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Plant Microbe Synergistic Rhizoremediation Mechanisms for Polycyclic Aromatic Hydrocarbon Contaminated Soils in the Nigerian Environmen

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Abstract

Polycyclic aromatic hydrocarbons (PAHs) constitute a formidable class of persistent organic pollutants with significant implications for environmental quality, ecosystem stability, and public health globally. In Nigeria, a nation characterized by extensive petroleum industry activities, rapid urbanization, and agricultural expansion, PAH contamination presents a critical and multifaceted environmental challenge. Conventional physicochemical remediation technologies are frequently constrained by high economic costs, substantial energy requirements, and the potential for secondary environmental disruption. Consequently, biological remediation strategies, particularly those leveraging the synergistic interactions between plants and microorganisms (rhizoremediation), have emerged as a scientifically robust, ecologically sustainable, and potentially cost-effective alternative. This comprehensive review article meticulously examines the intricate molecular, biochemical, and ecological mechanisms that underpin the synergistic degradation of PAHs by plant-microbe partnerships. We provide a detailed analysis of microbial catabolic pathways, including the pivotal role of dioxygenase enzyme systems in aerobic bacteria and the non-specific oxidative mechanisms employed by ligninolytic fungi. The review elucidates the active role of plants in facilitating remediation through rhizosphere engineering, focusing on the critical function of root exudates as biochemical signals and bioavailability enhancers. A dedicated and substantial section of this work contextualizes these mechanisms within the Nigerian environment, analyzing prevalent contamination sources, screening indigenous biological resources with demonstrated or potential bioremediation capabilities, and discussing the unique pedoclimatic and socio-economic factors that influence implementation. We further explore advanced enhancement strategies such as tailored bioaugmentation, targeted biostimulation, and the integration of novel materials, alongside the transformative potential of omics technologies for understanding and optimizing these complex biological systems. Finally, the article proposes a forward-looking framework for translating this green technology from controlled research settings to effective field-scale application within Nigeria, emphasizing its integration into a broader sustainable bioeconomy and land management strategy to address the nation's specific pollution legacy.

Keywords

Polycyclic Aromatic Hydrocarbons (PAHs), Plant-Microbe Interactions, Biodegradation Mechanisms, Rhizosphere Dynamics, Bioavailability, Environmental Biotechnology, Sustainable Soil Remediation

1. Introduction

1.1 The Global and Local Imperative of Addressing PAH Contamination

Polycyclic aromatic hydrocarbons (PAHs) are a large group of organic compounds comprising two or more fused benzene rings arranged in linear, angular, or cluster formations. Their pervasive presence in the environment stems primarily from pyrolytic processes-the incomplete combustion of carbonaceous materials such as fossil fuels, biomass, and waste. Anthropogenic activities, including industrial operations, vehicular transport, energy generation, and improper waste incineration, constitute major sources. Additionally, natural events like forest fires and volcanic activity contribute to their global distribution. The environmental and health concerns associated with PAHs are profound and well-documented. Their chemical stability and hydrophobic nature lead to high persistence and a strong tendency to bioaccumulate in soil, sediment, and living tissues. Toxicologically, many PAHs and their metabolic derivatives are mutagenic, teratogenic, and carcinogenic, with compounds like benzo[a]pyrene classified as potent human carcinogens. The Stockholm Convention on Persistent Organic Pollutants recognizes the need for global action against such toxicants, underscoring the international regulatory concern.

In Nigeria, Africa's largest economy and a major oil-producing nation, the issue of PAH contamination is particularly acute and multi-sourced. The Niger Delta region, the heart of the country's petroleum industry, has experienced decades of environmental degradation due to crude oil spills from pipeline vandalism, operational failures, and sabotage, alongside continuous gas flaring. These activities release complex mixtures of hydrocarbons, including significant loads of low- to high-molecular-weight PAHs, into terrestrial and aquatic ecosystems. Beyond the oil sector, other significant sources include dense vehicular traffic and industrial emissions in megacities like Lagos and Port Harcourt, widespread practice of open biomass burning for agriculture and land clearing, and inefficient municipal solid waste management that often involves open burning. This confluence of factors has created a significant environmental liability, threatening agricultural productivity, aquatic biodiversity, and the health of local communities who rely on these ecosystems for sustenance and livelihood. A comparative environmental study has highlighted the severity of PAH impacts in Nigerian soils and waters, establishing a clear scientific and social imperative for developing effective, context-appropriate remediation solutions.[1]

1.2 The Evolution from Conventional to Biological Remediation

Traditional approaches to remediating PAH-contaminated sites have predominantly relied on engineering-intensive methods. These include physical techniques like soil excavation and disposal or soil washing, and chemical methods such as solvent extraction, chemical oxidation (e.g., using peroxides or ozone), and thermal treatment (e.g., incineration). While these methods can be effective in achieving rapid contaminant reduction, they suffer from significant drawbacks. They are often prohibitively expensive, especially for treating large volumes of contaminated soil or groundwater. Their energy footprint is substantial, and they can be highly disruptive to soil structure, microbial ecology, and overall site functionality, rendering the land unfit for immediate subsequent use. Crucially, these methods often simply transfer the contamination problem from one medium to another (e.g., soil to air via incineration emissions) or generate toxic secondary waste streams, failing to align with the principles of sustainable environmental management.

The limitations of conventional methods have catalyzed extensive research into biological alternatives-collectively termed bioremediation. This paradigm leverages the innate metabolic capacities of living organisms, primarily microorganisms and plants, to transform, degrade, or immobilize environmental contaminants into less toxic or harmless forms. Initial bioremediation strategies often focused on single-agent systems: *microbial remediation*, involving the inoculation or stimulation of pollutant-degrading bacteria or fungi; and *phytoremediation*, utilizing plants to extract, stabilize, or degrade pollutants. While successful in certain contexts, these standalone approaches revealed inherent constraints. Microbial degradation *ex situ* or in bulk soil can be limited by poor survival of introduced strains, competition with indigenous microbiota, and, most critically, the low aqueous solubility and high soil-sorption affinity of PAHs, which severely restricts their bioavailability to microbial cells. Plants, on the other hand, can suffer from phytotoxicity at high contaminant concentrations, have limited direct enzymatic capability to degrade complex HMW PAHs, and may only be effective for contaminants within the root zone (rhizosphere).[2]

1.3 The Synergistic Paradigm: Plant-Microbe Partnerships in Rhizoremediation

The convergence of phytoremediation and microbial remediation has given rise to a superior, integrated strategy known as plant-microbe synergistic remediation or, more specifically, rhizoremediation. This process is founded on the mutually beneficial interactions that occur in the rhizosphere-the narrow zone of soil directly influenced by living plant roots. The rhizosphere is a dynamically complex and nutrient-rich microenvironment, radically different from the surrounding bulk soil. Plants actively release a substantial proportion (up to 20-40%) of their photosynthetically fixed carbon into the rhizosphere through root exudates. These exudates are complex cocktails containing primary metabolites (sugars, amino acids, organic acids) and secondary metabolites (flavonoids, phenolics, terpenoids). This biochemical input creates a powerful "rhizosphere effect," stimulating microbial population density, diversity, and metabolic activity by orders of magnitude compared to bulk soil.

In the context of PAH contamination, this synergy is expertly co-opted. Root exudates serve a dual purpose: as a nutrient subsidy that selectively enriches for microbial taxa capable of utilizing both the exudates and, co-metabolically, the structurally similar PAHs; and as biochemical signals that can induce the expression of specific microbial catabolic genes. In return, the associated microbial consortium, often forming structured biofilms on root surfaces, directly degrades the PAHs, reducing phytotoxic stress. Furthermore, many of these microbes exhibit plant growth-promoting (PGP) traits, such as nitrogen fixation, phosphate solubilization, and production of phytohormones (e.g., indole-3-acetic acid) or the enzyme ACC deaminase (which lowers plant ethylene levels under stress). This reciprocal relationship enhances plant health, root biomass, and exudation, creating a powerful positive feedback loop that continuously drives the remediation process.[3] This review aims to provide a comprehensive, mechanistic dissection of this sophisticated partnership, with a dedicated and detailed focus on its application potential, necessary adaptations, and implementation pathways for addressing the pressing issue of PAH contamination in Nigeria.

2. Microbial Mechanisms of PAH Degradation: Biochemical Pathways and Key Actors

The biological transformation of PAHs is primarily executed by microorganisms, which possess diverse and specialized enzymatic machinery to break down these recalcitrant molecules. Understanding these pathways is fundamental to appreciating the microbial contribution to the plant-microbe synergy.

2.1 Bacterial Aerobic Degradation Pathways

Aerobic bacteria are the principal agents for the degradation of low- and medium-molecular-weight (LMW and MMW) PAHs (e.g., naphthalene, phenanthrene, anthracene, fluoranthene). The catabolic strategy is typically oxidative and follows a general sequence: activation, ring cleavage, and conversion to central metabolic intermediates.

The initial and most critical step is catalyzed by a family of enzymes known as dioxygenases. These multi-component enzyme systems incorporate two atoms of molecular oxygen into the aromatic ring, forming a *cis*-dihydrodiol intermediate. This reaction requires substantial redox potential and is often the rate-limiting step in the degradation pathway. The *cis*-dihydrodiol is subsequently dehydrogenated by a dehydrogenase enzyme to yield a dihydroxylated compound (a diol). This diol then undergoes a second dioxygenase-mediated reaction, where the aromatic ring is cleaved. Depending on the position of the hydroxyl groups and the specific enzyme, cleavage can occur either *ortho* (between the two hydroxylated carbons, leading to a carboxylic acid) or *meta* (adjacent to one of them, leading to a semialdehyde). The resulting aliphatic products (e.g., catechol, protocatechuate) are then funneled through further metabolic steps (e.g., the *ortho*-cleavage or *meta*-cleavage pathways) into the tricarboxylic acid (TCA) cycle, ultimately yielding carbon dioxide, water, and microbial biomass.

The genetic determinants for these pathways are often organized in operons (e.g., the *nah* operon for naphthalene, the *phn* operon for phenanthrene) located on chromosomes or large catabolic plasmids. This genetic organization facilitates horizontal gene transfer, allowing microbial communities to rapidly adapt to pollutant presence. Key bacterial genera renowned for their PAH-degrading capabilities include *Pseudomonas*, *Sphingomonas*, *Mycobacterium*, *Rhodococcus*, *Burkholderia*, and *Novosphingobium*. *Mycobacterium* and *Rhodococcus* species are particularly noted for their ability to attack HMW PAHs like pyrene and benzo[a]pyrene, sometimes via unique cytochrome P450 monooxygenase-initiated pathways.[4]

2.2 Fungal Degradation Pathways

Fungi, particularly basidiomycete white-rot fungi, play a complementary and crucial role, especially for HMW PAHs that are more resistant to bacterial attack. Fungi employ a fundamentally different, non-specific "enzyme combustion" strategy. These fungi naturally degrade lignin, a complex, irregular polymer in wood, using a suite of extracellular enzymes known as lignin-modifying enzymes (LMEs). Because the chemical bonds in lignin are diverse and non-specific, these enzymes have evolved to generate highly reactive, diffusible free radicals that can oxidize a wide range of structurally diverse compounds, including many xenobiotics like PAHs.

The key LMEs include:

•Laccases: Multi-copper oxidases that use molecular oxygen to oxidize phenolic compounds, generating phenoxy radicals that can subsequently react with non-phenolic structures.

•Manganese Peroxidases (MnP): Heme-containing peroxidases that oxidize Mn^{2+} to Mn^{3+}. The Mn^{3+}, often chelated by organic acids, acts as a diffusible low-molecular-weight mediator that can oxidize phenolic compounds and initiate lipid peroxidation reactions that can attack PAHs.

•Lignin Peroxidases (LiP): Powerful heme peroxidases capable of directly oxidizing non-phenolic aromatic rings with high redox potential, including those in PAHs, via the formation of cation radicals.

Fungi such as *Phanerochaete chrysosporium*, *Trametes versicolor*, and *Peniophora incarnata* have been extensively studied for their PAH degradation potential. Fungal degradation often results in partial oxidation, producing hydroxylated, quinoid, or dihydrodiol derivatives, which may be further metabolized or polymerized into soil organic matter. Sometimes, fungal pre-treatment can "open up" HMW PAHs, producing metabolites that are more bioavailable and susceptible to complete mineralization by associated bacteria-another layer of microbial synergy.

2.3 Anaerobic Degradation Pathways

While less efficient and slower than aerobic degradation, microbial degradation of PAHs under anaerobic conditions (nitrate-reducing, sulfate-reducing, iron-reducing, methanogenic) has been documented. This is environmentally relevant for contaminated sediments, deep subsurface soils, or groundwater aquifers where oxygen is limited. Anaerobic pathways likely involve novel biochemical strategies such as carboxylation, methylation, or the addition of fumarate to the PAH molecule, followed by stepwise ring reduction rather than oxidation. Although not the primary focus of most rhizoremediation systems (which are typically aerobic due to plant root respiration), the potential for anaerobic degradation in saturated root zones or in integrated treatment wetlands is an important consideration for comprehensive site remediation.[5]

Table 1. Key microbial taxa and their enzymatic arsenal for PAH degradation.

Microorganism Type	Example Genera/Species	Target PAHs	Key Enzymes/Mechanisms	Metabolic Context
Aerobic Bacteria	Pseudomonas putida, Sphingomonas paucimobilis, Mycobacterium vanbaalenii	Naphthalene, Phenanthrene, Anthracene, Pyrene	Ring-hydroxylating Dioxygenases (e.g., NDO, PDO), Dehydrogenases	Complete mineralization to CO_2 and H_2O via central metabolites.
Aerobic Bacteria	Rhodococcus spp., Novosphingobium spp.	Fluorene, Fluoranthene, Benzo[a]pyrene	Dioxygenases, Cytochrome P450 Monooxygenases	Often co-metabolic, partial or complete mineralization.
White-Rot Fungi	Phanerochaete chrysosporium, Trametes versicolor, Peniophora incarnata	Pyrene, Benzo[a]pyrene, other HMW PAHs	Laccase, Manganese Peroxidase, Lignin Peroxidase (Non-specific radical attack)	Partial oxidation, polymerization, or cometabolic conversion.
Anaerobic Consortia	Mixed cultures (e.g., sulfate-reducing bacteria)	LMW PAHs (Naphthalene, Phenanthrene)	Putative Carboxylases, Reductases	Slow, partial degradation under anoxic conditions.

Table 1: This table summarizes representative genera, target pollutants, key enzymes, and metabolic characteristics of different microbial types in the degradation of polycyclic aromatic hydrocarbons (PAHs).

Different microbial communities employ different degradation mechanisms for PAHs:

•Aerobic bacteria: Rely on oxidases, enabling efficient and thorough degradation, sometimes resulting in complete mineralization.
•White-rot fungi: Utilize strong oxidizing enzymes to treat high-molecular-weight, recalcitrant PAHs, often producing partial oxidation products.
•Anaerobic microbial communities: Degradation efficiency is lower, but degradation can proceed stably in anaerobic environments.
•This table helps in understanding PAH biodegradation strategies and the metabolic characteristics and advantages of various microorganisms.

3. The Plant's Multifaceted Role in Facilitating Synergistic Degradation

Plants are far from passive partners in rhizoremediation. They actively engineer their immediate soil environment to facilitate microbial degradation through a suite of interconnected mechanisms.

3.1 Rhizodegradation: The Core Synergistic Process

Rhizodegradation is the most significant mechanism for PAH removal in plant-microbe systems. It refers to the enhanced biodegradation of contaminants in the rhizosphere, driven by plant-derived factors. The continuous secretion of root exudates fundamentally alters the physical, chemical, and biological properties of the soil. Chemotactically, compounds like flavonoids and specific organic acids attract motile, beneficial bacteria towards the root surface. Trophically, the input of labile carbon (sugars, organic acids) and nitrogen (amino acids) alleviates nutrient limitations, allowing microbes to invest energy in the production of catabolic enzymes for PAHs, which are a less energetically favorable carbon source. This selective enrichment creates a competent, self-sustaining degrading community tightly associated with the root system.[6]

3.2 Modulation of PAH Bioavailability

The low bioavailability of PAHs is arguably the greatest challenge in their bioremediation. Plants and their associated microbes have evolved synergistic strategies to overcome this.

•Physico-chemical Mobilization by Root Exudates: Many low-molecular-weight organic acids (e.g., citric, oxalic, malic acid) present in exudates can act as mild biosurfactants or co-solvents. They can modify soil pH and chelate metal ions, potentially disrupting soil-PAH interactions and increasing the apparent solubility and desorption rate of PAHs from soil organic matter and clay particles.

•Induction of Microbial Biosurfactant Production: More importantly, the rhizosphere environment stimulates certain associated bacteria (e.g., *Pseudomonas aeruginosa*, *Bacillus subtilis*) to produce potent surface-active compounds called biosurfactants. These are amphiphilic molecules (e.g., rhamnolipids, surfactin, sophorolipids) that dramatically reduce the interfacial tension between PAHs and water. By emulsifying and solubilizing PAH droplets or crystals, biosurfactants increase their aqueous concentration and accessibility to microbial cells by several orders of magnitude. This process is a cornerstone of efficient rhizoremediation.[7]

•Biofilm-Enhanced Accessibility: Rhizosphere microbes frequently exist in structured, matrix-enclosed communities known as biofilms, adhering to root surfaces (rhizophane) or soil particles. The extracellular polymeric substance (EPS) matrix of biofilms not only protects cells but also concentrates hydrophobic compounds like PAHs at the cell surface, effectively increasing local concentration and uptake efficiency.[8]

3.3 Complementary Phytoremediation Mechanisms

While rhizodegradation is dominant, plants contribute through other parallel mechanisms:

•Phytoextraction: Some plant species can uptake and translocate more water-soluble LMW PAHs (e.g., naphthalene, anthracene) via transpirational pull. Within plant tissues, these may be metabolized by plant enzymes (e.g., cytochrome P450 monooxygenases, peroxidases, glycosyltransferases) and stored in vacuoles or cell walls as non-toxic conjugates. This direct removal is generally minor for most PAHs but contributes to the overall cleanup.[9]

•Phytostabilization: Extensive root systems physically bind soil particles, reducing wind and water erosion that could spread contaminants. Root growth can also sequester PAHs in the rhizosphere, stabilizing them and preventing leaching into groundwater.

•Phytovolatilization: For a few very volatile LMW PAHs, plants may transport them from roots to leaves and release them into the atmosphere in modified form. This is generally undesirable as it transfers pollution to another medium.[10]

3.4 Molecular Signaling and Genetic Regulation of the Synergy

The dialogue between plant roots and microbes is governed by sophisticated molecular signaling. Specific compounds in root exudates can act as genuine gene inducers. For example, certain flavonoids or salicylate derivatives have been shown to bind to transcriptional regulators (like NahR in *Pseudomonas*) that control the expression of PAH-degradation operons (*nah*), turning them on even when the PAH itself is not present at a concentration high enough to induce its own degradation. This pre-emptive "priming" of the microbial community is a powerful aspect of the synergy. Conversely, microbial production of phytohormones (IAA, cytokinins) influences root architecture, increasing root hair density and branching, thereby expanding the rhizosphere zone and exudation surface area. Microbial ACC deaminase reduces plant stress ethylene levels, allowing the plant to tolerate higher contaminant concentrations and allocate more energy to root growth and exudation rather than stress responses.[11]

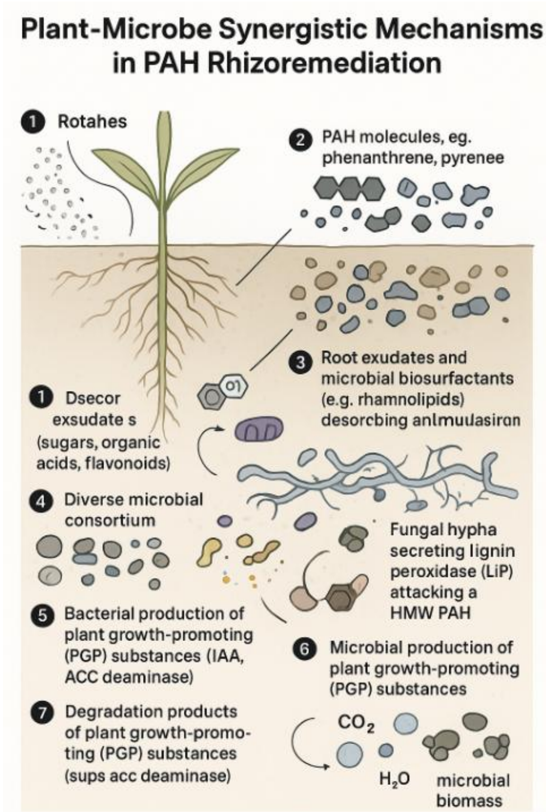

Figure 1. Schematic illustration of plant-microbe synergistic mechanisms in PAH rhizoremediation.

Figure 1:This Figure is summarizes the mechanism of plant-microbe synergy in the rhizosphere remediation of polycyclic aromatic hydrocarbons (PAHs). The core processes can be summarized as follows:

1.Plant root action: Plant roots and root hairs release root exudates (sugars, organic acids, flavonoids, etc.) into the rhizosphere, altering the rhizosphere microenvironment.

2.PAH form: PAHs (such as phenanthrene and pyrene) are initially tightly adsorbed onto soil organic matter and clay particles, exhibiting low bioavailability.

3.Desorption and solubilization: Root exudates and biosurfactants (such as rhamnolipids) produced by microorganisms promote the desorption of PAHs from soil particles and their emulsification into the aqueous phase.

4.Microbial community enrichment: A diverse microbial community and biofilm composed of bacteria, fungi, etc., forms in the rhizosphere and on the root surface.

5.Bacterial degradation: Bacteria produce key enzymes such as dioxygenases, breaking the aromatic ring structure of PAHs and initiating the degradation process.

6.Fungal synergistic degradation: Fungal hyphae secrete lignin peroxidase (LiP), which is particularly beneficial for the oxidative degradation of high molecular weight PAHs. Feedback effect on growth promotion: Microorganisms produce plant growth-promoting substances (IAA, ACC deaminase, etc.), which promote root growth and further enhance rhizosphere activity.

Overall significance: The gradual mineralization of PAHs into CO_2 and H_2O, and their conversion into microbial biomass, emphasizes the positive feedback synergy between plant roots, rhizosphere microorganisms, and their metabolites, jointly improving the bioavailability and degradation efficiency of PAHs.

4. The Nigerian Context: Contamination Landscape, Native Resources, and Implementation Strategy

4.1 Characterization of PAH Contamination Sources and Affected Ecosystems

Developing an effective national remediation strategy requires a precise understanding of contamination sources and their spatial distribution. In Nigeria, PAH pollution is heterogeneous and linked to specific economic activities:

•Petroleum Hydrocarbon Pollution in the Niger Delta: This is the most prominent and politically charged source. Chronic oil spills from aging infrastructure, pipeline vandalism, and accidental discharges during transportation contaminate vast areas of mangrove forests, freshwater swamps, and agricultural land. Crude oil contains a complex mixture of alkanes and PAHs. The brackish water and anoxic conditions of mangroves pose unique challenges for aerobic rhizoremediation, potentially requiring tailored approaches like constructed wetland systems.[12]

•Urban and Industrial Pollution: Major cities like Lagos, Ibadan, Kano, and Port Harcourt have high densities of old vehicles, informal industries (e.g., battery recycling, dyeing), power generators, and uncontrolled waste burning. This leads to diffuse atmospheric deposition of PAHs onto urban soils, road dust, and water bodies. These sites are often smaller but more numerous and closer to dense human populations.[13]

•Agricultural and Biomass Burning: The widespread practice of slash-and-burn agriculture and post-harvest residue burning is a significant seasonal source of PAHs across the country's savannah and forest zones, affecting agricultural soils.

The Nigerian environmental regulatory framework, including the *Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN)* and the *National Oil Spill Detection and Response Agency (NOSDRA) Act*, provides a basis for enforcement and remediation liability. However, the scale of contamination often outpaces institutional response capacity, underscoring the need for low-cost, scalable biological solutions.[14]

4.2 Bioprospecting Nigerian Native Flora and Microbiota for Remediation

The success of rhizoremediation in Nigeria hinges on using biological agents adapted to local tropical conditions (high temperatures, distinct wet/dry seasons, variable soil pH). Fortunately, Nigeria's rich biodiversity offers a vast reservoir of potential candidates.

•Indigenous Plant Species with Phytoremediation Potential: Research should prioritize native, perennial, fast-growing, and deep-rooted species known for hardiness in stressed environments. Promising candidates include:

○Grasses: *Panicum maximum* (Guinea grass), *Andropogon gayanus* (Gamba grass), and Vetiver grass (*Chrysopogon zizanioides*), the latter renowned globally for its massive root system and tolerance to hydrocarbons.

○Leguminous Trees and Shrubs: *Leucaena leucocephala* (Leucaena), *Acacia* species, and *Mimosa pudica*. Legumes can fix atmospheric nitrogen, improving soil fertility and supporting the overall plant-microbe system.

○Other Native Species: *Azadirachta indica* (Neem), known for its hardiness; and various mangrove species (*Rhizophora racemosa*, *Avicennia germinans*) for remediating oil-impacted coastal zones.

•Indigenous Microbial Consortia: Nigerian soils, particularly from hydrocarbon-polluted sites in the Niger Delta, harbor a wealth of adapted microbes. Studies have consistently isolated PAH-degrading bacteria (e.g., *Pseudomonas*, *Bacillus*, *Achromobacter*, *Micrococcus*) and fungi from these environments. The strategic bioprospecting, characterization, and formulation of these indigenous consortia into inoculants is a critical research frontier.[15] Using native microbes minimizes ecological disruption and improves survival and performance in field conditions compared to introduced foreign strains.

4.3 Challenges and Integrated Enhancement Strategies for the Nigerian Environment

Deploying rhizoremediation in Nigeria must account for site-specific challenges:

•Soil Constraints: Many Nigerian soils are acidic, low in organic matter, or nutrient-poor, which can limit plant and microbial growth. Soils in the Niger Delta may be waterlogged and saline.

•Scale and Mixed Contamination: Contamination is often over large areas and involves mixtures of PAHs, heavy metals, and other petroleum hydrocarbons, requiring a polyvalent approach.

•Land Use and Socio-Economics: Remediation strategies must be aligned with land use goals (restoration for agriculture, forestry, or conservation) and provide tangible benefits to local communities to ensure acceptance and stewardship.[16]

To overcome these challenges and boost efficiency, integrated strategies are essential:

•Tailored Bioaugmentation: Inoculating sites with well-characterized, high-performing, native microbial consortia alongside planting selected vegetation. This jump-starts the degrading community.

•Targeted Biostimulation: Amending soils with locally available, low-cost organic materials such as agricultural waste (rice husk, cassava peel), compost, manure, or biochar. These amendments improve soil structure, provide slow-release nutrients, and can also sorb contaminants, reducing toxicity. Biochar, in particular, has shown promise in enhancing PAH sequestration and providing a favorable habitat for microbes.

•Combined Remediation Technologies: Exploring the combination of rhizoremediation with other gentle technologies. For example, prior application of nano-scale zero-valent iron (nZVI) can chemically reduce some PAHs and create anaerobic/aerobic microsites that stimulate diverse microbial activity. Studies have demonstrated that nZVI combined with fungal treatment can elevate degradation rates of HMW PAHs significantly, from approximately 68% to over 90% in controlled settings.

•Rhizosphere Engineering and Plant Breeding: Using conventional breeding or molecular tools to develop plant varieties with enhanced traits for phytoremediation: deeper root systems, higher exudation rates, or specific exudate profiles that selectively recruit beneficial degraders.

•Phytomanagement as a Framework: Moving beyond mere cleanup to a management approach where the plant-based system provides economic return, such as using energy crops (e.g., for biomass) on remediating land, thus creating a financial incentive for implementation.[17]

5. Future Directions and Translational Research Framework for Nigeria

The transition from mechanistic understanding to widespread field application in Nigeria requires a coordinated, multi-disciplinary research and development agenda.

5.1 Priority Research Areas

1.Comprehensive Bioprospecting and Biobanking: Nationwide systematic collection, screening, and preservation of indigenous plant seeds and microbial isolates from contaminated and extreme environments. High-throughput screening should assess tolerance to PAHs, degradation efficiency, and PGP traits.

2.Mechanistic Field Validation: Moving from pot trials to well-designed, replicated field pilots in different geo-political zones (Niger Delta, urban Lagos, agricultural belt). These trials must monitor not only PAH concentration decline but also ecological parameters (microbial community shifts, soil health indicators, plant vitality) and the potential for food chain transfer.

3.Omics-Driven Discovery and Optimization: Employing metagenomics, metatranscriptomics, and metabolomics to decode the complex interactions in the Nigerian rhizosphere. This can identify key microbial players, critical catabolic genes, and inducing exudate compounds, informing the design of superior synthetic microbial communities (SynComs).

4.Economic and Lifecycle Analysis: Conducting detailed cost-benefit analyses comparing rhizoremediation to other options in the Nigerian context. Developing viable business models for phytomanagement (e.g., bioenergy production, sustainable forestry on remediated land) to attract private sector investment.[17]

5.2 A Proposed Implementation Pathway

•Phase 1 (Short-term: 1-3 years): Establish national research consortia focusing on bioprospecting and pilot-scale trials. Develop standardized protocols for screening and inoculant production. Conduct extensive stakeholder engagement and capacity building.

•Phase 2 (Medium-term: 3-7 years): Execute large-scale demonstration projects at selected high-priority contaminated sites (e.g., a former spill site, a polluted urban area). Validate environmental and economic performance, refine strategies, and develop national guidelines for biological remediation.

•Phase 3 (Long-term: 7-15 years): Facilitate full-scale commercial deployment integrated into national environmental restoration programs, oil spill response protocols, and urban land redevelopment plans. Establish a sustainable market for phytomanagement products and services.[18]

6. Conclusion

Plant-microbe synergistic remediation represents a paradigm shift in environmental restoration, transforming the challenge of pollution into an opportunity to harness and amplify natural ecological processes. The mechanisms-centered on the biochemical power of microbial dioxygenases and peroxidases, engineered by the rhizosphere environment created by plant root exudates-are a testament to the sophistication of biological systems. For Nigeria, this approach is not merely a technical option but a strategic necessity. It offers a path to address the environmental legacy of hydrocarbon exploitation and urban growth in a way that is aligned with sustainable development principles: it is solar-powered, enhances biodiversity, restores soil fertility, and can be integrated into local economies.

The scientific foundation is robust and growing. The challenge now is one of translation and contextual adaptation. By strategically investing in research focused on its unique biological resources and environmental conditions, Nigeria can develop home-grown, effective, and socially acceptable solutions to its PAH contamination problems. This will require sustained collaboration between microbiologists, plant scientists, environmental engineers, soil chemists, social scientists, policymakers, and local communities. The ultimate goal is to leverage the remarkable synergy between plants and microbes not only to clean the land but also to rebuild healthy, productive, and resilient ecosystems for future generations.

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