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Review Article

ADVANCES IN MICROBIAL BIOREMEDIATION OF HYDROCARBON-CONTAMINATED SOILS USING COMPOST-DERIVED BACTERIA AND FUNGI: A COMPREHENSIVE REVIEW

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ABSTRACT
Pervasive contamination of soil by petroleum hydrocarbons poses a serious threat to ecosystems and human health. Traditional physicochemical remediation methods are often costly and disruptive, prompting growing interest in bioremediation the use of microorganisms to degrade environmental pollutants, as a more sustainable alternative. This review explored the potential of bacteria and fungi derived from organic manure compost for the bioremediation of hydrocarbon-contaminated soils. To achieve this, a systematic literature review was conducted using databases such as Scopus, Web of Science, Google Scholar, and ScienceDirect, focusing on studies published within the last two decades. Search terms combined "bioremediation," "hydrocarbon," "compost," and relevant microbial taxa. Selected articles were thematically analyzed across contamination scope, compost microbiology, degradation mechanisms, application strategies, and influencing factors. Organic manure compost is a rich source of diverse, pre-adapted, and metabolically versatile microbial consortia, including hydrocarbon-degrading bacteria such as Pseudomonas, Bacillus, and Rhodococcus, and ligninolytic fungi such as Phanerochaete and Pleurotus. Mechanisms of hydrocarbon degradation both aerobic and anaerobic are discussed, with emphasis on key enzyme systems such as oxygenases, laccases, and biosurfactant production that enhance hydrocarbon bioavailability. Compost serves not only as a microbial inoculum but also as a bulking agent, nutrient source, and habitat modulator. Despite current challenges in large-scale deployment, compost-based bioremediation emerges as a promising, low-cost, and ecologically sound strategy for restoring hydrocarbon-polluted soils.

Keywords: Bioremediation; Microorganisms; Hydrocarbon Contaminated Soils; Bacteria; Fungi; Microbial Consortia; Organic Manure Compost

INTRODUCTION
Environmental pollution caused by hydrocarbons, heavy metals, and solid waste remains one of the most critical global challenges, posing significant threats to ecosystems and public health (Ali et al., 2021; Lawal & Shehu, 2024; Alao et al., 2025). Hydrocarbons originating from industrial discharges and oil spills infiltrate soil and water systems, disrupting aquatic ecosystems and bioaccumulating within food chains (Abarshi et al., 2017; Dubey et al., 2024). Heavy metals such as lead, cadmium, and mercury present acute hazards even at trace concentrations, as they are linked to neurological, renal, and developmental disorders in humans (Balali-Mood et al., 2021; Aliyu et al., 2023; Gusau et al., 2024; Namakka et al., 2024; Fardami et al., 2025). Similarly, improper solid waste disposal exacerbates environmental degradation by contaminating land and water resources, increasing greenhouse gas emissions, and promoting the spread of disease vectors (Shehu et al., 2020; Siddiqua et al., 2022; Yunusa et al., 2025). Collectively, these pollutants degrade environmental quality and heighten disease burdens in affected communities.

Among these contaminants, petroleum hydrocarbons are of particular concern due to their widespread use and persistence in the environment. Global dependence on petroleum as a primary energy source has resulted in extensive pollution from extraction, refining, transportation, and storage activities (Varjani, 2017; Allison & Mandler, 2018; Selvin et al., 2024). Accidental spills and improper disposal of petroleum products lead to the accumulation of toxic compounds in soils, posing severe ecological and health risks because of their cytotoxic, mutagenic, and carcinogenic properties (Abarshi et al., 2017; Dubey et al., 2024). Total petroleum hydrocarbons (TPH) a complex mixture of alkanes, cycloalkanes, and polycyclic aromatic hydrocarbons (PAHs)are particularly persistent, resulting in long-term soil infertility, groundwater contamination, and bioaccumulation across trophic levels (Kuppusamy et al., 2020; Dubey et al., 2024).

Conventional remediation methods such as soil incineration, landfilling, and chemical oxidation are often costly, energy-intensive, and environmentally disruptive (Trellu et al., 2016). As a result, there has been a growing shift toward in situ bioremediation, which harnesses the metabolic capabilities of microorganisms to transform or mineralize pollutants into less harmful end products such as CO_2 and H_2O (Singh et al., 2024; Boro et al., 2025).

Among the various bioremediation approaches, the use of organic amendments particularly manure compost has gained considerable attention. Compost serves not only as a nutrient source for biostimulation but also as a complex ecosystem rich in diverse microorganisms, including bacteria and fungi with notable catabolic versatility (Semple et al., 2001; Sani & Yong, 2021; Visconti et al., 2023). The composting process naturally enriches microbial populations capable of degrading complex organic polymers such as lignin and cellulose metabolic abilities that frequently extend to hydrocarbon degradation (Singh et al., 2022; Dubey et al., 2024). Thus, applying organic manure compost to contaminated soils provides dual benefits: bioaugmentation,

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through the introduction of potent hydrocarbon-degrading microbes, and biostimulation, by enhancing the soil's physicochemical properties (Omenna et al., 2024).
This review synthesizes current knowledge on the use of bacteria and fungi derived from organic manure compost for the bioremediation of petroleum hydrocarbons. It highlights the synergistic role of the compost matrix, key biochemical pathways involved, and the operational factors that influence bioremediation efficiency.

MATERIALS AND METHODS

This review was conducted through a systematic analysis of literature related to the bioremediation of hydrocarbon-contaminated soils using microorganisms derived from organic manure compost. Databases searched included Scopus, Web of Science, Google Scholar, and ScienceDirect. Search terms included combinations of ("bioremediation" OR "bioaugmentation" OR "biostimulation") AND ("hydrocarbon" OR "petroleum" OR "PAH") AND ("compost" OR "organic manure") AND ("bacteria" OR "fungi" OR "microbial consortium").
Studies published primarily within the past two decades were prioritized, with seminal older works retained for context. Selected full text articles were categorized thematically into contamination scope, compost microbiology, degradation mechanisms, application strategies, and influencing factors.

RESULTS AND DISCUSSION

The Scope of Hydrocarbon Contamination and Key Challenges

Petroleum hydrocarbons constitute a complex and heterogeneous group of contaminants whose environmental persistence and toxicity are governed by their molecular weight and structural complexity. Light aliphatic fractions, such as n-alkanes (C_{10}–C_{20}), are relatively labile and serve as preferential substrates for many microbes (Xu et al., 2025). In contrast, high-molecular-weight PAHs such as pyrene (4-ring) and benzo[a]pyrene (5-ring) are highly recalcitrant due to their hydrophobic nature, strong sorption to soil organic matter and clay particles, and low aqueous solubility, which collectively limit their bioavailability (Megharaj et al., 2011; Lawal et al., 2017; Kuppusamy et al., 2020).
The key challenges in remediating these contaminated soils are multifaceted and interconnected. The primary bottleneck is low bioavailability, whereby hydrophobic compounds are sequestered in soil micropores or bound to organic matter, rendering them inaccessible for microbial uptake (Semple et al., 2003). Furthermore, microbial degradation of hydrocarbons, a carbon-rich substrate is often constrained by severe deficiencies in essential nutrients, particularly nitrogen and phosphorus. This imbalance leads to a stalled biodegradation process (Leewis et al., 2016). Compounding these issues is the inherent microbial toxicity of many hydrocarbons, including BTEX compounds and certain PAHs, which can inhibit microbial metabolism and reduce the overall catabolic potential of the soil microbiome (Li et al., 2019).
Hydrocarbon contamination often leads to physical degradation of soil structure, resulting in the destruction of soil aggregates, reduction in pore space, and formation of hydrophobic surfaces that impede water infiltration and gas diffusion, thereby creating anoxic conditions unfavorable for aerobic degradation (Gomiero, 2016; Hossain et al., 2022; Naorem et al., 2023). These interconnected challenges underscore the inadequacy of relying solely on natural attenuation and highlight the necessity for biostimulation strategies that simultaneously address nutrient deficits, improve soil physicochemical properties, and enhance microbial activity. The use of organic manure compost represents a holistic approach that targets these multiple limitations concurrently.

Organic Manure Compost as a Microbial Reservoir

Composting is a controlled, aerobic, thermophilic biological process that stabilizes organic matter, resulting in a humus-rich, sanitized product. Beyond its value as a soil conditioner, the resulting compost acts as a "microbial seed bank," hosting a highly diverse, metabolically robust, and often pre-adapted consortium of microorganisms. This community structure is profoundly influenced by the feedstock composition and process parameters such as temperature and aeration (Rout et al., 2023; Jacob et al., 2025).
Key bacterial genera commonly identified include hydrocarbon degraders such as Bacillus, Pseudomonas, Acinetobacter, Streptomyces, and Rhodococcus (Awasthi et al., 2020). The genus Paenibacillus has gained prominence as a highly effective degrader, with genomic studies confirming the presence of catabolic genes such as alkB, which encodes alkane hydroxylases critical for n-alkane oxidation (Mhuantong et al., 2019; Feng et al., 2021). The fungal community is equally critical, comprising decomposers such as Aspergillus and Penicillium, as well as specialized ligninolytic white-rot fungi like Phanerochaete chrysosporium and Trametes versicolor (Kaur et al., 2021; Galazka et al., 2024). These fungi produce extracellular lignocellulolytic enzymes highly effective in attacking recalcitrant PAHs (Pointing, 2001; Baldrian, 2008). Yeasts such as Pichia spp. and Candida spp. also exhibit significant hydrocarbon-degrading capabilities through cytochrome P450 systems and biosurfactant production (Hashem et al., 2018; Xue et al., 2020; Padilla-Garfias et al., 2024; Aeini et al., 2025).

Mechanisms and Application of Hydrocarbon Degradation in Compost-Based Bioremediation

Microbial degradation of hydrocarbons follows specific biochemical pathways initiated by oxygenase enzymes that incorporate molecular oxygen into the inert hydrocarbon molecule. Aerobic bacteria typically initiate alkane degradation via terminal or subterminal oxidation catalyzed by monooxygenases such as AlkB or dioxygenases, converting them to alcohols and then to fatty acids for entry into the β-oxidation pathway (Rojo, 2009).Aromatic rings are attacked through dihydroxylation catalyzed by dioxygenases, forming catechols that undergo ring cleavage via the ortho or meta pathway (Fuchs et al., 2011; Phale et al., 2019).
Fungi employ complementary mechanisms, with white-rot fungi utilizing extracellular peroxidases—lignin peroxidase, manganese peroxidase—and laccases to oxidize PAHs co-metabolically (Baldrian, 2008). Yeasts employ cytochrome P450 monooxygenases for oxidation to trans-dihydrodiols (Padilla-Garfias et al., 2024). Biosurfactant production by Pseudomonas and Bacillus enhances substrate availability (Ron and Rosenberg, 2014; Santos et al., 2016).
Compost acts not only as a microbial inoculum but also as a nutrient source, bulking agent, and microhabitat modifier that optimizes pH, aeration, and nutrient availability (Margesin et al., 2007; Sayara et al., 2010). It also enhances soil structure, oxygen diffusion, and water retention (López et al., 2006). The priming effect—activation of indigenous microbes through labile compost

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carbon—further accelerates co-metabolic hydrocarbon degradation (Blagodatskaya and Kuzyakov, 2008; Fonti et al., 2015).
Application strategies include biostimulation, where compost addition stimulates native degraders, and bioaugmentation, where specific compost-derived strains or consortia are introduced to degrade recalcitrant pollutants (Azubuike et al., 2016; Tyagi et al., 2011; Poi et al., 2018). Integrated approaches combining both yield superior results.

Table 1. Summary of Findings from "Advances in Microbial Bioremediation of Hydrocarbon-Contaminated Soils Using Compost-Derived Bacteria and Fungi"

Thematic Area	Key Findings	Representative Microorganisms / Mechanisms	Supporting Studies / References (as cited)
Scope of Hydrocarbon Contamination	Hydrocarbon pollution causes long-term soil infertility, toxicity, and ecosystem disruption. High-molecular-weight PAHs are particularly recalcitrant.	Persistent hydrocarbons: n-alkanes, cycloalkanes, PAHs (e.g., benzo[a]pyrene).	Megharaj *et al.,* 2011; Lawal *et al.,* 2017; Kuqqppusamy *et al.,* 2020.
Challenges in Remediation	Main limitations include low bioavailability, nutrient imbalance, and hydrocarbon toxicity to microbes. Soil structure degradation worsens remediation challenges.	Deficiency of N, P; hydrophobicity; toxicity of BTEX and PAHs; anoxic soil conditions.	Semple *et al.,* 2003; Leewis *et al.*, 2016; Gomiero, 2016; Hossain *et al.,* 2022.
Role of Organic Manure Compost	Compost acts as a microbial reservoir, nutrient source, and bulking agent enhancing soil aeration and microbial activity.	Contains diverse bacteria, fungi, and yeasts adapted to degrade hydrocarbons.	Rout *et al.,* 2023; Jacob *et al.,* 2025.
Compost-Derived Bacteria	Compost harbors metabolically versatile bacteria capable of degrading alkanes and aromatics.	*Pseudomonas*, *Bacillus*, *Acinetobacter*, *Streptomyces*, *Rhodococcus*, *Paenibacillus* (alkB gene for alkane hydroxylase).	Awasthi *et al.,* 2020; Feng *et al.,* 2021; Mhuantong *et al.,* 2019.
Compost-Derived Fungi	Fungi produce extracellular enzymes for PAH degradation, particularly white-rot fungi.	*Phanerochaete chrysosporium*, *Trametes versicolor*, *Aspergillus*, *Penicillium*. Enzymes: laccases, lignin peroxidase, manganese peroxidase.	Kaur *et al.,* 2021; Baldrian, 2008; Galazka *et al.,* 2024.
Yeasts and Biosurfactant Producers	Yeasts degrade hydrocarbons via cytochrome P450 and biosurfactant synthesis, increasing bioavailability.	*Pichia spp.*, *Candida spp.*	Hashem *et al.*, 2018; Xue *et al.,* 2020; Aeini *et al.*, 2025.
Biochemical Mechanisms	Aerobic degradation via oxygenases (AlkB, mono-/dioxygenases); Fungal oxidation via laccases and peroxidases; co-metabolism and biosurfactant action enhance degradation.	Key enzymes: oxygenases, laccases, cytochrome P450, peroxidases.	Rojo, 2009; Phale *et al.,* 2019; Padilla-Garfias *et al.,* 2024.
Application Strategies	Two main strategies: (1) Biostimulation – compost enhances native microbial activity; (2) Bioaugmentation – inoculation with compost-derived microbes.	Integrated bioaugmentation + biostimulation yields superior TPH and PAH removal.	Azubuike *et al.,* 2016; Tyagi *et al.,* 2011; Poi *et al.,* 2018.
Factors Affecting Efficiency	Optimal pH (≈7), C:N:P ratio (100:10:1), moisture, temperature, and contaminant type determine success.	Compost buffers pH, supplies nutrients, improves aeration and structure.	Sarkar *et al.,* 2016; Xu *et al.,* 2018.
Performance Evidence (Case Studies)	Field and lab studies show high degradation efficiency with compost amendment.	90% TPH removal (biopiles), 73.6% oil degradation (desert soil), enhanced PAH degradation by white-rot fungi.	Onwosi *et al.,* 2017; Ali *et al.,* 2022; Zeng *et al.,* 2024.
Emerging Trends	Integration of omics, synthetic microbial consortia (SMCs), and nano-assisted compost systems for enhanced degradation.	Synthetic consortia, functional gene tracking, nanomaterial-assisted biodegradation.	Ding *et al.,* 2016; Karmakar *et al.,* 2024; De Lorenzo, 2023; Mukhopadhyay *et al.,* 2022.

Factors Influencing Bioremediation Success, Case Studies, and Future Perspectives

The success of compost-based bioremediation depends on soil pH (near-neutral), moisture, and optimal C:N:P ratio (100:10:1) (Sarkar et al., 2016). Temperature, contaminant type, and concentration also determine microbial activity and strategy choice (Varjani, 2017). Compost optimizes these parameters by acting as a bulking agent, buffer, moisture reservoir, and organic amendment (Kästner and Miltner, 2016; Xu et al., 2018).

Field studies confirm its effectiveness: Onwosi et al. (2017) reported 90% TPH removal using compost-amended biopiles; Zeng et al. (2024) demonstrated enhanced PAH degradation via white-rot fungi in compost. Ali et al. (2022) observed 73.6% oil degradation in desert soils through native microbial activity, underscoring compost's field viability (Tran et al., 2021).

Emerging trends include synthetic microbial consortia (SMCs) for predictable degradation (Ding et al., 2016; Ben and Or, 2017; Karmakar et al., 2024), omics-based monitoring (De Lorenzo, 2023), and nano-assisted bioremediation, integrating nanomaterials with compost to enhance pollutant breakdown (Galdames et al., 2020; Mukhopadhyay et al., 2022).

Conclusion

Compost-based bioremediation integrates microbial ecology with environmental engineering to deliver a sustainable, cost-effective, and environmentally sound solution for hydrocarbon-contaminated soils. The synergistic interactions between compost-derived bacteria and fungi—such as Paenibacillus and Pleurotus—and the compost matrix enhance degradation efficiency through nutrient balancing, structural improvement, and co-metabolic activity. Evidence from laboratory and field studies demonstrates high pollutant removal efficiencies, validating its scalability and real-world applicability.

Recommendations

1. Prioritize genomic and metabolic profiling of underexplored compost isolates to identify novel degradative pathways.
2. Implement standardized, long-term field trials across varied climatic and contamination conditions for performance validation.
3. Employ omics-based tools to monitor microbial community succession and functional gene expression in real time.
4. Establish clear biosafety guidelines and regulatory frameworks for the use of engineered xor synthetic microbial consortia.
5. Encourage interdisciplinary collaborations and policy incentives for the industrial-scale adoption of compost-based remediation technologies.

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