Review Article

Microbial Approaches for Bioremediation of Contaminated Environments: Industrial Perspectives

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Abstract: Microorganisms play an indispensable role in numerous industrial sectors due to their remarkable metabolic diversity and adaptability. This review highlights the beneficial applications of microbes in industries such as pharmaceuticals, agriculture, environmental management, food processing, and bioenergy production. Industrial microbiology has evolved from traditional fermentation processes to advanced biotechnological innovations involving genetic engineering, metabolic pathway optimization, and synthetic biology. Microbes such as *Bacillus*, *Aspergillus*, *Saccharomyces*, *Pseudomonas*, and *Streptomyces* are utilized for large-scale production of enzymes, biofuels, antibiotics, organic acids, biofertilizers, and bioplastics. Furthermore, microbial bioremediation offers sustainable solutions for detoxifying industrial effluents and heavy metal contaminants. Recent advancements in omics technologies and bioinformatics have enhanced the identification and manipulation of microbial strains with industrial potential, promoting a circular and green bioeconomy. This paper provides a comprehensive overview of microbial applications in modern industries, emphasizing their contribution to sustainable development and environmental conservation.

Keywords:- Industrial microbiology, bioremediation, biofertilizers, microbial biotechnology, sustainable industry, bioeconomy

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Introduction

Microbes are a diverse group of microscopic organisms, with bacteria representing the most extensively studied members. They play crucial roles across multiple domains, including agriculture, healthcare, environmental remediation, and industrial manufacturing. Their applications range from pollution mitigation to the production of enzymes, metabolites, and biosensors. This review focuses on compiling and analyzing information regarding microbial applications in contaminated water treatment, as well as their roles in the dairy, food, pharmaceutical, and cosmetic industries. Given that microbes represent primary sources of industrial enzymes, they are frequently cultured on a large scale and genetically modified by transferring target enzyme-encoding genes into well-characterized and manageable microbial hosts.

Industrial microorganisms, particularly environmental isolates, possess the inherent ability to synthesize enzymes when provided with appropriate nutrient media. Their rapid growth and ease of clonal expansion make them ideal candidates for large-scale applications. Historically, the first industrial exploitation of microbial enzymes was achieved by Dr. Jokichi Takamine, who derived them from fungi, followed by Boidin and Effront, who reported bacterial enzymes approximately two decades later. In industries such as food, dairy, and leather processing, microorganisms like *Saccharomyces cerevisiae* are directly applied to raw materials to initiate fermentation processes. In contrast, the pharmaceutical industry often cultures microbes to harvest medically significant compounds such as amino acids and enzymes, which are subsequently purified through techniques including bio-affinity chromatography and other advanced separation methods.

In addition to industrial production, microbes play a pivotal role in environmental remediation, particularly through bioremediation strategies. Industrial effluents discharged into soil and water bodies can be effectively degraded using bacteria, algae, and fungi. For instance, a study conducted in Prabumulih, South Sumatra, Indonesia, examined the bioremediation of liquid petroleum waste, assessing both process efficiency and degradation rates. Similarly, *Pseudomonas putida* and *Bacillus cereus* have been shown to degrade crude oil, with *P. putida* achieving 60% degradation of petroleum hydrocarbons in water samples within seven days. These findings underscore their potential as reliable bioremediation tools for addressing oil-contaminated environments.

Microbes in Various Industries

Dairy Industry

Lactococcus lactis

Lactococcus lactis is a Gram-positive, non-motile, facultatively anaerobic bacterium, widely recognized as one of the most important lactic acid bacteria (LAB) in the dairy sector. Its industrial relevance lies in its ability to ferment lactose into lactic acid via the hexose diphosphate pathway. The acidification process lowers the pH of milk, causing protein coagulation, which is a critical step in cheese production. Beyond coagulation, *L. lactis* contributes significantly to the development of flavor, aroma, and texture in a wide variety of cheeses. This bacterium thrives optimally at around 10 °C, but becomes immotile at temperatures exceeding 45 °C. It also demonstrates tolerance to acidic environments and saline conditions, making it highly adaptable for industrial fermentation. Together with *Streptococcus thermophilus*, *L. lactis* is used in yogurt production. Its applications extend beyond cheese and yogurt to fermented milk, sour cream, kefir, and butter. The widespread use of *L. lactis* in starter cultures makes it a cornerstone of dairy biotechnology [(1)].

Streptococcus thermophilus

Streptococcus thermophilus is a Gram-positive, thermophilic lactic acid bacterium capable of fermenting lactose, sucrose, glucose, and fructose. It is widely applied in the production of yogurt, Swiss cheese, and hard Italian cheeses. Its resilience against bacteriophage infection is enhanced by the CRISPR-Cas system, although it remains relatively sensitive to antibiotics and sanitizers. Optimal growth occurs at 40–45°C, with growth slowing at 20–25°C and inhibited above 50°C. *S. thermophilus* plays a dual role in dairy fermentation: (i) it produces lactic acid, thereby lowering pH and suppressing pathogenic microbes, and (ii) it enhances sensory qualities such as flavor and texture . Additionally, it is recognized as a probiotic, contributing to gut health when consumed in fermented products [(2)].

Propionibacterium freudenreichii

Propionibacterium freudenreichii is a Gram-positive bacterium best known for its role in Swiss cheese fermentation. During lactate metabolism, it releases carbon dioxide, producing the characteristic “eyes” (holes) in Swiss cheese. Its metabolic activity generates flavor-enhancing compounds such as propionate, acetate, short-chain fatty acids from amino acid catabolism, and free fatty acids from milk fat hydrolysis. Beyond organoleptic contributions, *P. freudenreichii* synthesizes bioactive compounds including vitamin B12 and folate, improving the nutritional quality of dairy products. The antimicrobial action of propionic acid helps extend shelf life by inhibiting spoilage organisms. Its subspecies, *P. freudenreichii shermanii*, is highly resilient to environmental fluctuations and can grow at temperatures as low as 3.8 °C, making it ideal for cheese maturation [(3)].

Lactobacillus helveticus

Lactobacillus helveticus is a proteolytic lactic acid bacterium extensively used in the manufacture of hard and extra-hard cheeses such as Parmesan and Swiss varieties. Its proteolytic activity enhances cheese flavor and texture during ripening. Moreover, *L. helveticus* produces bioactive peptides with antioxidant, antihypertensive, and antimicrobial properties. These peptides contribute to the health-promoting effects of fermented dairy products, such as improved cardiovascular health and enhanced immune defense. In vitro studies have also shown its antagonistic action against pathogenic fungi and bacteria, highlighting its role in natural food preservation.

Leather Industry

Microbes producing proteases and lipases play a crucial role in eco-friendly leather processing. They replace harsh chemicals in dehairing, degreasing, and bating, thus minimizing environmental pollution. Examples include *Bacillus subtilis*, which produces both proteases and lipases ; *Bacillus licheniformis*, a major source of proteases; *Pseudomonas fluorescens*, known for thermolabile lipases ; and *Aspergillus niger*, a fungal source of lipases used in leather treatment. These microbial enzymes improve leather quality by enhancing softness, flexibility, and appearance, while reducing chemical hazards in tannery operations.

Food Industry

Saccharomyces cerevisiae

Saccharomyces cerevisiae, a unicellular eukaryotic fungus with 16 chromosomes, is one of the most extensively studied eukaryotic organisms due to its genetic tractability.. It is employed in baking and brewing industries to produce bread, beer, wine, and other alcoholic beverages . Fermentation by *S. cerevisiae* converts sugars into ethanol, carbon dioxide, and flavor compounds, imparting desirable sensory qualities to foods and beverages. In bread making, CO_2 production creates air pockets that give bread its soft, porous texture, while flavor compounds such as phenylethanol and δ-decalactone contribute to its aroma. Due to its high protein and vitamin B content, *S. cerevisiae* is also used as a nutritional supplement. Furthermore, its antimicrobial metabolites serve as natural preservatives in fruit juices, alcoholic beverages, and processed foods.

Lactobacillus plantarum

Lactobacillus plantarum is a versatile Gram-positive lactic acid bacterium found in fermented foods such as pickles, kimchi, sauerkraut, and sourdough. It is also abundant in the human gastrointestinal tract, where it exhibits probiotic properties. *L. plantarum* enhances food quality by improving antioxidant capacity, scavenging hydroxyl and oxygen radicals, and enhancing nutritional content through increased vitamin and amino acid availability. It is also used in food preservation; for example, when combined with chitosan, *L. plantarum* extends the shelf life of fresh-cut apples by reducing microbial spoilage. Its dual role in food quality improvement and human health promotion makes it a valuable microorganism in functional food development.

Lactobacillus acidophilus

Lactobacillus acidophilus is a Gram-positive, microaerophilic LAB frequently applied in the fermentation of vegetables, fish, sausages, and silage. In addition to imparting characteristic flavor and texture, it acts as a bio-preservative by producing lactic acid and bacteriocins that inhibit foodborne pathogens. *L. acidophilus* demonstrates strong acid tolerance, enabling survival in gastrointestinal conditions, and is widely consumed as a probiotic supplement. Its probiotic activity contributes to gut microbiome balance and overall human health.

Role of Microbes in Pollutant Removal Process

Degradation of Organic Pollutants

Microorganisms are widely recognized as effective bio-remediators owing to their ability to degrade a broad spectrum of organic pollutants. Degradation typically occurs through co-metabolism, where microbial communities in the rhizosphere of aquatic and terrestrial plants break down complex carbon-based compounds to acquire organic carbon and electron acceptors.

In aquatic systems, the rate of biodegradation depends on both the density of microbial populations and the concentration of xenobiotics present. The abundance and activity of these microbes are strongly influenced by the species of macrophytes present. Plant roots provide organic carbon that supports microbial degradation of pollutants such as hydrocarbons and aromatic hydrocarbons. Additionally, many rhizospheric bacteria produce indole acetic acid (IAA), which not only enhances plant growth but also supports pollutant degradation. Biofilms associated with aquatic plants play a particularly significant role in breaking down organic compounds, including phenolics, amines, aliphatic aldehydes, polychlorinated biphenyls (PCBs), and atrazine. Moreover, methanotrophic bacteria enriched in wetland rhizospheres utilize methane as a carbon and energy source. These methanotrophs are capable of degrading a wide range of hazardous organic contaminants, including chlorinated ethenes, through enzymatic reactions. For instance, *Eichhornia crassipes* has been shown to remediate eutrophic waters by stimulating nitrogen gas production, thereby contributing to both pollutant removal and ecosystem restoration.[4]

Removal of Heavy Metals

The rhizospheric and endophytic microbes (including bacteria, fungi, algae, and cyanobacteria) play a prominent role in the removal and detoxification of heavy metals (Table1). Microbes promote the removal of metals through biosorption, bioaccumulation, biotransformation, and biomineralization processes. The microbial cell wall, rich in functional groups such as carboxyl, hydroxyl, and amino groups, can bind and immobilize toxic metal ions [5].

In addition, some microbes enhance metal uptake in plants by increasing metal bioavailability in the rhizosphere. Specific metal-binding proteins and peptides, such as metallothioneins and phytochelatins, produced by microbes, help in the sequestration of heavy metals. Transcription factors regulating these proteins facilitate hormonal and redox signaling under metal stress conditions [6].

Cyanobacteria such as *Anabaena spiroides* mitigate heavy metal toxicity by producing proteins that bind Cd, Cu, and Cr. **Fungi**, including *Aspergillus niger* and *Penicillium chrysogenum*, have strong biosorption capacities for Pb, Ni, and Zn. **Yeasts** like *Saccharomyces cerevisiae* accumulate Cu and Cd via intracellular sequestration [7].

Genetically modified microbes further improve remediation potential. For instance, *Ralstonia eutropha* reduces Cd(II) toxicity by expressing metallothionein on its cell surface, while *Escherichia coli* regulates Cd stress by producing detoxification proteins. Mercury-resistant microbes such as *Pseudomonas aeruginosa* and *Bacillus cereus* contain the *mer operon*, which reduces toxic Hg^{2+} to less toxic elemental mercury.

Some endophytic microbes, including *Enterobacter cloacae* and *Bacillus licheniformis*, influence plant phenotypic and functional traits, enhancing antioxidant enzyme activities to combat oxidative stress caused by heavy metals. Certain fungi also detoxify metals via methylation and redox transformations, converting highly toxic forms into less toxic species [8].

Thus, microbial interactions augment phytoremediation by supporting plant metal tolerance, producing stress-related proteins, and establishing active transport mechanisms such as efflux pumps to alleviate metal stress.

Table 1. Removal of Heavy Metals by Microbes

Microbe	Metal(s)	Reference
Lactobacillus delbrueckii, *Streptococcus thermophilus*	Fe, Zn	(09)
Acinetobacter sp., *Bacillus megaterium*, *Sphingobacterium sp.*	Fe, Mn	(10)
Anoxybacillus flavithermus	Fe, Cu	(11)
Leptothrix, *Pseudomonas*, *Hyphomicrobium*, *Planctomyces*	Mn	(12)
Methylobacterium organophilum	Cu, Pb	(13)
Herminiimonas arsenicoxydans	As	(14)
Enterobacter cloacae	Cd	(15)
Acetobacter sp.	Cu, Cr	(16)
Chryseomonas luteola	Pb, Cu, Mn	(17)
Ochrobactrum anthropic	Zn, Co	(18)
Anabaena spiroides (cyanobacterium)	Cd, Co, Cu, Ni	(19)
Ralstonia solanacearum	Cr, Cu	(20)
Proteobacteria and *Bacteroidetes*	Mn	(21)
Bacillus cereus	Pb	(22)
Bacillus licheniformis	Cu	(23)
Saccharomyces cerevisiae (yeast)	Cd, Cu	(24)
Aspergillus niger (fungus)	Pb, Zn	(25)
Penicillium chrysogenum (fungus)	Ni, Cd	(26)

Table2: Pathogen Risk and Health Concerns from Industrial Use of Microbes

Microbial Group / Species	Industrial Application	Potential Risk / Pathogenic Concern	Health or Environmental Impact	Preventive Measures / Biosafety Level
Bacillus subtilis	Enzyme and probiotic production	Generally regarded as safe (GRAS), but some strains may cause opportunistic infections in immunocompromised individuals	Rare allergic reactions or respiratory irritation	BSL-1; standard lab hygiene
Aspergillus niger	Citric acid and enzyme production	Certain strains can produce mycotoxins	Allergic reactions and respiratory issues upon exposure	BSL-1/2; dust control and PPE
Pseudomonas aeruginosa	Bioremediation and biosurfactant production	Opportunistic human pathogen	Infections in wounds, lungs (especially in cystic fibrosis patients)	BSL-2; strict containment and waste sterilization
Escherichia coli (non-pathogenic strains)	Recombinant protein and enzyme production	Risk of contamination with pathogenic strains (e.g., E. coli O157:H7)	Gastrointestinal illness if contamination occurs	BSL-1 for lab strains; BSL-2 for environmental strains
Streptomyces spp.	Antibioticand enzyme production	Generally non-pathogenic, but can cause actinomycetoma in rare cases	Minor skin or respiratory infection	BSL-1; controlled air circulation
Clostridium acetobutylicum	Solvent (acetone-butanol) fermentation	Some Clostridium species are pathogenic (*C. botulinum*)	Neurotoxic risk if mishandled strains mix	BSL-2; anaerobic handling safety
Saccharomyces cerevisiae	Brewing, baking,and bioethanol production	Rare infections in immunocompromised individuals	Fungemia in susceptible patients	BSL-1; good air filtration
Penicillium chrysogenum	Antibiotic (penicillin) production	Spore inhalation may cause allergies or respiratory issues	Hypersensitivity reactions	BSL-1; controlled spore dispersion
Mycobacterium smegmatis	Model organism for bioremediation research	Non-pathogenic but related to *M. tuberculosis*	Minimal risk under controlled use	BSL-2; PPE and biosafety cabinet
Rhodococcus erythropolis	Hydrocarbon degradation	Generally safe, but misidentified strains may be opportunistic	Mild skin infection (rare)	BSL-1; periodic strain verification

Bioremediation Process

Bioremediation is a sustainable and eco-friendly approach for the detoxification of hazardous pollutants, including heavy metals, by converting them into less harmful forms or by completely eliminating the agents responsible for toxicity. The process involves the utilization of microbial biomass, either living or dead, to degrade, transform, or immobilize recalcitrant contaminants. Ultimately, these conversions result in the formation of stable, non-toxic end products such as carbon dioxide (CO_2), water (H_2O), nitrogen gas (N_2), and other benign compounds. Bioremediation specifically targets toxic substances with minimal adverse effects on the environment and living organisms, making it a cost-effective alternative to conventional remediation methods [27].

For any successful bioremediation strategy, three essential components are required: microorganisms, nutrients, and energetics. In certain environmental settings, contaminants themselves can serve as carbon and energy sources through microbial redox reactions. Under aerobic conditions, contaminants act as electron donors, while microorganisms utilize oxygen as the terminal electron acceptor. Conversely, in anaerobic environments, microbes degrade pollutants using alternative electron acceptors such as nitrate, sulfate or carbon dioxide [28].

Based on the site of application, bioremediation can be broadly classified into *in situ* and ***ex situ*** processes.

- **In situ bioremediation** is conducted directly at the contaminated site without excavation. It involves the delivery of oxygen and nutrients into the polluted environment, thereby stimulating indigenous microbial communities to degrade contaminants. Techniques under this category include *bioventing, biosparging, bioslurping,* and *phytoremediation*. Two approaches exist within in situ bioremediation:

o *Intrinsic bioremediation*, which relies on the natural attenuation potential of native microorganisms, enhanced through nutrient and oxygen supplementation.

o *Engineered bioremediation*, which involves the deliberate introduction of specific microorganisms into the contaminated site to accelerate pollutant degradation.

- **Ex situ bioremediation**, on the other hand, requires removal of contaminated material from the site, followed by treatment under controlled conditions. Popular methods include *biopiles, windrows, bioreactors,* and *landfarming*, where microbial activity is optimized for efficient pollutant degradation(29,13)

In the context of heavy metal pollution, bioremediation employs two key mechanisms: bioaccumulation and biosorption. Bioaccumulation is a metabolism-driven process in which living microbial cells actively transport and sequester metal ions within their intracellular compartments[24]. In contrast, biosorption is a physicochemical process wherein dead or metabolically inactive biomass binds and concentrates heavy metals on cell surface structures such as polysaccharides, proteins, and lipids. Both processes are increasingly recognized as emerging tools for wastewater treatment due to their cost-effectiveness, environmental compatibility, and high removal efficiency(30).

Conclusion

Microorganisms play a central role in industrial processes, offering applications ranging from food fermentation, biofuel production, and pharmaceuticals to wastewater treatment and bioremediation. While their use has provided immense benefits to society, the large-scale deployment of microbes also raises ecological and health concerns. Certain industrial strains may contribute to the dissemination of antibiotic resistance, toxin production, or ecological imbalance if not carefully regulated. At the same time, microbial activity can also improve environmental quality by mitigating pollutants through natural or engineered pathways.

Bioremediation techniques, including bioaccumulation, biosorption, and microbial immobilization, have emerged as eco-friendly and cost-effective solutions for reducing the toxic impact of heavy metals and organic pollutants. In situ approaches such as bioventing, biosparging, and phytoremediation exploit native microbial communities, while *ex situ* methods such as biopiles, landfarming, and bioreactors provide controlled environments for optimized degradation. The success of these processes depends on selecting appropriate microbial strains, providing essential nutrients, and integrating innovative carriers for microbial immobilization.

Source of Support: Nil
Conflict of interest: Nil
Acknowledgment: None

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How to cite this article: Yadav P, Jain RK. Microbial Approaches for Bioremediation of Contaminated Environments: Industrial Perspectives. Subharti J of Interdisciplinary Research, Aug. 2026; Vol. 8: Issue 2, 30-5