INTRODUCTION

From centuries human species have been undergoing cultural, social, economic and industrial evolution. The most important revolutionary stage in history has been the Industrial Revolution which took place during a period from about 1760 and 1830-1840 (Eric Hobsbawm). This stage has been the turning point and has witnessed huge amounts of technological developments like textile manufacture, metallurgy, gas engine, mining and many more. Out of so many developments, the advancements seen in Mining have been of great importance which basically includes extraction of valuable minerals from ore body, iode, vein, seam or reef (Eric Hobsbawm). This includes metals, coal and oil shale, gemstones, lime stone, rock salt, gravel and clay. The basic source of these metals is a large Ore, which contains metal along with many impurities. These ores are purified by various processes to obtain the metal. Due to prolonged use of enriched ores for extraction has resulted in reduced amount of such ores. This problem demands a solution which is cost effective and time saving. The most promising solution to this problem is extraction of metals from low grade ores with the help of micro-organisms, a process known as Bio-mining.

Bio-mining, also known as bio-leaching, employs various micro-organisms for the processing of metal-containing ores and concentrates (Brierley, 2008; Rawlings et al, 2007). Micro-organisms such as bacteria and fungi, acts as bio-catalysts in the leaching process by converting metal compounds into their water soluble forms (Acharya, 1990; Siddiqui et al, 2009). Most economically important metals like iron, copper, gold, uranium can be easily extracted by using acidophilic and chemo-litho-autotrophic micro-organism (Olson et al, 2003; Rawlings, 2005) (Watling, 2006; Orell et al, 2008). This approach proves to be the best alternative against the traditional processing methods like pyro-metallurgy and chemical process (Brierley, 2008) (Siddiqui et al, 2009; Orell et al, 2008). The process is an energy-efficient and clean technology (Siddiqui et al, 2009) as it does not emit sulfur dioxide as emitted by other techniques such as roasting and smelting (Rawlings, 2005; Orell et al, 2008). Additionally the residue left after bio-mining process are less chemically active when exposed to rain and air as compared to physicochemical processes which generate unwanted acid and metal pollution (Rawlings et al, 2003). The risk of acid mine drainage production is the major downside, if not properly controlled (Olson et al, 2003; Orell et al, 2008; Rohwerder et al, 2003).

General Mechanism Of Bio-Mining And Bio-Film Development

Breaking down of minerals into constituent minerals is the basis of bio-mining. This provides energy to the micro-organisms involved (Das et al, 1999). The cascade of oxidation reaction consists of different intermediates. There are two mechanisms proposed for oxidation viz. thiosulphate mechanism and polysulphide mechanism.

Thiosulfate mechanism includes acid-insoluble metal sulfides like pyrite (FeS₂) and molybdenite (MoS₂) whereas polysulphide mechanism includes acid-soluble metal sulfides like chalcopyrite (CuFeS₂) or galena (PbS) (Das et al, 1999; Sand W et al., 1993).

In thiosulfate mechanism, the attack of ferric ion on acid-insoluble metal sulfides brings about solubilization via thiosulfate as an intermediate and sulfates as end-product. The
reactions are shown below (Das et al, 1999; Schippers et al., 1999), using pyrite as an example:

\[
\begin{align*}
\text{FeS}_2 + 6\text{Fe}^{2+} + 3\text{H}_2\text{O} & \rightarrow \text{S}_2\text{O}_3^{2-} + 7\text{Fe}^{3+} + 6\text{H}^+ \\
\text{S}_2\text{O}_3^{2-} + 8\text{Fe}^{3+} + 5\text{H}_2\text{O} & \rightarrow 2\text{SO}_4^{2-} + 8\text{Fe}^{2+} + 10\text{H}^+
\end{align*}
\]

Whereas in polysulfide mechanism, a combined attack of ferric ion and protons on acid-soluble metal sulfides causes the solubilization with sulfur as intermediate in its elemental form which can be oxidized to sulfate by sulfur-oxidizing microbes. Following are the reactions (Das et al, 1999; Schippers et al., 1999):

\[
\begin{align*}
\text{MS} + \text{Fe}^{3+} + \text{H}^+ & \rightarrow \text{MFe}^{2+} + 0.5\text{H}_2\text{Sn} + \text{Fe}^{2+} \quad (n \geq 2) \\
0.5\text{H}_2\text{Sn} + \text{Fe}^{3+} & \rightarrow 0.125\text{S}_8 + \text{Fe}^{2+} + \text{H}^+ \\
0.125\text{S}_8 + 1.5\text{O}_2 + \text{H}_2\text{O} & \rightarrow \text{SO}_4^{2-} + 2\text{H}^+
\end{align*}
\]

The Fe (II) is re-oxidized to Fe (III) by iron oxidizing organisms. Following is the reaction:

\[
2\text{Fe}^{2+} + 0.5\text{O}_2 + 2\text{H}^+ \rightarrow 2\text{Fe}^{3+} + \text{H}_2\text{O}
\]

The above reactions show the basic role of micro-organisms in solubilization viz.

1. Produce sulfuric acid for proton attack (eqn5)
2. To maintain iron in ferric state for oxidative attack on mineral. (eqn6)

This general mechanism of bio-mining occurs after the bacteria forms a composite community which develop on surfaces in varied environments known as Bio-film (Stoodley et al., 2002). The formation of bio-film is a linear process that initiate when free-floating bacterial cells attach to surface, followed by growth into a mature, structurally intricate biofilm and terminates in the dispersal of detached bacterial cells into the bulk fluid (Stoodley et al., 2002; Costerton et al., 2001; Sauer K. et al., 2002).

### Micro-Organisms Involved In Bio-Mining

Bio-leaching makes use of acidophilic micro-organisms which are autotrophic in nature and play a part in dissolution of metals from the sulfide ores. The acidophilic micro-organisms actively taking part are *Thiobacillus*, *Sulfolobus*, *Acidimans* and *Leptospirillum* (Das et al, 1999; Buchanan et al, 1974; Karavaiko, 1988; Blake et al, 1993). The biggest advantage of using these strains is that they can tolerate high concentrations of heavy metals (Asghari et al., 2013; Mousavi et al., 2007; Gholmi et al., 2010; Mishra et al., 2008). These micro-organisms can be categorized as mesophiles, moderate thermoacidophiles and extreme thermoacidophiles, based on their tolerance to temperature (Das et al, 1999).

### Mesophiles

Mesophiles are such micro-organisms which grow at normal temperature of about 28-37°C. In this category, the most prevalent strain is *Thiobacillusferroxidans* (Das et al, 1999; Sugio T. et al., 1996; Kai M. et al., 1989; Das A. et al., 1996; Bhattacharya et al., 1990) which is a lithotroph and draws energy by oxidizing Fe(II) to Fe(III) and sulfur, sulfide and oxymon of sulfur to sulfate (Das et al, 1999). *Leptospirillumferroxidans* is used as well but in a combination with *Thiobacillusferroxidans*, as the former cannot oxidize sulfur to sulfate (Das et al, 1999; Helle U. et al., 1988).

### Table 1 Efficiency of microorganism for metal extraction (Asghari et al., 2013)

<table>
<thead>
<tr>
<th>S.N</th>
<th>Microorganism</th>
<th>Biodeleaching efficiency</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><em>A. ferrooxidans</em> and <em>A. thiooxidans</em></td>
<td>Al: 29.3% Mo: 64.5% Ni: (45-50%)</td>
<td>Aung et al., 2004</td>
</tr>
<tr>
<td>2.</td>
<td>Ni-adapted and Mo-adapted fungal strains</td>
<td>Mo: (62–66%) Al: (30–33%)</td>
<td>Santhiya et al., 2006</td>
</tr>
<tr>
<td>3.</td>
<td>Al-adapted fungus</td>
<td>Mo: 45.1%, Al: 68.2%</td>
<td>Santhiya et al., 2006</td>
</tr>
<tr>
<td>4.</td>
<td>Ni:Mo:Al adapted fungus</td>
<td>Mo: 82.3%, Al: 65.2%</td>
<td>Santhiya et al., 2006</td>
</tr>
<tr>
<td>5.</td>
<td>Chemolithotrophic sulfur oxidizing bacteria</td>
<td>Mo: 95.8%, Al: 21.5%</td>
<td>Mishra et al., 2007</td>
</tr>
<tr>
<td>6.</td>
<td><em>A. ferrooxidans</em></td>
<td>Mo: 84%, Co: 96%</td>
<td>Gholami et al., 2010</td>
</tr>
<tr>
<td>7.</td>
<td><em>A. thiooxidans</em></td>
<td>Mo: 99%, Al: 2.4%, Co: 83%</td>
<td>Gholami et al., 2010</td>
</tr>
<tr>
<td>8.</td>
<td>Adapted Bacteria Culture (ABC)</td>
<td>Ni: 95% V: 95% W: 95%</td>
<td>Kim et al., 2010</td>
</tr>
<tr>
<td>9.</td>
<td>Unadapted Bacteria Culture (UBC)</td>
<td>Ni: 85% V: 85% W: 100%</td>
<td>Kim et al., 2010</td>
</tr>
<tr>
<td>10.</td>
<td><em>P. simplicissimum</em></td>
<td>Mo: 92.7%, Ni: 66.43%, Al: 25%</td>
<td>Amiri et al., 2011</td>
</tr>
</tbody>
</table>

### Moderate Thermophiles

Moderate thermophiles are such micro-organisms which grow in a range of temperature around 50°C. The study of these micro-organisms states that this category of micro-organisms is found in mine sites and geothermal environments (Das et al, 1999; Tuovinen OH et al., 1991). *Sulfacillusferroxidans* is, the most significant organism in this category, which has a capability of oxidizing sulfur and iron (Das et al, 1999; Lizama HM et al., 1989; Morris et al., 1985)

### Extreme Thermophiles

Extreme thermophiles are such micro-organisms which grow exponentially at high temperature as 80°C. The prevalent genus in this category is genus *Sulfolobus*. The most common examples are *Sulfolobusalcaldarius*, *Sulfolobussolfataricus*, *Sulfolobussalsuginosus*, and *Sulfolobus acidocaldarius*. Other examples are *Acidimans tararum*, *Acidimans sedis*, and *Acidimans arenosus*.
Sulfobus brierleyi, Sulfobus ambioalous (Das et al, 1999). They have ability to oxidize Fe(II) to Fe(III) and sulfur to sulfate (Das et al, 1999; Lindstrom et al., 1990).

Along with the above categories of micro-organisms, several species of fungi are also used in bio-mining. The popular ones include the two fungal strains viz. Aspergillus niger and Penicillium simplicissimum which mobilize copper and tin by 65% and aluminium, nickel, lead and zinc by more than 95% respectively (Siddiqui et al, 2009; Brauer H., 1991).

Case Study

Mathur et al, reported the use of Acidithiobacillus ferrooxidans for Uranium extraction by generating Biogenic ferric sulfate from the ore taken from Jaduguda mines, India. The study states the use of biogenic ferric sulfate produced by the strain which was then used for efficient Uranium extraction without causing any harm to the environment. It laid emphasis on reduced use of MnO₂ for the extraction. The process used for generating biogenic ferric sulfate was Bacfox process where they passed air saturated ferrous sulfate solution over Acidithiobacillus ferrooxidans sorbed on solid surface.

The determining factor for this method is permeability of the ore-body which can be increased by fragmenting of ores in place, called “rubblizing”. This method is generally used for the extraction of uranium, copper and gold (Haque et al.2013).

Techniques Applied In Bio-Mining

Bio-mining commercially employs following principle methods for extraction of metals from the ores viz. In-situ leaching, Dump leaching, Heap leaching and Vat leaching. According to the requirement, these methods are used for the extraction of various metals. The section discusses about the methods involved in bio-mining

In-situ leaching

In-situ leaching (ISL) is employed on underground ores to directly recover useful minerals and metals. The method is categorized under solution mining which involves drawing out the mineral from the earth by leaching and fluid recovery (Haque et al., 2013; Canterford J.H.,1982; Barlett R.W.,1992). It also comprises of drawing out minerals from the untouched ore. It is combined with mineral recovery operation time and again to pull out the minerals from recovered fluid solution or leachate. The large volume of solution is circulated with the aid of gravity flow and pumping. The extraction operation generates leachates known as “pregnant solutions” whereas the returning fluids to the extraction operation are known as “barren solution”. The determining factor for this method is permeability of the ore-body which can be increased by fragmenting of ores in place, called “rubblizing”. In-situ leaching was generally used for the extraction of uranium, copper and gold (Haque et al., 2013).

Dump leaching

Dump leaching basically includes the piling up of uncrushed waste rock in dumps (Siddiqui et al, 2009). It is used for mineral extraction which involves low grade ores. The bigger rocks are cracked by blasting in the pit and are carried as large fragments to dumps. These dumps contain run of mine ore in million tonnes. Acidified water is spread on the top surface which percolates in the dump and creates required conditions for the growth of micro-organisms, which will oxidize the mineral for extraction of the metal. Dump leaching was popularly used for the extraction of copper sulfide ores (Brierley, 2008).

Heap leaching

Heap leaching is slightly different than the above method in a way that the bigger rocks are crushed into particles and agglomerated in revolving drums which contain acidified water. It results in conditioning of the ore for the micro-organisms. The conditioned ore is spread on specially engineered pads which consist of perforated plastic drain lines to improve drainage of the mineral containing solution from the bottom of the ore. It is also supplied with air for the optimum growth of micro-organisms (Brierley et al.,1999) This type of leaching method is used to heap leach copper sulfide and to pre-treat gold ores to extract the occluded gold from sulfide minerals (Brierley, 2008).

The common principle of dump leaching and heap leaching is that both make use of lixiviant at the top of dump and heap. In addition, both include the recovery of mineral under the effect of gravity (Siddiqui et al, 2009; Rawlings D.E., 1997).
high gold content and to extract precious metals from ores (Siddiqui et al, 2009).

The techniques applied in bio-mining will be successful only when there is sufficient attachment of micro-organism to the surface which is achieved by a successful bio-film development. The next section describes about the steps involved in bio-film development and how it helps in extraction of metals from the ores.

Bio-Film Development

To initiate bio-film formation we have to scrutinize the properties of both the substratum (rock layer) and the cell surface. The attachment depends on surface of the substratum such as smooth or rough and also it depends on anti-microbial properties of some substratum. Hence, this feature of the substratum has a considerable effect on the rate and degree of attachment by microorganisms. Basically, the rougher and highly hydrophobic materials (with some exceptions) will build-up bio-film more swiftly (Donlan et al., 2001; Fletcher et al., 1979; Pringle et al., 1983; Characklis et al., 1990; Quirynen et al., 2000). The characteristics of cell surface also play a major role such as, existence of flagella, fimbriae, pili, curli fibers and outer membrane proteins or glycocalyx may influence the rate of microbial attachment. The microbial cell should be able to overcome the repulsive forces and these appendages facilitate the cell continue the attachment until more permanent attachment procedures are in place (Donlan et al., 2001).

Bio-film development occurs in following 5 steps

Initial Attachment

The initial attachment between any bacteria and non-living surfaces is facilitated by non-specific interactions such as hydrophobic interaction. But the attachment to living surface is carried out through specific molecular docking mechanism (Dunne et al., 2002). Further the specific adhesins such as polysaccharide intercellular adhesins (PIA) present in Staphylococcus epidermidis leads to cell to cell adhesion in bio-film on a non-living surface (Dunne et al., 2002; Rupp et al., 2001).

Irreversible Attachment

Cells attach to surface irreversibly by secreting an extra-cellular polymeric substance (EPS) which comprises of DNA, proteins, lipids and lipopolysaccharides which smooth the progress of adhesion between cells and the substratum (Lars et al., 2011; Flemming et al., 2010).

Maturation I

The cells attached on the surfaces replicate and grow into micro-colonies which have a diameter of tens or hundreds of microns. The encapsulation of bacteria in hydrogel formed due to the secretion EPS generates a physical barrier between the community and the extra-cellular environment. Different micro-organisms have different content of EPS which determines the growth conditions and chemical communication in cells in the community (Lars et al., 2011; Borlee et al., 2010). Quorum sensing is important for chemical communication in bacteria. It adjusts the cellular functions, nutrient acquisition, motility, conjugation, pathogenesis and secondary metabolite production (Harmsen et al., 2010).

Maturation II

The microbial community acquires a three-dimensional structure giving rise to a mature bio-film as a result of replication of cells and EPS accumulation. The EPS acts as glue for combining cells in an established bio-film to protect against mechanical stress and prevent the detachment from the surface (Lars et al., 2011).

Dispersion

Some microbial cells detach from the bio-film and disperse in bulk fluid forming new bio-films in different environmental niches. This step is important for propagation and self-renewal (Stoodley et al., 2004; Costerton et al., 1987).

Figure 4 Process flow for Vat leaching

Figure 5 Stages in Bio-film Formation

Mining Area

Mining is done generally in many countries but London is well-known capital of global “mining houses” (MacDonald, 2002). In South America, Chile and Peru are apparently the major mining countries. Table 2 shows bio-mining of some metals by different process along with the mining area.
Traditional Mining Process

The technique of extraction and purification of metals by using the application of heat is called as Pyro-metallurgy. It includes four processes: Calcining, Roasting, Smelting and Refining.

Calcination

In this process, thermal decomposition of ores and other solid materials are done by applying oxygen or in presence of air. It also results in phase transition or removal of volatile products.

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \quad \text{H (900°C)=3010 kJ/mol (Friederike C. Jentoft. 2003)}
\]

Roasting

Certain ores require this processing step which is a metallurgical process involving gas-solid reactions. These reactions occur at high temperatures in order to purify the metal components (Greenwood et al., 1997)

\[
\begin{align*}
2\text{Cu}_2\text{S} + 3\text{O}_2 & \rightarrow 2\text{Cu}_2\text{O} + 2\text{SO}_2 \\
2\text{ZnS} + 3\text{O}_2 & \rightarrow 2\text{ZnO} + 2\text{SO}_2
\end{align*}
\]

Smelting

In this processing step, the mineral is obtained as a metal or a simple compound, when heated beyond the melting point.

It takes place in the presence of oxidizing agents like air, and reducing agent as coke.

Refining

This brings us to the end of the extraction of metals where the last amount of small impurities are removed leaving practically a pure form of metal. There are 3 different methods to carry out refining viz. by fire, by electrolytic and by chemical methods.

Applications Of Bio-Mining And The Metals Extracted

<table>
<thead>
<tr>
<th>Metal</th>
<th>Commercially important ore</th>
<th>Abundancy</th>
<th>Mines</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Chalcopyrite Chalcocta Copper(I) oxide Cuprite Azureite Malachite</td>
<td>Earth's crust at a concentration of about 50 ppm</td>
<td>Chuquicamata in Chile, Bingham canyon mine in Utah, United States and El Chino mine in New Mexico, United States</td>
<td>In-situ</td>
</tr>
<tr>
<td>Iron</td>
<td>Hematite Magnetite</td>
<td>4th most common element in the Earth's crust</td>
<td>Brazil mining corporation &quot;Whale&quot;</td>
<td>Reduction of HAEMATITE (Fe2O3) with carbon</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Bauxite</td>
<td>After oxygen and silicon, and the most abundant metal, in the Earth's crust</td>
<td>Australia, Brazil, China, India, Guinea, Indonesia, Jamaica, Russia and Suriname</td>
<td>Chemical process (Bayer’s process)</td>
</tr>
<tr>
<td>Gold</td>
<td>Calaverte Krennerite Nayaragite Petzite Sylvanite</td>
<td>Present in the earth’s core</td>
<td>Witwatersrand basin in South Africa South Dakota and Nevada</td>
<td>Dump bleaching or heap bleaching</td>
</tr>
<tr>
<td>Silver</td>
<td>Argentite Chlorargyrite Pyrargyrite</td>
<td>0.075 ppm in earth’s crust</td>
<td>Cristosal (Bolivia), Antamina (Peru), Rudna (Poland), and Penasquito (Mexico)</td>
<td>Smelting</td>
</tr>
<tr>
<td>Vanadium</td>
<td>Patronite Vanadinite Carnotite</td>
<td>0.01% by weight in earth’s crust</td>
<td>Accent resources (Australia) American Vanadium Corporation (Canada)</td>
<td>Found as associated with other minerals, therefore process depends on the extraction of those minerals</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Dolomite Magnesite Brucite Camalite Talc Olivine</td>
<td>Eighth-most-abundant element in the Earth’s crust</td>
<td>China dominant producer Renco group companies in US</td>
<td>Silicothermic pigeon process (China) Electrolysis (US)</td>
</tr>
<tr>
<td>Manganese</td>
<td>Pyrolusite</td>
<td>12th most abundant element in earth’s crust</td>
<td>near Hotazel in the Northern Cape Province</td>
<td>By leaching manganese ore with sulfuric acid and a subsequent electrowinning process.</td>
</tr>
<tr>
<td>Tungsten</td>
<td>Wolframite Scheelite Ferberite Hubnerite</td>
<td>1.25 ppm of earth’s crust</td>
<td>Hemerdon mine in England</td>
<td>Pyrolytic decomposition</td>
</tr>
<tr>
<td>Nickel</td>
<td>garnierite, and pentlandite</td>
<td></td>
<td>Australia, New Caledonia, Canada (which is thought to be of meteoric origin), New Caledonia in the Pacific, and Norilsk in Russia.</td>
<td>Mond process</td>
</tr>
</tbody>
</table>
organisms particularly to human beings as well as to the environment. Therefore, the industries are obligated to enforce such environmental management system to prevent the environment strictly (Hoque et al., 2011; Bosecker, 2001; Verstraete, 2002). Limited research has been done to show the use of bio-leaching in extracting metals from wastes (Hoque et al., 2011; Chen et al., 2004; Swinkels et al., 2004; Dudney et al., 2004; Mitchell et al., 2004).

**Metal recovery from electronic waste**

Electronic goods like cell phone, laptops, desktop, and television sets etc. play a major role in human life. Therefore, world production of electronic waste is increasing persistently and posing a potential threat to environment and mankind. For that reason, we need to carry out bio-leaching of these electronic wastes which will not only decrease the hazardous nature but will help to recover the valuable metals (Hoque et al., 2011). Micro-organisms such as Acidithiobacillus ferrooxidans, Acidithiobacillus thiooxidans, Sulfabacillus thermosulfidooxidans are involved in bioleaching of electronic waste.

The electronic scrap being a mixture of various metals such as Cu, Al, Fe, Ni and their alloys is an interesting kind of waste. In case of copper (Cu), Acidithiobacillus ferrooxidans create Fe₂ (SO₄)₃ which oxidizes elemental Cu present in the waste to the copper in form of ion (Willner et al., 2013).

\[
\text{Cu + Fe}_2 \text{(SO}_4\text{)}_3 \rightarrow \text{Cu}^{2+} + 2\text{Fe}^{2+} + 3\text{SO}_4^{2-} \quad (1)
\]

\[
2\text{FeSO}_4 + \text{H}_2\text{SO}_4 + 0.5\text{O}_2 + \text{bacteria} \rightarrow \text{Fe}_2 \text{(SO}_4\text{)}_3 + \text{H}_2\text{O} \quad (2)
\]

The presence of alkaline particulate components in waste may delay the bio-leaching process and slow down its dynamics (Brandl et al., 2001; Yang et al., 2009) for example, Al concentration in high amount in the environment inhibits the growth of bacteria. By adding acidifying agent we can improve the efficiency of the process [72]. This efficiency can be further improved by higher dose of A. ferrooxidans, iron ions Fe²⁺ to the system and adjusting the pH using H₂SO₄ in the range of 1.5-2.0. Similarly a consortium of various strains from the category of acidophilus thermophile (Thermosulfidooxidans sulfobacillus) and heterotrophic acidophilus (Thermoplasma acidophilum) can be used for leaching of Ag, Al, Cu, Fe, Ni, Ph, Zn, Sn (Ilyas et al., 2007).

**Metal recovery from mine wastes**

Acid mine drainage (AMD) is the major form of waste from metal mines which has considerable amount of metal content which is a chief pollutant in water resource. The capability of bacteria to leach the metals can be exploited to retrieve metals from AMD. Iron and sulfur oxidizing bacteria show a promising iron oxidation potential in AMD sites (Hallberg et al., 2003; Sandstrom et al., 2001). Zinc and aluminum have been successfully retrieved from AMD with the help of A. ferrooxidans (Solisio et al., 2002; Bojinnova et al., 2001). In addition, it has been reported that nickel can be recovered from aqueous waste with the help of polycrystalline hydrogen uranyl phosphate (HUP) bound to immobilized cells of Citrobacter sp. (Gabriela et al., 1997).

**Metal recovery from contaminated sediments**

Contaminated sediments like anaerobic sludge, river sediments are a great source of heavy metal residues by bio-mining. It has been described that Cu, Co, Ni, Mn and Fe have been retrieved from ocean manganese nodules in the pyrite and reducing agents (Wong et al., 2004). Iron and sulfur oxidizing bacteria have been shown to solubilize 90% of Ni, Zn, Cu and Cr at an optimum temperature of 37°C (Debaraj et al., 2004). Nickel and Cobalt have been recovered from residues of Caron technology process by using sulfuric acid produced by Acidithiobacillus thiooxidans (Diaz et al., 2009).

**Metal Recovery from fly ashes**

Fly ashes produced from combustion are considered as a secondary source for extraction of heavy metals like Zn, Al, Cu, Ni and Cr using a mixed culture of iron and sulfur oxidizing bacteria (Debaraj et al., 2004). The same mixed culture can be used to attain high metal-leaching ability and tolerability for extraction of Cu, Zn, Cr and Cd from municipal solid waste incineration (MSWI) fly ash (Ishigaki et al., 2005).

**Metal recovery from battery wastes**

Bio-mining techniques have been put into operation to extract toxic metals from hazardous spent batteries in developing countries. Leaching metals from Ni-Cd spent batteries have been effectively done (Zhu et al., 2003). With proper culture conditions provided, 95-98 % Co and nearly 1% Ni can be recovered from spent lithium ion batteries. This was reported by Kang et al wherein they recovered cobalt sulfate from crushed and screened prismatic type spent lithium ion batteries (Kang et al., 2010).

**CONCLUSION AND FUTURE PROSPECTS**

Bio-mining, which makes use of natural micro-organisms for the extraction of the metals from low grade ores, can be a promising approach which will help in reducing the environmental pollution due to mining tailings, acid mine drainage, and release of sulfur into atmosphere. It can prove to be an alternative to traditional mining techniques which contributes to environmental pollution. Not only low grade ores but metal waste can also be considered as a source for metals by bio-mining. The future of bio-mining is thought-provoking, which is set to increase its application commercially because it not only offers operational simplicity but also offers low capital investment, low operating cost and shorter construction time.

It is seen that most of the research based on the type of micro-organisms used, their colonies which help in bio-mining, is limited to institutes, universities and academic departments. For bio-mining technology to be applied commercially there is a dire need of cooperation and synchronization between mining companies and these research institutes. Also the government agencies need to demonstrate the technology at a large scale which would help in convincing the mining companies to adopt the technology for a better environment and better tomorrow.

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