



## Biotechnology in Environmental Pollution Control and Remediation

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Environmental pollution is one of the biggest problems facing our planet today. Rapid industrialization, urbanization, and intensive agricultural practices have significantly increased environmental pollution, posing serious threats to ecosystems and human health. Traditional methods to control pollution, such as chemical treatments and physical removal, are often costly, energy-intensive, and may generate secondary pollutants. This is where biotechnology offers a safer, natural, and eco-friendly solution for the management of environmental pollution.

### Biotechnology in pollution control

Biotechnology involves using living organisms like microorganisms like bacteria, fungi, and algae and plants to reduce or remove pollutants from the environment. These organisms are utilized mainly for monitoring and naturally break down harmful substances into simpler and less toxic forms.

### Major biotechnological approaches

#### 1. Bioremediation

Bioremediation is one of the most effective and widely used methods. Microorganisms feed on pollutants such as oil, pesticides, and heavy metals and convert harmful substances into harmless products like water and carbon dioxide. *In situ* involves cleaning pollution at the site itself while *ex situ* involves removing polluted material and treating it elsewhere. Oil spills and synthetic plastics in oceans can be cleaned using bacteria viz. *Alcanivorax*, *Pseudomonas*, and *Halomonas* that digest them and their efficacy can be improved by protein engineering, synthetic biology, etc as reviewed by Muriel-Millán *et al.* (2021).

#### 2. Phytoremediation

Certain plants that can absorb pollutants from soil and water. Plants like sunflower and water hyacinth absorb heavy metals and store pollutants in their tissues or convert them into non-toxic forms (Lwanga *et al.*, 2025). It involves genetic modification in plants, phytoextraction, endophytic microorganism utilization, phytostabilization, phytovolatilization, phytodegradation, phytofiltration, etc (Barathi *et al.*, 2023; Lwanga *et al.*, 2025).

#### 3. Biofiltration

Biofilters use microorganisms attached to filters to remove pollutants from air (Devinny *et al.*, 2017). It is used in industries to remove bad odours and harmful gases by use of microbes break down gases into harmless substances.

#### 4. Biosensors

Biosensors are analytical devices that use biological components such as enzymes, antibodies, whole cells, or genetically engineered organisms linked with a transducer to convert the presence of a target substance into a measurable electrical signal. They exploit the high specificity of biological molecules to detect pollutants accurately. They consist of four

main components: bioreceptor, transducer, signal processing system and display unit. Bioreceptor specifically recognizes biological or chemical substances in the sample. Transducer converts the biological interaction into a measurable electrical, optical or thermal signal. Biosensor that detects aromatic pollutants was developed by Roy *et al.* (2021) by including Luciferase gene that shows fluorescence in *E. coli* in presence of aromatic compounds in water.

### 5. Molecular techniques

Molecular biology techniques such as PCR, qPCR and DNA barcoding are applied to identify and quantify environmental pollutants. PCR is used for qualitative detection while, qPCR (real-time PCR), detects and measures the DNA concentration as the reaction progresses. These techniques offer high precision in detecting microbial populations involved in pollutant degradation, enabling effective monitoring of biological responses to contamination. Gerlicz *et al.* (2024) identified keratin-degrading bacteria from soil and zoonotic keratin sources like *Exiguobacterium*, *Priestia*, *Curtobacterium*, *Stenotrophomonas*, *Bacillus*, *Pseudomonas*, etc. were identified through molecular and 16S rDNA analysis.

### 6. Genetic engineering for pollution control

Genetic engineering allows for the modification of microorganisms to enhance their pollutant-degrading, sequestration, or sensing capabilities. These can be utilized in cleaning up environmental contamination from oil spills, industrial waste, and hazardous chemicals. Gene coding for 2,4-dinitrotoluene degradation from *Burkholderia sp.* strain was engineered in *Pseudomonas fluorescens* and 2,4-dinitrotoluene was found completely degraded (Monti *et al.*, 2005).

Genome editing technology CRISPR-Cas systems are powerful tools for improving phytoremediation by precisely editing genes involved in metal uptake, transport, detoxification, and sequestration. CRISPR has been used to enhance metal uptake and tolerance by modifying transporter proteins and detoxification genes like phytochelatin synthase and metallothioneins. While some edits increase metal accumulation, excessive uptake can reduce plant tolerance, showing the importance of balancing accumulation with detoxification. Tang *et al.* (2026) developed cadmium tolerant rice by pyramiding alleles of OsHMA3 and OsNRAMP5 which improved cadmium regulation, and altered vacuolar transporters enhanced intracellular metal sequestration thereby proposed an effective approach to develop rice cultivars that combine low cadmium accumulation in grains with strong adaptability across diverse environmental conditions.

### Advantages of Biotechnological Methods

- Eco-friendly and sustainable
- Cost-effective compared to chemical methods
- Minimal secondary pollution
- Can be applied in various environments

### Limitations

- Slower compared to chemical methods
- Effectiveness depends on environmental conditions.
- Requires careful monitoring

### Conclusion

Biotechnological approaches offer a highly promising and sustainable solution to the growing problem of environmental pollution. By harnessing natural processes and utilizing living organisms such as microorganisms, plants, and enzymes, these methods can effectively degrade, transform, or remove harmful pollutants from soil, water, and air. Techniques like bioremediation, phytoremediation, molecular techniques and genetic engineering not only restore contaminated ecosystems but also minimize secondary pollution, making them environmentally friendly alternatives to conventional methods. Furthermore, advances in genetic engineering and molecular biology are enhancing the efficiency and adaptability of

these biological systems. As research continues to evolve, biotechnology is expected to play an increasingly vital role in ensuring a cleaner, safer, and more sustainable environment for future generations.

## References

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