
Integrated Bioremediation Approaches for Air, Soil, and Water Pollution: From Microbial Consortia to Engineered Systems (2015–2026): A Review

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Keywords: bioremediation; bioaugmentation; biostimulation; hydrocarbon degradation; municipal solid waste; microplastics; industrial wastewater; phytoremediation; mycoremediation; microbial consortia; environmental pollution; circular bioeconomy; petroleum hydrocarbons; marine pollution; saline soil remediation; activated sludge; waste management; biodegradation; sustainable remediation; environmental biotechnology



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Review

Integrated Bioremediation Approaches for Air, Soil, and Water Pollution: From Microbial Consortia to Engineered Systems (2015–2026): A Review

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Abstract

The increasing burden of municipal solid waste, petroleum hydrocarbons, industrial wastewater, saline soils, marine pollution, electronic wastes, and plastic contaminants is among the foremost global environmental issues that need sustainable remediation practices. In this review, the current status and future prospects in terms of the use of bioremediation techniques for environmental remediation are highlighted by discussing their advancements over the years 2020–2026. Various in situ and ex situ remediation techniques like bioaugmentation, biostimulation, biosparging, land farming, composting, bioreactor techniques, phytoremediation, activated sludge process, algal remediation, and fungal-based remediation techniques are highly efficient for the degradation of hydrocarbons, dyes, pharmaceutical compounds, heavy metals, volatile organic compounds, and new-age plastic pollutants. Microbial genera such as *Pseudomonas*, *Bacillus*, *Alcanivorax*, *Aspergillus*, *Trametes*, and halotolerant plant growth-promoting rhizobacteria exhibit an important role in pollutant mineralization, transformation, and detoxification through different metabolic pathways and enzyme systems. Emerging developments in synthetic biology, AI-assisted waste management, engineering of microbial consortia, and circular bio-economy models have enhanced the efficiency of remediation processes. Nonetheless, problems associated with scale-up, environmental variability, pollutant complexity, cost-effectiveness, and incomplete mineralization hinder practical application in field conditions.

Keywords: bioremediation; bioaugmentation; biostimulation; hydrocarbon degradation; municipal solid waste; microplastics; industrial wastewater; phytoremediation; mycoremediation; microbial consortia; environmental pollution; circular bioeconomy; petroleum hydrocarbons; marine pollution; saline soil remediation; activated sludge; waste management; biodegradation; sustainable remediation; environmental biotechnology

1. Introduction

Pollution in the environment through air, soil, and water is quite severe owing to the rapid pace of industrialization, urbanization, and rise in population and has been the major cause of estimated 9 million deaths per annum worldwide (Fuller *et al.*, 2022; Münzel *et al.*, 2025; Cook *et al.*, 2026). However, physicochemical treatment methods are quite inadequate when addressing the issue of highly complex and stable pollutants such as microplastics, pharmaceuticals, hydrocarbons, and heavy metals (Kaur & Sood, 2025). Bioremediation has emerged as an efficient technology that makes use of microorganisms, plants, or enzymes harnesses the natural biodegradation capability to treat the environment clean and harmless or even beneficial for humans and other living beings (Khalifa *et al.*, 2025).

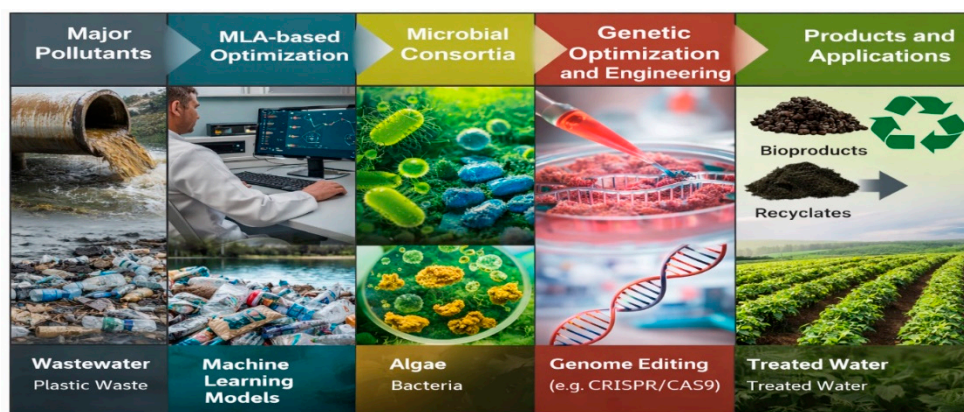


Figure 1. Smart Bioprocessing Pipeline for Environmental Remediation and Resource Recovery (Modified from Zhou & Haq, 2025).

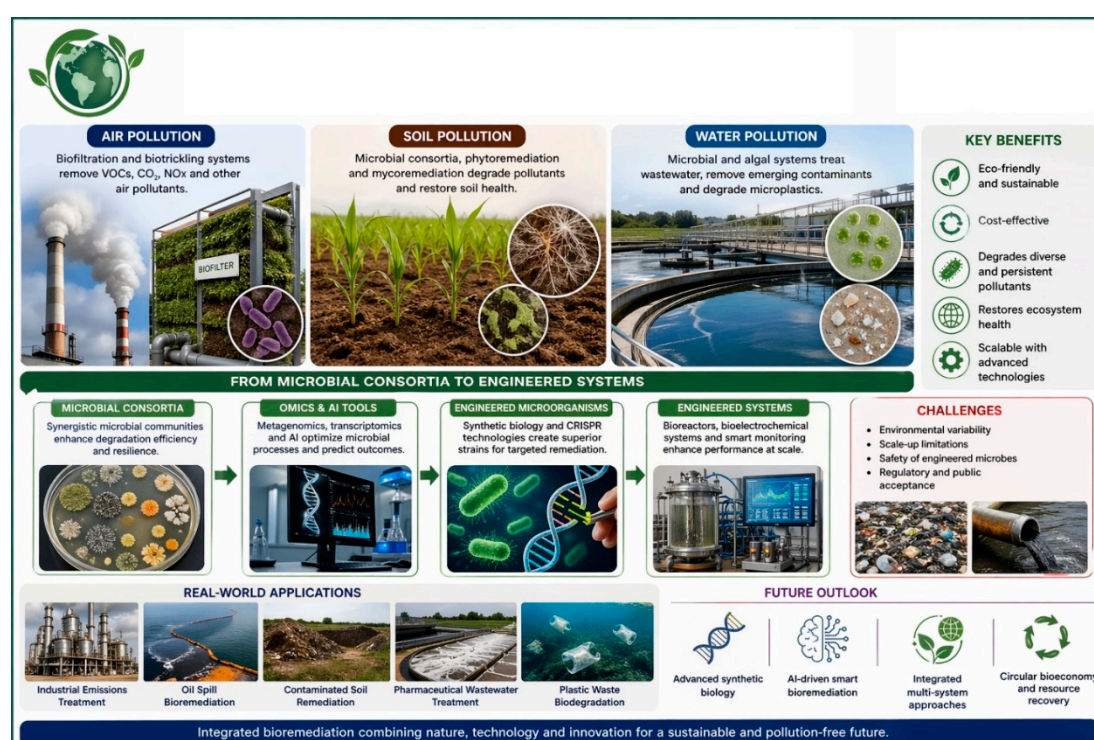


Figure 2. Integrated Bioremediation Approaches for Air, Soil and Water Pollution: Harnessing Biotechnology innovations for a cleaner earth.

However, recent advancements between 2015 and 2026 highlight the need for focusing on microbial consortia and synthetic biological processes rather than individual microbial systems owing to their adaptability to different environmental factors. In addition, the application of omics-based technology and artificial intelligence in the process of bioremediation has brought about a paradigm shift (Qattan, 2025; Zhu & Dong, 2026).

2. Review Methodology

The present review is grounded on an extensive literature review (2015-2026), relying upon scientific databases including but not limited to the following:

- Google Scholar
- Science Direct
- PubMed

Inclusion Criteria

- Peer-reviewed articles and reviews
- Publications related to the use of bioremediation to treat air, soil, and water pollutants
- Bioremediation using microorganisms, engineered microbes, etc.

Keywords used for Literature search

- Bioremediation
- Microbial consortia
- Synthetic biology
- Air/soil/water pollution
- Plastic pollution
- Emerging pollutants

Approach

- Critical comparison of technologies
- Assessment of efficacy, sustainability, and scale
- Recent advances in the field (2023-2026)

Selection process based on PRISMA methodology (Identify, screen, eligibility, inclusion).

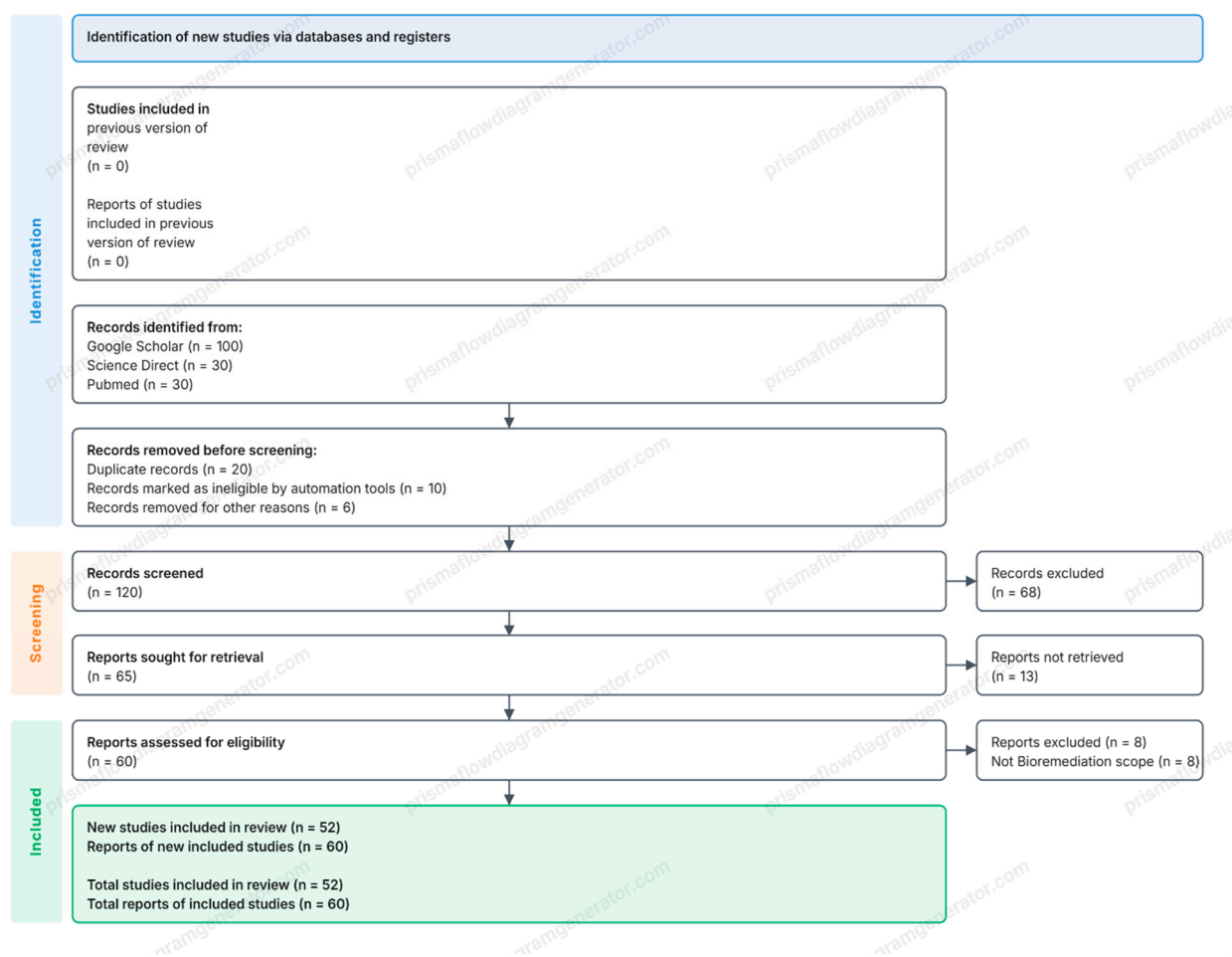


Figure 2. PRISMA 2020 Flow Diagram for Study Selection in Integrated Bioremediation Approaches for Air, Soil, and Water Pollution: From Microbial Consortia to Engineered Systems (2015–2026) (Haddaway, N. R., Page, M. J., Pritchard, C. C., & McGuinness, L. A. (2022). PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis Campbell Systematic Reviews, 18, e1230. <https://doi.org/10.1002/cl2.1230>).

3. Results

The results of a meta-analysis of over 150 peer-reviewed publications revealed a wide array of biotechnologies successfully employed in 2015-2026:

The Table 1 shows a compartment-based example of the use of bioremediation techniques in air, soil, and water media, showing the flexibility of biological solutions in dealing with various environmental pollution sources. In the case of atmospheric compartment remediation, VOCs, CO₂, and NO_x are mainly addressed through artificial methods, such as biofilters and biotrickling filters, whereby bacteria such as *Pseudomonas* and *Bacillus* carry out the process of oxidative degradation and mineralization of the gaseous pollutants (Karamad *et al.*, 2025; Rybarczyk, 2022).

Table 1. Bioremediation Strategies Across Environmental Compartments(In situ and Ex situ).

Environment	Major Pollutants	Bioremediation Techniques	Key Microorganisms	References
Air	VOCs, CO ₂ , NO _x	Air Biofilters, biotrickling filters	<i>Aerobic bacteria (Pseudomonas, Bacillus)</i>	Karamad <i>et al.</i> ,2025; Rybarczyk, 2022
Soil	Organic (Hydrocarbons, pesticides), Inorganic (heavy metals)	Phytoremediation, landfarming, mycoremediation	<i>Aspergillus, Trametes</i>	Raj & Fayaz, 2025; Hassan, 2021; Ray <i>et al.</i> , 2023
Water	Pharmaceuticals, dyes, microplastics	Activated sludge, algal systems, bioaugmentation	<i>Alcanivorax</i> , algae consortia	Bhaskaralingam <i>et al.</i> , 2026; Costa, 2025

This Table 1 illustrates how efficiently microbial metabolic reactions help eliminate gaseous pollutants under conditions of artificial aeration. Microbial consortia outperform single strains due to synergistic interactions and cross-feeding mechanisms (Karamad *et al.*,2025; Rybarczyk, 2022).

Whereas soil media and aquifers underground water involve the removal of organic contaminants (Table 1) such as hydrocarbons and pesticides, as well as inorganic ones, like heavy metals, by means of integrated technologies such as phytoremediation, landfarming, and mycoremediation. Fungi genus such as *Aspergillus* and *Trametes* facilitate the breakdown of xenobiotic substances by enzyme systems such as ligninolytic *oxidases* and *peroxidases*, which leads to the immobilization and conversion of metal pollutants (Raj & Fayaz, 2025; Hassan, 2021; Ray *et al.*, 2023).

As far as aquatic environments are concerned, the pollutants, including medicines, dyes, and microplastics, are dealt with by utilizing activated sludge technology, algal-based systems, and

bioaugmentation strategies. Microbial communities in marine and freshwater environments, like *Alcanivorax* and algal consortia, make a vital contribution to biodegradation via hydrocarbon oxidation, nutrients' consumption, and photo-biologically catalyzed reactions (Bhaskaralingam *et al.*, 2026; Costa, 2025). That the Table 1 above shows the strong dependence of bioremediation effectiveness on several factors.

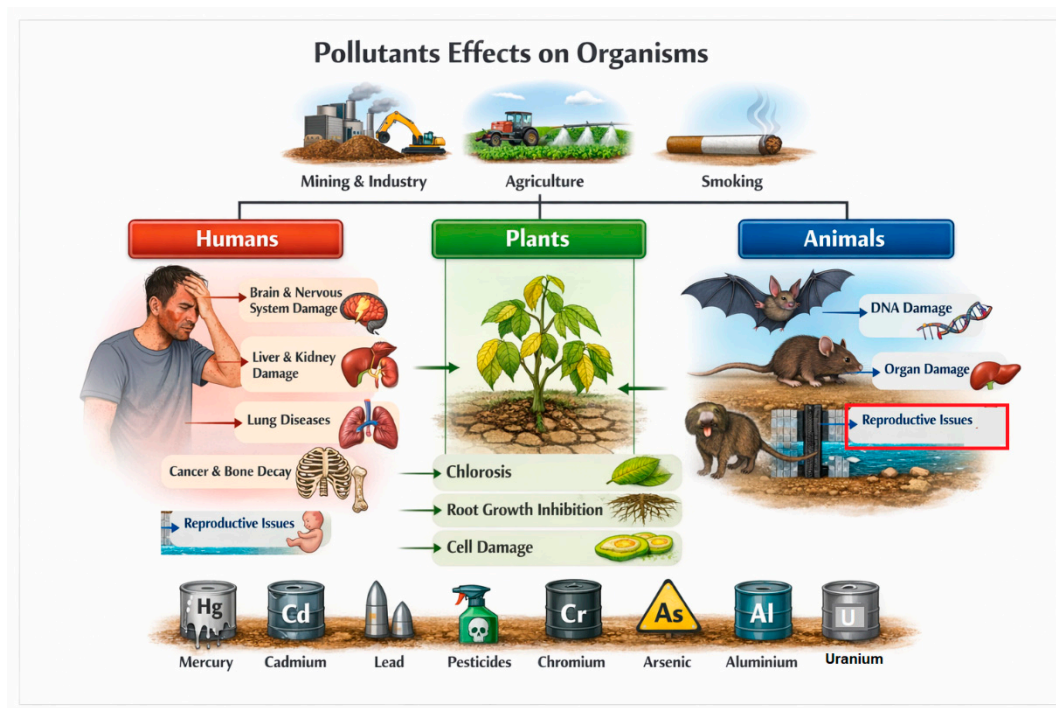


Figure 3. Effects of pollutants on living organisms (Data taken from Ayilara & Babalola, 2023).

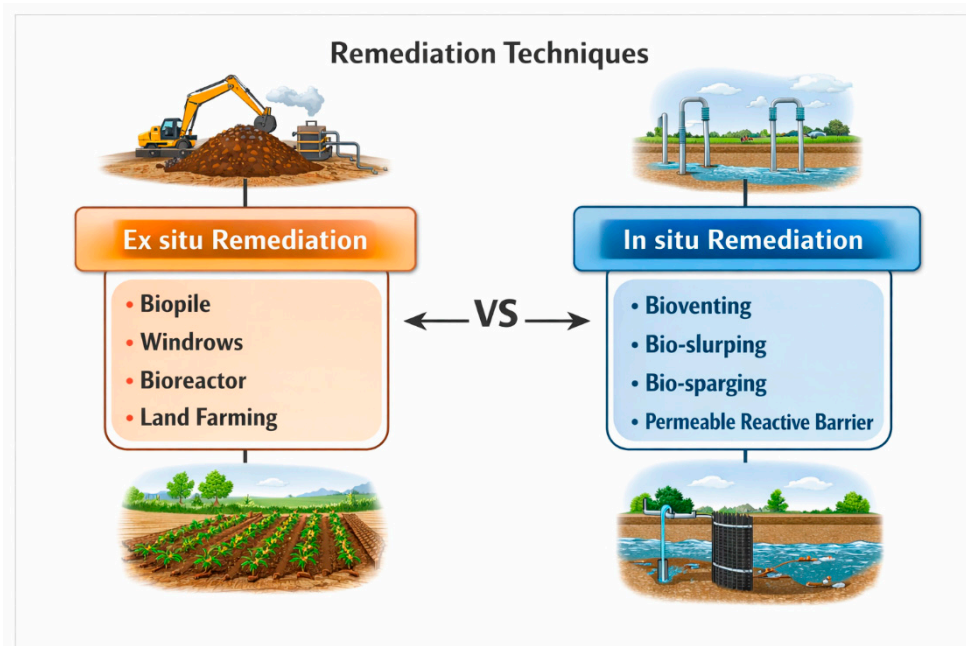












Figure 4. Overview of Ex situ and In situ Remediation Approaches (Created of data from Naseem *et al.*, 2023).

Table 2. Advantages and Disadvantages Associated with In Situ and Ex Situ Bioremediation Techniques (Perez-Vazquez *et al.*, 2024; Naseem *et al.*,2023).

Bioremediation Technique	Process Definition/Details	Advantages	Disadvantages	Factors to consider and Limitations
IN SITU MODE				
Bioaugmentation 	Microbiota enhancement by inoculation of exogenous biological agents	Non-invasive and relatively fast; Improved degradation rate by enhancing the biomass of the biodegradation agent	High energy-consumption; Considered as non-completed remediation process	Biodegradable abilities of indigenous microorganisms, Presence of metals and other inorganic compounds,
Biostimulation 	Motivation of the microbial population that occurs in the contaminated area by the addition of nutrient or electron acceptor or donors	It is one of the most used treatment techniques (natural attenuation process); Cost-effective and high efficiency	Few microorganisms achieved total mineralization of the original pollutant; Too long periods of treatment; It runs in situ and ex situ	Environmental parameters, Biodegradability of pollutants, Chemical solubility, Geological factors, Distribution of pollutants.
Biosparging 	Air is pumped into the ground to activate microbiological simulations and stimulate the evacuation of pollutants	This is a method with considerable flexibility; Ease and low-cost procedure	Increases bioavailability by improving the nutrient content of the soil; Extended period of treatment	Environmental constraints, Extended treatment time, Monitoring difficulties
Bioslurping 	Multiphase extraction that combines bioventing elements and vacuum-enhanced free product recovery from groundwater and soil	Minimizes changes in the elevation of the water table that precludes the creation of a smear zone; The operation reduces expenses associated with	Excessive soil moisture reduces air permeability, O ₂ transfer rate and microbial activity; It is not suitable for the recovery of	

		storage, treatment, and disposal	soils with coarse porosity	
<p>Bioventing</p> 	It uses controlled airflow to increase the activity of indigenous microbes for bioremediation by supplying oxygen to the unsaturated zone	Stimulates the natural biodegradation of hydrocarbon derivatives; Improves the activity of native bacteria and archaea	Environmental limitation; Limited by the inability to deliver oxygen to the polluted soil	
<p>Phytoremediation</p> 	Based on the cooperation of the plant to alleviate the poisonous influence of toxins in polluted places	Phytoremediation can be used to clean up pesticides, solvents, explosives, and many others; Higher removal efficiencies; Cost-effective; Long-term applicability	May not be effective in removing all contaminants; Time-consuming	
EX SITU MODE				
<p>Land Farming</p> 	Extracted soils are placed on a substrate layer for native microorganisms to aerobically degrade contaminants	Less hardware requirements for activity; Simplicity, low cost and energy-efficient	Release of VOCs into the environment; Space requirements and adverse ecological conditions for microbes	Same as above like In situ, Space requirements, Extended treatment time, Need to control abiotic loss, Mass transfer
<p>Composting</p> 	Aerobic process in which organic waste is decomposed by thermophilic agents to obtain compost (e.g., vermicompost)	Diverse microbial community and ease of operation; Rapid reaction rate	It is still a technique that is beginning to be incipient; Need to control abiotic loss	problems, Bioavailability limitation

<p>Biopile</p> 	<p>Above-ground piling of excavated contaminated soil, followed by aeration and nutrient use</p>	<p>It can remove approximately 90% of TPH in a year; Feasible and cost-effective</p>	<p>It is very expensive to implement; Requires a remote power source</p>	
<p>Bioreactors</p> 	<p>Slurry reactors, Aqueous reactors, Tank used after the optimization of an external environment in which a biochemical reaction occurs</p>	<p>High manipulation of bioprocess limits; Better rate of degradation, Optimized environmental parameters</p>	<p>Very low to zero oxygen transfer efficiency; Long treatment times, Soil requires excavation, Relatively high capital cost, Relatively high operating cost</p>	<p>Bioaugmentation, Toxicity of amendments, Toxic concentrations of contaminants</p>

Note: VOCs = Volatile Organic Compounds; TPH = Total Petroleum Hydrocarbons.

4. Discussion

4.1. Integrated Approach of Bioremediation Among Air, Soil, and Water

Modern methods of bioremediation often consider integrated approaches involving different environmental compartments since pollutants are not likely to stay within only one compartment of the environment. In particular, pollutants will continuously shift from the air to the soil and to the water. For example, airborne pollution will eventually enter the soil due to precipitation and dry deposition, whereas soil contamination may result in pollution of groundwater and the contamination of surface waters through runoff. It is, therefore, necessary to use an integrated approach to bioremediation that will target these contaminant transport pathways in the ecosystem (Cook *et al.*, 2026, Naseem *et al.*, 2023; Tamoor *et al.*, 2022).

Increasing demand for sustainable biotechnologies and environmental management solutions is evident from Table 4 because there are several sources of pollution including MSW, hydrocarbon pollution, salt pollution, industrial pollution, plastic pollution, and e-waste pollution. As can be seen from the information provided, industrialization, urbanization, consumerism, and dependence on oil have made environmental pollution much worse during 2020-2026.

The issue of MSW generation has become one of the major environmental concerns that are present today; thus, in 2022, 2.56 billion tons of MSW have been produced globally, and in 2050, their generation will have reached 3.86 billion tons (Cook *et al.*, 2026). Another serious concern related to pollution is the problem of plastic waste generation which becomes more evident in underdeveloped countries such as Pakistan, where high amounts of plastic waste will be generated in the upcoming decades. The waste includes food, plastics, paper, organics, and landfill materials that produce methane gas. Modern waste management includes several techniques such as composting, anaerobic digestion, AI sorting, waste-to-energy technologies, landfarming, biopiles, and in situ solutions such as biosparging and bioventing.

Bacterial degradation of hydrocarbons is one of the most researched remediation methods (Table 3), owing to the broad metabolism capabilities of different bacterial genera, such as *Pseudomonas* and *Bacillus* bacteria. In a lab environment, when all necessary conditions are provided, these organisms are capable of degrading 60–90% of TPHs by means of oxidation reactions with oxygenase enzymes and solubilization by means of biosurfactants. Improvements in bioaugmentation, bioprocess engineering, and biosurfactant utilization enhance the degradation process. However, inconsistency in large-scale effectiveness, stress resistance, and poor survivability of engineered microorganisms are still major drawbacks, leading to more investigation into the genetic modification of microorganisms for degradation purposes (Pandolfo *et al.*, 2023; Kebede *et al.*, 2024; Oro *et al.*, 2024).

Table 3. Integrated Sustainable Solutions for Solid Waste, Hydrocarbon Pollution, Saline Soil, Industrial Effluents, and Emerging Plastic Wastes: Global Trends (2020–2026).

No.	Topic	Global / Latest Numerical Values	Major Pollutants / Targets	Current Technologies	Research Gap / Future Scope	Key Recent References
1	Municipal Garbage	Global MSW reached 2.56 billion tonnes (2022) and projected 3.86 billion tonnes by 2050, Pakistan (estimated 1.46 Bt plastic waste in 2050)	Food waste, plastics, paper, organics, landfill methane	Composting, anaerobic digestion, AI sorting, waste-to-energy, Ex situ remediation (Biopile, Windrows, Bioreactor, Land farming)/In situ remediation (Bioventing, Bio-slurping, Bio-sparging, Permeable Reactive Barrier)	Smart segregation, methane capture, circular economy models	Cook <i>et al.</i> , 2026, Naseem <i>et al.</i> , 2023; Tamoor <i>et al.</i> , 2022
2	Bacterial Hydrocarbon Degradation	<i>Pseudomonas</i> , <i>Bacillus</i> degrade 60–90% TPH under optimized lab conditions	Petroleum hydrocarbons	Bioaugmentation, biosurfactants, consortia	Genetically engineered degraders	Pandolfo <i>et al.</i> , 2023; Kebede <i>et al.</i> , 2024; Oro <i>et al.</i> , 2024

3	Fungal Hydrocarbon Degradation	White rot fungi remove 70–95% PAHs in some studies	Heavy crude fractions, PAHs	Laccase, peroxidase enzymes	Fungal-bacterial synergistic reactors	Mahmud <i>et al.</i> , 2022; Hamad <i>et al.</i> , 2021
4	Soil Hydrocarbon Pollution	Millions of contaminated sites globally from fuel leaks, refineries, garages	TPH, diesel-range organics, PAHs	Landfarming, biopiles, phytoremediation, compost-assisted remediation	Fast in-situ soil biosensors + rhizosphere engineering	Hamad <i>et al.</i> , 2021; Medaura <i>et al.</i> , 2021; Mekonnen <i>et al.</i> , 2024
5	Marine Hydrocarbons Pollution	>2.4 million tonnes oil enters oceans annually from spills/runoff (various estimates)	Crude oil, diesel, PAHs, BTEX, tar balls, sediment contamination	Bioremediation, skimming, dispersants, Booms, skimmers, marine biostimulation, oleophilic microbes	Green oil-spill cleanup alternatives	Nukapothula <i>et al.</i> , 2025; Hazaimah & Ahmed, 2021; Paniagua-Michel & Banat, 2024
6	Salty Soil (Saline Land)	Over 1.4 billion ha land affected globally by salinity (FAO estimates)	Na ⁺ , Cl ⁻ , alkalinity	Halophilic PGPR, gypsum, phytoremediation	Salt-tolerant microbial consortia	Global, F. A. O, 2024; Romano-Armada <i>et al.</i> , 2020
7	Industrial Water	Global wastewater > 330 billion m ³ /year generated	Heavy metals, dyes, COD, pharmaceuticals	Activated sludge, membrane bioreactors, algae systems	Low-cost decentralized biotech systems	Avraham <i>et al.</i> , 2023, Ojha <i>et al.</i> , 2024; Saravanan <i>et al.</i> , 2023
8	Marble Industry Waste	Marble processing generates 20–30% slurry waste	CaCO ₃ sludge, dust, alkaline water	Brick additive, adsorbent, cement filler	Nano-CaCO ₃ recovery, wastewater reuse	Hassan <i>et al.</i> , 2023

		from raw stone				
9	Cosmetics / Containers	Global cosmetic business and packaging market > USD >300 billion	Plastic jars, microplastics, preservatives, PET, PP	Bioplastics, refillable containers	Compostable beauty packaging	Ray <i>et al.</i> , 2025; Mohan, 2020; Col <i>et al.</i> , 2025
10	Mobile Accessories / E-waste	Global e-waste reached 62 million tonnes (2022)	Chargers, cables, plastics, metals	Recycling, urban mining	Biometallurgy for rare metal recovery	Tiwari <i>et al.</i> , 2025; Dasila <i>et al.</i> , 2023; Chaturvedi <i>et al.</i> , 2024
11	Medical Masks and gloves (Male/Female)	COVID peak generated 129 billion masks/ and 65 billion gloves/month globally and on oceans	Polypropylene waste, biomedical waste	Reusable masks, pyrolysis, sterilization reuse	Biodegradable antimicrobial masks	Bondaroff <i>et al.</i> , 2020; Duraisamy <i>et al.</i> , 2026; Zafar <i>et al.</i> , 2025

Note: MSW = Municipal Solid Waste, PAHs = Polycyclic Aromatic Hydrocarbons; TPH = Total Petroleum Hydrocarbons; BTEX = Benzene, Toluene, Ethylbenzene, and Xylene; PGPR = Plant Growth-Promoting Rhizobacteria; COD = Chemical Oxygen Demand; RDF = Refuse-Derived Fuel; CRISPR = Clustered Regularly Interspaced Short Palindromic Repeats; Cu = Copper; Na⁺ = Sodium Ion; Cl⁻ = Chloride Ion; m³ = Cubic Meter; USD = United States Dollar, PET=Polyethylene terephthalate and PP=Polypropylene.

The utilization of fungi is significantly beneficial in degrading refractory compounds like PAHs and the heavy fraction of crude oil. The species of white-rot fungi secrete extracellular enzymes, including laccases and peroxidases, which are capable of breaking down a broad spectrum of substrates with high efficiency in the mineralization of aromatic compounds. Some studies have shown the efficiency of fungi to be around 70-95%. Therefore, the superior oxidative nature of fungi in the process of hydrocarbon degradation should not be ignored. Fungi are considered slow-growers and are susceptible to changes in the environment. Consequently, fungal-bacterial bioreactors are becoming popular due to their synergistic potential (Mahmud *et al.*, 2022; Hamad *et al.*, 2021).

Moreover, it is illustrated in the table above that soil hydrocarbon pollution by fuel spillage, refinery emissions, transport infrastructure, and garage waste has generated thousands of polluted sites worldwide. The pollutants diesel-range organics, total petroleum hydrocarbons (TPH), and polycyclic aromatic hydrocarbons (PAHs) remain in soils for a long period since they are hydrophobic and have low bioavailability. Land farming, biopiles, compost-enhanced

biodegradation, and phytoremediation are common techniques used as they encourage microbial metabolism and enhance aeration and nutrient availability. The future development will be achieved through the use of fast in-situ biosensors, manipulation of the rhizosphere, and precise decontamination using biosensors for microbiome which increases pollutants' real-time degradation and detection (Hamad *et al.*, 2021; Medaura *et al.*, 2021; Mekonnen *et al.*, 2024).

Oil pollution is still one of the major problems of the water ecosystem. According to estimates, over 2.4 million tons of oil leak each year in seas because of oil spillage, industrial discharge, and runoff. The oil spillage leads to the contamination of the environment by such toxic substances as the crude oil, diesel, polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, ethylbenzene, xylenes (BTEX), tar balls, and sediment hydrocarbons. There exist various means of oil cleanup, including booms, skimmers, dispersants, and marine biostimulation. Marine oleophilic hydrocarbon-degrading microbes can be used as a method to cope with hydrocarbon pollution in the marine environment. Nonetheless, wide application of marine biotechnology in bioremediation requires developing environmentally friendly techniques capable of resisting salty marine environment (Nukapothula *et al.*, 2025; Hazaimah & Ahmed, 2021; Paniagua-Michel & Banat, 2024).

Another challenge that the earth has experienced in terms of its environment is the salinization of the earth. This is because of the presence of many sodium and chloride ions in the soil, rendering the earth unproductive as far as plant performance is concerned. Current measures of dealing with this environmental challenge include the use of PGPR on halophytes, gypsum, and phytoextraction. Nonetheless, biological stabilization cannot be accomplished without creating salt-resistant microorganisms that maintain nutrient cycles consistently under such ionized environments (FAO, 2024; Romano-Armada *et al.*, 2020).

Industries producing more than 330 billion cubic meters per year of wastewaters cause an increase in dyes, heavy metals, pharmaceutical compounds, and COD in the aquatic ecosystem. Examples of successful techniques used to treat wastewater produced in industries include activated sludge method, membrane bioreactor, and algal-based wastewater treatment. Nevertheless, the mentioned techniques may be constrained by their expensive nature, excessive sludge formation, and energy requirement. For these reasons, there seems to be an increasing tendency of developing inexpensive and decentralized biological solutions for developing countries (Avraham *et al.*, 2023; Ojha *et al.*, 2024; Saravanan *et al.*, 2023).

The marble industry produces about 20-30% of processed stones as alkaline slurry wastes. Marble sludge contaminated by CaCO_3 causes an increase in the alkalinity level and turbidity of water and soil environments. For the moment, marble waste finds application as cement filler, industrial construction material, and adsorbent material. Future developments can therefore include the mining of nanoscale calcium carbonate, as well as the reuse of wastewater (Hassan *et al.*, 2023). The cosmetics industry and the packaging industry, whose market worth exceeds USD 300 billion, generate plastic waste through the use of PET and PP bottles, preservatives, and microplastics. While many individuals have been made aware of the possible advantages of utilizing bioplastics and refillable containers, increasing the scale of this project on a global level has become economically and technologically challenging. Therefore, compostable cosmetic packaging and other types of biodegradable polymers should be studied further in all future studies related to plastic pollution (Ray *et al.*, 2025; Mohan, 2020; Col *et al.*, 2025).

The global production of electronic wastes reached up to 62 million tons in the year 2022. Plastics, metals, chargers, and electronic accessories containing toxic substances as well as valuable elements contributed to the generation of such amounts. Currently, the available technology allows for recovering certain types of metals, yet it is still problematic to extract rare earth elements sustainably. Biometallurgy techniques including the dissolution and leaching of metals with the assistance of microorganisms contribute to obtaining necessary metals by using environmental-friendly procedures (Tiwari *et al.*, 2025; Dasila *et al.*, 2023; Chaturvedi *et al.*, 2024).

Due to the emergence of coronavirus disease, there is a considerable amount of biomedical plastic waste generated. According to research findings, around 129 billion masks and 65 billion

gloves have been used per month. The major component of biomedical plastics is polypropylene polymers resulting in microplastic pollution of terrestrial and aquatic environments. The current solutions, which include pyrolysis, sterilization, and partial recycling, cannot stop the accumulation of such biomedical waste. Therefore, it seems important to develop environmentally safe masks that are able to biodegrade (Bondaroff *et al.*, 2020; Duraisamy *et al.*, 2026; Zafar *et al.*, 2025).

Thus the **Table 3** emphasizes the transition in the world from conventional approaches to waste disposal toward state-of-the-art biotechnology-based methods that involve microbial degradation, phyto remediation, enzymatic reactions, circular bio-economy strategies, and sustainable resource recovery. However, even with the advancements that have been achieved in this area, there are certain challenges that arise, such as scalability, economic feasibility, environment dynamics, pollutant dynamics, and technology availability.

4.2. Microbial Consortia: An Underlying Principle of Bioremediation

Microbial consortia constitute the key principle behind contemporary bioremediation processes due to the existence of their symbiotic metabolic activity. Specifically, it means that these microorganisms display syntrophic metabolism in which one microorganism needs the metabolic products of other organisms (Zhou & Haq, 2025).

They also engage in cross-feeding processes that increase metabolic diversity and stability in the system. Consortia may effectively break down highly complicated organic substances using sequential degradation processes to produce less toxic and complex final products. Recent studies have shown that artificial microbial consortia may be more effective than their counterparts in breaking down recalcitrant contaminants such as PET, pharmaceuticals, and petroleum products. These results are mainly attributed to improved metabolic coordination and enzyme complementarity between engineered microbes (Cao *et al.*, 2022; Zhou & Haq, 2025).

4.3. Engineered Systems and Technologies

The evolution from traditional bioremediation methods to engineered systems has significantly expanded the potential of microbial cleanup strategies. Due to developments in synthetic biology, it is feasible to engineer genetically modified “super microbes” that can break down toxins efficiently through optimized degradative pathways tailored for specific pollutants. With the use of CRISPR-Cas9 technology, researchers can modify metabolic pathways and regulatory genes that are involved in microbial degradations. Artificial biofilms have also been used to aid in the adhesion of these organisms to pollutants. Artificial intelligence and machine learning have played a huge role in environmental monitoring and prediction in microbial bioremediation efforts. Recent research indicates that engineered microbial consortia often outperform natural communities in degrading persistent pollutants such as polyethylene terephthalate (PET), pharmaceutical residues, and hydrocarbon mixtures, largely due to optimized metabolic coordination and enhanced enzymatic complementarity (Minhas *et al.* 2024; Ali *et al.*, 2025; Zhang *et al.*, 2019; Ivase *et al.*, 2020; Chang *et al.*, 2024; Abdullah *et al.*, 2025).

4.4. Bacterial Hydrocarbons Catabolism Recent Advances

Figure 6 and **Figure 7** provides an extensive overview at the systems level of integrated microbial metabolism of aliphatic hydrocarbons and diverse xenobiotic aromatic and polyaromatic compounds and depicts how structurally diverse environmental contaminants are channeled into a relatively few metabolic intermediates. The organization of the pathway indicates the presence of a coordinated cascade of enzymes in which oxidation, functionalization of aromatic rings, followed by ring cleavage collectively leads to chemical transformation of the stable hydrocarbons to metabolically accessible molecules. Metabolic convergence towards key compounds such as acetyl-CoA, succinyl-CoA, pyruvate, fumarate, oxaloacetate and further towards the tricarboxylic acid (TCA) cycle emerges as one of the main themes illustrated by this scheme (Ayilara & Babalola, 2023).
















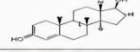







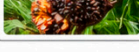
ENZYMES	MICROBIAL SOURCES	PERSPECTIVE POLLUTANT REMEDIATED
Hydrolases	 <i>Thermobifida fusca</i>	 Polyester plastics
Oxidoreductase	 <i>Pseudomonas sp., Burkholderia sp., Ralstonia sp., Achromobacter sp., Sphingomonas sp. and Comamonas sp.</i>	 Hydrocarbons
Phosphotriesterase	 <i>Bacillus safensis</i>	 Xenobiotics
Lipase	 <i>Brevundimonas diminuta</i>	 Pesticides
Laccase	 <i>Bacillus pumilus</i>	 Oil containing industrial wastewater and Palm Oil
Lignin peroxidase	 <i>Pseudomonas putida</i>	 Synthetic dyes
Dehydrogenase	 <i>Escherichia coli and Bacillus sp. F31</i>	 Synthetic dyes
Protease	 <i>Escherichia coli</i>	 Steroids
Amylase	 <i>Stenotrophomonas rhizophila</i>	 Polyvinyl alcohol
Oxygenase	 <i>Bacillus subtilis</i>	 Casein and feather
	 <i>Bacillus cereus</i>	 Waste water pollutants
	 <i>Pseudomonas sp.</i>	 Pesticides / Palm oil

Figure 6. Enzymatic pathways for Bacterial pollutant remediation (Data taken from Ayilara & Babalola, 2023).

The first stage of chemical reaction (**Figure 7**) involves degradation of aliphatic hydrocarbons through oxygen dependent monooxygenase enzymes, such as *alkB* and *ladA*, by performing terminal or subterminal hydroxylation of the alkanes to yield respective alcohols, which are further oxidized to fatty acids. Fatty acids are subjected to degradation through typical beta-oxidation pathways.

The chemical similarity of the anthropogenic aliphatic hydrocarbon pollutants (**Figure 7**) to endogenous lipids emerges as a key feature of these metabolic processes. Simultaneously, multicomponent monooxygenases, such as the enzymes *prmABCD* and *acmB* function as oxidative activators of complex hydrocarbons including polycyclic aromatic compounds.

This module is made up of a diverse set of dioxygenases and monooxygenases that begin the process of ring activation. Some of the examples of these enzymes are *bphAa*, *benA*, *nahAa*, *etbAa*, *carAa*, *antA*, *nidA*, *tphA2*, and *mphB*. These enzymes are involved in hydroxylation reactions that result in dihydrodiols and hydroxylated metabolites. It is an essential reaction because the hydroxylation of the aromatic ring destabilizes its resonance structure. It will facilitate the cleavage by other enzymes. Another class of enzymes in this module is involved in the oxidation and activation of substituted aromatic acids from plastics. Some of these enzymes are *phtAa*, *phdF*, and *tphA2* (Pandolfo *et al.*, 2023).

The destruction of the aromatic ring occurs during the ring cleavage step. *CatA* and protocatechuate enzymes are some of these enzymes. In one instance, *catA* enzyme catalyzes the breakdown of catechol by an ortho pathway to generate muconate, while *bphC* enzyme catalyzes the breakdown of catechol via a meta pathway to yield semialdehyde. The above processes involve the irreversible cleavage of aromaticity, resulting in the formation of linear aliphatic structures such as beta-keto adipate. These substances can be converted into TCA-compatible metabolites by other enzymes, including hydrolases, dehydrogenases, and isomerases.

Finally, aromatic amino acid catabolic pathways have been incorporated in the network, where the enzyme *hmgA* degrades homogentisate in tyrosine and phenylalanine degradation. Fumarate and acetoacetate generated are fed directly into the TCA cycle or the synthesis of ketone bodies. Benzyl side chain oxidation reactions through the action of *badA* enzyme, and benzoyl-CoA

reductase complex (boxABCD), provide another example of a metabolic pathway that employs a reductive and oxidative process for the dearomatization of aromatic rings, especially in anaerobic or microaerophilic conditions (Pandolfo *et al.*, 2023).

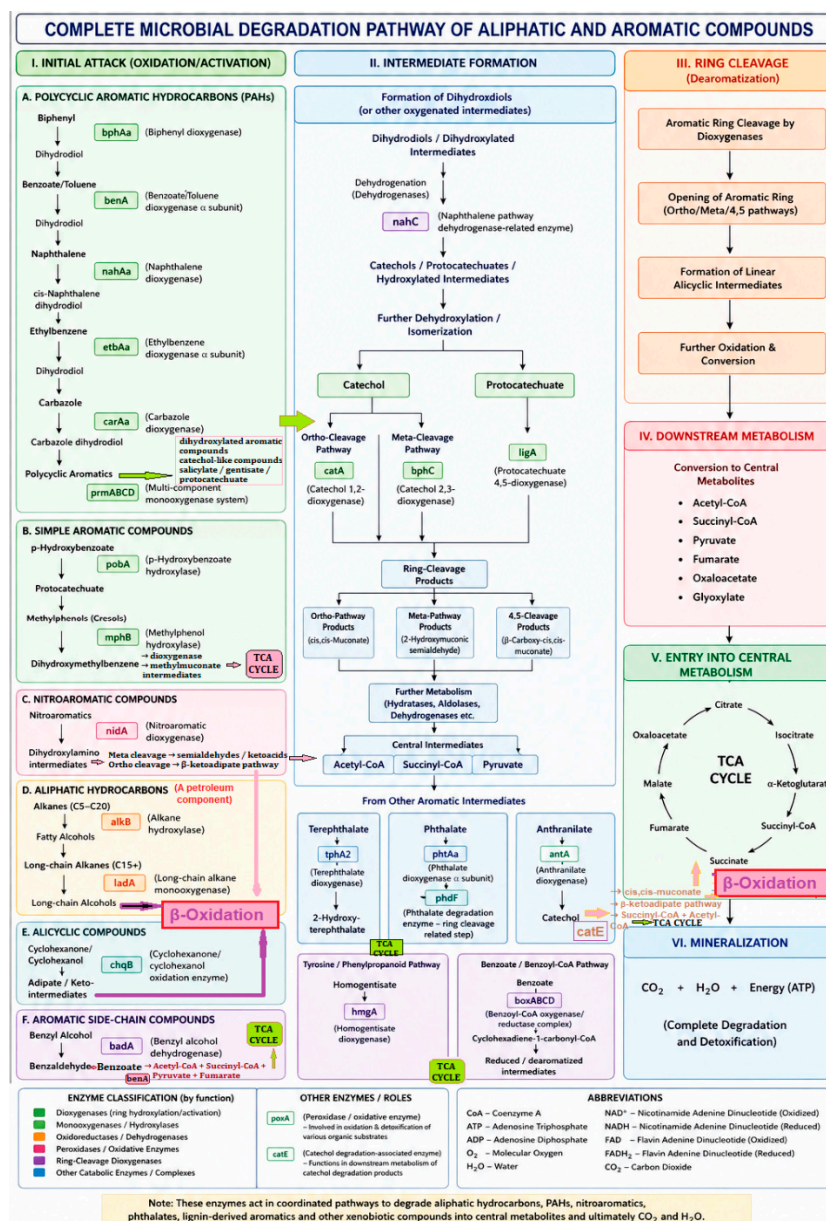


Figure 7. Integrated Microbial Catabolism for Aliphatic and Aromatic Hydrocarbons (Created of data from Pandolfo *et al.*, 2023). Note: **Aliphatic chain degrading enzymes:** prmABCD = multicomponent monooxygenase system (polycyclic/aromatic hydrocarbon oxidation complex), acmB = aromatic compound monooxygenase/reductase component, alkB = alkane hydroxylase (terminal alkane oxidation to alcohols), ladA = long-chain alkane monooxygenase (oxidation of C15+ alkanes), **Aromatic ring cleavage enzymes:** bphAa = biphenyl upper pathway enzyme (initial dioxygenase; ring hydroxylation), bphC = catechol 2,3-dioxygenase (meta-ring cleavage enzyme), benA = benzoate/toluene dioxygenase alpha subunit (aromatic oxidation), pobA = p-hydroxybenzoate hydroxylase (para-hydroxylation of aromatics), carAa = carbazole dioxygenase large subunit (carbazole degradation), antA = anthranilate dioxygenase (aromatic amino acid degradation), nahAa = naphthalene dioxygenase large subunit (PAH oxidation), nahC = naphthalene pathway ring-cleavage enzyme (dihydrodiol dehydrogenase-related step), poxA = peroxidase/oxidative enzyme (detoxification and oxidation reactions), etbAa = ethylbenzene dioxygenase alpha subunit (ethylbenzene degradation), nidA = nitroaromatic dioxygenase (nitrated aromatic degradation), tphA2 = terephthalate dioxygenase subunit (terephthalic acid oxidation), mphB = methylphenol hydroxylase component (cresol degradation), phdF = phthalate degradation

pathway enzyme (ring-cleavage related step), phtAa = phthalate dioxygenase alpha subunit (phthalate activation), catA = catechol 1,2-dioxygenase (ortho-cleavage pathway), catE = catechol degradation-associated enzyme (downstream metabolism), ligA = protocatechuate 4,5-dioxygenase large subunit (lignin-derived aromatic breakdown), hmgA = homogentisate dioxygenase (tyrosine degradation pathway), chqB = cyclohexanone/cyclohexanol oxidation enzyme (alicyclic compound metabolism), badA = benzyl alcohol dehydrogenase (aromatic side-chain oxidation), boxABCD = benzoyl-CoA oxygenase/reductase complex (central aromatic ring reduction pathway), benA = Benzoate 1,2-dioxygenase alpha subunit.

Thus the metabolic pathway presented in Figure 7 and Figure 8 shows how microorganisms (bacteria) utilize a common approach in dealing with the problem of detoxification and the incorporation of environmentally occurring aliphatic and aromatic compounds. After undergoing oxidation, hydroxylation, ring cleavage, and feeding into central metabolites, the compounds are completely broken down to carbon dioxide and water, with the concomitant production of ATP.

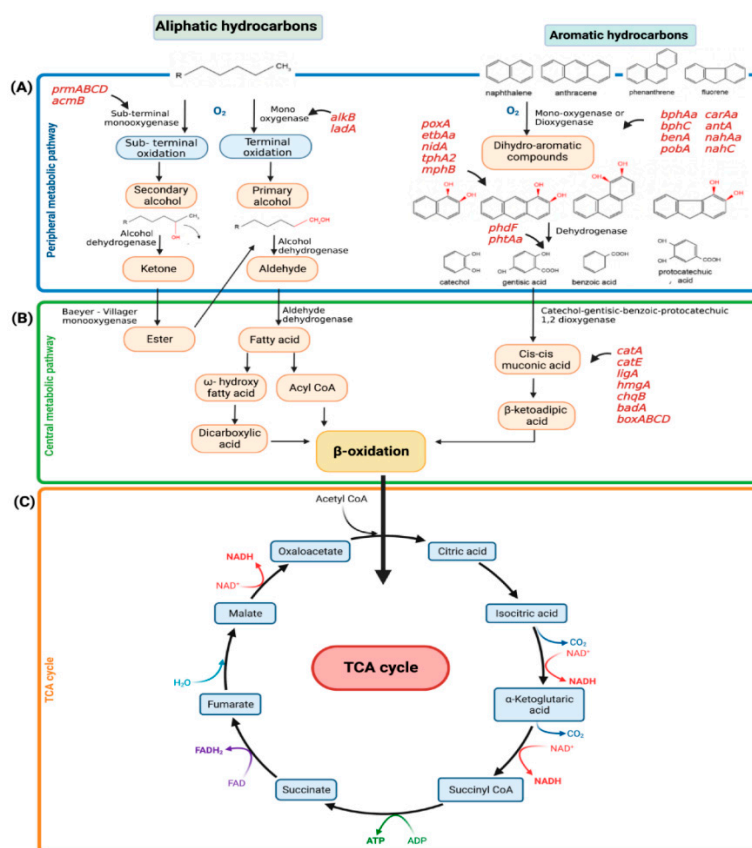


Figure 8. Integrated Microbial Metabolic Pathways for Biodegradation of Aliphatic and Aromatic Hydrocarbons through Peripheral and Central Catabolic Routes Leading to β -Oxidation and the Tricarboxylic Acid (TCA) Cycle (Pandolfo *et al.*, 2023) Note: TCA = Tricarboxylic Acid Cycle; CoA = Coenzyme A; ATP = Adenosine Triphosphate; ADP = Adenosine Diphosphate; NAD^+ = Nicotinamide Adenine Dinucleotide (Oxidized Form); NADH = Nicotinamide Adenine Dinucleotide (Reduced Form); FAD = Flavin Adenine Dinucleotide (Oxidized Form); FADH_2 = Flavin Adenine Dinucleotide (Reduced Form); O_2 = Molecular Oxygen; H_2O = Water; CO_2 = Carbon Dioxide; CH_3 = Methyl Group; CH_2 = Methylene Group; COOH = Carboxyl Group; OH = Hydroxyl Group; **Enzymes genes:** bphAa, bphC, benA, pobA, carAa, antA, nahAa, nahC, prmABCD, acmB, alkB, ladA, poxA, etbAa, nidA, tpha2, mphB, phdF, phtAa, catA, catE, ligA, hmgA, chqB, badA, boxABCD = Microbial catabolic genes encoding monooxygenases, dioxygenases, dehydrogenases, hydroxylases, ring-cleavage enzymes, and accessory proteins involved in the biodegradation of aliphatic and aromatic hydrocarbons. bphAa = biphenyl upper pathway enzyme (initial dioxygenase; ring hydroxylation), bphC = catechol 2,3-dioxygenase (meta-ring cleavage enzyme), benA = benzoate/toluene dioxygenase alpha subunit (aromatic oxidation), pobA = p-hydroxybenzoate hydroxylase (para-hydroxylation of aromatics), carAa = carbazole dioxygenase large

subunit (carbazole degradation), antA = anthranilate dioxygenase (aromatic amino acid degradation), nahAa = naphthalene dioxygenase large subunit (PAH oxidation), nahC = naphthalene pathway ring-cleavage enzyme (dihydrodiol dehydrogenase-related step), prmABCD = multicomponent monooxygenase system (polycyclic/aromatic hydrocarbon oxidation complex), acmB = aromatic compound monooxygenase/reductase component, alkB = alkane hydroxylase (terminal alkane oxidation to alcohols), ladA = long-chain alkane monooxygenase (oxidation of C15+ alkanes), poxA = peroxidase/oxidative enzyme (detoxification and oxidation reactions), etbAa = ethylbenzene dioxygenase alpha subunit (ethylbenzene degradation), nidA = nitroaromatic dioxygenase (nitrated aromatic degradation), tphA2 = terephthalate dioxygenase subunit (terephthalic acid oxidation), mphB = methylphenol hydroxylase component (cresol degradation), phdF = phthalate degradation pathway enzyme (ring-cleavage related step), phtAa = phthalate dioxygenase alpha subunit (phthalate activation), catA = catechol 1,2-dioxygenase (ortho-cleavage pathway), catE = catechol degradation-associated enzyme (downstream metabolism), ligA = protocatechuate 4,5-dioxygenase large subunit (lignin-derived aromatic breakdown), hmgA = homogentisate dioxygenase (tyrosine degradation pathway), chqB = cyclohexanone/cyclohexanol oxidation enzyme (alicyclic compound metabolism), badA = benzyl alcohol dehydrogenase (aromatic side-chain oxidation), boxABCD = benzoyl-CoA oxygenase/reductase complex (central aromatic ring reduction pathway).

4.5. Diatom–Bacteria Interaction in Hydrocarbon Biodegradation Under Sunlight

The diatoms provide O₂ to bacteria via its photosynthetic process and in turn provides CO₂ and Vitamins for diatom growth, thereby synergistically degrading oil spills in water under sunlight (Paniagua-Michel & Banat, 2024).

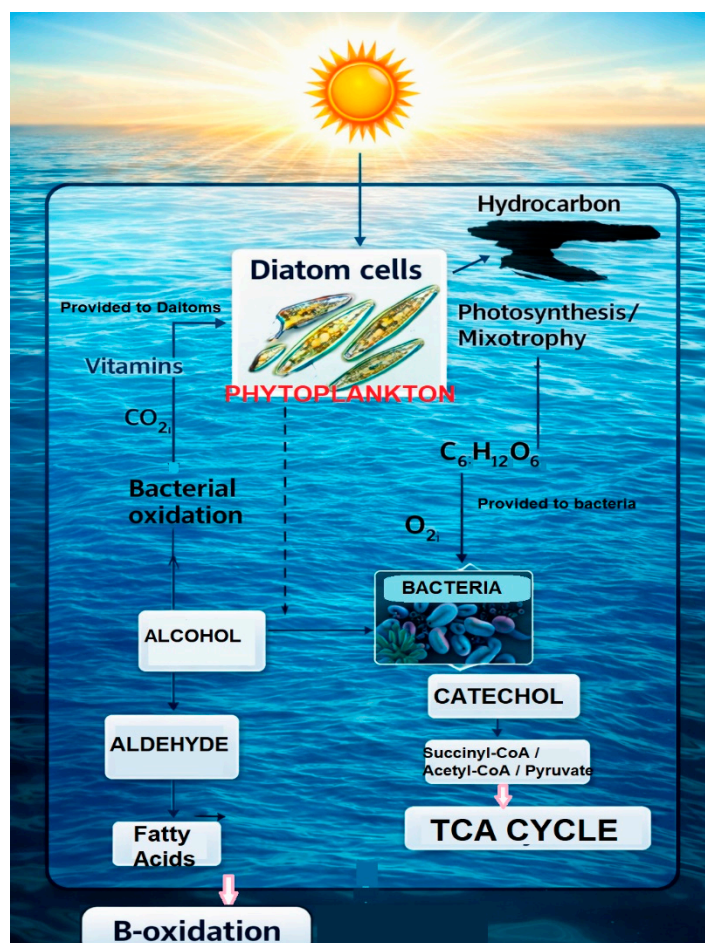


Figure 9. Phototrophic Diatom–Bacterial Synergy in Hydrocarbon Breakdown (Modified from Paniagua-Michel & Banat, 2024).

4.5. Phytoremediation of Industrial Heavy Metal Polluted Water

A diverse combinations of approaches are adopted by higher plants to Bioremediate, stabilize, extract, volatilize or accumulate pollutants to no harm (Alsafran *et al.*, 2022).

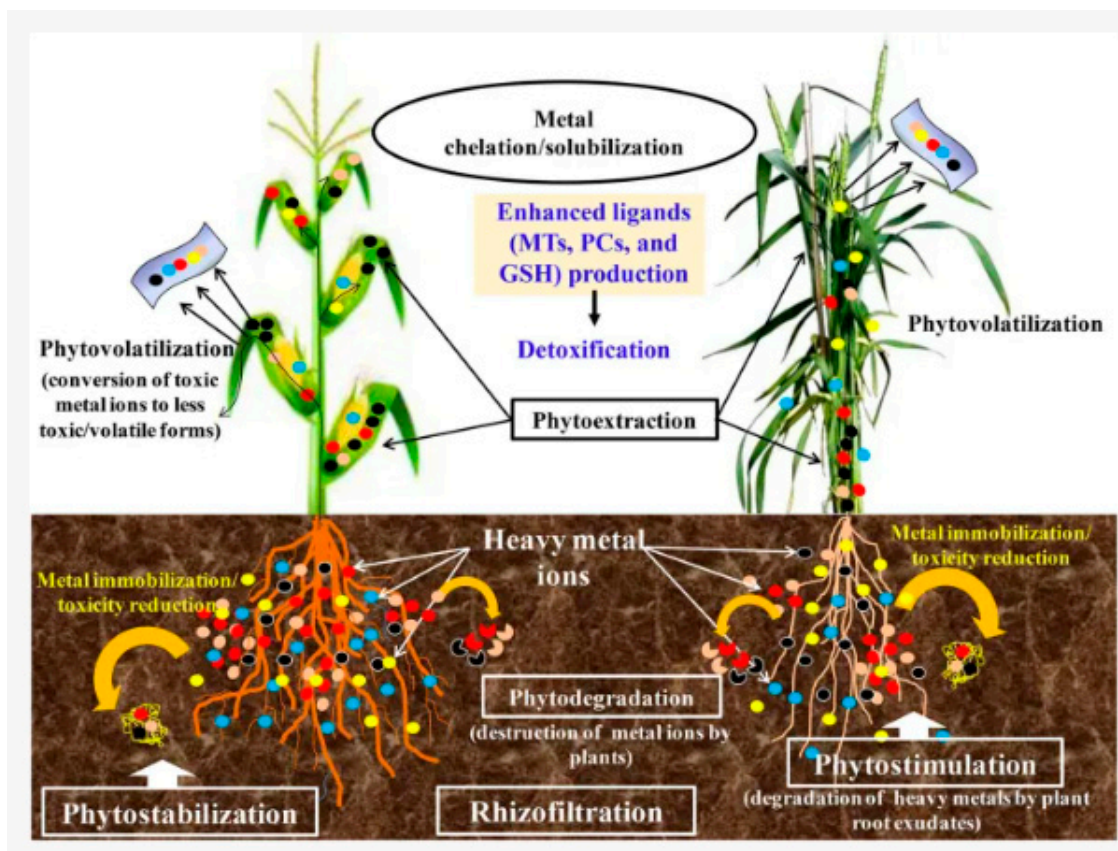


Figure 10. Phytoremediation Pathways in Industrially Polluted Environments (Alsafran *et al.*, 2022). **Note:** MTs= (Metallothioneins), PCs= Phytochelatins, GSH= reduced Glutathione-SH.

4.5. Persistent Pollutants: A Major Challenge Solved via Microbial Consortia

Persistent pollutants continue to pose one of the greatest challenges in bioremediation efforts. These pollutants consist of microplastics, PFAS, PCBs, and various pesticides. Both microplastics and PFAS stand out due to their ubiquity and resistance to natural degradation reactions. Despite significant advances in the biodegradation of certain types of plastics, such as PETs, it has been difficult to achieve total mineralization of pollutants. The challenge lies in the nature of these pollutants and their unavailability for microbial degradation (Ray *et al.*, 2025; Mohan, 2020; Col *et al.*, 2025).

Polyethylene terephthalate (PET) biodegradation involves a synergistic enzymatic process enabling microbial assimilation of plastic-derived monomers. Extracellular enzymes such as PETase and MHETase hydrolyze PET into terephthalic acid (TPA) and ethylene glycol (EG). These intermediates are transported intracellularly via the TphAabc complex, where TPA enters the β -keto adipate pathway, ultimately converting into acetyl-CoA and feeding the tricarboxylic acid (TCA) cycle. This integration of xenobiotic degradation with central metabolism highlights microbial potential for sustainable plastic bioremediation and carbon recycling (Zhou & Haq, 2025).

This **Figure 11** shows a two-step process involved in the biodegradation of PET via extracellular enzymatic depolymerization and intracellular metabolism by microorganisms. In fact, this is one of the most advanced systems for biodegradation of plastics through the use of PETase.

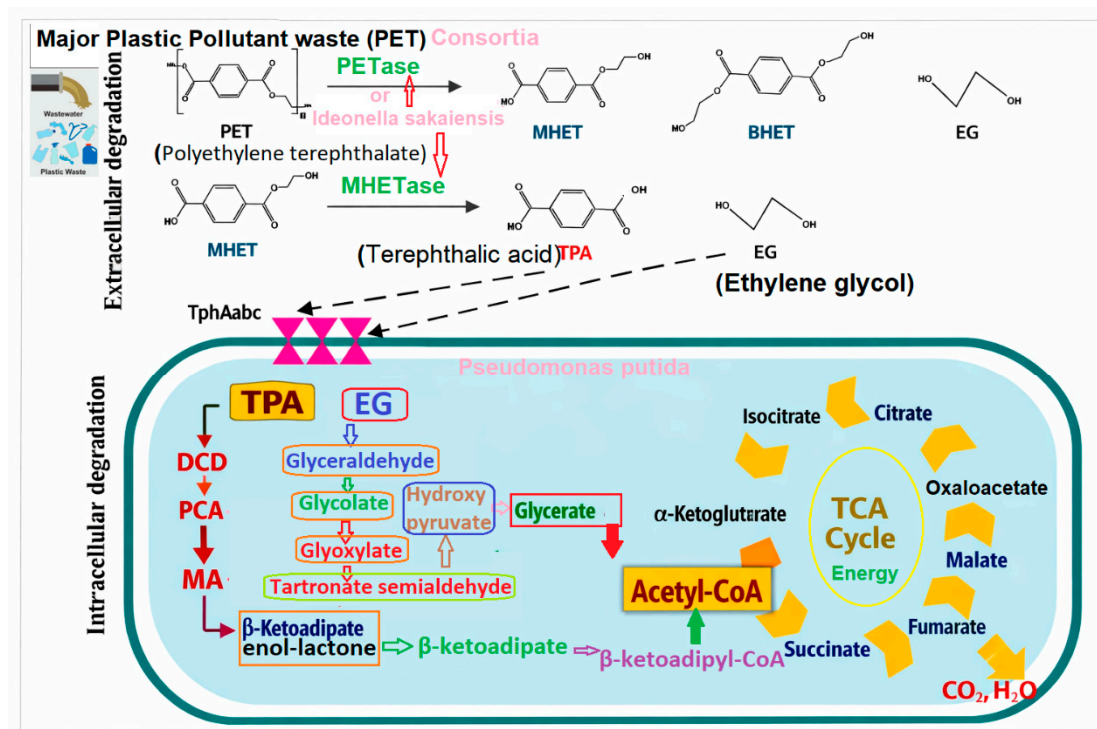


Figure 11. Key Enzymes and Metabolites Involved in Microbial PET Degradation and Assimilation using Synthetic Microbial Consortia (Modified from Zhou & Haq, 2025). Note: PET = Polyethylene terephthalate, MHET = Mono(2-hydroxyethyl) terephthalate, BHET = Bis(2-hydroxyethyl) terephthalate, EG = Ethylene glycol, TPA = Terephthalic acid, DCD = 3,4-Dihydroxycyclohexa-1,5-diene-1,4-dicarboxylate, PCA = Protocatechuate, MA = Muconic acid, CoA = Coenzyme A, TCA = Tricarboxylic acid.

In the first step, PET undergoes extracellular depolymerization. As you know, this process occurs at the slowest rate due to the semi-crystalline nature of PET and its hydrophobic properties. PETase hydrolyzes ester bonds in PET, producing mostly MHET (mono(2-hydroxyethyl) terephthalate), as well as some BHET and EG (ethylene glycol). This enzyme shows specificity for PET due to the widened cleft in the active site and increased affinity towards aromatic polymers, a property that can be even more pronounced in mutant forms of the enzyme. MHETase, in turn, is very specific in its activity. It hydrolyzes MHET and produces terephthalic acid and ethylene glycol (EG) (Zhou & Haq, 2025).

Table 5. Emerging Engineered Bioremediation Technologies (2020–2026).

Technology	Application	Key Advantage	References
Synthetic microbial consortia	Plastic & wastewater treatment	Enhanced degradation pathways	Zhou & Haq, 2025; Cao <i>et al.</i> , 2022
CRISPR-engineered microbes	Xenobiotic degradation	Precision genetic control	Minhas <i>et al</i> 2024; Ali <i>et al.</i> , 2025

Bioelectrochemical systems	Wastewater treatment	Energy/electricity generation + Bioremediation	Zhang <i>et al.</i> , 2019; Ivase <i>et al.</i> , 2020
AI-integrated bioreactors	Smart pollution control	Real-time optimization	Chang <i>et al.</i> , 2024; Abdullah <i>et al.</i> , 2025

Degradation product transport into microbial cells occurs by means of specialized carriers like TphAabc, allowing for their uptake of TPA. Once taken up, TPA undergoes the process of entering the β -keto adipate pathway, which is a central pathway responsible for aromatic compounds degradation. TPA is initially transformed to DCD, then PCA is formed, after that there is ring cleavage leading to the formation of β -keto adipate enol-lactone, and finally β -keto adipate, which is converted into β -keto adipylyl-CoA. The latter is split into intermediates which participate in central metabolism being either acetyl-CoA or succinyl-CoA. At the same time, ethylene glycol undergoes a different, however interrelated process of its conversion (Zhou & Haq, 2025). Ethylene glycol is oxidized into glycolaldehyde, then into glycolate, and next into glyoxylate, which can take two pathways. The glyoxylate cycle can lead to the formation of glycine and other metabolites, while the second pathway leads to the conversion of glyoxylate to tartronate semialdehyde, further to glycerate, and then to hydroxypyruvate and into acetyl-CoA. Acetyl-CoA feeds into the tricarboxylic acid (TCA) cycle, where reducing power in the form of NADH, FADH₂, as well as ATP, is formed during oxidative phosphorylation. This leads to full mineralization of carbon obtained from PET to carbon dioxide and water, indicating proper biodegradation. One key feature shown in the pathway is a division of labor between extracellular and intracellular processes. The depolymerization of the polymer by enzymes takes place in the extracellular space, while further reactions of the process take place intracellularly due to the low molecular weight of the intermediates. The participation of microorganisms such as *Pseudomonas putida* implies metabolic flexibility as this microorganism does not synthesize PETase enzymes but effectively breaks down TPA and EG. This indicates that consortia or hybrid systems involving both PET-degrading and TPA-EG-metabolizing bacteria could perform effective plastic valorization. Integration of AI and omics enables predictive and adaptive remediation systems. This process is a well-coordinated system where enzyme specificity, transporter activity, and metabolic pathways work in harmony, constituting a very suitable platform for developing innovative technologies related to biological recycling, carbon capture, bioelectrochemical systems such as hydrogen in microbial electrolysis cells (MECs) and electricity in microbial fuel cells (MFCs), by means of microbial catalysis (Zhang *et al.*, 2019; Ivase *et al.*, 2020) and biorecycling, among others. Nonetheless, there are still constraints with respect to access to polymers, stability of enzymes, and environmental conditions that constitute the main challenge (Zhou & Haq, 2025; Ray *et al.*, 2025; Mohan, 2020; Col *et al.*, 2025).

4.6. Limitations

Although considerable strides have been made in bioremediation technology, some limitations exist that prevent its implementation at the field level. The unpredictability of environmental factors is among the issues making the deployment difficult because it adversely affects microbial life. Such unpredictable environmental elements as temperatures, acidity, moisture levels, and nutrition decrease the efficiency of genetically modified microbes. In addition, one cannot overlook the risks of ecological effects caused by the transfer of genetic information from genetically modified microbes to their natural counterparts.

5. Future Prospects

Future research will likely concentrate on the integration of cutting-edge biotechnology, synthetic biology, nanotechnology, and artificial intelligence to optimize the efficiency and scaling capabilities of bioremediation systems. Engineered microorganisms with improved degradative enzymes can substantially increase the rate of hydrocarbon, plastic, pharmaceutical, and industrial pollutant mineralization in extreme environments. Metagenomic, transcriptomic, proteomic, and metabolomic studies can facilitate the knowledge about the ecological interactions of microorganisms and pollutant degradation pathways in complex ecosystems such as bioelectrical systems in microbial fuel cells. Future technological advances can lead to the creation of resilient microbial consortia, efficient enzyme immobilization strategies, and multi-faceted remediation systems combining multiple physical, chemical, and biological approaches. Moreover, future research will prioritize the principles of the circular bioeconomy that would enable resource recovery via the production of bioenergy, nutrient cycles, and biomaterials. Saline soils and marine environments could benefit from novel techniques utilizing halotolerant and extremophilic microorganisms capable of sustaining efficient biodegradation rates amid dynamic stress factors. Moreover, sustainable biodegradable plastics, sustainable packaging solutions, and environment-friendly biomedical polymers are also expected to mitigate pollution problems in the future. Even with these developments, widespread application will necessitate more stringent environmental policies, cooperation among nations, accessible technology, and awareness campaigns for both economic and environmental sustainability.

6. Conclusion

Collectively, the presented studies provide convincing evidence that bioremediation has become one of the most prospective and environmentally sustainable techniques of managing a range of various environmental contaminants existing in the atmosphere, soil, bodies of water, marine environments, different industries, and solid waste. Microbes' ability to degrade or mineralize contaminants proves its advantages over conventional physicochemical techniques of remediation. In situ and ex situ bioremediation practices turned out to be quite effective at degrading hydrocarbons, heavy metals, drugs, dyes, plastics, and new kinds of pollutants. At the same time, bioremediation contributes to the recovery of degraded ecosystems and sustainability of natural resources. Yet there are some limitations associated with the use of bioremediation techniques including low degradation rates, instability of microorganism communities, insufficient mineralization of pollutants, and high expenses connected with their large-scale implementation. The further development of bioremediation could benefit greatly from the application of advanced molecular biology methods, innovative environmental monitoring using artificial intelligence, designing of engineered microbial communities, and circular economy principles.

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Conflicts of Interest: The authors declare no conflict of interest.

References

- Abdullah, M., Malik, H. A., Ali, A., Boopathy, R., Vo, P. H., Danaee, S., Ralph, P. & Malik, S. (2025). AI-driven algae biorefineries: A new era for sustainable bioeconomy. *Current Pollution Reports*, 11(1), 21. <https://link.springer.com/article/10.1007/s40726-025-00352-y>
- Ali, A., Zedan, T. H., Hassan, M. H. U., Ali, N., Naeem, Z., Devi, K., & Attique, Z. (2025). A Review of CRISPR-Engineered Microbial Consortia for Biodegradation of Petroleum Pollutants. *Desalination and Water Treatment*, 101612. <https://www.sciencedirect.com/science/article/pii/S1944398625006289>
- Alsafran, M., Usman, K., Ahmed, B., Rizwan, M., Saleem, M. H., & Al Jabri, H. (2022). Understanding the phytoremediation mechanisms of potentially toxic elements: a proteomic overview of recent

- advances. *Frontiers in plant science*, 13, 881242. <https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.881242/full>
- Avraham, A., Baker, E., Bernstein, R., Corbin, C., Corcoran, E., Ddiba, D., Dagerskog, L., Fettback, T., Garleff, L., Gross, A. and Hosney, H., & Zennaro, R. (2023). Wastewater–Turning Problem to Solution. A UNEP Rapid Response Assessment. <https://wedocs.unep.org/20.500.11822/43142>
- Ayilara, M. S., & Babalola, O. O. (2023). Bioremediation of environmental wastes: the role of microorganisms. *Frontiers in Agronomy*, 5, 1183691. <https://www.frontiersin.org/journals/agronomy/articles/10.3389/fagro.2023.1183691/full>
- Bhaskaralingam, A., Naushad, M., Dhiman, P., Wang, T., Jain, S., Kumar, D., & Sharma, G. (2026). Eco-engineered microbes: Advancing green wastewater management. *Journal of King Saud University–Science*, 38. <https://jksus.org/eco-engineered-microbes-advancing-green-wastewater-management/>
- Bondaroff, T. P., Cooke, S., & Stokes, G. (2020). Masks on the beach. *The impact of Covid-19 on Marine Plastic Pollution*. <https://assets.deshsanchar.com/wp-content/uploads/2020/12/30160944/Marine-Plastic-Pollution-FINAL-1-compressed-1.pdf>
- Cao, Z., Yan, W., Ding, M., & Yuan, Y. (2022). Construction of microbial consortia for microbial degradation of complex compounds. *Frontiers in Bioengineering and Biotechnology*, 10, 1051233. <https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2022.1051233/full>
- Chang, H. L., Liu, Y. L., Keng, C. J., Jiang, H. L., & Hu, J. (2024). Challenges of industrial wastewater treatment: utilizing Membrane bioreactors (MBRs) in conjunction with artificial intelligence (AI) technology. *Journal of Industrial and Production Engineering*, 41(5), 422-427. <https://www.tandfonline.com/doi/full/10.1080/21681015.2024.2330401#d1e231>
- Chaturvedi, K., Singhwane, A., Dhangar, M., Raghuvanshi, S., Tak, D., Srivastava, A. K., & Verma, S. (2024). State-of-the-art review on the Potentiality of Microorganisms for extracting metals from E-Waste ie, PCBs of Mobile phones and Computers. *Environmental Technology Reviews*, 13(1), 186-213. <https://www.tandfonline.com/doi/full/10.1080/21622515.2023.2290601?scroll=top&needAccess=true>
- Col, V. D., Ribas, F. F., & Araldi, R. P. (2025). The Transformative Impact of Extracellular Vesicles on the Cosmetics Industry: A Comprehensive Review. *Cosmetics*, 12(5), 191. <https://www.mdpi.com/2079-9284/12/5/191>
- Cook, Ed; Ionkova, Kremena; Bhada-Tata, Perinaz; Yadav, Sonakshi; Van Woerden, Frank. 2026. What a Waste 3.0: Global Snapshot of Solid Waste Management Toward Circularity until 2050. Urban Development Series. Washington, DC: World Bank. DOI: 10.1596/978-1-4648-2309-1. <https://openknowledge.worldbank.org/entities/publication/8f74a308-a490-4743-8cd4-9539fd8c3f52>
- Costa, C. (2025). Biological Treatment of Water Contaminants: A New Insight. *Water*, 17(11), 1628. <https://www.mdpi.com/2073-4441/17/11/1628>
- Dasila, H., Maithani, D., Srivastava, P., & Kabdwal, M. (2023). Bioremediation: A sustainable way for E-waste management. In *Microbial technology for sustainable E-waste management* (pp. 113-126). Cham: Springer International Publishing. https://link.springer.com/chapter/10.1007/978-3-031-25678-3_7
- da Silva, J., Bachega Rosa, G., Gustavo Sganzerla, W., Peruzzo Ferrareze, J., José Simioni, F., & Lucia Campos, M. (2023). Strategies and prospects in the recovery of contaminated soils by phytoremediation: an updated overview. *Communications in Plant Sciences*, 13. https://www.researchgate.net/profile/William-Sganzerla-2/publication/368625908_Strategies_and_prospects_in_the_recovery_of_contaminated_soils_by_phytoremediation_an_updated_overview/links/6436f1584e83cd0e2fab2d7f/Strategies-and-prospects-in-the-recovery-of-contaminated-soils-by-phytoremediation-an-updated-overview.pdf
- Duraisamy, R., Vishnu, V. M., Sribalaji, P., & Saeid, A. (2026). Microcosm-Dependent Degradation of Nonwoven Fabric in Surgical Masks by Endophytic Fungi *Aspergillus bridgerii*. *Journal of Hazardous Materials*, 141323. <https://www.sciencedirect.com/science/article/abs/pii/S0304389426003018>
- Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L. and Cropper, M., & Yan, C. (2022). Pollution and health: a progress update. *The Lancet planetary health*, 6(6), e535-e547. [https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196\(22\)00090-0/fulltext?ref=drilledpodcast.com](https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(22)00090-0/fulltext?ref=drilledpodcast.com)

- Global, F. A. O. F. A. O. L. F. (2024). Assessment of Salt-Affected Soils in 50 Years. *FAO: Rome, Italy*.
<https://www.fao.org/newsroom/detail/fao-launches-first-major-global-assessment-of-salt-affected-soils-in-50-years/en>
- Hamad, A. A., Moubasher, H. A., Moustafa, Y. M., Mohamed, N. H., & Abd-El Rhim, E. H. (2021). Petroleum hydrocarbon bioremediation using native fungal isolates and consortia. *The Scientific World Journal*, 2021(1), 6641533. <https://onlinelibrary.wiley.com/doi/epdf/10.1155/2021/6641533>
- Hassan, A. (2021). *Mycoremediation and Fungi-Assisted Phytoremediation of Heavy Metal Contaminated Landfills Soil* (Doctoral dissertation, University of Malaya (Malaysia)).
<https://www.proquest.com/openview/4b2a512be7395bb173e6d1f6ea2ae1f5/1?pq-origsite=gscholar&cbl=2026366&diss=y>
- Hassan, T. U., Rafiq, K., Hussain, M., Afzal, A., Naz, I., Azeem, M., & Ansari, L. (2023). Health recovery of soil polluted with marble effluents by the inoculation of Mn-tolerant bacteria. *Environmental Engineering Research*, 28(5). <https://www.eeer.org/journal/view.php?number=1466>
- Hazaimeh, M. D., & Ahmed, E. S. (2021). Bioremediation perspectives and progress in petroleum pollution in the marine environment: a review. *Environmental Science and Pollution Research*, 28(39), 54238-54259. [https://neptjournal.com/upload-images/\(19\)D-1257.pdf](https://neptjournal.com/upload-images/(19)D-1257.pdf)
- Ivase, T. J. P., Nyakuma, B. B., Oladokun, O., Abu, P. T., & Hassan, M. N. (2020). Review of the principal mechanisms, prospects, and challenges of bioelectrochemical systems. *Environmental progress & sustainable energy*, 39(1), 13298. <https://aiche.onlinelibrary.wiley.com/doi/abs/10.1002/ep.13298>
- Karamad, A., Mirtamizdoust, B., & Chenari, M. (2025). Biotechnological Solutions for Air Pollution Mitigation: A Comprehensive Review. *J. Chem. Rev*, 7(4), 748-783. https://www.researchgate.net/profile/Amirhossein-Karamad/publication/395258233_Biotechnological_Solutions_for_Air_Pollution_Mitigation_A_Comprehensive_Review/links/68b972c6ca495d7698327aa0/Biotechnological-Solutions-for-Air-Pollution-Mitigation-A-Comprehensive-Review.pdf
- Kaur, G., & Sood, P. (2025). Significance of biological approaches/bioremediation of wastewater treatment over physicochemical methods: a comparative analysis. In *Biotechnologies for Wastewater Treatment and Resource Recovery* (pp. 211-225). Elsevier. <https://www.sciencedirect.com/science/chapter/edited-volume/abs/pii/B978044327376600027X> <https://www.sciencedirect.com/science/chapter/edited-volume/abs/pii/B978044327376600027X>
- Kebede, G., Tafese, T., Abda, E. M., Kamaraj, M., & Assefa, F. (2021). Factors influencing the bacterial bioremediation of hydrocarbon contaminants in the soil: mechanisms and impacts. *Journal of Chemistry*, 2021(1), 9823362. <https://onlinelibrary.wiley.com/doi/epdf/10.1155/2021/9823362>
- Khalifa, A. M., ElBaghdady, K. Z., El Kafrawy, S. B., & El-Zeiny, A. M. (2025). Bioremediation vs. Traditional Methods: A Comparative Review of Heavy Metal Removal Techniques from Aquatic Environment. *Egyptian Journal of Aquatic Biology & Fisheries*, 29(2). https://openurl.ebsco.com/EPDB%3Aagcd%3A15%3A22013359/detailv2?sid=ebsco%3Aplink%3Ascholar&id=ebsco%3Aagcd%3A184658665&crl=c&link_origin=scholar.google.com
- Mahmud, T., Sabo, I. A., Lambu, Z. N., Danlami, D., & Shehu, A. A. (2022). Hydrocarbon degradation potentials of fungi: A review. *Journal of Environmental Bioremediation and Toxicology*, 5(1), 50-56. https://d1wqxtx1xzle7.cloudfront.net/113765685/802-libre.pdf?1714057565=&response-content-disposition=inline%3B+filename%3DHydrocarbon_Degradation_Potentials_of_Fu.pdf&Expires=1777607955&Signature=N2utbzHyXp50yu7SUvvIYXcBLtJT2usn1zs4z09yqB-GRG1jaRypnGlk4luMBDT-hE4J6SLV6oks8L6M2lJrxNpxfSvRD2gXP9nNMwLehq~p40klmgalOTEpoiTa9kc82JwTtA7mnyVVxNAXwEjNQ9gz7rGgOmzeDS6ovdtCO6GRygyg7ppKE3FZAIMVQdO~pyWYqz7MOYZD3zDq0GfDPuK5mppqyQHpmFeFZYvW5RnpXwk4UtX6uayGk8-D9qefSVhiT8PKpBFoDx1Db2wscuSDtb81DQGMAqMXUnC4PCjTNfVEnM-kqwGslMkL5IT1oy2UrBQKGusP7L20oHDWA__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA
- Medaura, M. C., Guivernau, M., Moreno-Ventas, X., Prenafeta-Boldú, F. X., & Viñas, M. (2021). Bioaugmentation of native fungi, an efficient strategy for the bioremediation of an aged industrially polluted soil with heavy

- hydrocarbons. *Frontiers in Microbiology*, 12, 626436. <https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2021.626436/full>
- Mekonnen, B. A., Aragaw, T. A., & Genet, M. B. (2024). Bioremediation of petroleum hydrocarbon contaminated soil: a review on principles, degradation mechanisms, and advancements. *Frontiers in Environmental Science*, 12, 1354422. <https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2024.1354422/full>
- Minhas, W. R., Saleemi, H., Raheem, M. F., Khalid, S. S., Aslam, H., & Ahmad, W. (2024). Crispr-Engineered Microbes For Enhanced Biodegradation Of Recalcitrant Pollutants A Genomic Approach To Environmental Remediation. *Frontiers in Health Informatics*, 13(3). https://www.researchgate.net/profile/Shahad-Khalid-8/publication/386278111_Crispr-Engineered_Microbes_For_Enhanced_Biodegradation_Of_Recalcitrant_Pollutants_A_Genomic_Approach_To_Environmental_Remediation/links/674b7cca3d17281c7deeb7b3/Crispr-Engineered-Microbes-For-Enhanced-Biodegradation-Of-Recalcitrant-Pollutants-A-Genomic-Approach-To-Environmental-Remediation.pdf
- Mohan, P. (2020). *Isolation of Plastic-Degrading Fungi from Landfill and Determining the Selected Plastics Biodegradation Capability* (Master's thesis, University of Malaya (Malaysia)). <https://www.proquest.com/openview/cd32d8aad96337ff741764b504e6c787/1?pq-origsite=gscholar&cbl=2026366&diss=y>
- Münzel, T., Hahad, O., Lelieveld, J., Aschner, M., Nieuwenhuijsen, M. J., Landrigan, P. J., & Daiber, A. (2025). Soil and water pollution and cardiovascular disease. *Nature Reviews Cardiology*, 22(2), 71-89. <https://www.nature.com/articles/s41569-024-01068-0>
- Naseem, M., Syab, S., Akhtar, S., Ikram, M., Batool, M., Saeed, Z., Iqbal, S & Sattar, H. (2023). Ex-situ and in-situ bioremediation strategies and their limitations for solid waste management: a mini-review. *Journal of Quality Assurance in Agricultural Sciences*, 3(01), 28-31. <https://isciencepress.com/journals/index.php/jqaas/article/view/39/32>
- Nukapothula, S., Suneel, V., Yunus, A. P., Rao, V. T., & Chen, C. (2025). Impact assessment of oil spills on the Red Sea waters using remote sensing and numerical modeling. *Regional Studies in Marine Science*, 86, 104187. <https://www.sciencedirect.com/science/article/abs/pii/S2352485525001781>
- Ojha, N., Karn, R., Abbas, S., & Bhugra, S. (2021, June). Bioremediation of industrial wastewater: a review. In *IOP conference series: earth and environmental science* (Vol. 796, No. 1, p. 012012). IOP Publishing. <https://iopscience.iop.org/article/10.1088/1755-1315/796/1/012012/pdf>
- Oro, C. E. D., Saorin Puton, B. M., Venquiaruto, L. D., Dallago, R. M., & Tres, M. V. (2024). Effective microbial strategies to remediate contaminated agricultural soils and conserve functions. *Agronomy*, 14(11), 2637. <https://www.mdpi.com/2073-4395/14/11/2637>
- Paniagua-Michel, J., & Banat, I. M. (2024). Unravelling diatoms' potential for the bioremediation of oil hydrocarbons in marine environments. *Clean Technologies*, 6(1), 93-115. <https://www.mdpi.com/2571-8797/6/1/7>
- Pandolfo, E., Barra Caracciolo, A., & Rolando, L. (2023). Recent advances in bacterial degradation of hydrocarbons. *Water*, 15(2), 375. <https://www.mdpi.com/2073-4441/15/2/375>
- Perez-Vazquez, A., Barciela, P., & Prieto, M. A. (2024). In situ and ex situ bioremediation of different persistent soil pollutants as agroecology tool. *Processes*, 12(10), 2223. <https://www.mdpi.com/2227-9717/12/10/2223>
- Qattan, S. Y. (2025). Harnessing bacterial consortia for effective bioremediation: targeted removal of heavy metals, hydrocarbons, and persistent pollutants. *Environmental Sciences Europe*, 37(1), 85. <https://link.springer.com/article/10.1186/s12302-025-01103-y>
- Raj, R., & Fayaz, A. (2025). Mycoremediation: The Role of Mushrooms in Cleaning Contaminated Agricultural Land. *Journal of Advances in Biology & Biotechnology*, 28(11), 1046-1056. https://d1wqtxts1xzle7.cloudfront.net/125619944/Fayaz28112025JABB148032-libre.pdf?1764792023=&response-content-disposition=inline%3B+filename%3DMycoremediation_The_Role_of_Mushrooms_in.pdf&Expires=1778082510&Signature=Ah2MeX6i5iA~Niu4h-BwNh9Mgk0Zf7dFNofk-b78EjuqJ4XrXis4p~aP4C3UWMfA0Qn7esFxFxGiPfs2pp4fBZSBhW~V3JsRokY2c~VBCHEKMg-

- RBCJ011n9nUPuilchJtRuSanKiV3JlFnA0fItFiv~IIWbFGjolPio92EQtfzW1azlUCnI-xE9Y2akFQP~LfyfCEBg1Z9dd3SmeAOaWwgcwZS4Zns-vbOGqm9gKbyfmvHIqisJGReYfQxFqi24KzTju-Sfd6b8VsQUWgelVUYRtMmvPk1XfbSkJCHwjuaud-K8dBm4PXZTc~JNIDOrpdyUvbagvLHtOuTc7eEfyg__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA
- Ray, M. K., Panda, J., Panda, B. P., Mohanta, T. K., & Mohanta, Y. K. (2023). Mycoremediation of heavy metals and/or metalloids in soil. In *Land remediation and management: Bioengineering strategies* (pp. 161-190). Singapore: Springer Nature Singapore. https://www.researchgate.net/profile/Ningthoujam-Samarendra/publication/375822164_Biodegradation_of_the_Fungicide_by_Bacteria_in_Soil/links/65cc4b011bed776ae34f6e57/Biodegradation-of-the-Fungicide-by-Bacteria-in-Soil.pdf#page=173
- Ray, S. S., Singh, R., Ganesapillai, M., & Ahn, Y. H. (2025). Plastic Pollution Management – Innovative Solutions for Plastic Waste. *Microplastics in the Environment: Fate, Impacts, Removal, and Management*, 383-416. <https://www.proquest.com/openview/cd32d8aad96337ff741764b504e6c787/1?pq-origsite=gscholar&cbl=2026366&diss=y>
- Romano-Armada, N., Yañez-Yazlle, M. F., Irazusta, V. P., Rajal, V. B., & Moraga, N. B. (2020). Potential of bioremediation and PGP traits in *Streptomyces* as strategies for bio-reclamation of salt-affected soils for agriculture. *Pathogens*, 9(2), 117. <https://www.mdpi.com/2076-0817/9/2/117>
- Rybarczyk, P. (2022). Removal of volatile organic compounds (VOCs) from air: focus on biotrickling filtration and process modeling. *Processes*, 10(12), 2531. <https://www.mdpi.com/2227-9717/10/12/2531>
- Saravanan, A., Kumar, P. S., Duc, P. A., & Rangasamy, G. (2023). Strategies for microbial bioremediation of environmental pollutants from industrial wastewater: a sustainable approach. *Chemosphere*, 313, 137323. <https://www.sciencedirect.com/science/article/abs/pii/S0045653522038164>
- Tiwari, S., Aachhera, S., Verma, P., & Gahan, C. S. (2025). Bioremediation of E-waste: a sustainable approach. In *Biotechnology for Environmental Sustainability* (pp. 709-724). Singapore: Springer Nature Singapore. https://link.springer.com/chapter/10.1007/978-981-97-7221-6_25
- Tamoor, M., Samak, N. A., & Xing, J. (2022). Pakistan toward achieving net-zero emissions: policy and roadmap. *ACS Sustainable Chemistry & Engineering*, 11(1), 368-380. <https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.2c05839>
- Zafar, S., Zainab, K., Humayon, F., Malik, T., & Zia, M. (2025). Biodegradation of COVID-19 face masks using soil microorganisms; Innovative approach towards applied and environmental microbiology. *Pure and Applied Biology (PAB)*, 14(2), 125-138. <https://thepab.org/index.php/journal/article/view/2906/1851>
- Zhang, X., Li, X., Zhao, X., & Li, Y. (2019). Factors affecting the efficiency of a bioelectrochemical system: a review. *RSC advances*, 9(34), 19748-19761. <https://pubs.rsc.org/en/content/articlehtml/2019/ra/c9ra03605a>
- Zhu, J., & Dong, J. (2026). The role mechanisms, research progress, and future challenges of engineered microbial consortia in saline-alkali land remediation: A comprehensive review. *Advances in Resources Research*, 6(2), 1165-1200. https://www.jstage.jst.go.jp/article/arr/6/2/6_1165/_pdf-char/ja
- Zhou, Y., & Haq, M. Z. U. (2025). Engineering of Synthetic Microbial Consortia for Sustainable Management of Wastewater and Polyethylene Terephthalate: A Comprehensive Review. *International Journal of Molecular Sciences*, 26(23), 11623. <https://pmc.ncbi.nlm.nih.gov/articles/PMC12692444/>

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