Lecture 1

Biology – Materials Interface And Biomaterials Processing

Keywords: Biomaterials Processing, Biomimetics, Nanosynthesis

History of the biology-materials interface is several billion years old. Nucleosynthesis of materials in the stellar level goes back almost 20 billion years. Nonbiotic materials processing by mother earth dates back to almost 4.5 billion years after which comes biologically-mediated processing of materials (about 3.5 billion years ago).

In this cosmic scale, human efforts to synthesis of materials is relatively new, coming only after stellar and microbiological contributions. In this respect, we have to learn a lot from the tiny microorganisms inhabiting earth and ocean floors. Microorganisms, which can be termed, extremophiles bringing about biogenesis biomineralization and biomaterials processing since more than billion years ago have undergone mutational and genetic changes to survive in extreme environments with respect to acidity, oxygen availability, temperature and metal toxicity.[1]

Biotechnology-materials cycle in nature involves biogenesis of ore minerals, biooxidation and dissolution of metals from ores, biosynthesis of bulk and engineering materials, biodegradation, biofouling and biocorrosion of materials, and lastly, bioaccumulation and bioremediation of polluted environments. What had been produced and processed through biogenic processes ultimately assimilates back to mother earth completing the biological cycle.

In this respect, the microbial cell functions as a fully- automated bioreactor capable of different functions such as production of bioreagents and catalysts, inter-and intracellular metal accumulation and sorption, dissolution and corrosion of metals, as well as degradation and remediation of environment. Plasmid genes have evolved over a period of time for defence against stress and metal toxicity. Most of the toxic metal resistance may be plasmid-mediated. New populations possessing higher tolerance to metal ion concentrations, pH, temperature, pressure differences and oxygen concentration gradients emerge as microbial evolution progresses with time. Genetic engineering of such mining and metal-specific microorganisms has now become possible. Coding genes from plasmids can be cut by restriction enzymes, classified within different fractions and reinserted into a vector plasmid through enzymatic action. The recombinant DNA can then be located within a host cell for replication. Such genetic engineering procedures can lead to mass production of 'super bugs' capable of performing a desired engineering feat due to their newly acquired capabilities such as metal and high temperature resistance and synthesis of useful bioreagents.

Materials processing capabilities of a microbial cell are illustrated below.(Fig.1.1)

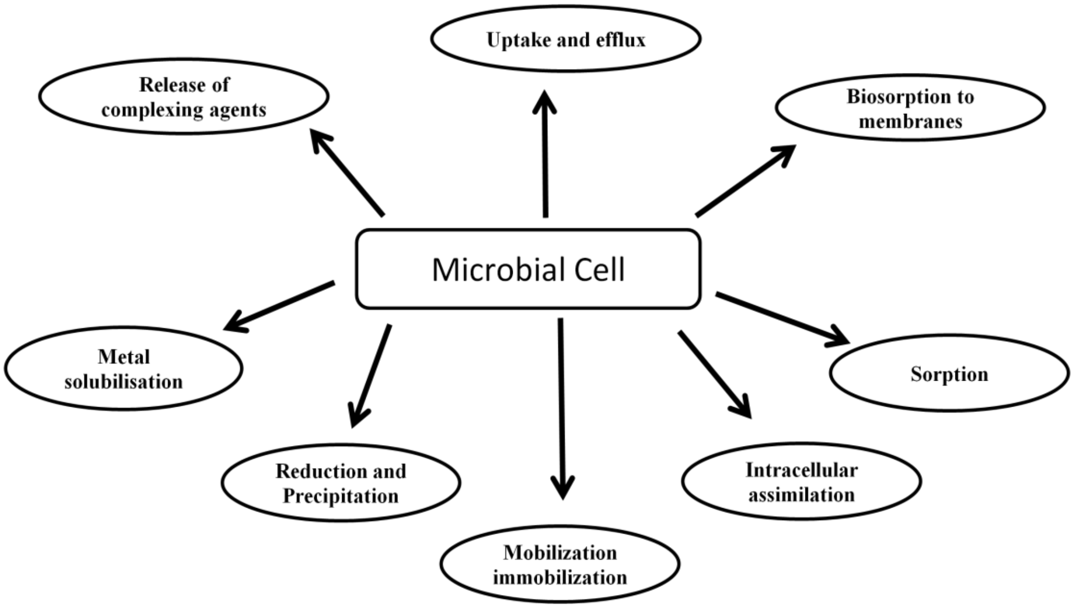

Fig.1.1: Microbial cell with its potential functions.

Biology-materials interface include several materials processing steps and cycles such as

- Biogenesis, Biomineralization
- Biomaterials processing
- Bioextraction of metals (Biohydrometallurgy)
- Biobeneficiation to produce acceptable quality raw materials for process engineering.
- Biofouling, Biodeterioration and Biocorrosion
- Environmental degradation
- Bioremediation and environmental protection.

Many of the above biological functions and processes are welcome developments in modern biotechnology. For example, an understanding of biogenesis and biomineralization of earthly resources such as fossil fuels and ore minerals will lead to isolation and industrial use of many natural organisms to extract metals and synthesize modern bulk materials and nano materials. This would also pave the way for developments in nanobiotechnology and use of environmentally-benign, cost-effective and energy-efficient bioreagents in place of toxic petroleum-based chemicals. Biohydrometallurgy and biobeneficiation processes are potential routes for environmentally-acceptable production of raw materials and finished metals. Not so advantageous and often destructive aspects of this interface include biofouling, biodeterioration, biocorrosion of metals and alloys and environmental pollution brought about by microbial activities. Thanks to positive developments in biotechnology, all the above deleterious activities can be controlled and minimized to a greater extent. While several microorganisms are implicated in environmental pollution, there exists in the same polluted environments, potential bioremediating organisms that can be harvested and utilized for detoxification of contaminated soils and waters.

Biomaterials and biomimetics

There are several minerals and metals which are classified as biogenic. Some very common examples are limestone ($CaCO_3$) and silica (SiO_2) which are formed through participation of several microorganisms. Iron oxides such as magnetite (Fe_3O_4) are formed by the action of several anaerobes and magnetotactic bacteria. Many sulfide, sulfate and oxide minerals also have associated bacterial cycles in nature. Among the metals gold, silver, selenium and tellurium are biological products, so also sulfur and volatile mercury. Bacteria, algae, fungi and plant forms participate in mineral generation, conversion and speciation. Most of the metals have a bacteria-involved cycle involved and mineral-metal-bacteria cycles in nature are important in geomicrobiology and biogeochemistry.[2-3]

Simpler organisms such as bacteria and higher organisms like mollusks and plants bring about biogenesis of minerals and metals. Bacterial activity involves surface binding of metal ions, oxidation-reduction, bioaccumulation and precipitation. It is through the intervention of higher organisms, more structurally-ordered materials are generated-structural polymer-mineral composites such as sea shells, conches and other silica-calcite based architectures. Growth of polymer $CaCO_3$ composites on mollusk shells is a classical example. Involvement of ferritin - the protein shell that contains channels to permit permeation of metal cations (such as iron and manganese) and anions such as carbonates, sulfates and chlorides in the formation of biomaterials such as magnetite, apatite and manganic compounds is known.

Significant progress has been achieved in the bioprocessing of several engineering materials utilizing the principles of biomineralization. Biomimetic materials processing are governed by the following principles:

- Mineral specificity
- Incremental net shape formation
- Compartmentalized processing

Micro-emulsions and reversed micelles are used to synthesize inorganic nanoparticles with controlled sizes and shapes. By sequential deposition procedures, high density ceramics can be formed.

Biomineralization presents enough scope for newer developments in materials science. Relevance of organic supramolecular assemblies in biomaterial systems is significant. Interaction between molecular architecture and materials science through biomineralization and biomimetic strategies is very important. Many metallic elements such as copper, iron, lead and zinc can be deposited on bacterial cell walls in the form of sulfides, oxides or carbonates. Biominerals are formed in well defined sites-intra or inter-cellular. Close association of organic and inorganic phases occurs in biomineralization.

Biogenic iron oxides include magnetite, goethite and ferrihydrite. Both biologically- controlled and - induced processes are common with participation of bacterial proteins and enzymes. In nano-scale, biomineralization consists of discrete, self assembled supramolecular parts such as vesicles and micelles. Mann classifies four constructional processes of biomineralization, namely, supramolecular preorganization, interfacial molecular recognition, vectorial regulation and cellular processing.

Bioconcepts, biomolecules and biosystems form the major divisions of biomimetic materials science. Nano-scale synthesis of materials and composites involve strategies such as host-guest and ligand capping. Crystal engineering of materials involve templating, directed growth and micro - structural fabrication.

Biogenesis is mimicked to construct special materials. Artificial polymerized vesicles can be designed to mimick biological functions. For example, colloidal gold, silver and platinum and compounds such as metal sulfides, metal oxides and chlorides can be synthesized in different shapes, sizes and in crystalline or amorphous states.

Metal cycles in nature are driven by microorganisms since they provide microbial nutrition (Mg, Fe, Ni, Zn, Co, Cu etc). Number of redox couples, such Fe(II / III), As (III / V) and Mn (II/IV) provide energy for bacterial metabolism. Metal ions such as silver, mercury, copper, uranium, lead, cobalt, molybdenum and zinc can also impart toxicity to microbial growth in varying concentration levels.

For example, the sulfur-bacteria cycle in nature is very important with respect to bacterial oxidation of mineral sulfides and bacterial reduction of sulfate to sulfides. *Aerobic acidophiles* such as *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans* participate in mineral sulfide oxidation to sulfur, tetrathionates and ultimately to sulfate.

Both *At.ferrooxidans* and *Leptospirillum ferrooxidans* are capable of oxidising iron in the sulfide minerals, resulting in the formation of acidic ferric sulfate. Anaerobic heterotrophs such as Sulfate Reducing Bacteria (SRB) reduce the biogenic sulfates back to sulfides. Biogenic formation of elemental sulfur, and metal sulfides in nature becomes thus possible.