In the past few years, rapid urbanisation and industrialisation have led to an enormous increase in the amount of industrial waste generated, including heavy metals like arsenic, cadmium, chromium, copper, nickel, lead and mercury. Metal contaminants are usually found in a variety of sources, including soils, sediments and water.

Metal pollutants can be produced through industrial processes such as mining, refining and electroplating. Although they have major roles in industrial and economic development, these metals also exert toxic effects if present in high concentrations in the environment. They are not only toxic to living cells, but can also cause cancers and mutations.

Due to rigorous exploitation of the available resources, levels of heavy metals have become alarmingly high in air, soil and water. The existence and persistence of the heavy metals...
in the environment results in their entry and bioaccumulation in the food web, thus disturbing the ecosystem.

There are many examples of the toxic accumulation of metals leading to disastrous effects. These include mercury poisoning in Minamata Bay of Japan, arsenic poisoning in Bangladesh (one of the largest mass poisoning incidences in history), lead poisoning that accounts for approximately 1,43,000 deaths every year worldwide, and cadmium accumulation in the offal (mainly kidney and liver) of grazing animals in New Zealand and Australia making them unsuitable for human consumption.

Removing Heavy Metals
Even though metals are non-biodegradable, they can be transformed through processes such as sorption, methylation and complexation, and changes in valence state.

The current treatment practices for heavy metal removal from industrial wastes primarily rely on physical processes such as land filling, leaching, chemical precipitation, oxidation or reduction, filtration, ion-exchange, reverse osmosis, membrane technology, evaporation and electrochemical treatments (Gunatilake, 2015). These techniques are not only expensive and labor intensive; they do not offer an effective solution for removal of heavy metals from contaminants as well.

In recent years, the focus has shifted to biological methods of heavy metal remediation, which involve the use of plants (phytoremediation) or microbes (bioremediation). These methods, owing to their advantages, such as in situ treatment of contaminants, cost-effectiveness and ability to reduce the amount of secondary pollution, have become an attractive alternative to the physico-chemical methods.

### Bioremediation Strategies
Bioremediation involves degradation or transformation of metals to their to less hazardous forms by the use of microbes, their metabolites and other biological systems. The efficacy of bioremediation depends on a number of metal-microbe interactions, including biotransformation, bioaccumulation and biosorption. Some of these processes are outlined below.

#### Biotransformation:
Biotransformation involves enzymatic oxidation (removal of electrons) or reduction (addition of electrons) of heavy metals by microbes. Mainly seen in metals such as iron (Fe), uranium (U), technetium (Tc), and chromium (Cr), the process converts these soluble metals to their insoluble forms, which are less toxic. For instance, microbes can reduce uranyl carbonate to highly insoluble U (IV), which tends to precipitate from solution as the uranium oxide mineral uraninite. Another mechanism by which biotransformation reduces metal toxicity is by increasing the solubility of the metal to enhance its ‘flush-off’ by the system.

#### Bioaccumulation:
Some microorganisms possess the ability to physically remove heavy metals from solution by retaining and concentrating the contaminant intracellularly. This phenomenon is known as bioaccumulation. During bioaccumulation, metals are transported inside the cell through various transport pumps present on the cell membrane. Inside the cell, the metal is sequestered in the cytoplasm by metal-chelating proteins, e.g., metallothioneins.

#### Biosorption:
Biosorption is the metabolism-independent association of metals with the microbial cell wall. Both dead and live microbial biomass have been used as metal

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Heavy metal</th>
<th>Organism</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>2.</td>
<td>Chromium (VI)</td>
<td><em>Aeromonas caviae</em>, <em>Bacillus coagulans</em>, <em>Bacillus licheniformis</em>, <em>B. megaterium</em>, <em>Chryseomonas luteola</em>, <em>Zoogloea ramigera</em></td>
<td>Vijayraghavan and Yun, 2008</td>
</tr>
<tr>
<td>3.</td>
<td>Copper</td>
<td><em>Bacillus subtilis</em>, <em>Enterobacter sp. J1</em>, <em>Pseudomonas aeruginosa</em>, <em>Streptomyces coelicolor</em>, <em>Thiobacillus ferrooxidans</em></td>
<td>Vijayraghavan and Yun, 2008</td>
</tr>
<tr>
<td>5.</td>
<td>Lead</td>
<td><em>Bacillus sp.</em>, <em>P. aeruginosa</em>, <em>Corynebacterium glutamicum</em>, <em>Pseudomonas putida</em>, <em>Streptomyces rimosus</em>, <em>Streptothricillum cinnamoneum</em></td>
<td>Vijayraghavan and Yun, 2008</td>
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</table>
biosorbents. Several advantages associated with biosorption such as its low cost, high efficiency, no additional requirement for nutrients, easy regeneration of biosorbent and the possibility of metal recovery, make it a method of choice for bioremediation practices. A number of microbial species have been used as potent metal biosorbents such as bacteria (Bacillus, Pseudomonas and Streptomyces) and fungi (Aspergillus, Rhizopus and Penicillium).

Practical Applications
The potential of a number of bacterial and fungal strains has been studied in bioremediation. Some strains used in bioremediation of heavy metals are listed in Table 1.

The potential of several fungal genera like Penicillium, Aspergillus and Rhizopus to remove heavy metals from aqueous solutions has been extensively studied. Fungi have also been exploited as potential biocatalysts for transformation of heavy metals to less toxic compounds. Other fungal species like Klebsiella oxytoca, Allescheriella sp., Stachybotrys sp., Phlebia sp., Pleurotus pulmonarius, Botryosphaeria rhodina have been used in the process, owing to their metal binding properties.

Future Perspectives
High metal concentrations in soil, sediments and water are a potential threat to human and animal health. In situ bioremediation has an edge over the conventional methods used in heavy metal removal.

The application of the process in industry, however, faces certain constraints such as non-specific biotransformation of toxic metals, inhibition of microbial metabolism by the by-products of bioremediation and optimisation of application protocols of the microbe in the industrial set-up.

Therefore, more elaborate studies are warranted to overcome these limitations and to increase the potential of the microbial bioremediation technology. This should focus on screening more microorganisms, which could be used efficiently under industrial environments or at other contaminated sites; or alternatively, use of genetically engineered micro-organisms, with a better efficiency and adaptability to extreme environments. For the practice to be adopted by the industries, the involvement of federal, state and local governments, as well as private players would be warranted.

Dr. M. V. Rajam is Professor in the Department of Genetics, University of Delhi, South Campus, Benito Juarez Road, New Delhi110021; Email: rajam.mv@gmail.com/venkat.rajam@south.du.ac.in
Anamika Upadhyay and Aadyaa Singhania are also in the Department of Genetics, University of Delhi, South Campus