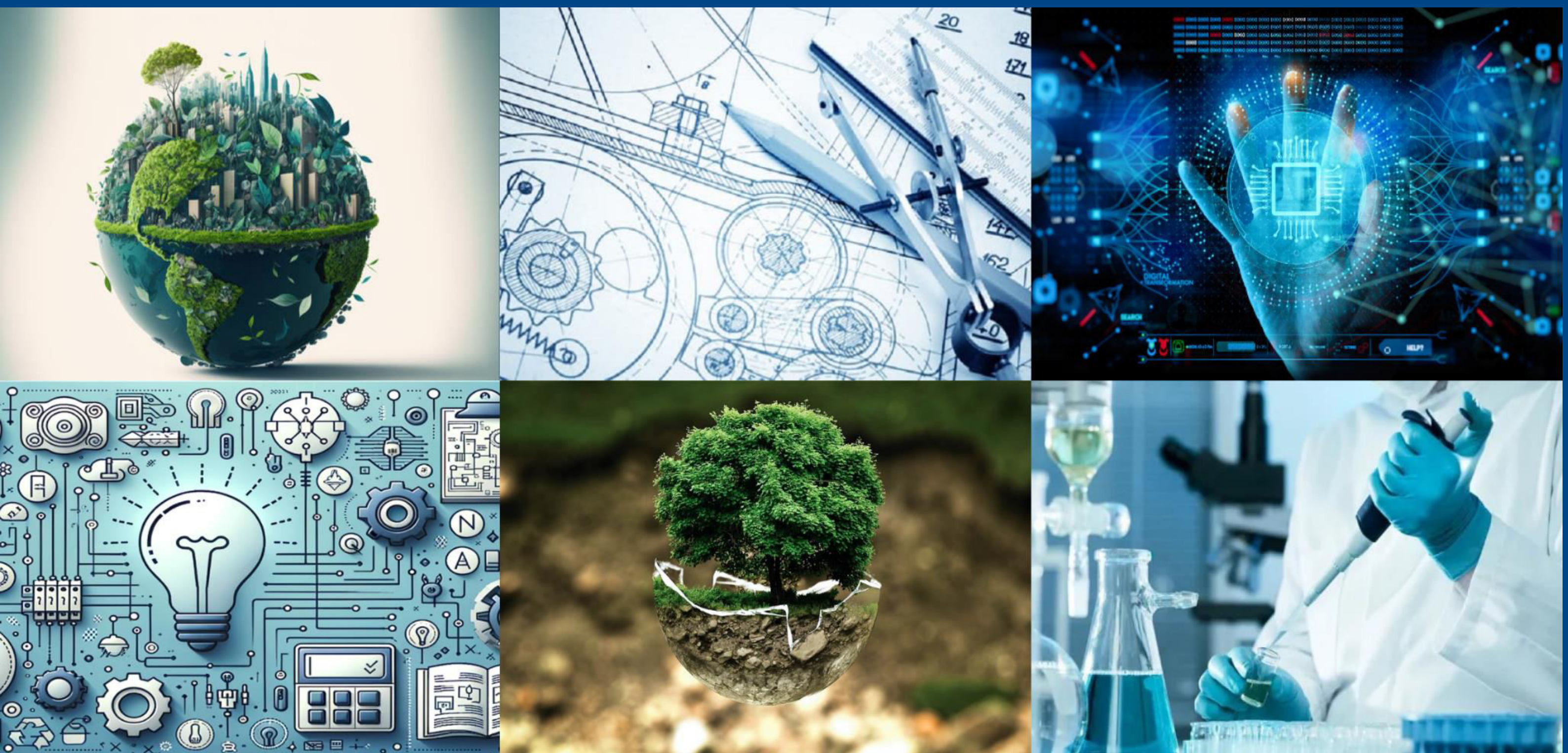
ISSN: 2582-7219

International Journal of Multidisciplinary Research in Science, Engineering and Technology

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.206

Volume 9, Special Issue 1, April 2026

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International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

| ISSN: 2582-7219 | www.ijmrset.com | Impact Factor: 8.206| | Monthly Peer Reviewed & Refereed Journal |

|| Volume 9, Special Issue 1, April 2026 ||

International Seminar on Green Trends-Pioneering Environmental Sustainability (ISGTPES – 2025)

Organized by

Department of Botany, Babu Jagjivan Ram Government Degree College (Autonomous), Hyderabad, Telangana, India

|DOI:10.15680/IJMRSET.2026.0904601|

Bioremediation: Letting Nature Fix What We Break

E.M.Sunitha [1], B.Ravi [2] B. Judson Finny[3]

Associate Professor, Department of Botany, B.J.R. Government Degree College (A), Vittalwadi, Narayanguda, Hyderabad, India [1]

Lecturer, Department of Botany, B.J.R. Government Degree College (A), Vittalwadi, Narayanguda, Hyderabad, India [2]

B. Sc MB-Z-CS II Year, B.J.R. Government Degree College (A), Vittalwadi, Narayanguda, Hyderabad, India[3]

ABSTRACT: Bioremediation is a natural and environmentally friendly process involving the use of microorganisms to decontaminate contaminated soil and groundwater, thus transforming contaminants into harmless products like water and carbon dioxide. This process offers a sustainable alternative to traditional energy-intensive clean-up technologies that are frequently used for the treatment of toxic wastes generated from industrial processes such as mining, agriculture, manufacturing, and the burning of fossil fuels. By stimulating native microbes or adding specialty bacteria and fungi, this technology increases the inherent ability to biodegrade toxins, such as petroleum hydrocarbons, heavy metals, pesticides, and volatile organic compounds, to restore habitats without invasive drilling or toxic chemical treatment.

KEYWORDS: Bioremediation, fossil fuels, hydrocarbons, heavy metals, pesticides.

I. INTRODUCTION

In India, the pace of industrialization and urbanization has exposed the environment to many toxic pollutants. Pollutants released during industrial operations have become leading causes of soil and water contamination. Heavy metals are emitted during production and released as effluents. Wastewater from dye production plants in India, for instance, has been shown to contain antimony, chromium, and mercury. Likewise, the extensive application of fertilizers, pesticides, and herbicides in agriculture adds contaminants like aluminium, copper, zinc, nickel, lead, and arsenic to the environment. Release of untreated effluents from agri-food industries into rivers also accelerates environmental degradation.

These metals are extremely poisonous to aquatic and terrestrial environments. In humans, metal exposure from mercury, cadmium, and lead may be damaging to the central nervous system—particularly in infants—and could lead to liver and kidney damage, cardiovascular disease, and impaired reproductive and immune functions. Long-term exposure to cadmium, for example, has been linked with cancers, bone diseases, and other serious health problems. If disposed of improperly, such pollutants not only cause the death of aquatic life but also bioaccumulate in the food chain and cause long-term disease in animals and human beings. Because of such problems, there is a need to rehabilitate environmental pollutants by physical, chemical, or biological means. Therefore, in this review, emphasis is given to the types, mechanisms, challenges, and factors affecting microbial bioremediation in India, along with suggestions on its optimization in both aquatic and terrestrial ecosystems.

Types of pollutants and their toxic effect on living things:
Different pollutants pose serious health risks to both humans and the environment in India. Air pollutant exposure—like particulate matter, nitrogen oxides, sulfur dioxide, and volatile organic compounds—can result in developmental disorders, respiratory and cardiovascular illnesses, cancers, and other health ailments.For example, high levels of particulate matter in urban areas have been linked to an increased risk of premature death, while nitrogen oxides and sulfur dioxide released on combustion and combustion of fossil fuels result in coughing, breathing difficulty, and exacerbation of diseases like asthma. Volatile organic compounds released by paints, cleaning products, and automobile emissions may lead to irritation of eyes, nose, and throat and are carcinogenic, e.g., benzene. Water pollution is another vital concern, where pesticides, heavy metals, and organic chemicals enter water bodies

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through industrial effluent and agricultural runoffs.These pollutants get bioaccumulated in the food web and cause cancers, neurological damage, and reproductive problems among humans, while heavy metal toxicity causes hypertension and kidney disease.

In addition, pollutants have negative impacts on animals and plants in India. Airborne particulate matter may irritate the animal's respiratory systems, causing inflammatory diseases, chronic in nature. If wildlife has ingested polluted water containing injurious substances, it might incur reproductive disorders, liver impairment, and even develop cancer. Sulphur dioxide in plants depresses growth as well as crops, while nitrogen dioxide leads to acid rain as well as accelerates soil pollution. Too much nitrogen in marine and freshwater leads to algal blooms, displacing fish variety and general equilibrium in the system.

Types-of-Remediation

In India, there are different remediation approaches applied to combat pollution, ranging from physical, chemical, and biological processes. Physical remediation employs skimmers, sorbent materials, and booms—barriers that soak up oil pollutants and hinder their spreading until further clean-up can be completed. Skimmers and sorbents are utilized to trap more pollutants, though limitations like the reliance on the buoyancy and roll response of booms can hamper their effectiveness.

Chemical remediation is the process of introducing compounds such as clay minerals, phosphates, biochar, aluminium salts, and other substances to stabilize and eliminate heavy metals from the environment. The process operates through mechanisms such as adsorption, reduction, oxidation, complexation, precipitation, and ion exchange, providing a quick and easy solution, although the chemicals involved at times may cause additional pollution. Bioremediation, in contrast, employs organic agents like plants and microbes to detoxify pollutants in a sustainable, cost-effective, and safe process. Microbes are generally used in India for their fast growth and ease of manipulation, which makes them a valuable tool towards increasing environmental sustainability.

Mechanisms-of-Microbial-Bioremediation

In India, microbes help remove pollutants using two broad types of mechanisms: mobilization and immobilization. Mobilization transforms pollutants into less harmful or more removable forms using processes such as enzymatic oxidation, enzymatic reduction, bioaugmentation, and biostimulation. Conversely, immobilization transforms contaminants into less bioavailable forms, by mechanisms such as bioaccumulation, complexation, biosorption, and precipitation.

Enzymatic-Oxidation

By excreting oxidoreductase enzymes, microbes are able to decrease the toxicity of harmful chemicals in the pollution by converting the chemicals into a lower oxidation state. Since enzymes such as laccase catalyze reactions that transform complex substances such as dyes and phenols into less toxic molecules, this process is particularly efficient at degrading them.

Enzymatic-Reduction

In enzymatic reduction, microorganisms reduce pollutants to an insoluble form in which they are less toxic.Carried out by both obligate and facultative anaerobes, this process is effective against contaminants like certain chlorinated compounds. There are enzymes such as chrome reductase, which convert very harmful chromium substances to less harmful forms.

Bioaugmentation

Bioaugmentation is applying specific or genetically engineered microbes to contaminated areas in order to speed up the natural degrading process.

It has been done in India by isolating and sometimes changing indigenous microbial strains so they can degrade pollutants more efficiently. The success of bioaugmentation relies on the capacity of introduced strains to compete with the native microbes and sustain viability under local-conditions.

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Biostimulation
Biostimulation enhances the activity of native microbes by supplementation with essential nutrients (e.g., nitrogen, phosphorus, and potassium), metabolites, or electron acceptors and donors, which are lacking in the polluted environment.It is inexpensive and a nonharmful strategy because it relies on utilizing the prevailing microbial flora for degradation improvement of the contaminants.

Bioaccumulation
Bioaccumulation is a phenomenon in which microorganisms accumulate toxicants at a higher rate compared to excreting them, resulting in an increase in harmful substances within the cells. It has been observed in various microbe species of India by the process of carrier-mediated transport, protein channels, and ion pumps to trap heavy metals.

Precipitation
Precipitation is the process of transforming heavy metals or other contaminants into insoluble precipitates or crystals and thus lowering their toxicity. Microbial processes may initiate biogeochemical processes that lead to the deposition of metals in mineralized form. For example, some bacteria are capable of modifying the chemical conditions (e.g., pH) to favor the development of precipitates, and this is a significant natural process employed in the remediation of polluted sites in India.

II. RECENT-DEVELOPMENTS-IN-MICROBIAL-BIOREMEDIATION

Microbial-Glycoconjugates
In recent research work conducted in India, it has been established that microbial glycoconjugates are capable of lowering the surface tension, making pollutants more bioavailable, and forming a solvent interface to enhance the degradation of organic pollutants like petroleum hydrocarbons.

Microbial-Biofilms
The application of microbial biofilms, which consist of polysaccharides, extracellular DNA, and proteins, has enhanced the remediation of recalcitrant organic pollutants. Improvements in the control of quorum sensing, environmental conditions, and adhesion surfaces have made them more effective, as evidenced by dramatic decreases in arsenic concentrations in treated wastewater.

Nanotechnology
Nanomaterials are also being studied as potential bioremediation agents. Their size, shape, chemical composition, and surface modification all affect how effective they are. For example, carbon dot nanoparticles are gaining popularity due to their abundance, nontoxicity, and unique optical characteristics that facilitate the breakdown of pollutants.

III.CONCLUSION

Current advances in microbial bioremediation in India have highlighted the possibilities of exploiting natural processes in controlling environmental pollution. Microbial glycoconjugates, biofilms, bio-electrochemical systems, and nanotechnology integration are among the techniques that have been proven to boost significantly the breakdown of organic pollutants as well as decreasing the concentration of heavy metals in the ecosystems. These new technologies not only aid in the construction of a healthier and cleaner surroundings by lowering amounts of pollutants present in soil, water, and air, but also enable sustainable and economically feasible alternatives to old, more contaminating remediation practices.

IV.FUTURE-PROSPECTS

More Microbial Skills Are Needed:
There is room for more research to find new bacteria and enzymes to break down different pollutants more rapidly and effectively, especially industrial pollutants.

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More Genetic Manipulation and Monitoring:
Further research should focus on developing systems for the rapid detection of biodegradation rates and genetic modifications of existing microorganisms for enhanced degradation of pollutants. The use of multiple microbial consortia in combination may further enhance remediation-efficiency.

Treatment of Inorganic Pollutants:
Expansion of research to include microbes capable of degrading long-term inorganic pollutants—e.g., those from nuclear effluent and other industrial waste—is a major area to be developed.

Integration with Nanotechnology and Policy Awareness:
It is possible to enhance the activity and stability of remediation agents by integrating microbial bioremediation with nanomaterials. Additionally, increasing awareness among policymakers and the public will lead to the integration of these green technologies with conventional methods.

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