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ECO-RESTORATION THROUGH INDIGENOUS MICROORGANISMS: A REVIEW OF ADVANCES IN BIOREMEDIATION AND WASTE CONVERSION

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ABSTRACT

Environmental protection from hazardous and toxic chemical deposition is a critical global concern. Bioremediation, an economical and eco-friendly method, has emerged as a promising solution. Among various strategies, the use of Indigenous Microorganisms (IMOs)–microbes naturally present in a given environment–offers significant advantages. These autochthonous microbial populations play essential roles in biodegradation, bioleaching, biocomposting, nitrogen fixation, toxicity reduction, fertility enhancement, and the synthesis of plant growth-promoting hormones. IMOs contribute to mineral extraction, sustainable agriculture, and effective waste management across various regions. Their absence would negatively impact all life forms and ecosystem functions. This chapter emphasizes the importance of conserving and utilizing indigenous microbes to transform waste into valuable bioresources, thereby facilitating environmental restoration. The diversity of IMOs depends on their collection and isolation methods, which are influenced by specific environmental conditions. Overall, the promotion of IMO-based technologies can bridge the gap between anthropogenic waste generation and ecological balance.

1. INTRODUCTION

Microorganisms possess remarkable diversity and biosynthetic potential that can be modulated by their environment, making them ideal candidates for solving complex biological and environmental challenges. Harnessing native microbial communities for sustainable development offers economic, social, and ecological benefits, reflecting a shift from conventional methods to advanced biotechnological interventions (Birgovan (Rhazzali) et al., 2025; Lofthus et al., 2021). The widespread use of agrochemicals–such as synthetic fertilizers, pesticides, and herbicides–has indeed boosted crop productivity. However, the environmental degradation and decline in soil health associated with their use have prompted a search for eco-friendly alternatives (Derpsch et al., 2024; Firincă et al., 2023; Kundu & Biswas, 2025). One such alternative lies in utilizing soil-dwelling microbes as bioinoculants, which can promote plant growth, enhance nutrient uptake, and offer protection through antibiotic and siderophore production. In recent decades, advances in molecular tools and biotechnological techniques have significantly deepened our understanding of microbial diversity and its application in sustainable agriculture (Athanassiou et al., 2018; Derpsch et al., 2024). The recognition of microbes' vital role in ecological balance has further accelerated interest in exploiting both cultured and uncultured microbial resources. High-throughput sequencing and metagenomic analyses have revealed vast unexplored microbial genomes that harbor novel genes and bioactive molecules, some of which have already been developed into marketable products. Many bio-based chemicals like ethanol, butanol, organic acids, and amino acids, traditionally synthesized using petrochemical processes, are now also obtained via microbial fermentation (Lin et al., 2023; Vassilev et al., 2021).

The cultivation process for IMOs typically involves multiple stages:

- IMO-1: Microorganisms are first cultured on cooked rice in wooden boxes;
- IMO-2: The culture is stabilized with brown sugar;
- IMO-3: The mixture is propagated further using rice bran or wheat mill run;
- IMO-4: The final culture is blended with local soil, such as clay or anthill soil.

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This mature culture is then used in composting or directly applied to agricultural fields. Additional natural inputs like fermented plant juices, calcium from eggshells, fish-based amino acids, and phosphate from animal bones are used in synchrony with plant growth stages to enhance fertility and crop yield. These inputs are environmentally safe and cost-effective, making natural farming a sustainable optionThe benefits of using IMOs include: reduced input costs (up to 60%), enhanced crop quality and yield, improved plant health and resistance, environmentally safe with zero chemical emissions.

Although much research has been conducted with microbial biotechnology, the coupling of IMOs and waste conversion/eco-restoration is still fairly limited. Most previous studies focus on microbial diversity or biofertilizer elaboration only (Díaz-Rodríguez et al., 2025; Gadd, 2010; D. P. Singh et al., 2016). The current study attempts to address this gap by investigating the potential of locally adapted IMOs for both bioremediation and bioresource recovery. The unique focus on indigenous microbial communities versus laboratory-developed strains and assessment of their applicability for affordable, decentralized environmental treatment has strengthened the scope of this review.

The review is mainly dedicated to the role of Indigenous Microorganisms (IMOs) in soil and waste enriched ecosystems, underlining their potentiality for bioremediation, composting and sustainable production of crops. Through highlighting the role of autochthonous microbial communities rather than exogenously introduced species, our study reinforces that context-specific strategies should be adopted for environmental recovery.

In general, this review intends to establish ecological and functional importance of indigenous microorganisms (IMOs) in waste conversion and environmental remediation. It discusses the cultivation and application of IMOs in various ecological systems, their potential to improve soil health and remediate pollutants, and how to include IMO into practical, sustainable eco-restoration projects. It focuses on naturally evolved microbial consortia. The discussion highlights their potential as low-cost, sustainable tools for enhancing environmental sustainability and circular bioresource recovery.

1.1 List of abbreviations

- ABA Autochthonous Bioaugmentation
- ATP Adenosine Triphosphate
- DCE Dichloroethylene
- DDT Dichlorodiphenyltrichloroethane
- EDTA Ethylenediaminetetraacetic Acid
- EMs Effective Microorganisms
- IAA Indole-3-Acetic Acid
- IMO Indigenous Microorganism
- IMOs Indigenous Microorganisms
- PAHs Polycyclic Aromatic Hydrocarbons
- PCE Tetrachloroethene
- RDX Research Department Explosive (Cyclotrimethylenetrinitramine)
- SVE Soil Vapor Extraction
- SVOCs Semi-Volatile Organic Compounds
- TCE Trichloroethylene
- VOCs Volatile Organic Compounds
- 2,4-D 2,4-Dichlorophenoxyacetic Acid

2. POLLUTION: A GLOBAL CHALLENGE

Environmental pollution, especially from hydrocarbons, heavy metals, oil spills, and synthetic herbicides like 2,4-D, remains a pressing concern. Microbial biodegradation has emerged as an effective remediation strategy. “Intrinsic bioremediation” refers to the natural breakdown of contaminants by native microbes without external intervention. This process typically involves microbial enzymatic conversion of pollutants into less toxic or inert products. Under aerobic conditions, oxygen acts as the terminal electron acceptor, enabling the complete oxidation of organic compounds. In contrast, anaerobic degradation produces intermediates like methane, organic acids, and hydrogen, with electron acceptors such as nitrate, sulfate, or bicarbonate (Aitken et al., 2004). The success of these processes depends on several factors, including soil pH, moisture, oxygen availability, nutrient content, and microbial diversity. Excellent degradation efficiencies have been observed in the field. For instance, in situ microbes from petroleum reservoirs and deep subsurface have been reported to be efficient in hydrocarbons degradation, reaching more than 99% removal of n-alkanes and PAHs in Dagang oil fields China (Lofthus et al., 2021). Analogous native consortia have been described in other polluted habitats where they orchestrate detoxification of pollutants by mediating enzymatic oxidation, biosorption and redox cycling.

Studies have shown that indigenous microbes are also present in petroleum reservoirs and deep subsurface environments, playing significant roles in hydrocarbon degradation (Magot et al., 2000).

These findings underscore the ecological value of site-specific microbial populations in mitigating pollution. However, the full potential of such indigenous microorganisms (IMOs) remains underutilized, particularly in integrated frameworks combining waste conversion and environmental restoration. Understanding and harnessing these naturally adapted consortia aligns directly with the broader objective of this study–to promote IMOs as sustainable, low-cost agents for achieving pollution mitigation and ecosystem resilience.

3. INDIGENOUS MICROORGANISMS AS BIOFERTILIZERS

Native Microbial Consortia (Indigenous microorganisms; IMOs) are the local environmental microbial diversity which develop into complex and adaptive ecosystems. In contrast to commercial EMs, IMOs are harvested from indigenous soils in situ with the ecosystemic structure and functional diversity intact. These organisms play a key function in the cycling of nutrients such as biological nitrogen fixation, and phosphate solubilization, posing beneficial effects on soil structure through poly - saccharides production and soil aggregation. They also produce plant growth promoting hormone (indole-3-acetic acid; IAA) and suppress soil borne pathogens by secreting antibiotics and siderophores (Kumar & Gopal, 2015; Solanki et al., 2023). Similarly, inoculation with fluorescent Pseudomonas species increased Vigna mungo yield by almost 300% as compared to uninoculated controls. These results demonstrate that locally adapted microbial communities can remediate nutrient imbalance and reliance on synthetic fertilizers.

Apart from nutrients management the ecological resilience of IMOs enhances sustainability in agriculture by maintaining soil health, decreasing greenhouse gas generation and conserving biodiversity. These characteristics of inherent fertility-building and the potential for adaptation make them especially useful for low-input and organic farms. By adopting and promoting the connection between microbial ecology and agronomic performance, IMOs are in essence the focus of this paper–accelerating microbe-based methods for sustainable maintenance of long-term soil fertility and ecological reconciliation (Hayat et al., 2010).

4. BIOLEACHING OF HEAVY METALS

Managing metal-contaminated water from mining and metallurgical industries is crucial both for economic recovery and environmental safety. Bioleaching, or microbial-assisted metal removal, is a cost-effective and environmentally friendly alternative to traditional physicochemical methods (Dianatdar & Etemadifar, 2024; Dong et al., 2023; Sarkodie et al., 2022). Indigenous microbes–adapted to the specific conditions of mine sites–often show superior performance in bioleaching under acidic or metal-rich environments. Studies have utilized native strains of *Shewanella, Bacillus subtilis, and Brevundimonas* to remove calcium, magnesium, and iron from contaminated surface waters. Both living and non-living microbial biomass have demonstrated efficient metal biosorption through passive and active mechanisms. Indigenous strains are preferred due to their inherent tolerance to local environmental stresses and higher biosorption efficiencies (Fosso-Kankeu et al., 2009, 2010; Li et al., 2024; Priya et al., 2021). Figure 1 illustrates the the management objectives and remediation strategies used to address metal pollution. The primary goals–economic recovery and environmental safety–guide the selection of remediation approaches. Among these, bioleaching using indigenous microbes such as *Shewanella, Bacillus subtilis, and Brevundimonas* represents a sustainable alternative to conventional physicochemical methods.

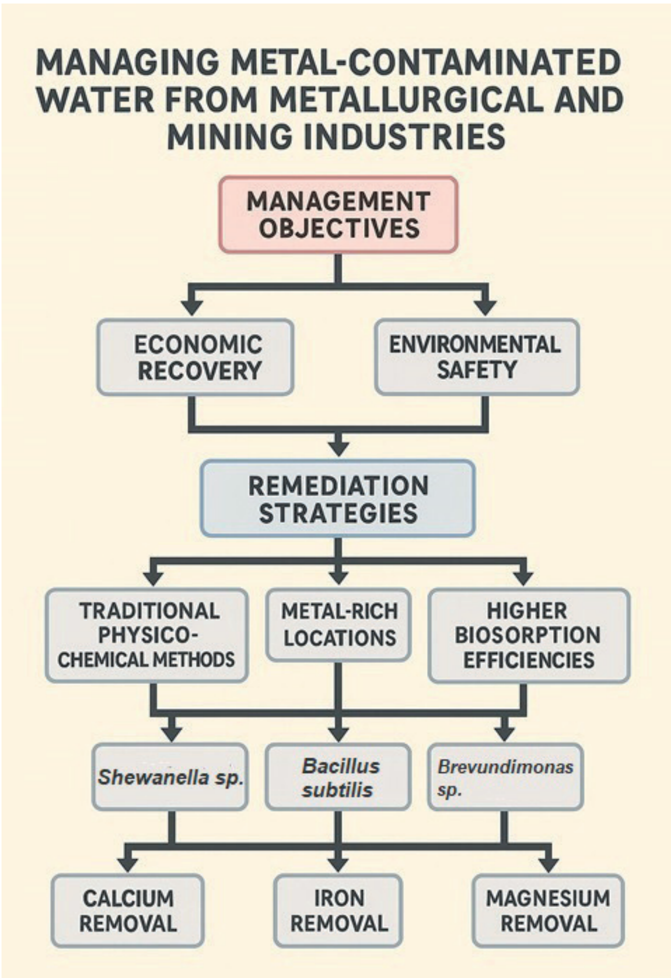

FIGURE 1: Conceptual framework for managing metal-contaminated water. The flowchart illustrates the hierarchy of management objectives and remediation strategies used to address metal pollution in mining and metallurgical industries.

These microbial systems exhibit high biosorption efficiencies in metal-rich environments, facilitating the removal of metals like calcium (Ca), iron (Fe), and magnesium (Mg) from contaminated waters. The process underscores the role of native microbial communities in achieving efficient, eco-friendly metal remediation and resource recovery.

4.1 Metal removal mechanisms by microorganisms

Microbial removal of metals from aqueous solutions occurs through two primary mechanisms: biosorption and bioaccumulation. Biosorption is a passive, energy-independent process in which functional groups—such as carboxyl, hydroxyl, amino, or phosphate groups—on microbial cell surfaces bind metal ions from the surrounding environment. Conversely, bioaccumulation involves the active uptake of metals into the microbial cytoplasm, relying on energy expenditure through ATP hydrolysis (Molaey et al., 2024).

4.2 Bioleaching of heavy metals using indigenous iron-oxidizing microorganisms

The increasing global population has led to a rise in heavy metal concentrations within municipal sewage sludge. Conventional methods such as EDTA-assisted extraction or acid leaching are often inefficient, particularly for elements like Fe, Ni, and Cr, and they pose cost and environmental challenges (Luo et al., 2023). Bioleaching, an emerging microbial technique, offers an eco-friendly and cost-effective solution for heavy metal removal from sludge (S. Singh et al., 2016). Experimental studies by Chen C, et al. demonstrated that iron-oxidizing indigenous bacteria, when supplemented with $FeSO_4$, efficiently solubilized metals such as Cu, Zn, Ni, and Pb from anaerobically digested sewage sludge (Chen et al., 2022). More than 80% of these metals were removed after 16 days. Similarly, Pathak et al. observed that indigenous iron-oxidizing strains showed enhanced leaching performance compared to non-inoculated controls (Pathak et al., 2014). Factors such as pH, solid concentration $FeSO_4$ dosage, and inoculum concentration significantly influenced the bioleaching efficacy. The microbial species *Acidithiobacillus ferrooxidans* and *A. thiooxidans* are widely recognized for their critical role in bioleaching. Iron-based leaching is often more effective than sulfur-based pathways due to its superior sludge acidification capacity. Research by the same group also revealed that parameters such as pH, redox potential, agitation time, and sulfate levels are key in optimizing metal removal from industrial sludge using *A. ferrooxidans* (Zhou et al., 2013). Table 1 presents a comparative overview of various bioremediation techniques employed in environmental cleanup using indigenous microorganisms. It includes aerobic, anaerobic, and cometabolic bioventing, natural farming, and bioleaching among others. Each method is described by its target pollutants, the role of indigenous microbes, oper-

TABLE 1: Summary of current remediation methods using indigenous microorganisms.

Remediation Method	Target Pollutants / Application	Key Microbial Action	Limitations	References
Aerobic Bioventing	Non-chlorinated VOCs, SVOCs, hydrocarbons	Aerobic degradation with added oxygen	Ineffective in highly permeable or overly aerobic soils	(Frascari et al., 2015)
Cometabolic Bioventing	Chlorinated solvents like TCE, DCE	Cometabolism via monooxygenase enzymes	Limited data; design challenges for shallow or moist soils	(Sui et al., 2006)
Anaerobic Bioventing	Highly chlorinated compounds like PCE, TCE, DDT	Anaerobic reductive dechlorination and cometabolism	Slow process, requires reducing conditions, gas distribution complexity	(Baczynski & Pleissner, 2009)
Natural Farming with Indigenous Microorganisms	Improves soil health, nutrient cycling, structure	Mycorrhizae and beneficial IMOs improve soil and plant health	Climatic sensitivity, requires consistent microbial propagation	(B. L. Kumar & Gopal, 2015)
Biocomposting with Indigenous Microorganisms	Composting agro-waste (e.g., corn stalk, paddy husk)	Microbial breakdown of crop waste into humic substances	Quality dependent on feedstock; variable decomposition rates	(B.L. Kumar & Gopal, 2015)
Bioremediation of Organic Pollutants	Organic compounds (e.g., diesel, pesticides)	Indigenous microbes degrade hydrocarbons and VOCs	Dependent on pollutant type and site conditions	(Kuppan et al., 2024)
Bioaugmentation and Biostimulation	Hydrocarbons, crude oil	Enhanced degradation via nutrient addition or native microbes	Requires balance of nutrients, environmental parameters	(Nikolopoulou & Kalogerakis, 2016; Yaman, 2020)
Ozonation + Indigenous Microbes	PAHs in diesel-contaminated soils	Ozone oxidizes pollutants, microbes degrade byproducts	Microbial population reduction due to prolonged ozone exposure	(Caniani et al., 2021)
2,4-D Bioremediation using Fe3O4 Nanoparticles + Indigenous Microbes	Herbicide 2,4-D	Enhanced mineralization of herbicide with synergistic action	Requires nanoparticle synthesis, site-specific microbial matching	(Fang et al., 2012)
Arsenic Bioremediation with Indigenous Bacteria	Arsenic (As) in contaminated soils	Arsenic methylation, volatilization under aerobic/anaerobic conditions	Limited to arsenic-tolerant strains; requires enriched conditions	(Majumder et al., 2013; Naiel et al., 2024)

VOCs – Volatile Organic Compounds, SVOCs – Semi-Volatile Organic Compounds, TCE – Trichloroethylene, PCE – Tetrachloroethene, DDT – Dichlorodiphenyltrichloroethane, IMO – Indigenous Microorganisms, PAHs – Polycyclic Aromatic Hydrocarbons, SVE – Soil Vapor Extraction, ABA – Autochthonous Bioaugmentation ational limitations, and recent supporting references (from the last five years). The table provides a concise framework for understanding the scope, applicability, and challenges associated with each strategy in sustainable environmental remediation.

4.3 Microbial mitigation of arsenic pollution

Arsenic (As), a toxic metalloid of both geogenic and anthropogenic origin, poses severe risks to human and environmental health. Microorganisms have evolved several tolerance mechanisms, such as efflux pumps encoded by the ars operon, enabling survival in arsenic-rich environments (Navarro et al., 2022). Bioremediation of arsenic typically involves its conversion into less toxic or volatile methylated forms by bacteria and fungi (Periferakis et al., 2022). Indigenous bacterial strains isolated from submerged paddy soils have demonstrated high tolerance to arsenite and arsenate–the more toxic inorganic forms of arsenic (Majumder et al., 2013).The isolate AMT-08, in particular, was capable of removing up to 16% of arsenic in 60 days when supplemented with organic manure. These microbes outperform strains from other sources (e.g., geothermal sites or gold mines), making them promising agents for cost-effective, eco-friendly arsenic bioremediation (Kaur et al., 2009; Keren et al., 2022). Their enhanced volatilization potential, especially under anaerobic conditions, supports their use as alternatives to genetically engineered organisms for real-world applications (Naiel et al., 2024).

5. OIL SPILL BIOREMEDIATION

Oil spills remain a serious environmental concern, particularly in marine and coastal ecosystems. Bioremediation has emerged as an effective approach, primarily through bioaugmentation (introducing specific degraders) and biostimulation (stimulating indigenous microbes with nutrients) (Nikolopoulou & Kalogerakis, 2016; Tribedi et al., 2018). While native microbial communities may struggle to degrade the complex mixture of hydrocarbons in crude oil, supplementation with specialized oil-degrading microbes can enhance the process (Bôto et al., 2021). A promising advancement in this field is autochthonous bioaugmentation (ABA), which involves isolating, enriching, and reintroducing indigenous strains from contaminated sites to enhance remediation. This method, proposed by Yaman offers superior adaptability and survival compared to external inocula. As proposed by Natural Biodegradation Guidance in 2003, effective bioremediation also depends on optimizing physicochemical conditions like nutrient availability, aeration, and surfactant activity (Yaman, 2020). Field study applications have demonstrated that the adjustment of these factors according to the local site conditions, including salinity temperature, hydrocarbon composition, can promote enhanced bioremediation. Such tailor-made development to ensure that indigenous consortia are kept active metabolic and environment-wise, further contributes towards a better recovery of oil-polluted coastal zones. One such recent study reports the bioremediation of coastal sand contaminated by fuel: over ~106 days the total petroleum hydrocarbon level dropped from ~5,753 mg/kg to ~37 mg/kg (~98.2% removal)(Ben Laish et al., 2025).

To further enhance degradation, techniques such as ozonation have been applied to increase the bioavailability of hydrophobic compounds. While ozone can break down polycyclic hydrocarbons, prolonged exposure reduces microbial viability. Thus, a combined approach of pre-ozonation followed by biostimulation of surviving indigenous microbes, as studied by Caniani et al., has proven effective (Caniani et al., 2021). This combination of chemical oxidation with biostimulation is indicative of how hybrid nature can be optimized for site-specific remediation. Under field conditions, these strategies support a sequential pollutant degradation: hydrocarbons are first decomposed into simpler intermediates by ozonation and then composed to harmless end product by microorganisms. Indigenous microorganisms are especially well-suited for these successive treatment plans due to their flexibility (Olak-Kucharczyk et al., 2023; Tamizhdurai et al., 2022).

This strategy not only improves the bioavailability of contaminants but also supports microbial regrowth over time. Figure 2 elaborates the combined use of these methods in an explicit way. The combination strategy will enhance the broader mission of developing resilient indigenous microbial systems as a model strategy for engineering practical, sustainable and locally-applicable solutions to oil spill remediation and environmental restoration. The process involves bioaugmentation, where specialized oil-degrading microorganisms are introduced to enhance hydrocarbon degradation, and biostimulation, which optimizes nutrient levels, aeration, and surfactant activity to support indigenous microbial populations. Autochthonous bioaugmentation (ABA) utilizes site-derived microbial strains for improved adaptability and persistence under local environmental conditions. Ozonation is applied as a pre-treatment to increase hydrocarbon bioavailability by partially oxidizing complex hydrocarbons, followed by aeration to sustain the activity and regrowth of indigenous microbial communities, ensuring long-term ecosystem recovery.

6. COMBINED BIOREMEDIATION OF 2,4-D HERBICIDE USING FE_3O_4 NANOPARTICLES AND INDIGENOUS MICROBES

The combined use of Fe_3O_4 nanoparticles and native soil microorganisms has been shown to improve the degradation of herbicide residues like 2,4-dichlorophenoxyacetic acid (2,4-D). Fang et al. demonstrated that this synergistic approach outperformed treatments using either agent alone. Enhanced breakdown of 2,4-D into its intermediates –2,4-dichlorophenol, chlorophenol, and phenol – was observed, offering a viable solution for remediating pesticide-contaminated soils (Fang et al., 2012).

7. ROLE OF INDIGENOUS MICROORGANISMS IN NATURAL FARMING

In natural farming, indigenous microorganisms (IMOs) support plant nutrition through the development of my-

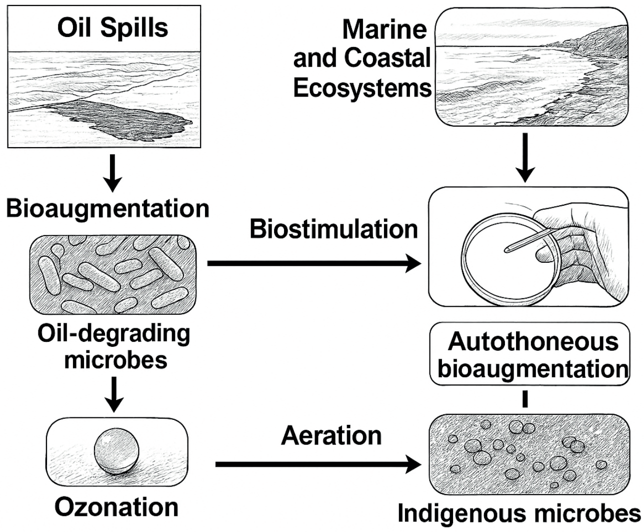

FIGURE 2: Integrated bioremediation framework. Conceptual graphics for microbial degradation of oil spills in marine and coastal environments. The process involves bioaugmentation, biostimulation, and ozonation.

corrhizal fungi, which form symbiotic associations with plant roots and extend root networks via extensive fungal filaments. These fungi convert complex nutrients into simpler, bioavailable forms and promote soil carbon sequestration through glomalin production, which improves soil aggregation and structure. The use of IMO-based inoculants in farms across 30+ countries has shown improvements in soil texture, tilth, and earthworm activity, contributing to plant vigor and ecosystem resilience (Surpura et al., 2025).

7.1 Biocomposting with indigenous microorganisms

Traditional practices of burning agro-industrial residues such as paddy husk or corn stalk release harmful pollutants and contribute to soil erosion. Composting with IMOs offers a sustainable alternative, converting waste into nutrient-rich amendment. Recent research demonstrated that combining corn stalk with IMO inoculant yields compost with significantly better chemical properties compared to paddy husk-based compost. IMOs accelerate composting processes, enrich microbial diversity, and enhance soil fertility–making biocomposting both eco-friendly and economical (Surpura et al., 2025).

8. FACTORS INFLUENCING MICROBIAL BIOREMEDIATION

Environmental parameters critically shape the effectiveness of native microbe-based bioremediation. Key factors include:

- pH: Near-neutral pH levels optimize bacterial growth and metabolic activity, accelerating biodegradation rates;
- Temperature: Mesophilic temperatures (20-40°C) support efficient microbial activity, while thermophilic species can perform degradation at elevated ranges (60-70°C);
- Water Content: Soil moisture levels with water activity ≥0.9 are essential for microbial metabolism and contaminant breakdown;
- Soil Texture: Porous, well-structured soils enhance oxygen diffusion and microbial mobility, improving remediation kinetics;
- Nutrient Levels: Supplementing nitrogen and phosphorus boosts microbial growth and contaminant degradation rates;
- Electron Acceptors: Adequate oxygen availability, or addition of oxidants like hydrogen peroxide, supports aerobic degradation;
- Bioavailability: Adding biosurfactants or solvents can improve desorption of hydrophobic pollutants from soil particles;
- Cometabolism: Some microbes degrade non-growth substrates (e.g., DDT, PCBs) in the presence of growth-supporting co-substrates;
- Gene Expression: Sufficient pollutant concentration is required to induce expression of degradative enzymes and operons.

These elements must be optimized to harness the full potential of indigenous microbes for in situ remediation (Sonawane et al., 2022).

8.1 Aerobic bioventing and cometabolic strategies

Aerobic bioventing injects air or oxygen into contaminated unsaturated soil, stimulating native microbial degradation of hydrocarbons and semi-volatile organic compounds like benzene, toluene, phenol, and light PAHs. Cometabolic bioventing involves adding volatile substrates (e.g. propane, methane) alongside air, which induces enzyme systems (e.g., monooxygenases) capable of transforming chlorinated solvents such as TCE or DCE. Successful in situ applications have demonstrated that indigenous microbial consortia can support simultaneous treatment of multiple dilute contaminants when engineered properly, though substrate competition and toxicity must be monitored (Skinner et al., 2024). Figure 3 is a schematic representation

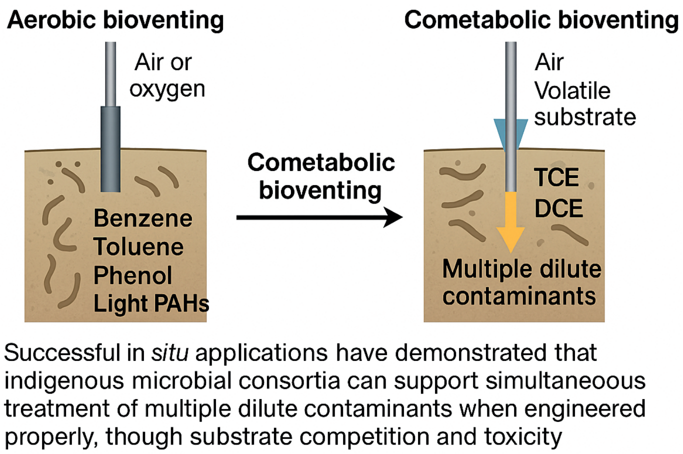

FIGURE 3: Mechanism of Bioventing Strategies. Aerobic bioventing and cometabolic bioventing strategies for in situ remediation of hydrocarbon- and solvent-contaminated soils.

showing the mechanisms of aerobic and cometabolic bioventing. In aerobic bioventing, air or oxygen is injected into the unsaturated zone to stimulate indigenous microbial communities that degrade hydrocarbons and semi-volatile organic compounds such as benzene, toluene, phenol, and light PAHs. In cometabolic bioventing, air is co-injected with volatile substrates (e.g., methane, propane) that induce microbial enzyme systems such as monooxygenases, enabling the transformation of chlorinated solvents including trichloroethylene (TCE) and dichloroethylene (DCE) (CLU-IN, 2020). Field applications have demonstrated that properly engineered systems can support simultaneous degradation of multiple dilute contaminants by indigenous microbial consortia, though substrate competition and toxicity must be managed. Table 2 provides a comparative overview of aerobic and cometabolic bioventing strategies

TABLE 2: Global aerobic and cometabolic bioventing strategies for in situ bioremediation of contaminated soils.

Country / Region	Contaminant Type	Strategy Applied	Key Microbial / Process Insight	Outcome / Efficiency
United States	BTEX (Benzene, Toluene, Ethylbenzene, Xylene)	Aerobic Bioventing	Air injection stimulated native hydrocarbon-degrading bacteria (Pseudomonas, Acinetobacter) in unsaturated soil	>90% BTEX removal within 6 months
Canada	Diesel and light PAHs	Aerobic Bioventing	Continuous oxygen flow increased the oxidation rate of hydrocarbons by indigenous microbes	85–95% reduction of TPH; minimal secondary pollution
Germany	TCE, DCE	Cometabolic Bioventing	Methane-induced monooxygenase activity by methanotrophic consortia facilitated chlorinated solvent degradation	Complete TCE removal in ~150 days
Japan	Aromatic hydrocarbons, chlorinated solvents	Aerobic + Cometabolic Hybrid	Co-injection of methane + oxygen induced Pseudomonas putida and methanotroph enzyme systems	Dual degradation of hydrocarbons and chlorinated solvents; stable microbial population
India (Vadodara, Gujarat)	Petroleum hydrocarbons, phenol, and light PAHs	Aerobic Bioventing	Indigenous consortia (Bacillus, Pseudomonas, Rhodococcus) enriched from refinery soils under oxygen injection	70–95% degradation within 90 days; reduced phenol toxicity and improved soil respiration
India (Assam Oil Fields)	Crude oil and diesel residues	Aerobic + Bioaugmentation	Integration of oxygen sparging with native Alcanivorax and Marinobacter strains	Enhanced hydrocarbon breakdown in 45 days; increased biosurfactant production
China (Dagang)	TCE, DCE in industrial soil	Cometabolic Bioventing	Methane + oxygen injection promoted Methylosinus trichosporium activity	80% solvent removal; reduced substrate competition under optimised ratios
Norway (Arctic Marine Sediments)	Weathered crude oil	Aerobic Bioventing	Oxygen diffusion supported Alcanivorax and Cycloclasticus spp.	>99% n-alkane and >90% PAH removal
Australia	Hydrocarbons, semi-volatile compounds	Aerobic Bioventing	Nutrient-supplemented oxygen injection enhanced microbial metabolism	Efficient degradation with minimal volatilisation
Poland	Chlorinated pesticides (DDT, HCH)	Cometabolic Bioventing	Propane-induced cometabolism under controlled aeration	Slow kinetics; >60% DDT transformation after 12 weeks
South Korea	Mixed hydrocarbon and chlorinated solvent contamination	Sequential Aerobic–Cometabolic	Alternating oxygen + methane pulses enhanced cometabolic enzyme expression	Simultaneous degradation of BTEX and TCE achieved >85% removal efficiency

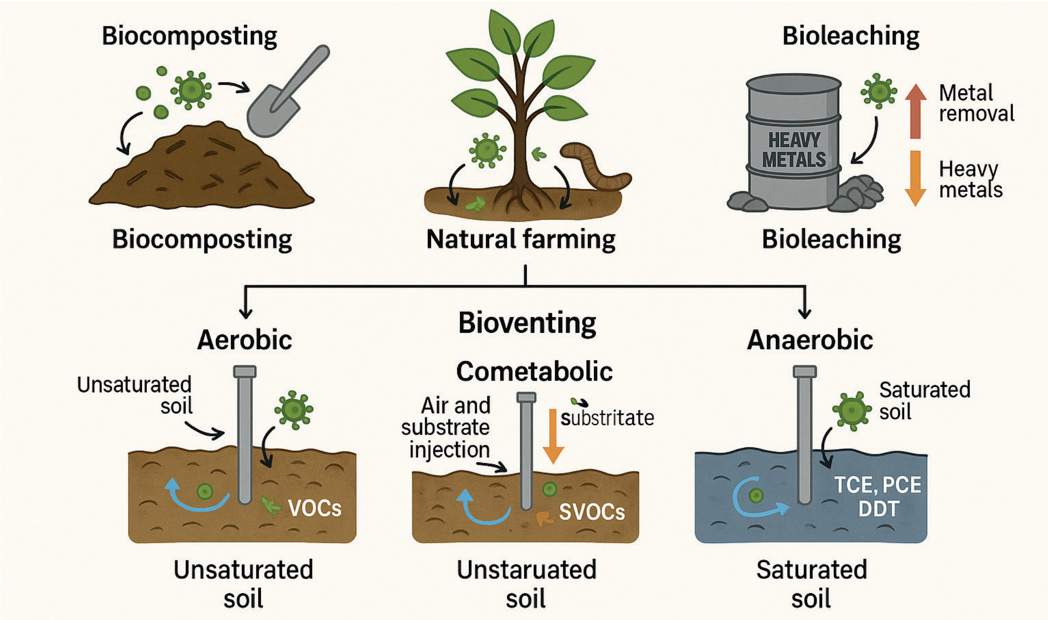

FIGURE 4: Bioremediation with Indigenous Microorganisms. This figure summarizes the multifaceted roles of indigenous microorganisms (IMOs) in environmental remediation strategies. It illustrates the three primary bioventing approaches—aerobic, cometabolic, and anaerobic—highlighting their applications in removing hydrocarbons and chlorinated compounds under varying subsurface conditions.

implemented worldwide, emphasizing in situ applications that use indigenous microbial consortia for the degradation of hydrocarbons and chlorinated solvents. Indian case studies demonstrate the potential of refinery-derived native microbes and soil bioaugmentation under oxygen-enriched conditions to achieve high hydrocarbon removal efficiency while maintaining ecological stability.

8.2 Limitations of cometabolic bioventing

Cometabolic bioventing faces key challenges related to gas distribution in subsurface environments. In low-permeability soils or those with high moisture content, it becomes difficult to uniformly deliver both oxygen and co-substrate gases. As per Federal Remediation Technologies Round table (FRTR), newer tools such as Technology Screening Matrix can improve the designing of Bioventing Designing systems to effectively reach shallow contamination zones without causing vapor intrusions or inadequate aeration presents significant engineering complexities (https://frtr.gov/matrix/bioventing/). The technology is relatively novel and lacks broad field experience. While cometabolic bioventing has shown promise in limited pilot projects, its performance across diverse contaminant profiles remains uncertain. Regulatory acceptance and public familiarity are still evolving, and comprehensive treatability and pilot studies are essential before full-scale deployment As more applications are pursued, these constraints may diminish (Frascari et al., 2015).

8.3 Anaerobic bioventing

Anaerobic bioventing extends the concept of gas delivery into subsurface zones by injecting inert gases like nitrogen, along with electron donors such as hydrogen or CO_2, to establish reducing conditions conducive to anaerobic dechlorination. This method is particularly suited for treating highly chlorinated solvents, such as PCE, TCE, RDX, and DDT, which resist aerobic breakdown. However, the effectiveness of this approach heavily depends on the ability to uniformly distribute gases within the soil matrix. Soils that are waterlogged or low in gas permeability may require complex system designs and extended remediation timelines–often spanning multiple years–making it less suitable for time-sensitive cleanup efforts (Frascari et al., 2015). Figure 4 depicts the beneficial impacts of IMOs in natural farming, bio-composting, and metal removal, showcasing their ecological compatibility and synergistic potential in improving soil structure, enhancing nutrient cycles, and detoxifying pollutants. The interconnected arrows emphasize the integration of these microbial processes into sustainable environmental management. Key elements shown:

- Mycorrhizal symbiosis improving plant-soil interactions;
- Bioventing systems using oxygen or alternative gases for in situ soil remediation;
- Microbial cometabolism pathways utilizing added organic substrates;
- Application of IMOs in agro-industrial waste management and bioleaching of heavy metals;
- Future prospects for climate-resilient, microbe-driven sustainable agriculture.

9. CONCLUSIONS

Environmental sustainability has become a research priority, driving interest in technologies that minimize ecological impact. Indigenous microorganisms offer multifunctional benefits, including contaminant degradation (hydrocarbons, chlorinated solvents, herbicides), nutrient cycling (nitrogen fixation, phosphorus solubilization), soil fertility enhancement, and natural hormone production for plant growth. Because IMOs consist of diverse, acclimated microbial consortia, they integrate effectively into soil ecosystems and often outperform cultured strains in resilience and ecological compatibility. When inoculum density is adequate, IMOs establish positively associative communities that can exert control over native soil microbiota, promoting ecosystem stability and crop productivity. However, further research is needed to optimize strain selection, application protocols, operational conditions, and field-scale performance metrics. Addressing these gaps will enable IMOs to play a central role in future sustainable agriculture and environmental restoration strategies. The review highlights the ecological and functional contribution of Indigenous Microorganisms (IMOs) in promoting waste conversion, soil fertility improvement, and pollutants treatment. The discussion enriches that IMOs, in consideration for locality, as a sustainable and resilient tool for ecological restoration. Despite this, several major knowledge gaps still exist, including the best practices regarding the selection of strains, standardization of method application across different ecosystems and understanding long-term ecological effects under field conditions. Future research needs to focus on the integration of microbial diversity with quantifiable restoration results through field level assessments. Reinforcing these avenues for research would push towards the practical use of IMOs in large-scale, cost-effective bioremediative and sustainable agriculture systems that contribute to global agenda on environmental resistance and resource circularity.

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