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Bioremediation with Simultaneous Recovery and Reuse of Resources

Ramakrishnan B*
Division of Microbiology, Indian Agricultural Research Institute, New Delhi-110 012, India

Chemical industries are vital to the global economy, employ the billions and produce more than 140,000 different products. The products include those derived from the processing of organic or inorganic raw materials to everyday life and modern products. These industries process organic or inorganic materials from the Earth with heat, air and water to make chemicals and products that drive modern economies. There are suggestions that the physical limits of minerals and metals, the two important Earth resources for the chemical industries have been reached [1,2]. The 'building block' or 'bulk' chemicals such as benzene, chlorine, toluene and propylene are used to make highly refined 'intermediate' chemicals that are essential inputs for the consumer products such as glass, steel and paper. Intermediate chemicals are processed and combined with one another to make "specialty" chemicals, which include agricultural chemicals such as pesticides and fertilizers. The relationships between chemical production and consumption within these industries are highly complex. The global chemical output can be more than US$ 4.12 trillion, which have greater influences on human employment, trade and economic growth [3]. More importantly, the patterns of distribution, production and use of chemical substances have consequences for environmental health. Each year, about 700 new chemicals are listed in the Toxic Substances Control Act (TSCA) inventory of US Environmental Protection Agency [4].

The chemical life cycle of material resources begins with mining from the environment and ends with its disposal in numerous forms or products in the environment itself. The opportunities for both the human and environmental exposures exist at every stage of the chemical life cycle. Several of the chemical substances that are used in the manufacturing of electronics pose serious occupational and environmental health risks. Heavy metals, rare earth metals, polymers and solvents are routinely used in the electronics. More than half of the elements in the Periodic Table are now used in modern computer chips [5]. Some of these chemical substances are reported to cause birth defects in the children of workers and even terminal illness in workers [6,7]. The global electronic chemicals and materials market is huge and can reach more than US$ 51.6 billion [8]. The global unit shipments of personal computers are expected to be about 260.9 million units [9]. Asian countries account for more than 75 per cent of the chemicals used for the production of integrated circuits and printed circuit boards. The sizable proportion of the global metal production in terms of cobalt (8%), palladium (6%), gold (1.5%), silver (1.5%), platinum (0.2%) and copper (0.08%) are used at present to produce more than a billion mobile phones. The global patterns in electronics manufacturing thus suggest new developments in the use of metals and rate earth minerals. For example, gallium arsenide (GaAs) is used in the semiconductor technology for electronics and its demand may increase. Both the extraction of raw materials and the disposal of electronic waste will have significant health and environmental impacts.

The chemical contamination of water and soil resources occurs in rural, urban, agricultural or industrial environments. The impacts to specific ecosystem resources can vary depending on the chemical substances. Stringent environmental regulations for waste disposal are to be considered for mitigating the environmental impact of chemical substances. The 'Cap and Contain' method for disposal of wastes and for remediating the contaminated soil or water has numerous potential liabilities. The biological agents offer low-cost and simple technology options for detoxification or degradation of contaminants that are desirable at many contaminated sites. But, several contaminants in wastes include raw materials for chemical industries and these materials are becoming short in supply. In addition, the economic and environmental costs of extraction and downstream processing of materials are colossal. The search for new or alternative sources for extraction and recovery needs innovations. The microbial agents can also become a new option for the resource recovery and remediation of contaminated sites. The microbial mineralization, adsorption or precipitation can be effectively used for recovery and reuse of metals and metalloids from the wastes.

The microbial growth and activity are influenced by metals and minerals in different environments. Many minerals including calcium carbonates, silicates and iron oxides/sulphides are biogenic in origin. Several bacteria that are capable of oxidizing and reducing iron, manganese and sulphur and eukaryotes can form or degrade silicates, carbonates and phosphates [10]. The diverse groups of microorganisms can form minerals during the formation of cellular structures such as magnetosomes composed of magnetite by magnetotactic bacteria and carbonate plates or scales by eukaryotic algae (coccolithophores) and from the sorption phenomena, redox transformations, or precipitation. The microbial metabolites such as oxalate and sulphide can precipitate metals leading to the formation of secondary minerals. On the contrary, microorganisms can also dissolute or fragment both the geological and biogenic minerals. The microbial transformation, especially of metal speciation, changes the solubility and toxicity of several metals. About thirteen metals and metalloids are considered as the priority pollutants [11]. Some metals and metalloids and organometals can show toxicities towards microorganisms, affecting different indices of microbial activity. But several microorganisms show excellent survival mechanisms against these metal or metalloid pollutants by redox transformation, the production of metal-binding proteins (e.g., metallothioneins), active transport, enzymatic detoxification, and precipitation.

The microbial leaching which brings metals into their water soluble form and the microbial oxidation processes that oxidize minerals with metals in the solid residues are employed in biomining industries since long. The bioleaching which is a natural process is now used for the uncontrolled dump leaching as well as the designed bioheaps of low grade copper, gold and uranium. *In situ* dump, heap and stirred tank

***Corresponding author:** Ramakrishnan B, Division of Microbiology, Indian Agricultural Research Institute, New Delhi-110 012, India, Tel: +911125847649; Fax: +911125847649; E-mail: ramakrishnanbala@yahoo.com/brama@iari.res.in

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leaching are some of the common techniques and copper bioheap plants, and gold-, uranium- and cobalt biominig are now commercially successful. In addition to the recovery of metals from low grade ores, the microorganisms can also be employed to treat the industrial and electronic wastes to recover and reuse the metals as well as to mitigate the environmental impact of these wastes. Such bioremediation approaches can effectively recover the resources for reuse and decrease the excessive demand for extraction and processing of minerals and metals. *Chromobacterium violaceum* and *Pseudomonas fluorescens* were used to produce cyanide ions to form water soluble gold cyanide from the electronic waste [12]. The maximum gold concentration of 3.7 mg L^{-1} was obtained at the 2% pulp density of the electronic scrap material. Simultaneous biooxidation using the acidophilic *Acidithiobacillus ferrooxidans* helped to extract gold better even in the presence of competing metals such as copper at the 4% pulp density by *C. violaceum*. The extraction of gold and silver by cyanidation was found to be better after bioleaching by *A. ferrooxidans* of arsenopyrite and pyrite earlier [13]. Bioleaching is preferred to chemical leaching for zinc and lead from the municipal solid waste incineration fly ash [14].

Several microorganisms are capable of mediating oxidative and reductive processes which are useful for their survival and adaptation in the toxic environments. These microorganisms can be isolated and used as biocatalysts for the recovery of resources. Efforts are on to program the dynamics of individual populations and their activities related to the specific applications. Nevetheless, the natural consortia of microorganisms are selected and used in dairy industries, and beer and wine fermentation for several millennia [15]. Since the naturally occurring microbial consortia endure and do better than the monocultures, the engineering of synthetic microbial consortia can become an innovative strategy for the remediation of contaminated environments with simultaneous recovery of resources [16,17]. The success of microbial consortia has been attributed to the division of labor across organisms. Inorganic material recognition and binding abilities of microbial metabolites such as protein/peptide molecules can be taken advantage for mining metals and metalloids that are present in wastes or in the natural materials. This necessitates a better understanding of the microbial interactions and the molecular mechanisms such as the regulation of interspecific signalling processes and spatial structuring of communities, especially for the optimal design of synthetic microbial consortia [18].

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