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生物技术在矿产资源开发中的应用及前景

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摘　要:介绍生物技术在矿产资源开发中的发展和应用,并确定主要挑战和未来方向。传统矿产开发方式面临成本高、环境污染以及对低品位矿石利用率低等诸多困境,而生物技术的兴起为该领域带来了新的希望。生物技术在矿产资源开发中的核心在于借助微生物独特的代谢活动。例如生物冶金技术,其具有显著优势,成本相较于传统开采大幅降低,同时对环境更加友好,能够处理低品位矿石,有效提升资源利用率;生物浸矿技术,微生物通过氧化或还原作用,显著提高金属浸出率,降低开采成本。此外,生物技术在矿山污染原位修复方面也发挥着关键作用。微生物的生物吸附和生物转化功能,可有效减少重金属污染,助力矿山生态环境的改善。微生物还能溶解金属矿物,释放金属离子,经电解获取纯金属,植物对金属的积累以及矿物质结合肽对矿物质的分离,都为矿产资源开发提供了新的思路和方法。微生物已经被用来溶解金属矿物并将金属离子释放到溶液中,通过电解可以从溶液中获得纯金属。植物在其根和叶中积累金属已被用于富集金属,而矿物质结合肽可用于分离矿物质。数十亿年来,微生物一直在与金属相互作用,而利用生物技术探测地球中的金属和提取金属将是一个活跃的研究和开发领域。矿物来源中及其附近的微生物群落是丰富的遗传信息来源,可用于创建富集金属的合成或改性微生物组。了解矿物质微生物组遗传机制的努力才刚刚开始,可以开发一套工具来修改特定的矿物微生物组,以便以自然的方式提取金属。这将是一个彻底的范围式转变,具有巨大的应用前景。

关键词:生物技术;金属矿物;微生物;提取

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Application and Prospect of Biotechnology in Mineral Resources Development

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Abstract: This article delves into the development and application of biotechnology in the realm of mineral resource exploitation, with the aim of identifying the primary challenges and charting future directions. Traditional methods of mineral exploitation are encumbered by a host of issues. High costs are a major concern, as the extraction, processing, and transportation of minerals often demand substantial financial resources. Moreover, environmental pollution is an inevitable by-product of traditional mining. The discharge of large amounts of waste rock, tailings, and wastewater not only contaminates soil and water sources but also contributes to air pollution. Additionally, the utilization rate of low-grade ores is distressingly low, leading to a significant waste of resources. The advent of biotechnology has ushered in new possibilities for the mineral resource industry. The essence of biotechnology in mineral resource exploitation lies in harnessing the unique metabolic activities of microorganisms. Bio-metallurgy, for example, has emerged as a revolutionary technology. Bioleaching, a key component of bio-

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metallurgy, stands out with its remarkable advantages. Cost-effectiveness is one of its most prominent features. By relying on the natural metabolic processes of microorganisms, bioleaching significantly reduces the need for expensive chemical reagents and energy-intensive operations compared to traditional mining methods. This not only cuts down on direct production costs but also reduces the overall economic burden associated with mineral extraction. Furthermore, bioleaching is far more environmentally friendly. It produces fewer harmful by-products and minimizes the generation of waste materials, thus reducing the environmental footprint of mining activities. This technology also excels in handling low-grade ores. Microorganisms can selectively extract valuable metals from low-grade ores, which were previously considered uneconomical to mine using traditional methods. As a result, the utilization rate of mineral resources is substantially enhanced, ensuring a more sustainable supply of minerals. In the process of bioleaching, microorganisms play a crucial role. Through oxidation or reduction reactions, they can break down the chemical bonds in metal minerals, releasing metal ions into the solution. This significantly increases the metal leaching rate. For example, certain bacteria can oxidize sulfide minerals, converting insoluble metal sulfides into soluble metal salts, which are then easier to extract. This microbial-mediated process not only improves the efficiency of metal extraction but also reduces the energy consumption and chemical usage typically required in traditional leaching methods. In addition to bio-metallurgy, biotechnology also plays a vital role in mine pollution remediation. The in-situ remediation of mine-contaminated areas is a complex and challenging task, but microorganisms offer a promising solution. Microorganisms possess unique functions of biological adsorption and biotransformation. They can adsorb heavy metals onto their cell surfaces through various mechanisms, such as ion exchange and complexation. Once adsorbed, microorganisms can further transform the heavy metals into less toxic or more stable forms through biotransformation processes. This effectively reduces the concentration of heavy metals in the environment, thereby alleviating the pollution pressure on soil and water sources. Moreover, microorganisms can dissolve metal minerals and release metal ions. After the metal ions are dissolved into the solution, electrolysis can be employed to obtain pure metals. This provides an alternative and more sustainable approach to metal extraction. In addition, plants also contribute to the field of mineral resource exploitation. Some plants have the ability to accumulate metals in their roots and leaves, a phenomenon known as phytoremediation. This can be used to enrich metals from low-grade ores or contaminated soils. Mineral-binding peptides, on the other hand, can specifically bind to minerals and facilitate their separation, offering new ways to process and purify minerals. Microorganisms have been interacting with metals for billions of years. The utilization of biotechnology for exploring and extracting metals from the earth is an area of active research and development. The microbial communities present in and around mineral sources are a rich reservoir of genetic information. This genetic information can be harnessed to create synthetic or modified microbiomes that are more efficient at metal enrichment. Although the understanding of the genetic mechanisms of the mineral microbiome is still in its infancy, ongoing research efforts are gradually unraveling these mysteries. In the future, it may be possible to develop a comprehensive set of tools to precisely modify specific mineral microbiomes, enabling the extraction of metals in a more natural and sustainable manner. This represents a significant paradigm shift with far-reaching implications for the mineral resource industry. However, the application of biotechnology in mineral resource exploitation is not without challenges. The growth and activity of microorganisms are highly sensitive to environmental factors. Temperature, pH value, and nutrient composition can all have a profound impact on the metabolic activities of microorganisms. For example, if the temperature is too high or too low, the enzymes within microorganisms may become denatured, inhibiting their growth and metal-extraction capabilities. Fluctuations in pH can also affect the solubility of metal minerals and the activity of microbial enzymes. In addition, the large-scale application of biotechnology requires substantial capital investment. Developing and maintaining the necessary infrastructure, such as bioreactors and monitoring systems, can be costly. There are also technical bottlenecks that need to be overcome, such as optimizing the growth conditions of microorganisms in large-scale industrial settings and improving the selectivity and efficiency of metal extraction. Looking ahead, to

drive the development of biotechnology in mineral resource exploitation, several key steps need to be taken. First, there is a pressing need to strengthen basic research. Understanding the intricate interaction mechanisms between microorganisms and minerals at the molecular and genetic levels is essential. This will enable the development of more efficient and stable biotechnological processes. Secondly, interdisciplinary cooperation should be actively promoted. Combining the knowledge and technologies of biology, geology, chemistry, and materials science can provide a more comprehensive approach to solving the complex problems associated with mineral resource exploitation. For example, geologists can help identify suitable mineral deposits for biotechnological applications, while chemists can contribute to the development of new reagents and extraction methods. Finally, continuous innovation in both technology and management is crucial. New biotechnological methods and tools need to be developed to address the challenges faced in mineral resource exploitation, and effective management strategies should be implemented to ensure the sustainable and efficient use of resources. In conclusion, biotechnology holds great promise for revolutionizing the mineral resource industry. By addressing the current challenges and capitalizing on future opportunities, biotechnology can contribute to a more sustainable, efficient, and environmentally friendly approach to mineral resource exploitation.

Key words: biotechnology; metallic minerals; microorganisms; extract

生物技术是利用生物体(微生物、动物细胞和植物细胞)或其组成部分(细胞器和酶)来生产有用物质,或为人类提供某种服务的技术[1]。现如今,世界上矿物资源的迅速枯竭给现代社会带来了严峻的挑战。研究表明,全球勘探矿床支出的经济成本已从2005年的75亿美元增加到2012年的近230亿美元,但重大发现的数量已从约70个减少到30个。此外,除了勘探经济成本的难题,我们所发现的矿床的平均品位也在下降,这一趋势预计将继续下去[2-4]。形成矿床的地质系统横跨地壳,这表明矿床存在于1公里或更深的深度,但在这样的深度,高温和岩体的稳定性对开采造成了严重的物理限制[5-6]。用于支持我们生活方式的矿产资源是通过开采和加工大量岩石获得的,完成这一过程的基本顺序可以描述为“钻孔、爆破、装载、拖运、倾倒、破碎、研磨、分离、加工”,其中分离是指将具有经济利益的矿物颗粒与其他矿物颗粒分离,并且加工(例如,熔炼、精炼、电解)以获得纯金属产品,但采矿和矿物加工产生的废物数量惊人[7-9]。目前,进入加工厂的大多数矿石以尾矿的形式排出,以矿石品位为1 g/t黄金为例,假设回收率为100%,这就意味着每生产1 g黄金,就有999.999 kg尾矿;为了生产1 t铜品位为25%的铜精矿,需要100 t铜品位为0.25%的矿石,从而需要具有这种矿石品位的矿山每天加工数万吨矿石。在露天矿中,必须清除废石,才能获得矿石,由此产生了大量尾矿池和废石堆[10]。这些严峻的问题都表明矿产资源开发给人类社会形成了重大的工程挑战、环境问题和经济压力。

为了改变当前采矿模式,摆脱其限制,必须提出一些“大挑战”问题,如“是否有可能以减少75%的能源获得金属?”或者“我们能在获得金属的同时产生很少或根本不产生废物吗?”需要采取不同的办法来应对这些挑战。矿物的细菌加工为克服普遍存在的地质、物理和环境限制提供了一种替代方法[10]。本文综述了几种不同的生物技术,并表明生物技术有可能完全重新定义当前的金属提取方式。

1 微生物提取

微生物可通过各种各样的机制与矿物质和金属相互作用。从40亿年前的大约1 500种矿物到今天已知的4 400多种矿物,微生物在矿物的进化中发挥了重要作用[11-12]。在金属提取中应用的一个重要例子是从硫化物中生物提取金属铁,通过铁或硫氧化细菌溶解金属硫化物,溶解自然发生并产生亚铁和硫酸根离子,细菌利用酶将二价铁氧化成三价铁,从电子转移中获得能量,从而提高溶解速率,如图1所示。三价铁是一种强氧化剂,会进一步氧化硫化物,这是一种正反馈机制,导致硫化物的溶解速度比没有细菌时快一百万倍[13]。溶解后,硫化物中含有的有价值金属释放到溶液中(称为沥滤物),并可通过电解等方法分离[14]。

生物沥滤可从多金属矿石以及矿山废物和尾矿中提取各种金属。低品位硫化铜矿石的生物浸出是在被称为堆的破碎矿石堆中进行的,这些矿石堆被灌溉和通气以促进原生氧化细菌种群的生长,氧化过程会产生相当大的热量,并产生金属离子的酸性溶液[15-16],如图2所示。细菌群落的复杂性在堆中最为

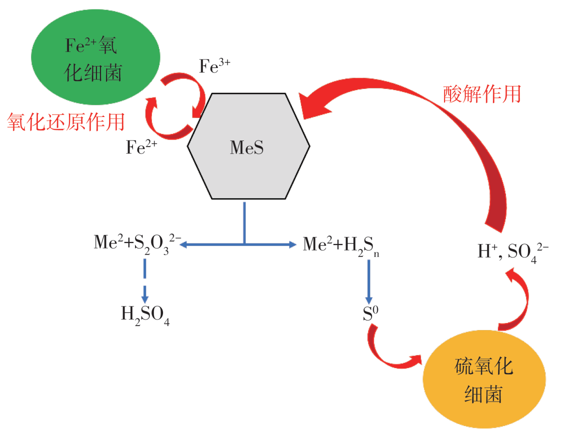


图 1　从硫化矿物中生物提取金属铁的示意图（红色箭头表示生物反应，蓝色箭头表示非生物反应，MeS 代表金属硫化物）

Fig. 1　Schematic diagram of biological extraction of metallic iron from sulfide minerals(Red arrows indicating biotic reactions, while blue arrows indicating abiotic ones, MeS standing for metal sulfide)

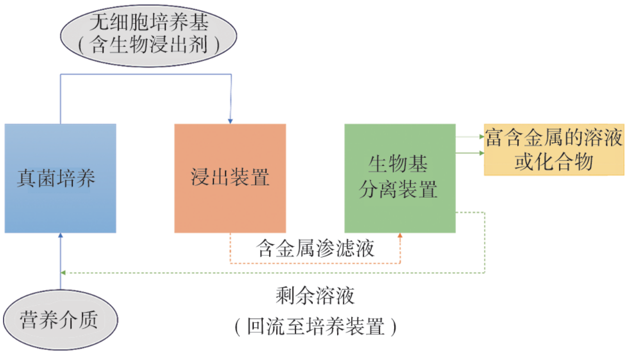


图 2　生物技术从矿石中回收金属元素的流程

Fig. 2　Process diagram of biotechnology for recovering metal elements from the ore

明显，其中物理、化学和矿物学条件存在较大的空间变化，表明微生物群落对不同矿石类型和条件的生态位适应性。可以使用几种不同的细菌，这些细菌通常形成一个极端微生物的聚生体，这些聚生体适应沥滤液的热量、酸度和金属离子浓度[17]。极端微生物进行群体感应、对化学刺激作出反应、在硫化矿物上形成生物膜、氧化矿物以及保护自身免受由此产生的高金属浓度影响的能力的遗传基础是当前许多工业和学术研究工作的焦点[18]。

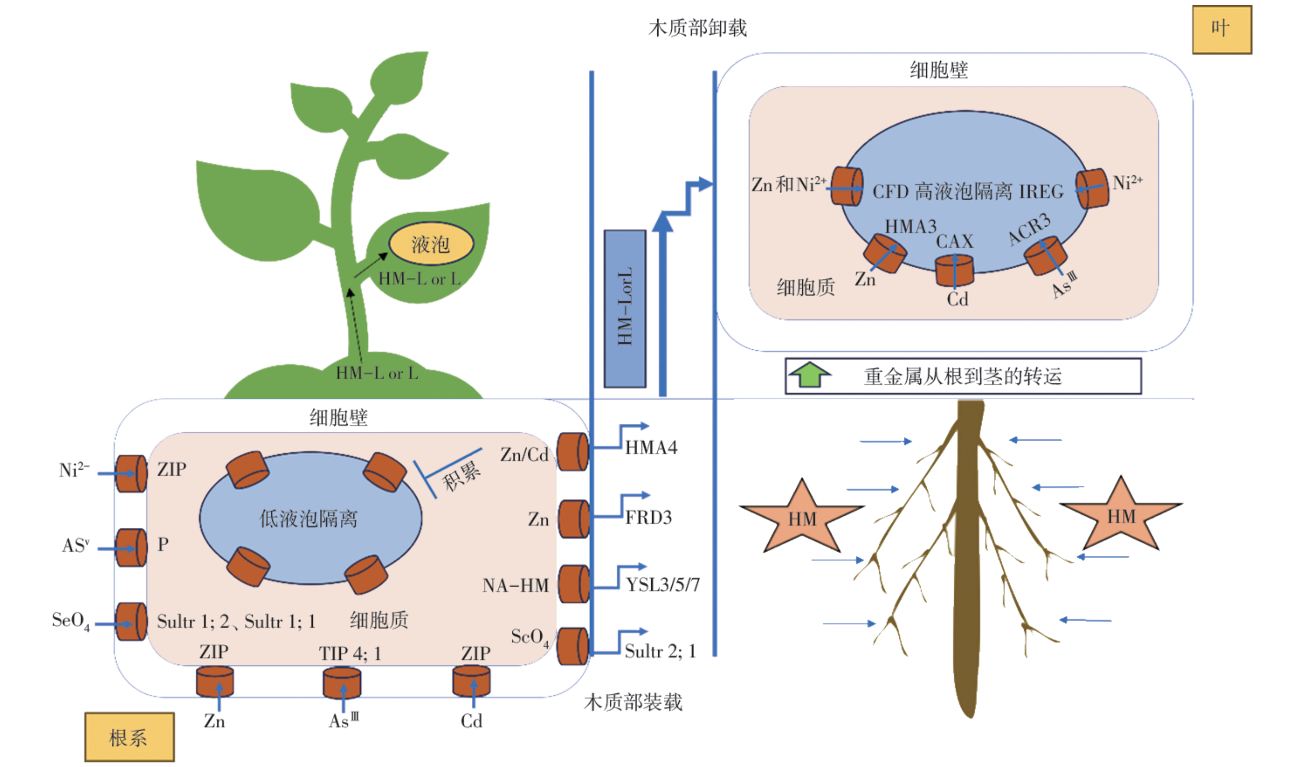
2　植物提取

植物提取被称为超富集植物的植物通过根系吸收金属，并在其气生器官中积累金属，这一过程被称为植物提取[19-20]，如图 3 所示。植物挖掘是该方法的一种应用，其中超富集植物在具有足够金属浓度的基质上生长，然后收获并加工以提取金属。加工包括在收获后焚烧植物以产生灰，通过熔炼或应用试剂从灰中回收金属。由于植物生长是一个缓慢的过程，作物需要很长时间才能积累足够的金属来收回收获和加工的成本，因此植物采矿具有一定的经济效益[21-22]。另一个应用是植物修复，例如：冶炼厂周围受污染土壤中的金属被植物吸收，然后收获植物并直接送入冶炼厂。这实际上是植物采矿和植物修复的一个例子。植物要积累金属，金属必须在溶液中，而在根系中和根系附近存在的细菌可以促进金属的移动并改变根系的吸收特性[23]。超积累植物也调节和表达基因使它们能够抵抗金属的毒性作用，因此，这些植物是可用于增强积累的遗传信息的来源。

3　肽-矿物质相互作用

氨基酸（肽）的特定链将与无机材料结合，并且这种效应已被用于开发构建纳米级材料和装置的方法[24]。利用噬菌体展示已经鉴定了与具有经济价值的矿物质结合的肽。例如：存在闪锌矿（ZnS）颗粒（一种常见的锌矿物）和两种其他矿物（二氧化硅（SiO_2）和黄铁矿（FeS_2））颗粒的混合物，将含肽（TPTTYKV）的噬菌体引入混合物中，所述肽（TPTTYKV）结合闪锌矿，并用荧光标记物标记，噬菌体在闪锌矿上显示为红点，但在其他矿物颗粒上不显示[25]。肽与有经济价值的矿物的特异性结合是从矿浆中的废矿物中分离矿物的方法基础。肽的工业化生产是肽在矿物分离中应用的潜在障碍。然而，已有研究表明，在生物反应器中可以获得展示特定肽的丝状噬菌体的高产量[26]；另一种可能性是通过基因工程使细菌（如大肠杆菌）在其外表面表达这种肽。

在实际应用中，肽常被用于中性 pH 环境，而不是用于矿物分离的碱性环境。然而，如果肽要附着在矿物质上，就必须在适宜的环境中操作[27]。因此，目前正在研究的一种可能性是用肽对磁性纳米粒子进行功能化，这样一旦发生结合，磁铁就可以分离矿物质[28]。结合肽可以连接到聚合物大分子上，聚合物大分子中还含有溶解矿物的试剂，这样一旦与矿浆中的特定矿物结合，试剂就会释放出来溶解矿物，如图 4 所示。这种溶解将所需的金属离子置于溶液中，然后可以通过螯合或电解从溶液中提取金属离子[29-30]。



注:ACR3—抗砷化合物3外排泵;CAX—阳离子交换剂系列;CDF—阳离子扩散促进剂;FRD3—多药和毒素外排剂家族;HM—重金属;HMA3和HMA4—P型金属ATP酶;HM-L—重金属-配体复合物;IREG—铁调节/铁转运蛋白家族;L—配体;P—蛋白质类;P/At—磷酸盐/砷酸盐转运蛋白;Sultr 1;2、Sultr 1;1、Sultr 2;1—硫酸盐/硒转运蛋白;TIP 4;1—液泡膜内在蛋白;YSL 3/5/7—黄条纹状家族转运蛋白;ZIP—锌调节转运蛋白。

图3 超富集植物通过根系吸收金属并累积金属机制示意图

Fig. 3 Schematic diagram of the mechanism by which hyperaccumulating plants absorb and accumulate metals through their roots

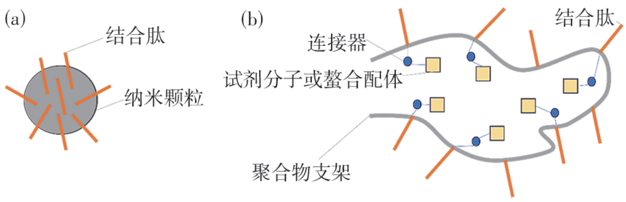


图4 (a)磁性纳米颗粒通过结合肽进行功能化示意图;(b)结合肽连接到带有试剂分子或螯合配体的聚合物支架示意图

Fig. 4 (a)Schematic diagram of the functionalization of magnetic nanoparticles by binding peptides; (b)Schematic diagram of binding peptides connected to polymer scaffolds bearing reagent molecules or chelating ligands

4 设计矿物微生物组

由于天然存在的微生物群落一直与矿物相互作用,因此无论矿物位于何处,都存在微生物群落。其被称为“矿物微生物组”,是地球微生物组的一个子集[31],包含了巨大的遗传信息库。利用这种遗传信息来设计或修改矿物微生物组以提高金属提取的可能性是可观的[32],如图5所示。有学者建议应用合成生物学来改变与金属提取和金属污染相关的微生物聚生体的性能或行为,或使用从化学添加到基因转移再到基因编辑工具的一系列方法对微生物组进行原位作和维持[33]。另一种方法是从现有的微生物组中提取有用的基因组材料和信息,并将其用于特定的应用。例如,研究显示古代低阶(或富含木质素)煤层包含有关木质素分解的遗传信息,其中木质素是植物中的有机聚合物,也是生物燃料的来源[34]。细菌遗传物质也是从低级煤层的岩屑中获得的,开发以大肠杆菌为探针,建立检测木质素降解产物的荧光生物传感器。将传感器与细菌遗传物质和牛皮纸木质素一起温育,鉴定、编码木质素降解产物的基因[35]。这些技术可用于改造现有的工业菌株,并构建生物精炼系统,快速分解植物生物质,以生产能源和材料。

这种方法在矿物微生物组中的类似应用尚未进行。矿物微生物组修饰方法的开发尚处于初期阶段。最重要的是减少矿物微生物群落的“全球化”,并将其空间范围局限于存在金属的特定位置,如浸出池、尾矿池或金属废料场。但由于我们对微生物群落的认识

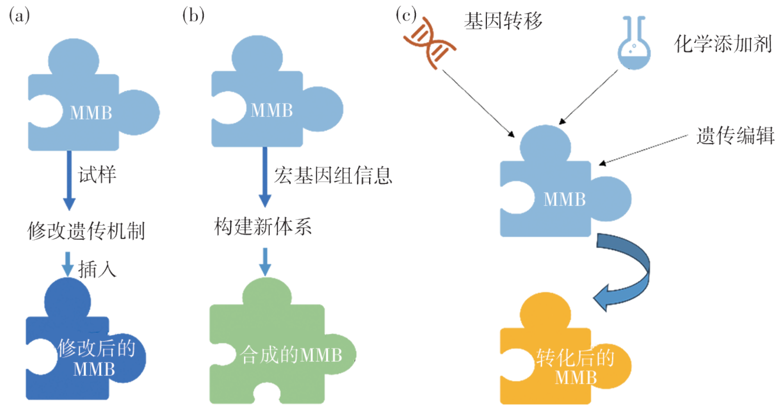


图 5　矿物微生物群工程

Fig. 5　Mineral microbiota engineering

和理解仍存在着巨大的差距，任何微生物群落的改造都是一项挑战，矿物微生物群落也不例外。与采矿废水和矿山废物相关的微生物群落的遗传结构已经被表征，并且提供了与表征矿物微生物群落相关挑战的例子[36-37]。如，科学家们对加利福尼亚州铁山里士满矿区高酸性矿井排水中的生物膜样本进行了测序，从而重建了两种铁氧化细菌的近乎完整的基因组，这两种细菌已经发展出非凡的代谢途径，可以在无碳或氮输入的极端环境(pH<1，30～50 ℃，高的金属浓度)中生存，随后的工作揭示了另外两个物种的基因组片段[38]。由于极端条件，使得酸性排水中的微生物群落仅由少数不同的物种占主导地位；以及在油砂尾矿和铜生物浸出堆中发现了多样性群落，但尚未为这些微生物群构建完整的基因组[39-40]。幸运的是，低成本、高通量测序技术的出现使得快速采样和测序上述微生物群落的DNA成为可能。还开发了能够处理样品而不需要扩增DNA的廉价便携式“第三代”单分子DNA序列读取器，这些有可能导致一种更具交互性和适应性的测序方法[41]。大规模生产和开放源码的设备设计将促进一个“生物勘探”共同体的发展，有助于知识库的建立。

5　结论与展望

生物技术是释放矿产资源价值的关键，为克服普遍存在的地质、物理和环境限制以及人们对适合于开采和加工低品位矿石的技术需求提供了许多创新的替代方法。上文讨论的一些生物技术可有助于克服目前采矿模式的制约因素，能螯合特定金属的细菌可用作矿物勘探中的高灵敏度金属探测器。低品位和多金属矿床的选择性矿物分离是一个重要的问题，可以通过使用肽黏合剂来解决。

如果矿物质微生物组可以被适当地修改，那么开发一种可编程的“炼金术”的诱人前景就可以实现，这种炼金术可以利用活细胞的群落自然地生产金属。因此，部分运营或闲置的矿山、垃圾填埋场、植物过度繁殖场、金属回收和电子废物设施、尾矿池、矿山废物倾倒场和金属加工厂都可以转化为大型生物反应器，能够在溶液中生产金属或其他有用的矿物形式。这将是采矿模式以及社会与材料之间的关系的彻底改变。一家矿业公司将成为一家金属供应公司，根据需求和成本，从矿石、废物或回收中供应金属。进入这一行业的障碍将降低，从个人到整个国家的社会各阶层都可以决定如何组织起来获取材料，其结果将是一个真正灵活的金属和材料生产、供应系统。

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