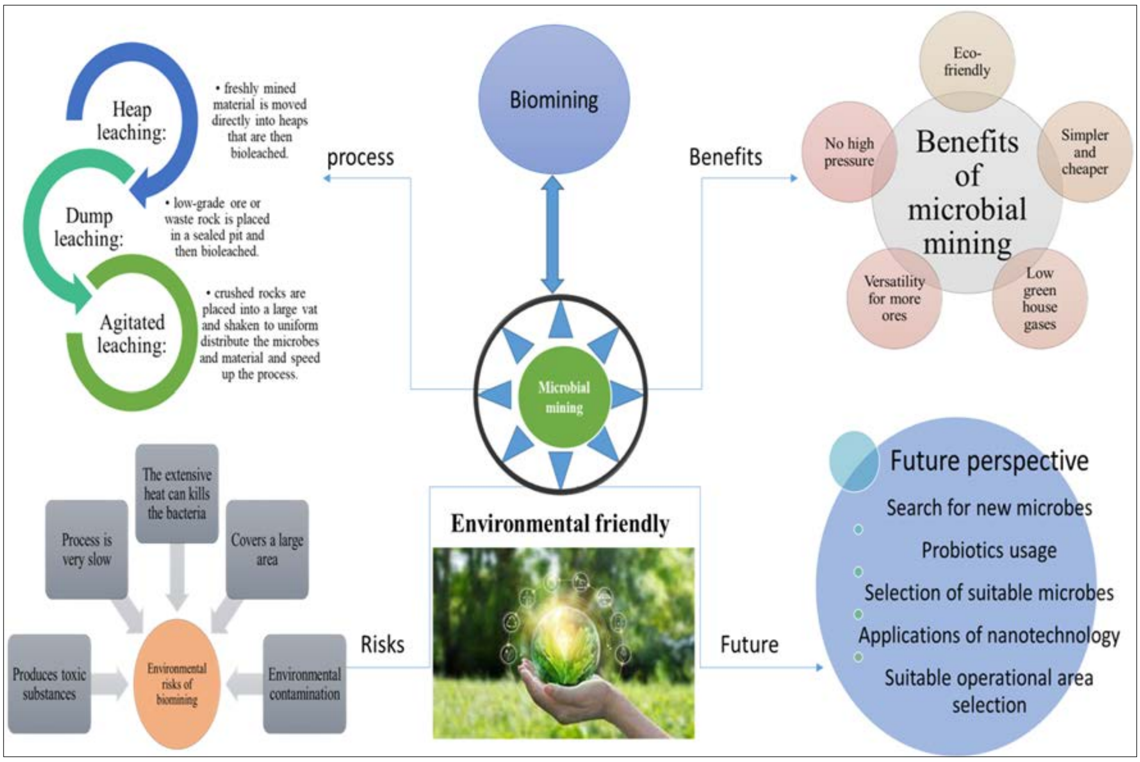

Fig. 5: Different spectrum of biomining (microbial mining)

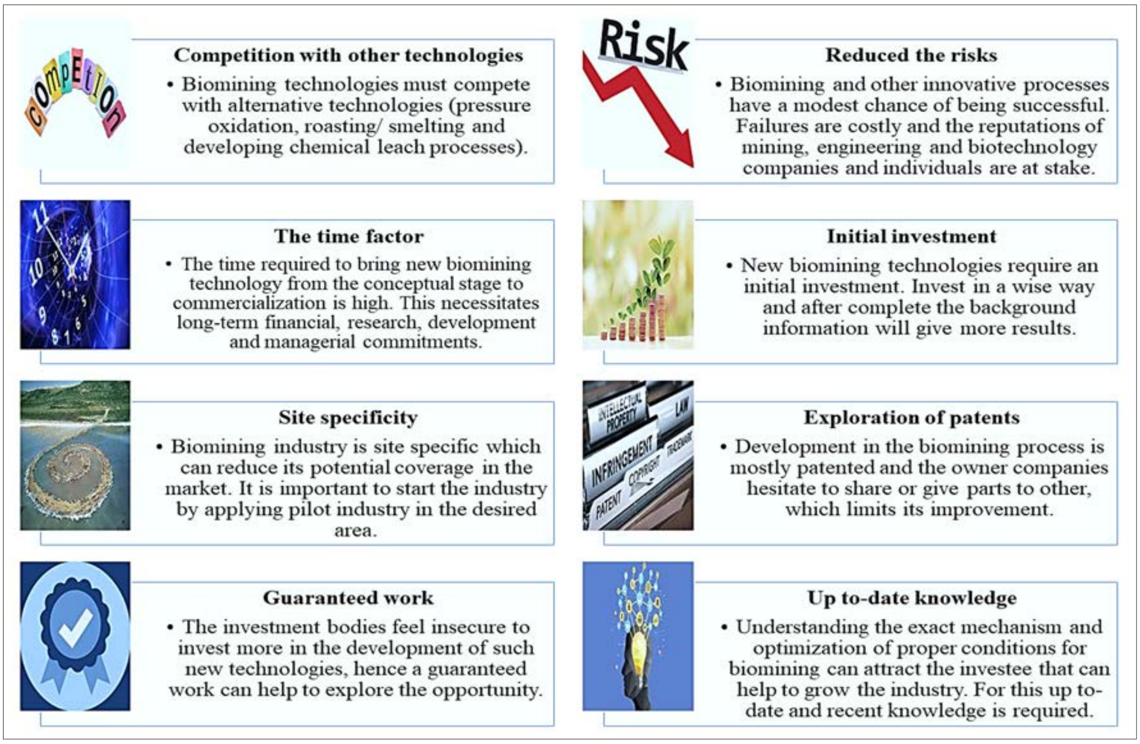

Fig. 6: Practical guidelines that help to advance the biomining technology and effectively used in multiple applications

As already mentioned, biomining microorganisms have some peculiar characteristics, like being grown at low pH and surviving at higher temperatures, etc. Similarly, it is conceptualizing that probiotic microorganisms can also be used for biomining potential. Due to the similar properties and versatile applications of probiotics, such microbes may be used for their biomining potential. Another promising aspect of this scenario is that most probiotic strains are from the *Lactobacillus* followed by *Bifidobacterium* and *Enterococcus* genera[44] and it is evident that most of the biomining microbes are from *Acidithiobacillus*, hence make the remarkable idea of probiotics as biomining microbes.

Future perspective of microbial mining: In the twenty-first century, biological systems will probably play a bigger role in waste cleanup and mineral processing. This will be driven by the need to process ores with increasingly low concentrations of the target metal(s), the potential and need to reuse the waste spoils and tailings, economic constraints, and the potential environmental impact of more conventional approaches like pyro metallurgy. Future biomining applications will probably target more complex, low-grade ores, so it is essential that research and development concentrate on the technological challenges related to these biomining applications. Such research should focus on understanding how the different groups of microbes' colonies function during their ore heaps and to fully explain the microbial development and related activities in such processes[13]. Microbes from the ocean can also be targeted for this potential. The role of microorganisms in climate change in relation to biomining can also be explored.

At present, bioleaching is being used commercially for a few costly metals, but in the future, it may be used for the recovery of other common metals. Due to their low cost, it is possible to install the plants in ore-rich areas. Likewise, its easy operation and relative sample size make it suitable for use by low-income countries[3]. The current process is enhanced by improving the proper microbe selection and knowing the status of the ores[38].

Another potential area of this process is the understanding of the molecular processes and genetic analysis of the microorganisms. Similarly, the birth of nanotechnology also holds its application in the mining process by developing nanoparticle-based biosensors[2,10].

CONCLUSION

Biomining, or microbial mining, is an environmentally friendly approach to extracting low-grade metals from their ores using microorganisms. In comparison to traditional mining processes like smelting, microbial mining has a number of advantages, like being cost-effective, green mining, and contributing less to environmental pollution, but time-consuming, low productivity, and toxic substance production are considered disadvantages. Microbial mining comprises many sub-processes, like heap and dump leaching, etc. Currently, different metals like nickel, cobalt, etc., are extracted via this technology. Due to its friendly nature, industrialists took an interest in and adopted this technology, which showed its company-based nature and thus lacked international collaboration. In conclusion, microbial mining can be developed and made more productive if a suitable place, proper microorganisms, and good collaboration among the ore-extraction industries are developed.

SIGNIFICANCE STATEMENT

This study discovered the potential of microbial mining to offer a sustainable, cost-effective, and environmentally friendly alternative to traditional metal extraction methods. By utilizing microorganisms, this approach provides a viable solution for extracting metals from low-grade ores with minimal environmental impact. The research emphasizes the role of microorganisms like *Acidithiobacillus ferrooxidans*, which can thrive in harsh conditions, making them ideal candidates for biomining processes. This study will help researchers uncover critical areas of microbial mining, particularly those related to increasing productivity and overcoming existing challenges, that have not been fully explored. As a result, a new theory on optimizing microbial mining techniques may emerge, fostering advancements in efficient and eco-friendly metal extraction.

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