Bioremediation (i.e., green technologies or phytotechnologies when relied upon plants) mainly deals with biological interventions aimed at environmental contamination assessment and alleviating pollution. Both industrialization and natural resource extraction resulted in the release of large amounts of toxic and waste compounds into the biosphere. These pollutants belong to two main classes: inorganic and organic ones. According to EEA (European Environment Agency) estimates 1.4 million areas are contaminated (Puschenreiter and Wenzel, 2003). In India alone there are about 20,000 abandoned mine sites covering about 60 different kinds of minerals. Biological interventions mediated by some wide array of biological species (none of which will be able to “remove everything”) can be used to remove unwanted compounds from the biosphere, thus contribute significantly to the fate of toxic spills.

Phytotechnologies deal with the use of plants in pollution control and removal as well as on aspects related to plants from polluted environments as a source of food, fodder, fuel and fertilizer. Plants are able to indicate, exclude, accumulate, hyperaccumulate or metabolise toxic inorganic or organic substances. Thereby they contribute significantly to the fate of chemicals, and they can be used to remove unwanted compounds from the biosphere. On the other hand, chemicals can enter the food chain via plants, which cause unwanted/causing harmful effects (Schroeder and Schwitzgue´bel, 2004).

As of May 2009, about 10,684 articles have been published on various aspects of bioremediation starting with only 11 in 1989 (Fig. 1). Thus, there has been a steep rise in scientific investigations and a real knowledge explosion in green technologies. An environmental watchdog survey revealed that Russia, China and India are among the “top ten” most polluted places/countries in the world (Anonymous, 2007). In the developed nations as well as developing nations there have been several convincing evidences for applications of green technologies.

Therefore, the field of bioremediation belongs to the realm of environmental biotechnology and is not to be confused with biodegradation, which tackles the biological bases of the (mostly bacterial) metabolism of unusual and/or recalcitrant compounds. Depending on the degree of such intervention, bioremediation is generally considered to include natural attenuation (which entails little or no human action), or bio-stimulation (requiring addition of nutrients, and electron donors/acceptors to promote the growth or metabolism of certain micro-organisms), or bio-augmentation, the deliberate addition of natural or engineered micro-organisms with the desired catalytic capabilities.

Bioremediation is exploitation of biological interventions of biodiversity for purposes of mitigation (and wherever possible complete elimination) of the noxious effects caused by environmental pollutants in a given site (Fig. 2). If the process occurs in the same place which was afflicted by pollution then it is called in situ bioremediation. In contrast, deliberate relocation of the contaminated material (soil and water) to a different place to intensify biocatalysis, is referred to as ex situ treatment. Biodiversity is the precondition for bioremediation. Quite a variety of plants, natural, transgenic, and/or associated to rhizosphere micro-organisms are extraordinarily active in these biological interventions cleaning up pollutants by removing or immobilizing. Diverse microbes are the most active agents, fungi and their strong oxidative enzymes are key players in recycling recalcitrant polymers and xenobiotic chemicals as well (Loeffler and Edwards, 2006; Kawahigashi, 2009).
Phytoremediation can be used in combination with other traditional and innovative remediation technologies. Cleanup can be accomplished to certain depths below ground level, within the reach of plants’ roots. Such sites need to be maintained (watered, fertilized, and monitored). Phytoremediation may yet be slower than mechanical cleanup methods such as excavation and proper disposal and is limited to soil depths that are within the reach of plants’ roots. Phytoremediation can, however, be used in combination with other remediation technologies.

Plant physiology, agronomy, microbiology, hydrogeology, and engineering are combined to select the proper plant and conditions for a specific site. Phytoremediation is a procedure that can reduce remedial costs, restore habitat, and cleanup contamination in place rather than entombing it in place or transporting the problem to another site.

Phytoremediation is the use of certain plants and trees to cleanup soil and water contaminated with metals and/or organic contaminants such as solvents, crude oil, and polyaromatic hydrocarbons (PAHs). Phytoremediation is an aesthetically pleasing, solar-energy driven, passive technique that can be used along with-or, in some cases, in place of-mechanical cleanup methods at sites with shallow, low-to-moderate levels of contamination.

Thus, phytoremediation of contaminated environment offers an environmentally friendly, cost effective, and carbon neutral approach for the cleanup of toxic pollutants in the environment. Plants with abilities to hyperaccumulate, accumulate, exclude and indicate heavy metals are important in environmental remediation (Fig. 3).
Plants with ability to take up volatile organic compounds, and sequester pollutants have been proposed as a solution to the treatment of toxic contamination in situ. However, the use of plant-based technologies has a number of limitations, primarily due to the fact that plants are autotrophic and not ideally suited for the metabolism and breakdown of organic compounds. One of the major limitations with current phytoremediation is the often slow time-scale for remediation to acceptable levels and also toxicity to the plants themselves. To some extent, this can be addressed through interactions with the natural microflora associated with plants; endophytic bacteria, rhizosphere bacteria and mycorrhizae have been shown to have the potential to degrade organic compounds in association with plants (Dowling and Doty, 2009; Weyens et al., 2009) (Figs. 4–6).

The use and transformation of over 100,000 individual compounds whose current locations are largely unknown
resulted in the establishment of new fields of research, which have one thing in common: they link ecological, physiological, and chemical/analytical lines (Markert, 1996; Markert et al., 2008). This complex system of interactions and interrelations requires intensified efforts to provide integrated information on the status and development of environmental quality. Bioindicators and biomonitors have proven to be excellent tools in many of these cases and could provide information which cannot be derived from technical measurements alone (Markert et al., 2003; Prasad, 2008).

Bioindicators and biomonitors yield extensive information. Thus an increasing knowledge of ecology gave way to the insight that organisms, cells and subcellular compounds likewise can be used as indicators for ecosystem qualities and for assessment of the impact of environmental stress on the composition and functioning of ecosystems. Indicators can be used to assess (environmental) quality, but also to investigate trends, e.g. monitoring systems with measurements to be repeated in time, what is of highest interest with respect to any phytotechnological method in use.

Fig. 6. Detoxification of xenobiotics. Pharmaceutical residues are common contaminants of ground water in many cities (based on COST action 859, Szeged April 2009 workshop presentations).

Fig. 7. Degradation of pharmaceuticals (and other organic compounds) capable of or meant to attack micro-organisms including those in soil after their disposal into the environment along wastewater disposal and cattle breeding. In the very end, compounds which are refractory may show in drinking water again (including steroids such as EE2 [ethinylestradiol]). (based on COST action 859, Szeged April 2009 workshop presentations).
Biotechnology and systems biology approaches are gaining considerable importance in fostering bioremediation (De Lorenzo, 2008; Van Aken, 2009). It is strongly believed that there are three dimensions for the effectiveness of vital bioremediation process, i.e., chemical landscape (nutrients-to-be, electron donors/acceptors and stressors), abiotic landscape and catabolic landscape of which only the catabolic landscape is “genuinely” biological. The chemical landscape has a dynamic interplay with the biological interventions on the abiotic background of the site at stake. This includes humidity, conductivity, temperature, matrix conditions, redox (O₂) status, etc. (De Lorenzo, 2008).

Conventionally the efficacy of bioremediation has been determined chemically, by measuring changes in total pollutant concentrations usually by an assemblage of sophisticated instruments. However, recently attempts have been made to use biosensors, especially microbial whole-cell biosensors to monitor pollution (Fig. 7).

Information is encoded in DNA (desoxyribonucleic acid) and transferred through RNA (ribonucleic acid) to ribosomes to make proteins or enzymes which are used to operate systems within the organism. In this regard enzymes are responsible for the degradation of organic contaminants which is used by the bacterial cell to produce both the building blocks of life and energy. The degradation of any organic molecule, including contaminants, requires the production and efficient utilization of enzymes (Table 1), as a rule.

### Table 1

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Target pollutant</th>
<th>Examples of plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dehalogenase</td>
<td>Chlorinated solvents</td>
<td>Populus, Myriophyllum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>spicatum Nitella, Spirogyra</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and Anthocerus</td>
</tr>
<tr>
<td>Laccase</td>
<td>Explosives</td>
<td>Nitella, Myriophyllum spicatum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lemna minor, Nitella</td>
</tr>
<tr>
<td>Nitroreductase</td>
<td>Explosives</td>
<td>Populus, Myriophyllum spicatum</td>
</tr>
<tr>
<td>Peroxidase</td>
<td>Phenols</td>
<td>Armoracia rusticana</td>
</tr>
<tr>
<td>Phosphatase</td>
<td>Organophosphates</td>
<td>Duckweeds</td>
</tr>
<tr>
<td>Cytochrome P450</td>
<td>Xenobiotics (PCBs)</td>
<td>Brassica sp.</td>
</tr>
</tbody>
</table>

Fig. 8. Knowledge explosion in the field of bioremediation – progressing fields of advanced research.

Fig. 9. Scope and limitations of bioremediation – the hierarchy of complexity (De Lorenzo, 2008; Van Aken, 2009).
In some instances, degradation is merely a complex oxidation/reduction reaction. The electrons or reducing equivalents (hydrogen or electron-transferring molecules) produced must be transferred to a terminal electron acceptor (=TEA, bacteria are grouped into three categories, namely aerobes, facultative aerobes/anaerobes and anaerobes). Herbicide phytoremediation using transgenics is one of the most successful examples. Transgenic plants engineered for the transformation of explosives and metabolic pathway engineering for degradation of xenobiotics are in progress (Van Aken, 2009).

Much progress has been made in the field of bioremediation in Europe and North America. The costs, benefits and residual risks thereafter need to be investigated to present the final outcome to the decision makers. Further, particularly countries with vast biodiversity and high environmental pollution must implement and evaluate the exciting and feasible biotechnological options. The obvious approach to address some of the aforesaid limitations is the application of recombinant DNA technology to express specific genes from heterotrophic organisms such as bacteria and mammals to increase plant tolerance for metabolism of organics and decontamination of inorganics such as toxic trace metals (Figs. 8 and 9) (Scow and Hicks, 2005; Singh et al., 2008; Wood, 2008; Abhilash et al., 2009; Ruiz and Daniell, 2009).

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