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Geo microbiology underground – Opportunities for geo biotechnology

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ABSTRACT

Geomicrobiology is the interdisciplinary study of the interactions between microorganisms and geological processes. This field examines how microbial activities influence mineral formation, rock decomposition, and the biogeochemical cycles of elements such as carbon, nitrogen, and sulfur. Geobiotechnology applies these principles to develop practical solutions for environmental and industrial challenges. Through bioremediation, microbes degrade pollutants in contaminated sites, while biomining uses microbial processes to extract metals from ores. Additionally, microbial fuel cells and bioelectrochemical systems utilize microbes to generate electricity and produce biofuels. The integration of geomicrobiological research with advanced techniques in molecular biology, bioinformatics, and nanotechnology drives innovation in geobiotechnology. This synergy fosters sustainable approaches to environmental management, resource recovery, and energy production, highlighting the crucial role of microorganisms in both natural and engineered systems. As our understanding of microbial interactions with geological materials deepens, the potential for novel geobiotechnological applications expands, paving the way for advancements that benefit both the environment and industry.

KEYWORDS
Microbial interactions; Biogeochemical cycles; Bioelectrochemical systems; Subsurface microorganisms; Metal extraction

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Introduction

Geomicrobiology is an interdisciplinary field that studies the interactions between microorganisms and geological materials and processes. This branch of science explores how microbial life influences the formation, transformation, and degradation of minerals and rocks, as well as how geological processes affect microbial communities. By investigating these interactions, geomicrobiology sheds light on the role of microbes in shaping the Earth's surface and subsurface environments. Geobiotechnology, on the other hand, applies the principles of geomicrobiology to develop innovative solutions for various environmental and industrial challenges. This emerging field leverages the metabolic capabilities of microorganisms to address issues such as pollution, resource recovery, and energy production. Geobiotechnological applications include bioremediation, where microbes are used to clean up contaminated environments, and biomining, where microbial processes extract valuable metals from ores. Additionally, microbial fuel cells and bioelectrochemical systems harness the power of microbes to generate electricity and produce biofuels [1].

The synergy between geomicrobiology and geobiotechnology presents numerous opportunities for advancing our understanding of the Earth's biosphere and developing sustainable technologies. By studying subsurface microbial life, researchers can uncover novel metabolic pathways and extremophilic organisms that thrive in harsh conditions, potentially leading to new biotechnological applications. Moreover, the integration of geomicrobiological insights with cutting-edge techniques in molecular biology, bioinformatics, and nanotechnology holds great promise for the future of geobiotechnology. As our knowledge of the complex interactions between microbes and their geological environments continues to grow, so too will the potential for innovative geobiotechnological solutions. This intersection of biology and geology not only deepens our understanding of the natural world but also paves the way for sustainable advancements in environmental management, resource recovery, and energy production [2].

Subsurface Microbes and the Global Carbon Cycle: Hidden Players, Major Impacts

Subterranean microbes are essential for regulating biogeochemical processes, influencing carbon, nitrogen, sulfur, and iron cycles to a large extent. These microorganisms control key activities that manage the alteration and transportation of these substances within the Earth's crust, impacting both the environment and human actions [3].

Microbes role in the carbon, nitrogen, sulfur, and iron cycles

Microorganisms play a crucial role in the carbon cycle by aiding in the breakdown of organic materials and generating methane and carbon dioxide via methanogenesis and respiration. In the nitrogen cycle, underground microorganisms participate in nitrogen fixation, nitrification, and denitrification, transforming atmospheric nitrogen into usable forms and returning it to the atmosphere. Sulfur-reducing and sulfur-oxidizing bacteria play a key role in the sulfur cycle by converting sulfate into hydrogen sulfide and back again, impacting the movement and accessibility of sulfur in underground surroundings. In the same way, bacteria that reduce and oxidize iron play a role in the iron cycle by changing iron from ferrous to ferric states, affecting the creation and breakdown of minerals [4].

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Organic and inorganic compounds interact with microbes

Subterranean microbes have extensive interactions with organic and inorganic substances. They break down organic material, making it easier for nutrients to cycle and energy to flow. Moreover, microorganisms have the ability to convert inorganic substances, like metals and radionuclides, altering their movement and harmfulness. These interactions play a crucial role in bioremediation projects, with microbes working to clean up polluted areas by either breaking down or transforming toxins into less dangerous substances. In short, subsurface microorganisms play a crucial role in controlling biogeochemical processes, influencing mineral creation and breakdown, and engaging with various organic and inorganic substances. Their actions support numerous environmental processes and hold important consequences for geo biotechnological uses [5].

Microbe-MEOR techniques for enhanced hydrocarbon production

It has been well established for many years that methane is produced by microbes inside oil, gas and coal reservoirs. Anaerobic microorganisms transform hydrocarbons into methane in the absence of oxygen. Understanding these processes in deep oil, gas or coal deposits, along with other geo-systems like marine sediments, is both scientifically intriguing and economically and socially crucial due to the impact of oil quality on energy raw material exploration and recovery. Issues caused by microorganisms in oil and natural gas production include the creation of harmful hydrogen sulphide, difficult-to-exploit heavy crude oils, and biofilm-related corrosion in pipelines and production sites. Hence, evaluating the level of deterioration of storage deposits in the exploration industry is crucial [6]. Nonetheless, the microorganisms present in these deposits also have a positive impact. Utilizing them in MEOR tactics shows significant promise for maximizing reserve utilization. It is crucial to assess the level of methane production by microorganisms in coal and oil deposits, as well as identifying the specific microorganisms responsible. This is expected to result in a dependable forecast of the potential economic application of this procedure. A biotechnological method that is inexpensive could be used to transform hard-to-extract petroleum or coal into simpler compounds like methane, creating environmentally friendly energy resources. An alteration in the geological or geochemical conditions will also help improve the utilization of storage deposits. Examples of microorganisms catalysing reactions that can be utilized include the creation of bio-surfactants or acids to dissolve petroleum, generating significant amounts of gas to elevate pressure to close off the gaps in between pores. Specific biofilm formation can influence the behavior and direction of oil or water flow, known as selective plugging [7].

Storage of Hydrogen (H2) and Methane (CH4)

Due to the increasing variability in electricity production from renewable sources like wind and solar Energy and to meet the demand for new storage technologies, the conversion of electricity into hydrogen or methane is being considered, along with storing the gases in underground caverns. Additionally, there are talks about injecting biogas into the current gas network and potentially storing it in gas facilities. It has proven to be effective and reliable for many years Nevertheless, storing hydrogen gas or biogas (methane) underground in specific locations presents unique challenges because of the distinct physical, chemical, and biological characteristics of hydrogen. The presence of hydrogen in pore storage facilities can promote bacterial growth, leading to the formation of corrosive hydrogen sulfide and organic acids. Bacteria or their metabolic products may block pore spaces. Furthermore, gas loss from microbial degradation can reach significant levels [8]. Regrettably, there is limited documentation available on the storage of coke oven gas, which was commonly done until the 1970s to store hydrogen underground in pore storage facilities. There is a strong need for research to be conducted in this area [9].

Exploring Geothermal Energy as a Clean Energy Alternative

Deep geothermal energy provides a cost-effective and environmentally sustainable option to fossil fuels in numerous areas. Over the past few years, over 15 new geothermal power stations have been constructed in a number of Federal States. These plants utilize hot water from deep underground for both district heating and electricity production. Plant and production equipment requirements are dependent on fluid chemistry and temperature, dissolved gas quantity and composition, and desired production levels. Nonetheless, microbiology also has an impact: microorganisms present in the aquifers can enter the system through the thermal water. This may result in localized harm from microbial corrosion or decreased flow rates due to deposit and biofilm formation. Changes in temperature in the substrate also impact the hydro-geochemical conditions and microbial activity. Determining the operational safety over a period of time requires understanding the potential changes in microbial biocoenosis and local geochemistry in thermal water aquifers as it goes through the plant and during the re-injection of cooled thermal water [10].

Exploring Carbon Dioxide Storage (CCS) Technologies

A case study reveals on a study where Germany aims to decrease its greenhouse gas emissions by at least 80% by the year 2050. For this reason, the division and the exploration of storing CO_2 in deep geological formations is being investigated along with the main methods.

In order to promote energy efficiency and the use of renewable energy sources, the technology known as CCS (Carbon Dioxide Capture and Storage) has significant long-term implications, particularly for coal-burning power stations. The technology has undergone extensive testing on an industrial level for multiple years in Norway and Algeria. Many developed nations are currently getting ready for similar storage projects. Given what we currently know, it is impossible to forecast how the actions of microorganisms and their related chemical reactions impact the ability, effectiveness, and lasting stability of CO_2 storage sites [11]. Ongoing research projects aim to study the impact of elevated CO_2 concentrations on physiological activities and microorganism populations' composition, as well as the behavior of geochemical catalysts in storage deposit conditions. Living in extreme environments are

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active microorganisms that are highly adapted and play crucial roles in biogeochemical material cycles. They are essential for converting CO_2 into methane or biomass in the long run. Research findings will help determine suitable storage locations and evaluate the capacity, efficiency, and long-term reliability of planned CO_2 storage sites. Recent studies focus on the effects of potential leaks from CCS storage sites on groundwater and deep biogeochemical processes. The impacts of decreasing pH and high CO_2 levels on natural microbial communities in the environment have not been definitively explained and are crucial for the advancement of CCS practices [12].

Strategies for the final disposal of radioactive waste

Microbes are also involved in the final storage of radioactive waste underground. Studies were conducted on the geological obstacles of granite and argillaceous rock. A small amount of colonization by microorganisms could be established. Sulfate reducing bacteria play a crucial role as they produce the corrosive gas hydrogen sulfide, leading to corrosion issues in technical barriers like metal canisters. Additionally, microorganisms underground facilitate the formation and breakdown of carbon dioxide, hydrogen, and methane, as well as the production and decomposition of organic carbon, while also reducing atmospheric oxygen levels. Moreover, microorganisms impact both reducing and oxidising reactions. They are involved in the movement of metals and radio-nuclides, allowing for both their release and retention. Furthermore, metals can be taken in by biomass. It is still unclear the extent to which the dispersion of geological barriers and waste storage (temperature rise) stimulate microbial processes. Most importantly, the interfaces, like the surface of the geological barrier or the boundary between clay rock bentonite and the metal canister, play a crucial role. Incorporating microbial processes into mathematical models is crucial for strengthening the evidence in safety analysis by simulating and quantifying them [13].

Bioremediation of Organic Pollutants

Bioremediation utilizes the metabolic abilities of microorganisms to break down pollutants, providing an environmentally friendly and affordable method to clean polluted underground areas. Microorganisms have the ability to break down different pollutants like hydrocarbons, heavy metals, and radionuclides into less toxic compounds through metabolism [14].

Biological breakdown and challenges forward in bioremediation

Microorganisms break down hydrocarbons using both aerobic and anaerobic methods. Aerobic bacteria like Pseudomonas and Bacillus use oxygen to decompose hydrocarbons into carbon dioxide and water. Under oxygen-free conditions, microorganisms such as sulfate-reducing bacteria and methanogens break down hydrocarbons to produce methane and carbon dioxide. Certain bacteria have the ability to convert heavy metals into less harmful forms. An example of this is the ability of *Geobacter and Shewanella* species to convert soluble hexavalent chromium into insoluble trivalent chromium, thereby immobilizing it efficiently. In the same way, *Deinococcus radiodurans* and other microbes have the ability to alter radionuclides, lowering their solubility and movement [15].

Examples of bioremediation projects that have been successful as documented through specific cases

A significant instance is the bioremediation that occurred after the Exxon Valdez oil spill in Alaska. The degradation of oil hydrocarbons on impacted shorelines was greatly increased by the addition of nitrogen and phosphorus fertilizers, boosting microbial activity. One more successful endeavor focused on the bioremediation of uranium-contaminated groundwater at the Hanford Site in Washington, USA. By introducing acetate, researchers encouraged the Geobacter species to grow and help convert soluble uranium (VI) into insoluble uranium (IV), immobilizing and halting its dispersion in groundwater [16]. Although it has achieved successes, bioremediation encounters various obstacles. Microbial activity may be restricted by environmental factors like pH, temperature, and nutrient levels. The complications and unpredictability of contaminant combinations also present challenges. Additionally, it is important to take into account the durability of bioremediation products over time and the possible effects they may have on the environment [17].

Future directions in bioremediation research involve creating genetically modified microorganisms that have improved abilities to break down pollutants and withstand difficult environments. Progress in omics technologies such as genomics, proteomics, and metabolomics allows for a better understanding of microbial communities and their functions, leading to improved bioremediation tactics [18]. Moreover, the combination of bioremediation with other remediation methods like phytoremediation and chemical treatments shows potential in dealing with complicated contamination situations.

To sum up, bioremediation utilizes microorganisms to break down underground pollutants, providing an eco-friendly answer to environmental contamination. Despite still facing obstacles, continuous research and technological progress are improving the effectiveness and feasibility of bioremediation [19].

Biotechnological Potential of Extremophiles

Extremophiles, microorganisms that flourish in extreme conditions, have great potential for use in biotechnology. Deep-sea vents, hot springs, and underground caves are filled with extremophiles that have adapted to tough conditions such as high pressure, extreme temperatures, and scarce nutrients.

Extremophiles found in underground environments and their uses

Subsurface extremophiles consist of thermophiles, psychrophiles, acidophiles, alkaliphiles, halophiles, and piezophiles. These tiny organisms have evolved special traits that help them live and thrive in harsh environments. Scientists study extremophiles by utilizing advanced sampling methods and molecular tools to investigate these environments. Extremophiles' diversity and ability to survive make them important sources of unique enzymes and metabolites that can function in harsh conditions unsuitable for many other organisms [20].

Extreme-loving enzymes, like DNA polymerases from heat-loving organisms and proteases from high-pH organisms, are currently employed in a variety of industrial processes. An

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important component in molecular biology is Taq polymerase, obtained from the heat-resistant bacterium *Thermus aquaticus*, and is crucial in the commonly employed PCR (polymerase chain reaction) methods. Enzymes derived from halophiles and acidophiles show promise for use in the food and beverage industry, bioremediation, and pharmaceuticals because of their ability to remain stable and active in high-salt and low-pH environments. In addition, extremophile metabolites, such as antimicrobial compounds and bioactive molecules, present new opportunities for drug discovery and development [21].

Genetic engineering techniques to modify extremophiles

Progress in genetic and metabolic engineering allows for extremophiles to be optimized for particular biotechnological uses. Scientists can improve extremophiles' inherent abilities or introduce fresh metabolic pathways by altering their genetic composition. Extremophiles, for example, can be manipulated to generate biofuels, break down environmental contaminants, or create valuable chemicals. CRISPR-Cas9 and similar genome-editing tools enable accurate changes, enabling customization of extremophiles for industrial needs. Moreover, synthetic biology techniques can merge extremophilic characteristics with different microorganisms to form hybrid systems that have improved capabilities [22].

Challenges and Opportunities for Growth in Geobiotechnology

The merging of microbial processes with geological applications in geobiotechnology shows potential in solving environmental and industrial issues. Yet, there are multiple challenges that need to be addressed in order to fully harness its capabilities.

Technological and methodological improvements

The progress of geobiotechnology is impeded by existing technological and methodological constraints. Improved instruments for collecting and examining underground microorganisms are crucial. Advanced sensors and real-time data acquisition systems are required for enhanced understanding of microbial activities in their natural environments through improved in situ monitoring techniques. Moreover, high-throughput sequencing and bioinformatics tools play a crucial role in uncovering the genetic and metabolic variations of underground microorganisms. Creating strong bioreactors and expandable bioprocessing systems will help implement geobiotechnological solutions in different industries more easily [23].

Considerations pertaining to ethics and regulations

As geobiotechnology progresses, the significance of ethical and regulatory factors grows. Releasing genetically modified microorganisms into the environment comes with potential dangers, like unforeseen effects on the ecosystem and the transfer of genes horizontally. Therefore, strict regulations are necessary to guarantee the safe and ethical application of geo biotechnological advances. Public involvement and clear communication about the advantages and disadvantages are essential for obtaining societal approval. Ethical considerations also apply to preventing the exploitation of natural resources and finding a balance between technological progress and environmental protection [24].

Possible Research Paths for The Future

Future studies in geobiotechnology need to concentrate on investigating and utilizing the metabolic variation of underground microorganisms. Combining multiple omics methods (such as genomics, proteomics, metabolomics) will offer a thorough understanding of microbial functions and relationships. Improvements in synthetic biology and genetic engineering provide chances to create customized microbes for particular tasks like bioremediation, resource recovery, and bioenergy production. Cooperation among microbiologists, geologists, and engineers will propel the creation of new and creative solutions [25]. Possible advancements consist of finding new extremophiles with distinct metabolic pathways, improving bioleaching and bioremediation methods, and inventing bio-inspired materials and procedures. With the growth of our knowledge about how microbes interact with rocks, geobiotechnology will advance and provide environmentally friendly solutions for current challenges in the environment and industry. To sum up, overcoming technological obstacles, navigating ethical and regulatory realms, and pursuing inventive research will drive geobiotechnology forward, unleashing its complete potential for sustainable progress [26].

Conclusions

In particular, the field of geomicrobiology - examining interactions between microbes and minerals - holds promise spurred on by opportunities in geobiotechnology for subsurface environments. Deep biosphere subsurface habitats are unique and extreme, influenced by microbial life affecting geochemical cycles and mineral formations. There is scope for wide applications of geomicrobiological approaches within geobiotechnology. Microbes, for example can be applied in bioremediation to detoxify polluted environment through natural process. Microbial activity also aids in bioleaching, which is the process by metals are extracted from ores and can make mining operations more sustainable with less environmental impact. Moreover, the shallow subsurface biosphere has natural solutions for carbon sequestration: some microbes can turn CO_2 into minerals and store carbon in stable forms that does not contribute to climate change. In addition, knowledge about the role of microbes in underground ecosystems can stimulate progress in biotechnology (e.g., discovery and exploitation of new antibiotics or industrial enzymes from extremophiles). It not only underlines the impact microbes have on almost all natural and engineered systems, but it also provides examples of innovative geomicrobiological applications that contribute to solve environmental challenges (as well as waste management), resource recovery or creation of new bioproducts.

Disclosure statement

No potential conflict of interest was reported by the authors.

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