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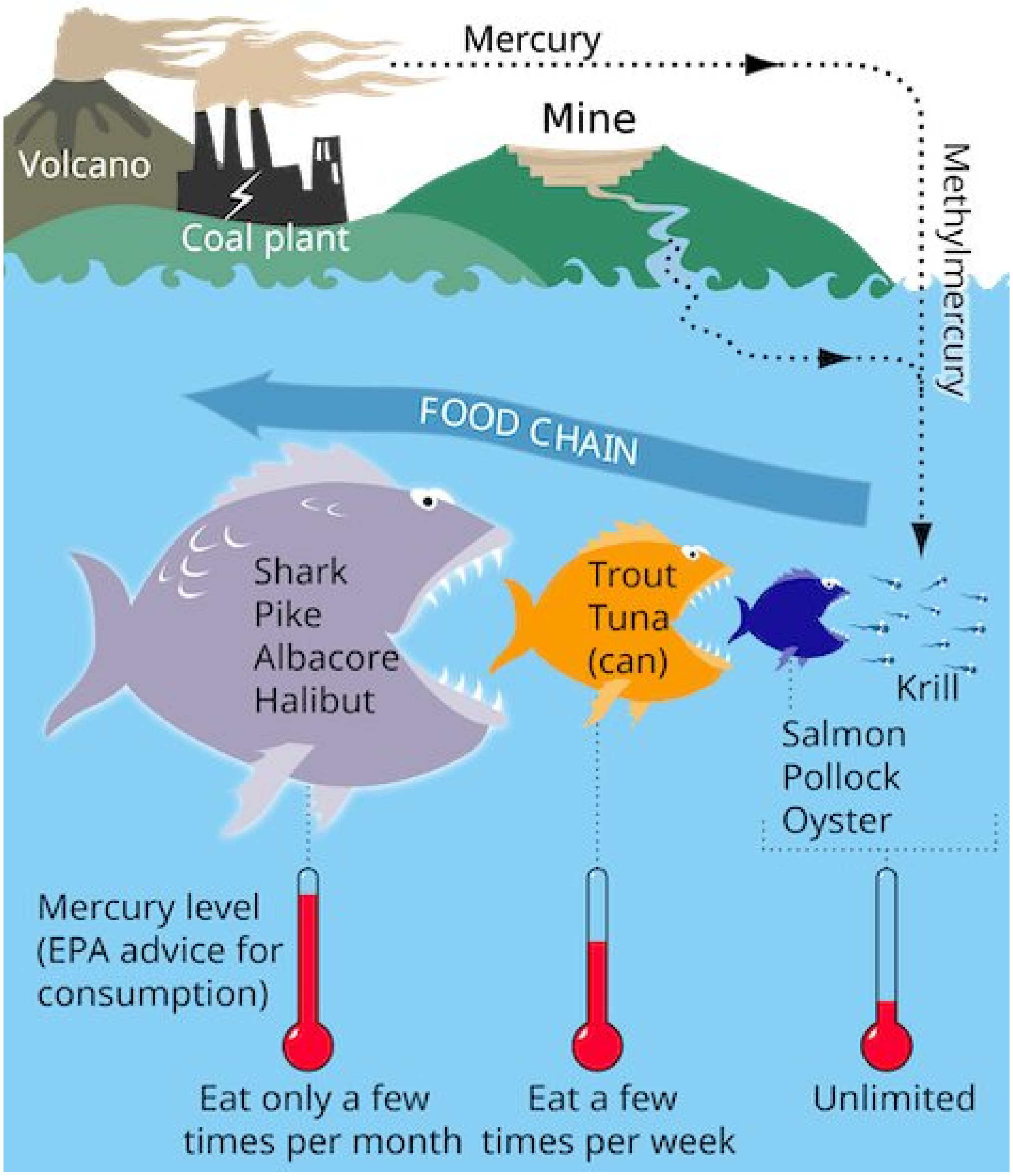
Metallophiles and their bioremediation applications

April 17 2023, by Tanya Puccio



Mercury cycling through the environment. Credit: Wikipedia

Certain species of microbes have evolved to survive in harsh environments, even those that were previously thought to be too extreme to support life. These include environments, such as mines and industrial sewage, that are rich in heavy metals. On the other hand, human exposure to toxic levels of metals, like cadmium and mercury, is known to lead to health risks, including cancer and damage to multiple organ systems.

Heavy metals induce cellular damage through competition with optimal metals for vital protein binding sites or through oxidative stress, which can damage DNA and other cellular components. With the increase in heavy metal pollution in the environment since the Industrial Revolution, there has been a mounting need for effective remediation methods.

Bioremediation of heavy metals

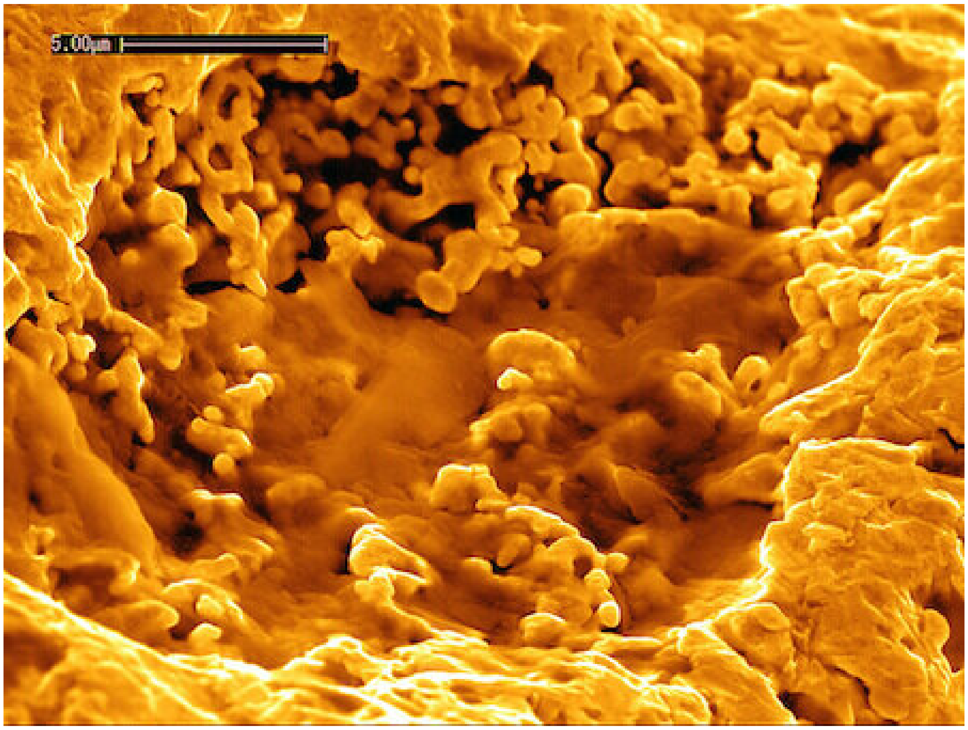
Bioremediation is the use of either naturally-occurring or deliberately-introduced organisms to consume and break down environmental pollutants and clean up a polluted site. Microbes have been utilized for large-scale bioremediation since the 1960s and 1970s, when researchers first began using mixtures of bacterial species to help clean up oil spills.

While much research, thus far, has focused primarily on the bioremediation possibilities of singular species, some studies have found that mixed cultures of microbial species may have more advantages. Recently, research into the role of microbes in the bioremediation of heavy metals has become a topic of considerable interest due to the expense and toxicity of other remediation methods.

Metal resistance mechanisms

Understanding how microbes withstand exposure to heavy metal concentrations that are toxic to humans and other organisms is foundational to the development of effective bioremediation techniques. While most bacteria have evolved some mechanisms for metal tolerance, metallophiles (metal-lovers) have adapted to survive in extremely high concentrations. This enables them to avoid the toxic effects of exposure, which would normally lead to cell death through oxidative damage and binding of suboptimal metal cofactors to protein binding sites. There are several mechanisms by which microbes can tolerate high levels of metals:

- Sequestration: Cells might use cell wall components, such as exopolysaccharides or siderophores, to sequester toxic metals and/or intracellular metal binding proteins (e.g. metallothioneins) to mitigate heavy metal poisoning and alleviate superoxide stress.
- Conversion: Enzymes convert metals to more innocuous forms, which may either be less toxic, less bioavailable or both (e.g. reduction into insoluble forms).
- Efflux: Precise efflux systems reduce the intracellular concentrations of specific metals.



A scanning electron microscope image of a gold nugget, revealing bacterioform (bacteria-shaped) structures. Credit: Wikipedia

Bioremediation applications for metallophiles

Metallophiles span 3 taxa of microbes: bacteria, fungi and archaea. Thus, members of all 3 groups have been evaluated for bioremediation potential.

Bacteria

Bacterial metal tolerance mechanisms have been studied intensively since the 1970s. The discovery of the "bacterial alchemist," Cupriavidus metallidurans, in a Belgian zinc factory in 1976, and later on biofilms in a gold mine in Australia, was groundbreaking and led to the search for additional metallophiles. C. metallidurans is not a true alchemist (one that turns matter into gold), since it utilizes preexisting gold to precipitate solid gold nanoparticles, but it can be used to decontaminate heavy metal-containing wastewater. This organism confirmed that bacteria are actively involved in the biogeochemical cycling of rare and precious metals and has since been used as a model organism for research concerning metallophiles.

Many other bacterial metallophiles besides C. metallidurans have been discovered, and some have also been utilized in the bioremediation of heavy metals. One example is the bioremediation of lead in soil by Rhodobacter sphaeroides through precipitation of inert compounds, including lead sulfide and lead sulfate. Lead toxicity causes impaired development, short-term memory loss and cardiovascular disease in humans. Contamination sources include leaded gasoline, lead pipes and industrial processes, and lead contamination remains a serious concern, especially in developing countries with older buildings that still have many lead-containing materials.

Fungi

Because they include many metallophilic species, which grow readily in a variety of habitats, fungi also have enormous potential for removing heavy metals from terrestrial and aquatic environments. Brown-rot fungus (Gloeophyllum sepiarium) was shown to reduce the toxic chromium IV levels in the soil to the nontoxic form, chromium III by 94% after 6 months. Repeated exposure to high levels of chromium may lead to increased risks of cancer incidence, decreased blood cells and renal damage in humans. Chromium is present in many foods, but levels are dependent on the concentrations present in the soil and water used to produce them. It is often leached into soils and waterways from sources, such as electroplating, leather tanning and textile industries.

Marine environments are another environment where fungi can be utilized for bioremediation. Marine sediments containing Aspergillus niger and Trichoderma sp. showed significantly higher bioleaching (a process in mining that extracts metals from a low-grade ore with the help of microorganisms) of arsenic, zinc and cadmium than with traditional chemical methods, or with bacterial species. These metals are naturally occurring. However, levels in water and soil may be increased by anthropogenic activities, and human exposure may lead to increased risk of cancer, gastrointestinal dysfunction, anemia and impaired lung and kidney function.

Brown-rot fungus (Gloeophyllum sepiarium). Credit: Quartl/Wikimedia

Archaea

Archaea are known to thrive in extreme environments, so it is no surprise that multiple metallophilic species have been identified in this taxon. For example, Methanobacterium bryantii, a copper-resistant methanogen, excretes copper-binding proteins to reduce the negative effects of the highly toxic metal on itself and cohabitants of its ecosystem. Copper is naturally found in low levels in soil and water, but anthropogenic activities, such as copper mining for "clean" energy production (e.g., solar, hydro, thermal and wind energy), can lead to the introduction of toxic levels of copper into local water sources.

Pyrobaculum islandicum, an anaerobic hyperthermophile, can reduce several toxic metals, including uranium, chromium and cobalt, to their less toxic forms. These metals occur naturally in the environment, and cobalt is even a required micronutrient for humans, since it is required for proper function of the enzymatic cofactor cobalamin (vitamin B12). However, at mining and manufacturing sites, soil and water sources can become contaminated with toxic levels of these metals, which may lead to negative health implications, including heart and liver diseases, for the communities that utilize these sources.

Other potential roles for metallophiles

Probiotics

Humans can be exposed to toxic levels of heavy metals through food, water, products and the environment. Since not all of these potential exposure routes can be safely reduced, another area of study is bioremediation within the human body. Given the propensity of certain members of the human microbiota to metabolize metals, it has been hypothesized that probiotics could be used as a strategy for human metal detoxification. For example, strains of lactobacilli, often used as food additives, may contain plasmids that encourage the sequestration of heavy metals to their cell surfaces. The strain Lactobacillus rhamnosus GR-1 was found to protect pregnant people from further increases in mercury and arsenic. Recently, another probiotic bacterium, Pediococcus acidilactici GR-1, was found to reduce the level of heavy metals in the blood of human occupational workers from the metal industry through modulation of the gut microbiota, specifically through enrichment of Blautia and Bifidobacterium species.

Rare earth metal recovery

Rare earth metals (scandium, yttrium and the lanthanides) are used for many modern high-technology products because of their electromagnetic, catalytic and optical properties. However, they are difficult to isolate due to their similar chemical properties, and current techniques for separation are environmentally toxic and energetically unfavorable. Cyanobacteria, such as Nostoc sp. 20.02, have recently been identified as potent biosorbents of rare earth metals, which has the potential to greatly reduce the costs and dangers associated with current separation techniques, since cyanobacteria are easy to grow and do not require highly acidic or basic conditions or environmentally toxic chemicals.

The ability of microbes to survive in locations with high metal concentrations is a testament to their incredible adaptability. These species and communities represent a valuable resource for remediation of metals in all kinds of environments. Some limitations of current bioremediation methods include long acclimatization time, changes in the biodegradable efficiency of the isolate and generation of sludge.

Recent advancements in microbial genetic engineering provide researchers with an exciting opportunity to edit the growth of metallophilic microbes or generate metallophiles from native microbes. These improvements have the potential to overcome the current limitations of bioremediation techniques and provide industrial companies with a solution to minimize their negative impacts on the environment.

Provided by American Society for Microbiology