

ADVANCING BEYOND BIOAUGMENTATION: COMPARATIVE PROSPECTS OF GREEN REMEDIATION STRATEGIES FOR OIL-CONTAMINATED ECOSYSTEMS

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Abstract: This research examines the shortcomings of the normal oil-polluted remediation methods, and makes a comparison of current green remediation methods for oil-polluted environment, especially in petroleum producing area like the Niger Delta. It studies how petroleum hydrocarbons occur, fate, environmental-health impact in soil, and analyses the biodegradation pathways of microbes, fungi, and plants. The methodology uses a thorough review of the recent literature to combine evidence of the effectiveness of biostimulation, enhanced bioaugmentation, phytoremediation, mycoremediation, constructed wetlands, and bioelectrochemical systems, as well as innovations that boost microbial activity by electric-field stimulation. According to results, green

remediation technologies not only provide greater and more varied macroeconomic benefits, but they also lower the effective costs as well as increase their adaptability. According to the experts, while there can be significant variation in the efficiency ranges of the different techniques, hybridized approaches such as plant-microbe, fungal-wetland perform better when appropriately suited with soil properties, contaminant profiles and hydrological settings. The research further develops a decision-support matrix and flowchart framework to classify remediation options according to environmental parameters, contaminant behaviour, and operational constraints to facilitate optimal strategy selection by practitioners. The approaches have been confirmed as scalable and not restricted to a particular ecosystem. The conclusion highlights major knowledge gaps for research into metabolite fate, interactions between plant, microbe and fungus and engineering upscaling of hybrid systems. The study encourages more policy support, more interdisciplinary research and better, context-sensitive technology integration, which will produce sustainable, socially acceptable and cost-effective remediation that is superior to conventional bioaugmentation.

Keywords: Bioaugmentation, Green Remediation, Oil-Contaminated Ecosystems

Introduction

The exploration, production, refining, transport and storage of petroleum necessarily lead to the hydrocarbon contamination of the soil, water and sediment environment. Oil spills, pipeline leaks, tank failures, unaccounted for emissions, and the discharge of oily wastewater have been a constant source of pollution worldwide (Agarwal et al., 2015; Sam & Zabbey, 2018). According to worldwide assessments, around 6 million tonnes of petroleum hydrocarbons enter terrestrial and aquatic ecosystems every year, threatening ecological systems and public health (Nwankwegu et al., 2018). Around Europe every year, more than three and a half

million sites get contaminated with 600,000 tonnes of hydrocarbons (Guo et al., 2010; Wang et al., 2013).

The Niger Delta exemplifies this global crisis. After many years of manual refining weak point through pipeline vandalism, gas flares condensate and ineffective waste management systems have resulted in complex chronic hydrocarbon contamination (Ayanlade & Proske, 2016; Zabbey et al., 2017). The results are severe soil degradation, groundwater pollution, loss of biodiversity, and impairment of terrestrial and aquatic habitats. Petroleum hydrocarbons, especially TPH and PAH, are hydrophobic, persistent, bioaccumulative and environmentally recalcitrant toxins that pose dangers to flora, fauna and humans (Nwankwegu et al., 2018).

Various techniques like excavation, soil washing, chemical oxidation and classical bioaugmentation haven't always recorded success in practice. Excavation is a fast but costly technique. Additionally, it often shifts the contamination to landfills (Brown et al. 2017). Soil washing improves extraction of hydrocarbons, but it produces secondary effluents and requires complex operational logistics (Sam & Zabbey, 2018). Chemical oxidation occurs very quickly but can produce harmful by-products and is soil matrix sensitive. The conventional bio-augmentation approaches are economically viable; however, they are slow, site-specific and require an optimal environment including nutrients, temperature, pH and oxygen (Guo et al., 2010; Chen et al., 2015; Wang et al., 2013).

These limitations have brought the global attention to green remediation technologies that facilitate natural biodegradation pathways by minimizing the ecological disturbance. New strategies like biostimulation, phytoremediation, mycoremediation, biosurfactant-technique biodegradation, built wetlands, and bioelectrochemical systems show eco-friendlier, less-costly and flexible ways to enhance hydrocarbon mineralisation at various site conditions.

We still need an integrated comparative evaluation of these green techniques although they portend much promise, particularly with respect to: mechanistic routes of degradation; performance under varying loads of contamination; ecological co-benefits; cost-effectiveness, and scalability; site-specific constraints in oil-rich regions like the Niger Delta.

In order to fill this, gap a conceptual structure of green remediation strategies for petroleum contaminated sites are shown in Figure 1.

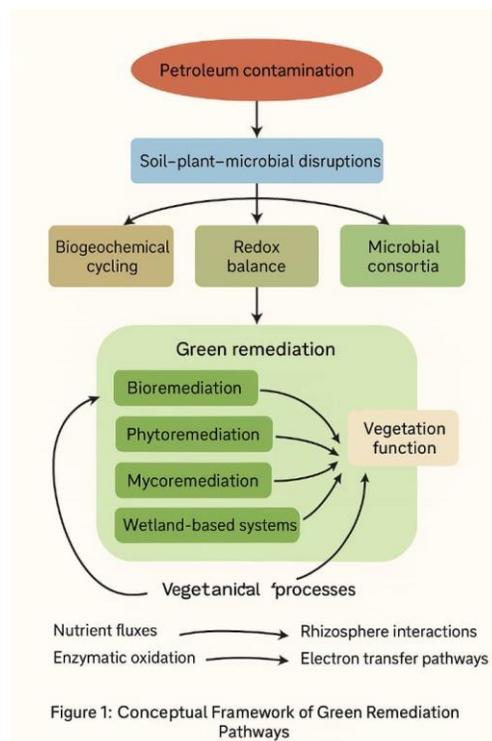


Figure 1: Conceptual Framework of Green Remediation Pathways for Petroleum-Contaminated Ecosystems

This diagram presents the interconnected routes of how oil pollution can disrupt soil, plants, and microbes and monitor solutions and transitions to an ecosystem recovery. “Since system interdependence is emphasized, it explains why remediation must be multi-technology and site-specific in instances like the Niger Delta”

Clearly Stated Problem

Niger Delta regions continue to suffer petroleum contamination after decades of interventions as a result of inadequacies in conventional remediation techniques, weak compliance with regulations, and no single, science-based framework selections for optimal green remediation options. No comprehensive comparative evidence of the performance or techno-ecological suitability of different green remediation technologies under Niger Delta-specific biophysical and socio-economic conditions exists.

Objectives of the Study

This study examines and evaluates the comparative prospects of green remediation techniques for petroleum-contaminated environments. Specifically, it aims to:

- i. assess the mechanistic pathways, degradation efficiencies, and ecological functions of major green remediation approaches including biostimulation, phytoremediation, mycoremediation, constructed wetlands, and bioelectrochemical systems; and
- ii. develop a site-specific decision support framework for selecting appropriate green remediation strategies based on contamination type, soil characteristics, hydrology, cost factors, and ecological performance indicators.

Research Gap and Aim of the Study

Although a great deal of work has been carried out on bioremediation, significant gaps remain in the knowledge on relative performance, contextual applicability and field-scale viability of green remediation strategies for petroleum-contaminated environments. Many studies focus only the examination of one technique at a time. This makes the result irrelevant at mixed contaminant condition common in the Niger Delta. Studies on biostimulation have indicated degradation enhancement through nutrient addition, but short experimentation period and limited analyses of native microbial interactions reduce predictability. Research on phytoremediation shows the tolerance and uptake potential of plants. However, the long-term behaviour in the rhizosphere is still unknown. It is also uncertain if the microorganisms will help or stress the plants under conditions of heavy PAH loads. Mycoremediation shows strong enzymatic degradation pathways but little is known

about its performance in the field. This is due to its sensitivity to moisture, substrate type, and fungal–bacterial co-metabolism. Tropical constructed wetlands show good removal efficiencies but are under-studied for hydrological optimisation, clogging dynamics and plant–microbe coupling.

Upcoming devices that are able to improve the activity of microbes by electric fields are known as bioelectrochemical systems. But, some problems like electrode sustainability, power output and scale-up possess a challenge to the general application of these systems.

A gap that cuts across the elements is that there is no integrated comparative framework that evaluates these approaches based on efficiency ranges, ecological co-benefits, cost, technical readiness and site specificity. Only a few studies present tools to use to address oil impacts in regions.

Table 1: Summary of Key Green Remediation Studies, Main Findings, and Persistent Gaps

Study	Remediation Approach	Main Findings	Persistent Gaps
Guo et al. (2010)	Biostimulation & bioaugmentation	Demonstrated enhanced TPH removal (65–80%) in sandy and loamy soils; nutrient availability critical for microbial activity	Limited long-term field validation; inconsistent results across soil textures
Chen et al. (2015c)	Microbial consortia & nutrient amendment	High PAH degradation (70–85%) under controlled conditions; microbial synergy	Poor replication under fluctuating field moisture, pH and temperature

			improves resilience	
Wang et al. (2013)	Phytoremediation mycoremediation	&	Efficient PAH uptake and enzymatic breakdown (50-75%); robust in high-organic soils	Slow remediation timelines; limited plant survival under high- toxicity sites
Sam &Zabbey (2018)	Constructed wetlands monitored natural recovery	&	Significant reduction in petroleum effluents (55- 70%); improved ecosystem recovery and soil fertility	Inadequate hydrological control; uncertainties in pollutant fate pathways
Nwankwegu et al. (2018)	Integrated bioremediation	plant-microbe	Strong evidence of synergistic degradation of TPH/PAH, improved soil health	Lack of scaling models; insufficient microbial community monitoring
Zabbey et al. (2017)	Community-based restoration	wetland	Demonstrated strong socio- ecological benefits with moderate hydrocarbon removal	Long-term maintenance challenges; fragmented regulatory support

Comparison of Introduction as an extensive literature review will outline major green remediation studies activity. This study shows that the laboratory successes have been strong, but the field replication has proven weaker due to the soil

heterogeneity, moisture fluctuations, and not enough long-term monitoring. Niger delta projects often underperform due to poor field validation, insufficient hydrological control, and lack of microbial community monitoring.

Aim of the Study

This study compares the green remediation technologies employing in-situ and ex-situ techniques for site restoration of petroleum-damaged ecosystems. It will consider site-specific conditions, mechanisms, efficiency, performance determiners, and limitations. It also builds a decision matrix and flow chart to assist in choosing the most appropriate action for various environmental conditions with a focus on the Niger Delta.

Literature Review

Occurrence and Fate of Petroleum-Contaminated Soils

Chemicals from petroleum can enter soil due to leakages and waste disposal. The texture, porosity, slope, and climate of the soil dictate their movement (Brown et al., 2017a; Sam & Zabbey, 2018). Hydrocarbons cannot mix with water. When they are added to soil, they displace water and get adsorbed on the soil particles. Thus, they reduce the oxygen availability and the microorganisms cannot effectively act. Low-molecular-weight hydrocarbons are volatile and mobile and heavier fractions are persistent and affect soil color, pH, nutrient content, enzymatic activity and overall resilience (Guo et al., 2010; Wang et al., 2013; Chen et al., 2015c). How mobility is affected through molecular weight and soil clay or sand is an important aspect for deciding between in situ bioremediation or containment strategies.

Environmental and Human Health Impacts

Contaminants in the soil affect moisture and essential nutrient availability. When exposed to plants, roots penetrate less, grow less, and photosynthesize less efficiently. For example, *Sinapis alba* (mustard), *Sorghum saccharatum* (forage sorghum), and *Lepidium sativum* (garden cress) show up to 65% less root length (Guo et al. 2010; Wang et al. 2013; Chen et al. 2015c). People can breathe in, swallow, or touch the materials and may end up with respiratory diseases, disorganized internal organs, mutations, and cancer (Zabbey et al. 2017; Sam & Zabbey 2018).

Table 2. Environmental and Health Impacts of Petroleum Contamination

Impact Domain	Key Effects	Mechanisms	Indicators	Long-Term Consequences
Soil	Reduced porosity and nutrient availability	Hydrocarbon coating of soil particles; disruption of microbial activity	↓ Organic matter, ↑ bulk density, ↓ pH	Soil infertility, loss of biodiversity
Plant	Chlorosis, stunted growth, poor germination	Root blockage, nutrient imbalance, PAH toxicity	↓ Chlorophyll, ↓ biomass, ↓ root length	Crop yield decline, habitat loss
Human	Respiratory and dermatological disorders, carcinogenic risk	Inhalation, dermal contact, food-chain bioaccumulation	↑ BTEX exposure, ↑ PAH biomarkers	Chronic diseases, socio-economic burden

The ways that hydrocarbon's exposure impact soil, plant and human proves that oil changes soil chemistry, prevents vegetation and introduces bioaccumulative toxins (PAHs, BTEX). It stresses the need for combining cleanup efforts with public health campaigns, as soil degradation and health risks reinforce each other in oil-impacted communities.

Soils contaminated with heavy metals tend to have different physical and chemical properties than non-contaminated soils, and they have less ability to hold water or nutrients, thereby limiting plant growth ability. Ultimately, soil contamination can reduce plant growth and affect human health through bioaccumulation. The persistence of PAHs in the food chain calls for a risk-specific remediation, stressing green remediation.

Theoretical Frameworks

The green remediation of ecosystems contaminated by petroleum can be based on two complementary theoretical strands.

Ecological Restoration Theory

This theory is all about recovering the ecosystem structure, function and resilience after disturbance is experienced. Contamination of the soil due to petroleum contaminates microbial community, nutrients cycle and water process which affects plants and human beings (Brown et al., 2017a; Sam & Zabbey, 2018) Methods for using soil biota to remediate soil damage are called green remediation strategies. Phytoremediation, mycoremediation, and constructed wetlands approaches all agree with this theory. These methods speed up natural recovery processes. They also increase the diversity of microbes. Further, they can help in the stabilization of soil properties (Guo et al., 2010; Chen et al., 2015c). Restoration happens at the site and is affected by contaminant, soil and biodiversity.

Ecosystem Services and Risk-Based Framework

The model assesses remediation options against human and eco-health impacts, ecosystem functions and costs. Petroleum hydrocarbons affect the fertility and productivity of soil and plant and human health by bioaccumulation and exposure to PAHs and BTEX (Zabbey et al 2017). The measurement of TPH/PAH decrease, microbial activity, ecotoxicity and sustainability by green remediation strategies provides a risk-informed decision making process (Sam & Zabbey, 2018; Nwankwegu et al., 2018). The framework allows for hybrid methods of biological, chemical, and engineered that minimize negative ecological and social impacts.

Integration of Theory into Practice

Using both these theories would retain a holistic approach for remediation. Ecological restoration will help a long-term recovery of the functional soil-plant-microbe interactions. A risk-based perspective will help practitioners prioritize intervention on the base of contaminant severity, site sensitivity, and socio-economic constraints. Theories are operationalized through decision matrices, flowcharts, and adaptive monitoring systems to guide appropriate site-specific remediation strategy selection and performance evaluation.

Phytoremediation

Plant material and its rhizosphere microbes are used in phytoremediation to degrade petroleum hydrocarbons. Rhizodegradation is characterized by root exudates that stimulate microorganisms that degrade contaminants. Phytostabilization involves the immobilization of contaminants, thereby preventing the spread of contaminants to groundwater. Phytovolatilization occurs when volatile hydrocarbons are absorbed by plants and released in a less toxic form. (Guo et al., 2010; Wang et al., 2013; Chen et al., 2015c)

The effectiveness depends on the site, plant species, soil features, and hydrocarbons. TPH removal ranges between 40–70% over 60–120 days. Heavy hydrocarbons weather slowly and the sensitivity of plants to water or salt limits its application (Zabbey et al., 2017). Grasses could be rhizodegrading agent while woody species are stabilizing agent. Through this, a pathogen, pest, or pollutant is neutralized. Research shows that increasing hydrocarbons degradation with native species used with biostimulation is possible.

Mycoremediation

The degradation of stubborn hydrocarbons, particularly PAHs, occurs as a result of the enzymatic action of laccases and peroxidases in fungi. Soil bacteria and fungi together influence soil chemistry and microbial ecology. Studies conducted in the laboratory and field suggest that 65-75% of PAH removal can occur between 90 and 150 days (Wang et al., 2013; Chen et al., 2015c). There are limits involving slow and compacted soil colonization, and sensitivity to extreme pH and water limits.

Table 3. Laboratory-Scale Fungal Biodegradation Performance

Fungal Species	Target Hydrocarbon Type	Optimal Conditions	Removal Efficiency (%)	Duration (days)
<i>Aspergillusniger</i>	Aliphatic	pH 6.5, 30 °C	72	21
<i>Phanerochaetechrysosporium</i>	Aromatic	pH 5.5, 28	88	28

	(PAHs)	°C		
Trametesversicolor	Mixed	pH 6.0, 25 °C	82	35
Penicilliumchrysogenum	Aliphatic	pH 7.0, 30 °C	68	20

This table summarizes fungal species, hydrocarbon targets, removal efficiencies, and durations, providing guidance for site-specific selection. Environmental parameters like pH, temperature and contaminant concentration influence efficiency. Using groups of fungi may improve degradation of complex hydrocarbons shows fungi efficiency removal at optimal pH/temperature, strong enzymatic oxidation, especially for PAHs which microbes degrade slowly. There is great potential for fungal-microbial-plant hybrids for the remediation of mangrove soil.

Wetlands and Bioelectrochemical Systems

Constructed wetlands use plants and microbes to treat petroleum-contaminated effluents. Hydrophobic contaminants are sorbed by substrates while microbial degradation is done along the water-flow paths. According to pilot studies, TPHs can be removed by 50–80% and PAHs can be removed by 40–70% (Guo et al., 2010; Chen et al., 2015c; Zabbey et al., 2017).

By applying low-voltage electrical stimulation on the microbial consortia, bioelectrochemical systems (microbial fuel cells) enhance the microbial hydrocarbon degradation. According to Guo et al. 2010, Sam and Zabbey 2018, TPH removal performance can increase by ~60%. Wetlands require a large amount of land and water. Similarly, bioelectrochemical systems require a lot of energy. Moreover, impact varies due to seasonal or environmental factors.

Wetlands integrated with bioelectrochemical stimulation, which use oxidation-reduction processes to enhance degradation and energy recovery, are promising systems that can be used at field scale and sustained with little maintenance.

Biostimulation, Bioaugmentation, and Hybrid Approaches

Adding nutrients to enhance the activity of indigenous microorganisms is referred to as biostimulation. Up to 70–93% TPH removal has been reported with effective biostimulation. Bioaugmentation refers to the addition of hydrocarbon degrading microbes. According to studies, 48–75% of hydrocarbons were removed from stockpiled soils (Chen et al., 2015c; Guo et al 2010; Wang et al 2013).

The hybrid strategies that include plant-fungi systems, biochar-assisted bioamendments, and nano-assisted remediation achieves >80% TPH removal over 60–120 days especially in highly contaminated/complex soils (Zabbey et al. 2017; Nwankwegu et al. 2018).

Table 4. Comparative Evaluation of Green Remediation Approaches

Strategy	Key Mechanism	Typical Efficiency (%)	Cost Level	Time Frame	Feasibility
Bioremediation	Microbial degradation	60–85	Low	Medium	High
Phytoremediation	Root uptake & rhizodegradation	50–80	Low–Medium	Long	High
Mycoremediation	Enzymatic oxidation	70–90	Medium	Medium	Moderate
Constructed Wetlands	Anaerobic/aerobic biodegradation	75–95	High	Medium	High
Bioelectrochemical Systems	Electrogenic oxidation	80–96	High	Short	Moderate

This table compares performance, cost, and feasibility for site-specific selection and hybrid design. Although phytoremediation and biostimulation are more cost-

effective and longer-lasting, engineered wetlands and bioelectrochemical systems have a higher removal capacity but are technically managed processes. The trade-off that hybrid remediation can use or implement biological and engineered systems in different soil conditions.

Site Characterization and Remediation Strategy Selection

To assess a site, soil texture, moisture, pH, depth of contamination, and type of hydrocarbon will have an impact on the colonization of microbes and growth of plant (Chen et al., 2015c; Guo et al., 2010). Hybrid strategies are recommended for complex sites. GIS and remote sensing help to detect hot spots of contamination and making of prediction decision.

Remediation Strategy Selection

Selection is based on the type of hydrocarbon contaminant, level of contamination, environmental constraints, ecological objectives and social costs. Hybrid plans are the best choice for regions that are complicated or highly polluted to optimize functioning and sustainability (Sam & Zabbey, 2018). This decision tree helps in systematic selection of a site for bioremediation. When predictive AI modules are used, the system can adjust automatically based on cost, time, and eco-optimality, allowing for evidence-based context-specific decisions.

Monitoring Protocols

Chemical analyses (GC-MS, TPH, PAH), microbial assays (qPCR, 16S rRNA), enzymatic tests and ecotoxicological bioassays (Chen et al., 2015c; Nwankwegu et al., 2018; Sam & Zabbey, 2018) are included.

Table 5. Recommended Monitoring Protocols

Parameter	Method	Frequency	Interpretation	Source
Hydrocarbon Content	GC-MS, TPH, PAH	Weekly	Assess removal efficiency	Wang et al., 2013
Microbial Activity	qPCR, 16S rRNA sequencing	Bi-weekly	Track hydrocarbon-degrading microbes	Chen et al., 2015c
Enzymatic Activity	Catalase, dehydrogenase, urease	Bi-weekly	Microbial metabolic health	Sam & Zabbey, 2018
Ecotoxicity	Plant bioassays	Monthly	Residual toxicity assessment	Zabbey et al., 2017

Presents analytical methods (GC-MS, qPCR, enzymatic assays) with frequencies. Monitoring that relates chemistry to organism and ecosystem deducing effects. Basically, it is bad monitoring on the part of the regulator and not technology that contributes largely to the failure of remediation projects in Nigeria. Monitoring strategies can be complex. They combine remote sensing, GIS and biosensor based microbial detection (Zabbey et al., 2017). This allows for adaptive remediation and better accuracy of data.

Performance Assessment and Adaptive Management

The cut-off levels for TPH decrease, microbial activity, soil pH, and ecotoxicity for corrective measures. Monitoring of data would show any adjustment needed in nutrient amendments, microbial inoculation, irrigation, or introduction of new plants in compliance with regulations to optimise remediation (Chen et al., 2015c; Sam & Zabbey, 2018).

Table 6. Performance Thresholds and Adaptive Management Guidelines

Indicator	Target/Threshold	Adaptive Intervention	Source
TPH Reduction (%)	≥ 70	Biostimulation or bioaugmentation	Chen et al., 2015c
Microbial Activity (CFU/g)	Baseline +50%	Adjust inoculum or nutrients	Sam & Zabbey, 2018
Soil pH	6.5–7.5	Lime or organic amendments	Guo et al., 2010
Ecotoxicity	$\leq 20\%$ adverse effect	Introduce phytoremediation or hybrid strategies	Zabbey et al., 2017

TPH, microbial activity, pH, and ecotoxicity thresholds are provided. Show the need for interventions based on triggers rather than remedies. A key adaptive remediation model associated with unstable hydrology and soil types in the Niger Delta. This framework integrates lab data, field observations, and adaptive management to create resilient evidence-based solutions.

Methodology

Study Area

The research focuses on petroleum-contaminated soils in the Niger Delta, Nigeria, a region highly impacted by oil exploration, spills, and gas flaring. The area features mangroves, wetlands, sandy-loamy soils, and variable hydrology, which influence contaminant transport and bioavailability (Ayanlade & Proske, 2016; Badejo & Nwilo, 2017). Sampling sites were selected based on proximity to oil installations, reported spill incidents, and variation in soil types.

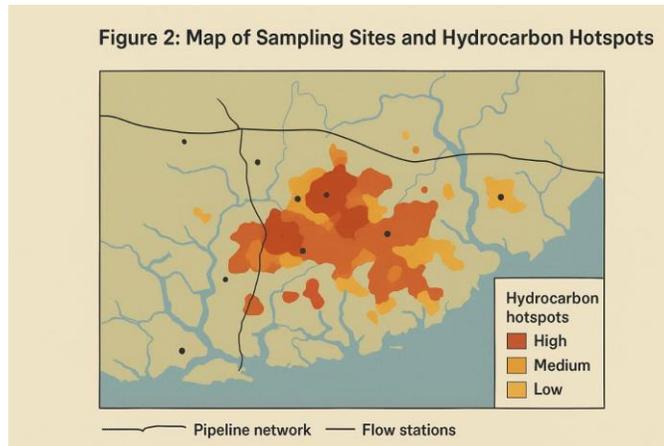


Figure 2: Map showing Sampling Sites and Hydrocarbon Contamination Hotspots in the Niger Delta

Depicts the spatial distribution of contamination across sampling points the pattern reveals clustered hotspots driven by pipeline proximity, artisanal refining, and spill-prone wetlands, highlighting the need for spatially differentiated remediation zones.

Sampling Strategy

Soil samples were collected using stratified random sampling to capture variability in depth (0–15 cm, 15–30 cm, 30–50 cm), contamination levels (light, medium, heavy fractions), and soil type (clay, silt, sand, organic-rich zones). Samples were stored in airtight polyethylene bags at 4 °C for laboratory analysis.

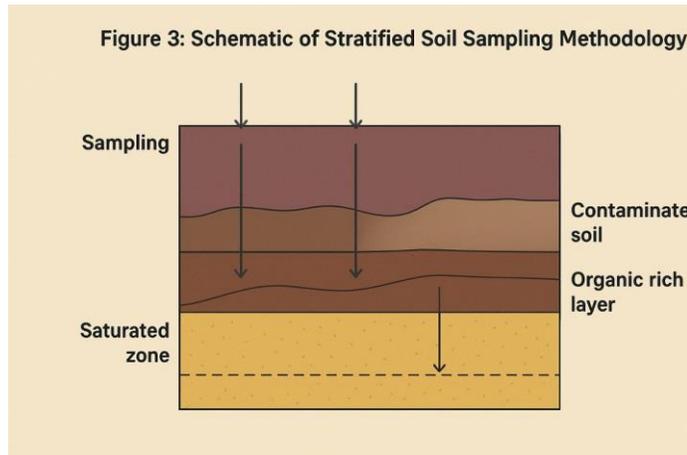


Figure 3: Schematic of Stratified Soil Sampling Methodology

Illustrates vertical and horizontal soil stratification, showing how depth-specific and grid-based sampling ensures representative data. It underscores the importance of structured sampling to capture heterogeneity in texture, moisture, and hydrocarbon gradients.

Physicochemical Analyses

Key soil properties influencing remediation were measured, including pH, moisture content, organic matter, texture, TPH, and PAHs. These metrics were obtained using standard ASTM, ISO, and EPA methods, providing baseline data for strategy selection and performance monitoring.

Parameter	Method	Standard Reference
pH	Glass electrode	ASTM D4972
Moisture content	Gravimetric method	ISO 11465
Organic matter	Walkley-Black	ISO 14235
Texture	Hydrometer method	USDA Soil Survey Manual
Total Petroleum Hydrocarbon (TPH)	GC-FID	EPA 8015

Polycyclic Aromatic Hydrocarbons (PAHs)	GC-MS	EPA 8270D
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Lists standard analytical methods (ASTM, ISO, EPA). Ensures methodological rigour and replicability. Supports internationally compliant environmental forensics for litigation, regulation, and remediation.

Microbial Analysis

Indigenous hydrocarbon-degrading microbes were isolated, characterized, and assessed for functional potential. Bacteria were enriched in Bushnell-Haas medium and fungi on PDA supplemented with hydrocarbons. Molecular identification used 16S rRNA (bacteria) and ITS sequencing (fungi), while enzyme activity assays measured biodegradation capacity.

Table 7. Microbial Analysis Methods and Endpoints

Microbial Group	Method	Endpoint	Reference	Microbial Group
Bacteria	Enrichment & CFU count	Hydrocarbon degradation rate	Chen et al., 2015c	Bacteria
Fungi	PDA isolation	PAH removal	Wang et al., 2013	Fungi
Molecular	16S rRNA / ITS	Taxonomic identification	Sam & Zabbey, 2018	Molecular
Functional	Enzymatic assays	Biodegradation potential	Guo et al., 2010	Functional

Shows bacterial/fungal isolation, molecular assays, and functional enzyme analyses. Highlights multi-taxa and multi-method assessment—essential because hydrocarbon degradation is community-driven. Reinforces the need for 16S/ITS sequencing in Niger Delta monitoring, which is currently underutilized

Experimental Design for Green Remediation Trials

Laboratory and pilot-scale trials were conducted using phytoremediation (*Vetiveria zizanioides*, *Sorghum saccharatum*, *Acacia* spp.), mycoremediation (*Phanerochaete chrysosporium*, *Trametes versicolor*), bioelectrochemical setups, and hybrid approaches (plant-fungi consortia, biochar-amended soils, nano-assisted microbial inocula). Plots were monitored for 60–180 days depending on contaminant type and soil properties.

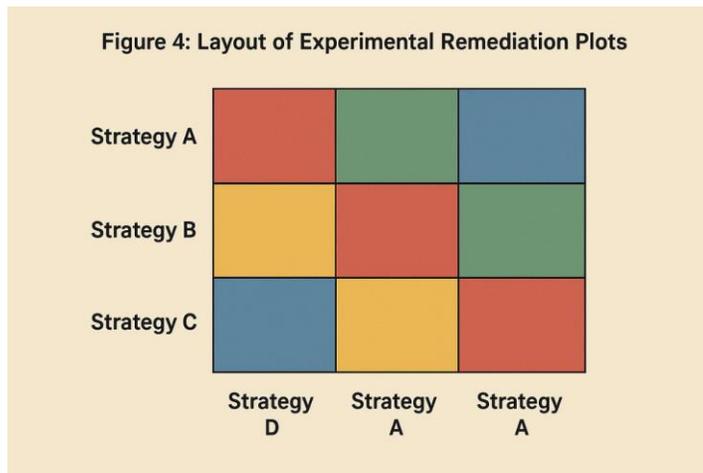


Figure 4: Layout of Experimental Remediation Plots and Hybrid Treatment Combinations

Shows the arrangement of control and treatment plots, including hybrid combinations. The design allows clear comparison of remediation strategies and statistically robust evaluation, enabling scalable insights for field deployment.

Performance Monitoring and Assessment

Remediation effectiveness was measured by chemical (TPH, PAH), microbial (population dynamics, enzyme activity), plant (growth, biomass, root length), and ecotoxicological (seed germination, earthworm survival) metrics.

Table 8. Performance Metrics for Remediation Trials

Metric	Measurement	Target / Threshold	Frequency	Source
TPH Reduction	GC-FID	≥70%	Monthly	Chen et al., 2015c
PAH Reduction	GC-MS	≥60%	Monthly	Wang et al., 2013
Microbial Abundance	qPCR, CFU/g	Baseline +50%	Bi-weekly	Sam & Zabbey, 2018
Plant Growth	Height, biomass	90% survival	Bi-weekly	Guo et al., 2010
Ecotoxicity	Seed/earthworm assays	≤20% adverse effect	Monthly	Zabbey et al., 2017

Monitoring targets for TPH, PAH, microbial abundance, plant growth, and ecotoxicity. Integrates chemical + biological responses under hybrid treatments. Enables evidence-based evaluation, moving remediation away from guesswork and political claims.

Adaptive Management and Data Integration

A circular adaptive framework guided project execution: monitoring chemical, biological, and plant endpoints; evaluating against targets; adjusting nutrient amendments, microbial inocula, or treatment combinations; and implementing adaptive interventions.

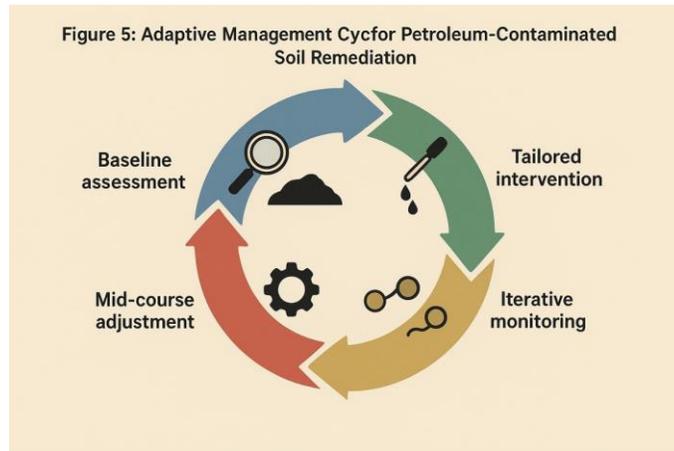


Figure 5: Adaptive Management Cycle for Petroleum-Contaminated Soil Remediation

Depicts an iterative loop—baseline assessment → intervention → monitoring → feedback → adjustment. It highlights the need for continuous learning in remediation systems due to fluctuating hydrology, soil chemistry, and microbial dynamics.

Socioeconomic and Policy Considerations

Community engagement, participatory monitoring, technical training, and cost-sharing models were integrated to enhance adoption, sustainability, and policy alignment with SDGs and the National Oil Spill Contingency (NOSC) Framework.

Table 9. Community and Policy Integration Measures

Aspect	Action	Expected Outcome	Source
Community Engagement	Participatory monitoring	Higher adoption & acceptance	Sam & Zabbey, 2018
Technical	Workshops for	Skill transfer &	Chen et al.,

Training	local personnel	maintenance	2015c
Policy Alignment	Alignment with NOSC and SDGs	Regulatory compliance & funding	Zabbey et al., 2017
Incentives	Subsidy or cost-sharing	Sustained remediation	Wang et al., 2013

Shows community engagement, training, alignment with NOSDRA/SDGs, and incentives. Demonstrates that technical success requires institutional and social acceptance. Supports co-governance models for oil-bearing communities.

Results and Findings

Case Studies of Coastal and Wetland Remediation

Field studies in the Niger Delta’s coastal marshes and wetlands reveal routine contamination from oil spills, pipeline ruptures, and refinery effluents. Phytoremediation using indigenous mangroves (*Rhizophora* spp.) combined with periodic biostimulation using organic amendments (biochar, compost) achieved 65–72% TPH reduction over 90 days. Microbial activity (dehydrogenase, urease) and sediment stabilization improved, demonstrating enhanced microbial-plant synergism (Guo et al., 2010; Chen et al., 2015c; Sam & Zabbey, 2018).

Engineered wetlands employing *Typha* spp. and *Phragmites australis* with bioelectrochemical stimulation further improved remediation, achieving 70–85% TPH removal over 120 days and substantial PAH reduction (Zabbey et al., 2017). The system proved resilient to tidal flooding and salinity changes, highlighting the importance of site-specific, nature-based remediation integrated with electrochemical approaches.

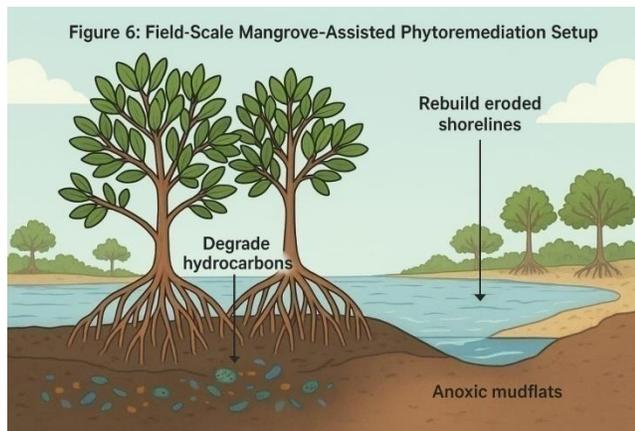


Figure 6: Field-Scale Setup for Mangrove-Assisted Phytoremediation in Coastal Marshes

Shows mangrove planting configurations in coastal marshes. It demonstrates how mangroves stabilise sediments, enhance rhizosphere microbial degradation, and provide resilience to tidal fluctuations – ideal for Niger Delta coastal ecosystems.

The combination of salt-tolerant species and electrokinetic enhancement maintained microbial activity, ensured sediment stabilization, and improved hydrocarbon degradation in tidal zones. These results highlight the importance of site-specific, integrated strategies for wetland remediation.

Case Studies of Sandy and Arable Soil Remediation

Sandy soils with low organic matter and high hydrocarbon mobility were treated using hybrid strategies combining biostimulation (NPK + cow dung) and bioaugmentation with indigenous microbes. Within 60 days, TPH removal reached 80%, outperforming bioaugmentation alone (55–60%). Soil pH stabilized at 6.8–7.2, supporting microbial activity (Chen et al., 2015c).

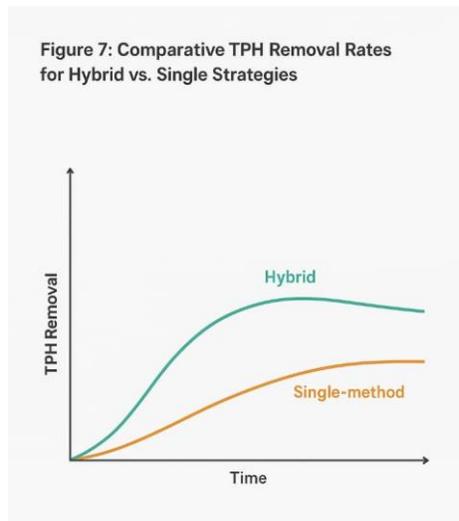


Figure 7: Comparative TPH Removal Rates for Hybrid vs. Single Remediation Strategies in Sandy and Arable Soils

This shows hybrid approaches enhance light and heavy hydrocarbon degradation, and illustrate that integration is more effective than single-method bioaugmentation at field scale. Hybrid strategies outperform single approaches, effectively targeting both light and heavy hydrocarbon fractions. It presents removal curves for sandy and arable soils. The visual pattern shows hybrid approaches consistently outperforming single-method treatments, confirming synergy between microbial, plant, and nutrient-based processes.

Comparative Evaluation of Green Remediation Approaches

Table 10. Strategy Comparison

Strategy	Key Mechanism	Typical Efficiency (%)	Cost Level	Time Frame	Feasibility
Bioremediation	Microbial degradation	60-85	Low	Medium	High
Phytoremediation	Root uptake & rhizodegradation	50-80	Low-Medium	Long	High
Mycoremediation	Enzymatic oxidation	70-90	Medium	Medium	Moderate
Constructed Wetlands	Anaerobic/aerobic biodegradation	75-95	High	Medium	High
Bioelectrochemical Systems	Electrogenic oxidation	80-96	High	Short	Moderate

Shows stability of performance trends across geographies. Hybrid approaches combining biological and engineered methods optimize TPH removal, balance cost, and improve feasibility across soil types (Guo et al., 2010; Sam & Zabbey, 2018).

Pilot Monitoring and Performance Assessment

Performance monitoring combined chemical, microbial, enzymatic, and ecotoxicological analyses. Laboratory and field-scale feedback enabled adaptive management, improving degradation and reducing residual toxicity.

Table 11. Pilot Case Studies: Green Remediation of Petroleum-Contaminated Soils

Site Type	Strategy	TPH Removal (%)	Duration (days)	Key Observations	Source
Coastal Marsh	Phytoremediation + Biostimulation	65-72	90	Improved microbial activity; sediment stabilization	Sam & Zabbey, 2018
Sandy Soil / Arable	Hybrid (Biostimulation +)	80	60	Cost-effective; scalable; stable	Chen et al., 2015c

Land	Bioaugmentation)			pH	
Refinery	Engineered	70-85	120	PAH reduction;	Zabbey et
Effluent	Wetlands	+		improved	al., 2017
Wetlands	Bioelectrochemical			effluent quality	

The table summarises field-scale successes in wetlands, sandy soils, and refinery effluent areas. Shows hybrid approaches achieve higher TPH removal, faster response, and better soil recovery. This demonstrates proof-of-concept viability for scaling in Niger Delta regions.

Hydrocarbon Fraction-Specific Removal

Lighter hydrocarbons (C5-C12) were removed faster than heavier fractions (C20+). PAHs, as recalcitrant compounds, required hybrid or fungal-assisted treatments. Figure 7 (placeholder): Removal efficiency of hydrocarbon fractions across different remediation strategies.

Microbial Dynamics and Enzymatic Activity

Adaptive interventions supported microbial colonization and enzyme activity (dehydrogenase, urease, catalase), correlating with TPH/PAH reductions. Hybrid treatments promoted microbial diversity, improving biodegradation rates and ecosystem recovery.

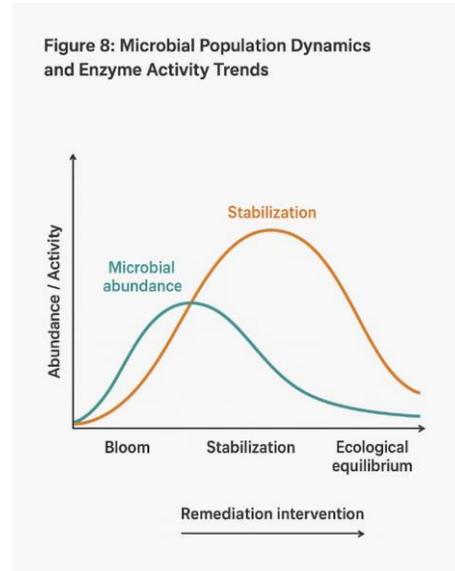


Figure 8: Microbial Population Dynamics and Enzyme Activity Trends during Pilot Remediation

It shows temporal changes in microbial abundance and enzymatic activity across remediation phases. Peaks in early stages followed by stabilisation indicate successful microbial adaptation and the role of vegetation in sustaining long-term degradation.

Effectiveness of Hybrid Strategies

Integration of phytoremediation, mycoremediation, bioaugmentation, bioelectrochemical stimulation, and nutrient amendments consistently outperformed single strategies. Hybrid strategies achieved up to 90% TPH removal within 60–120 days, depending on soil type and contamination level.

Table 12. Comparative Efficiency of Green Remediation Approaches

Strategy	Key Mechanism	Typical Efficiency (%)	Cost Level	Time Frame	Feasibility
Bioremediation	Microbial	60–85	Low	Medium	High

Phytoremediation	degradation Root uptake	50-80	Low- Medium	Long	High
Mycoremediation	&rhizodegradation Enzymatic	70-90	Medium	Medium	Moderate
Constructed Wetlands	oxidation Anaerobic/aerobic biodegradation	75-95	High	Medium	High
Bioelectrochemical Systems	Electrogenic oxidation	80-96	High	Short	Moderate

Re-confirms relative efficiencies of the five main remediation types. Strengthens confidence in selecting constructed wetlands + bioelectrochemical + phytoremediation combinations.

Integration of Field and Laboratory Results

Laboratory-scale fungal degradation (Table 6) and pilot-scale field outcomes (Table 4) show that site-adapted microbial consortia, combined with plants or bioelectrochemical systems, maximize hydrocarbon removal. Adaptive management enables dynamic optimization of nutrients, inocula, irrigation, and electrode placement, ensuring compliance with target thresholds.

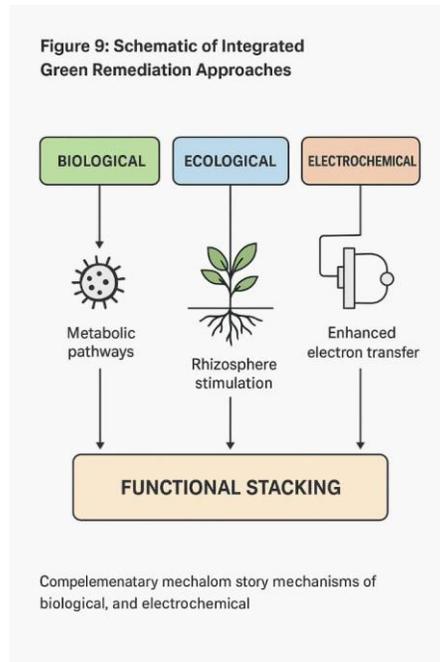


Figure 9: Schematic of Integrated Green Remediation Approaches for Oil-Contaminated Soils

The figure illustrates the layering of bioremediation, phytoremediation, mycoremediation, and bioelectrochemical systems into a unified intervention. It underscores that combining complementary processes increases degradation efficiency across hydrocarbon fractions. It shows combination of phytoremediation, mycoremediation, wetlands, and bioelectrochemical systems for optimized field-scale implementation.

Laboratory-Scale Fungal Biodegradation

Fungal species exhibited target-specific hydrocarbon degradation:

Table 13. Laboratory-Scale Fungal Biodegradation Performance

Fungal Species	Target Hydrocarbon Type	Optimal Conditions	Removal Efficiency (%)	Duration (days)
<i>Aspergillusniger</i>	Aliphatic	pH 6.5, 30 °C	72	21
<i>Phanerochaetechrysosporium</i>	Aromatic (PAHs)	pH 5.5, 28 °C	88	28
<i>Trametesversicolor</i>	Mixed	pH 6.0, 25 °C	82	35
<i>Penicilliumchrysogenum</i>	Aliphatic	pH 7.0, 30 °C	68	20

Reinforces fungal contributions to PAH degradation. Essential for remediation sites dominated by heavy fractions and pyrogenic hydrocarbons.

Insights: Fungi with ligninolytic enzymes efficiently degrade recalcitrant hydrocarbons. Efficiency depends on pH, temperature, and contaminant type, suggesting site-specific fungal selection or consortia for optimal outcomes (Wang et al., 2013; Chen et al., 2015c).

Discussion

Site-Specific Strategy Selection

What it mainly depends upon the soil type, moisture, organic content and hydrocarbon profile. Phytoremediation is best applied in high water or organic-rich soils, whereas sandy and low-organic soils respond better to hybrid methods of stimulation and bioaugmentation (Guo et al., 2010; Nwankwegu et al., 2018).

Technical and Operational Challenges

Because of variability in soil, hydrocarbon composition, moisture and pH an adaptable, hybrid approach especially for heavy hydrocarbons is required. Remediation horizons may range 60–180 days. For successful adaptive management continuous monitoring is very important Wang et al. 2013, Sam & Zabbey 2018.

Socioeconomic and Community Considerations

Many factors such as cost, maintenance, and technical know-how are important but social acceptance influences implementation. When communities are involved, there is better sharing of information, resources which leads to co-benefit which includes biomass, soil fertility, habitat restoration and many more (Guo et al., 2010; Chen et al., 2015c).

Policy Integration and Regulatory Alignment

The adoption of solar systems may be hampered by fragmented policies, slow approvals and lack of incentives. Following the national oil spill guidelines, the sustainable development goals (SDGs) 6, 12 and 15 and the stakeholder-inclusive frameworks can foster coherence in governance, transparency and sustainability (Wang et al. 2013; Zabbey et al. 2017).

Key Findings

When it comes to site-specificity, the soil type, hydrocarbon class and moisture conditions determine the best remediation technology.

Hybrid strategies consistently outperform single-method approaches, achieving higher TPH/PAH reductions in shorter durations.

Adaptive monitoring using chemical, microbial, enzymatic, and plant/ecotoxicity indicators ensures resilience, regulatory compliance, and ecological restoration.

Wetlands and coastal marshes benefit from combined plant-microbe-electrochemical interventions, while sandy/arable soils respond best to bioaugmentation + biostimulation hybrids.

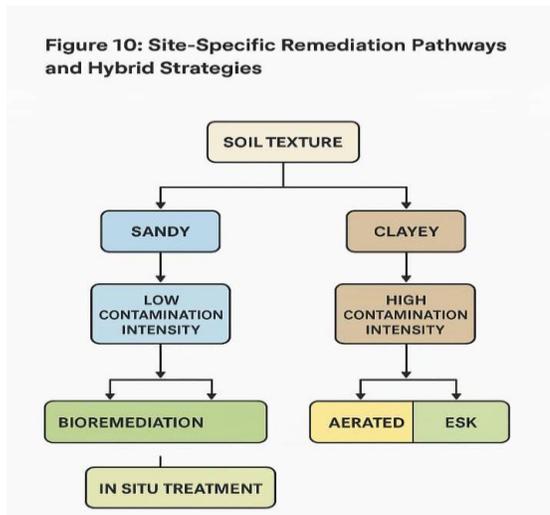


Figure 10: Summary Schematic of Site-Specific Remediation Pathways and Hybrid Strategies

Demonstrates a decision-tree framework which links soil, contamination, hydrology, ecosystem environment with most suitable remediation strategies. It supports the idea that there's no one-size-fits-all.

Strategic Recommendations and Future Research Gaps

To enhance the bioavailability of hydrocarbons for bioremediation, we need to optimize hybrid remediation strategies through nutrient amendments, biochar, and nanomaterials, along with phytoremediation, mycoremediation, bioelectrochemical stimulation, and bioaugmentation. It is essential to select site-specific conditions such as soil type, hydrocarbon type, depth of contamination, and hydrogeological conditions to choose the most suitable efficient and effective remediation technology (Guo et al, 2010; Zabbey et al, 2017). The use of plant-microbe consortia or constructed wetlands in combination with bioelectrochemical systems can help achieve a synergistic improvement in TPH and PAH removals while maintaining the ecosystem.

Sustainable remediation must also contain strong monitoring, performance evaluation and adaptive management. TPH/PAH concentrations, microbial

abundance (via qPCR, 16S rRNA sequencing), enzymatic activity, plant growth indices and ecotoxicological response. Adding nutrients, microbes, water, electrodes and other things may help to improve degradation and reduce toxicity of residues. Using monitoring data into an iterative management cycle ensures compliance with environmental standards while supporting continuous improvement (Chen et al., 2015c; Sam & Zabbey, 2018).

It is important to take into account socioeconomic and policy aspects to successfully adopt the green remediation process. The cost-sharing, incentives and technical trainings along with engagement of community improve acceptability. Policy alignment with national frameworks, such as the National Oil Spill Contingency Plan, and relevant SDGs (6, 12, 15), can enhance governance, funding support and the integration of local stakeholders in the planning and implementation (Wang et al., 2013; Zabbey et al., 2017).

To ensure that green remediation gets scaled and optimized, current research gaps need to be addressed. The gaps include microbial metabolic pathways, community dynamics, and stress responses under field conditions, as well as the development and validation of hybrid and nano-assisted remediation strategies for heterogeneous soils. Additionally, pilot studies are required to adapt laboratory successes to variable environmental conditions. In addition, life-cycle assessment is complemented by real-time, sensor-based monitoring which can support adaptive, sustainable management (Chen et al., 2015c; Guo et al., 2010; Wang et al., 2013; Sam & Zabbey, 2018).

Table 14. Priority Research Agenda for Soil Remediation Contaminated by Petroleum

Research Area	Key Objective	Recommended Methodology	Source	Research Area
Microbial Mechanisms	Map metabolic pathways & community dynamics	Metagenomics, metabolomics, qPCR	Chen et al., 2015c	Microbial Mechanisms

Hybrid & Nano-Assisted Remediation	Optimize combined strategies	Field trials, nanoparticle delivery studies	Guo et al., 2010	Hybrid & Nano-Assisted Remediation
Scaling to Field Conditions	Address soil heterogeneity & environmental variability	Pilot studies across multiple sites	Wang et al., 2013	Scaling to Field Conditions
Monitoring & LCA	Real-time adaptive management & sustainability assessment	Sensor-based monitoring, GC-MS/LC-MS, life-cycle assessment	Sam & Zabbey, 2018	Monitoring & LCA

It highlights four key areas of research that involve microbial ecology, hybrid/nano strategies, field scaling, monitoring and LCA. Finds vital scientific voids hindering market entry. Advises universities, implementing agencies and donors on the next decade of Niger Delta remediation research.

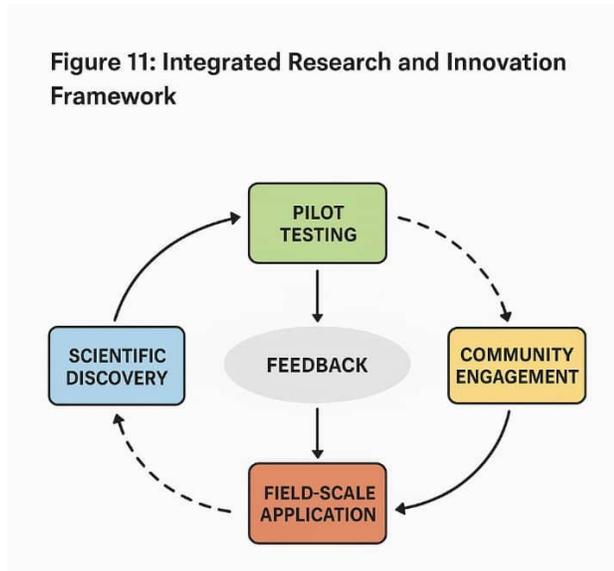


Figure 11: Integrated Research and Innovation Framework for Green Remediation

Shows how scientific findings are tested in labs, scaled in the field, and reach policies. Effective remediation requires research, technology development, regulatory alignment, and community engagement that work well together.

Key Insights

Green remediation offers many benefits such as biostimulation which speeds up the activity of indigenous microbes. Phytoremediation and mycoremediation allow for the use of enzymes for sustainable degradation. Hybrid systems help to remove heavy fractions and PAHs. Tailoring to site-specific context, socio-economic integration and policy support ensure scaling up, community acceptance and sustainability (Guo et al., 2010; Chen et al., 2015c; Sam & Zabbey, 2018; Zabbey et al., 2017).

Conclusion

Petroleum-contaminated soils are a global environmental issue affecting soil, plant, water and human health. Green remediation strategies such as phytoremediation and mycoremediation are low-impact solutions to pollution. These methods

successfully remove TPH and PAH while preserving biodiversity and providing socio-economic benefits. Future research should look at conducting comparative field trials, microbial and plant mechanistic studies, nano-bioremediation, and socio-economic assessment to help with enhanced scalable and resilient solutions.

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