International Journal of Multidisciplinary Research and Growth Evaluation.

Remediation Technologies for Petroleum Hydrocarbon Contamination in Mangrove and Freshwater Swamp Ecosystems: A Systematic Review of Methods Applied in the Niger Delta

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Article Info

ISSN (online): 2582-7138
Impact Factor: 5.307 (SJIF)
Volume: 04
Issue: 06
November-December 2023
Received: 07-10-2023
Accepted: 08-11-2023
Published: 07-12-2023
Page No: 1441-1451

Abstract

The Niger Delta region of Nigeria hosts Africa's largest mangrove ecosystem but has suffered extensive petroleum hydrocarbon contamination due to decades of oil exploration, production, and transportation activities. Remediation in this region is particularly challenging because of persistent waterlogging, anaerobic sediments, and high ecological sensitivity. This systematic review evaluates remediation technologies applied in mangrove and freshwater swamp ecosystems of the Niger Delta, with emphasis on effectiveness, feasibility, and limitations under wetland conditions. A comprehensive literature search was conducted across major scientific databases for studies published between 1990 and 2023. Forty-eight studies met the inclusion criteria and were synthesized.

Natural attenuation exhibited limited effectiveness, typically achieving only 5–15% annual total petroleum hydrocarbon (TPH) reduction. Individual biological approaches showed moderate performance, with bioaugmentation achieving 40–60% and biostimulation achieving 22–66% TPH reduction. In contrast, combined bioaugmentation and biostimulation consistently demonstrated the highest effectiveness, achieving 74–99% TPH reduction within 60–180 days. Enhanced rhizoremediation using wetland plants such as *Phragmites australis*, *Eichhornia crassipes*, and *Vetiveria zizanioides* further improved remediation outcomes while supporting ecosystem recovery. Chemical and physical methods were constrained by high costs, ecological disturbance, and limited suitability for wetland environments.

Overall, integrated biological remediation strategies represent the most effective and ecologically compatible approaches for petroleum-contaminated Niger Delta wetlands. Sustained funding, community engagement, long-term monitoring, and prevention of recurrent pollution are essential for successful restoration.

DOI: https://doi.org/10.54660/.IJMRGE.2023.4.6.1441-1451

Keywords: Petroleum Hydrocarbons, Niger Delta, Mangrove Ecosystems, Freshwater Swamps, Bioremediation, Phytoremediation, Bioaugmentation, Biostimulation, Wetland Restoration

1. Introduction

1.1. Background and Significance

The Niger Delta mangrove ecosystem covers approximately 1,900 km² and represents the largest mangrove forest in Africa, accounting for nearly 5% of global mangrove coverage (UNDP, 2006; UNEP, 2011). These ecosystems provide critical services, including carbon sequestration, shoreline stabilization, nutrient cycling, and fisheries support for millions of people. Despite their importance, Niger Delta wetlands have experienced severe environmental degradation due to chronic petroleum hydrocarbon pollution.

The region records an estimated 300 oil spills annually, making it one of the most petroleum-polluted environments globally (Ite et al., 2013; Elum et al., 2016) [6, 8]. The United Nations Environment Programme (UNEP) environmental assessment of Ogoniland revealed extensive contamination of soil, groundwater, and surface water, with benzene concentrations exceeding World Health Organization limits by up to 900-fold in some communities (UNEP, 2011). These findings highlighted the long-term persistence of petroleum hydrocarbons and the inadequacy of past remediation efforts. Environmental restoration of Ogoniland alone is projected to require 25–30 years and represents one of the most extensive oil cleanup operations ever proposed. UNEP recommended the establishment of an Environmental Restoration Fund with an initial capitalization of US$1 billion to support remediation, monitoring, and institutional capacity building (UNEP, 2011).

Petroleum Hydrocarbon Pollution
↓
Niger Delta Wetland Ecosystems
(Mangrove & Freshwater Swamps)
↓
Systematic Review (1990–2023)
↓
Remediation Technologies Evaluated
↓
Comparative Effectiveness & Constraints
↓
Evidence-Based Recommendations

Fig 1: Schematic overview of petroleum hydrocarbon contamination in Niger Delta mangrove and freshwater swamp ecosystems and the systematic evaluation of remediation technologies. Integrated biological approaches particularly combined bioaugmentation and biostimulation and enhanced rhizoremediation demonstrated the highest effectiveness under wetland conditions, supporting both contaminant removal and ecosystem restoration.

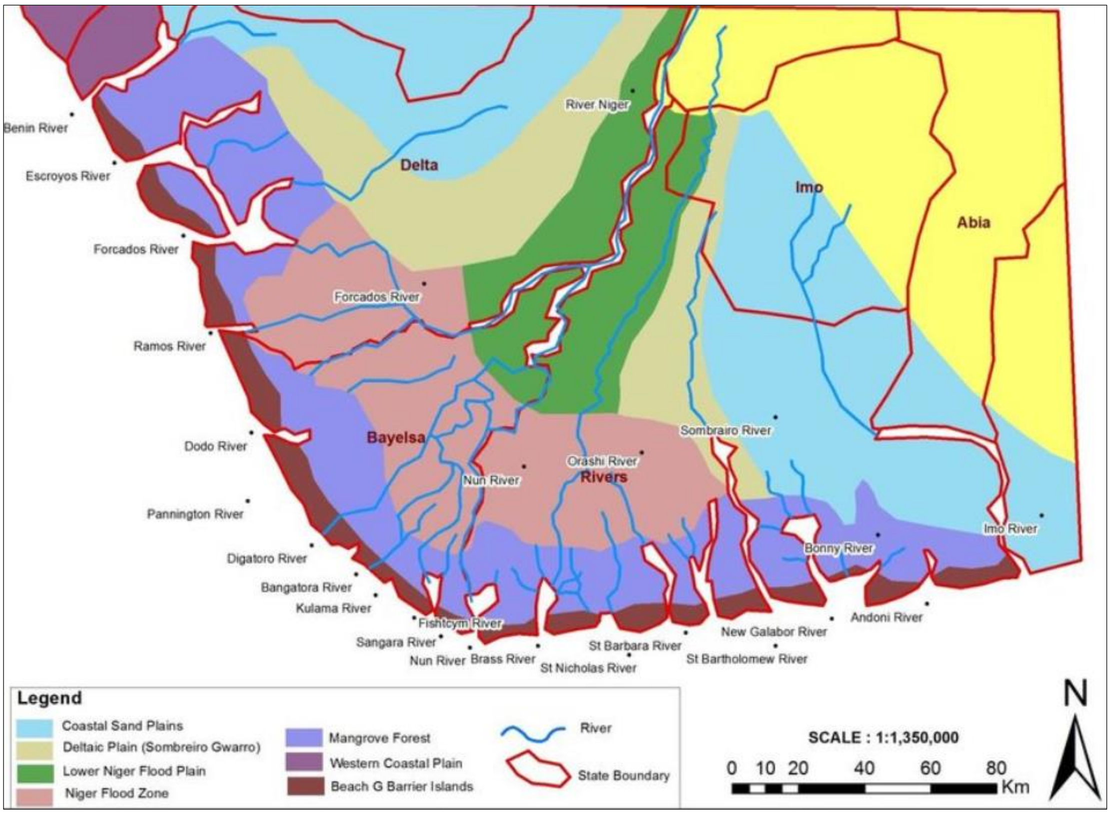

Fig 2: Map of the Niger Delta Study Context

1.2. Ecosystem Characteristics and Challenges

The Niger Delta consists of four major ecological zones: coastal barrier islands, mangrove swamp forests, freshwater swamps, and lowland rainforests. Mangrove ecosystems dominated by *Rhizophora*, *Avicennia*, and *Laguncularia* species are particularly vulnerable to petroleum contamination due to restricted gas exchange and high organic matter content (Zabbey and Uyi, 2014) [22].

Oil spills in mangrove environments acidify sediments, inhibit root respiration, disrupt cellular metabolism, and lead to extensive vegetation mortality (Yavari *et al*., 2015; Ossai *et al*., 2020) [16, 21]. Waterlogged and anaerobic conditions significantly slow natural biodegradation processes, allowing hydrocarbons to persist for decades compared with upland soils (Müller *et al*., 2001; Brown *et al*., 2017) [2, 11].

1.3. Objectives
This systematic review aims to:
1. Identify and evaluate remediation technologies specifically applied in Niger Delta mangrove and freshwater swamp ecosystems
2. Assess the effectiveness of these technologies under wetland conditions with quantitative data
3. Examine environmental, economic, and social factors influencing technology selection
4. Identify knowledge gaps and recommend future research directions
5. Provide evidence-based guidance for remediation practitioners and policymakers

2. Methodology
2.1. PRISMA 2020 flow diagram illustrating literature identification

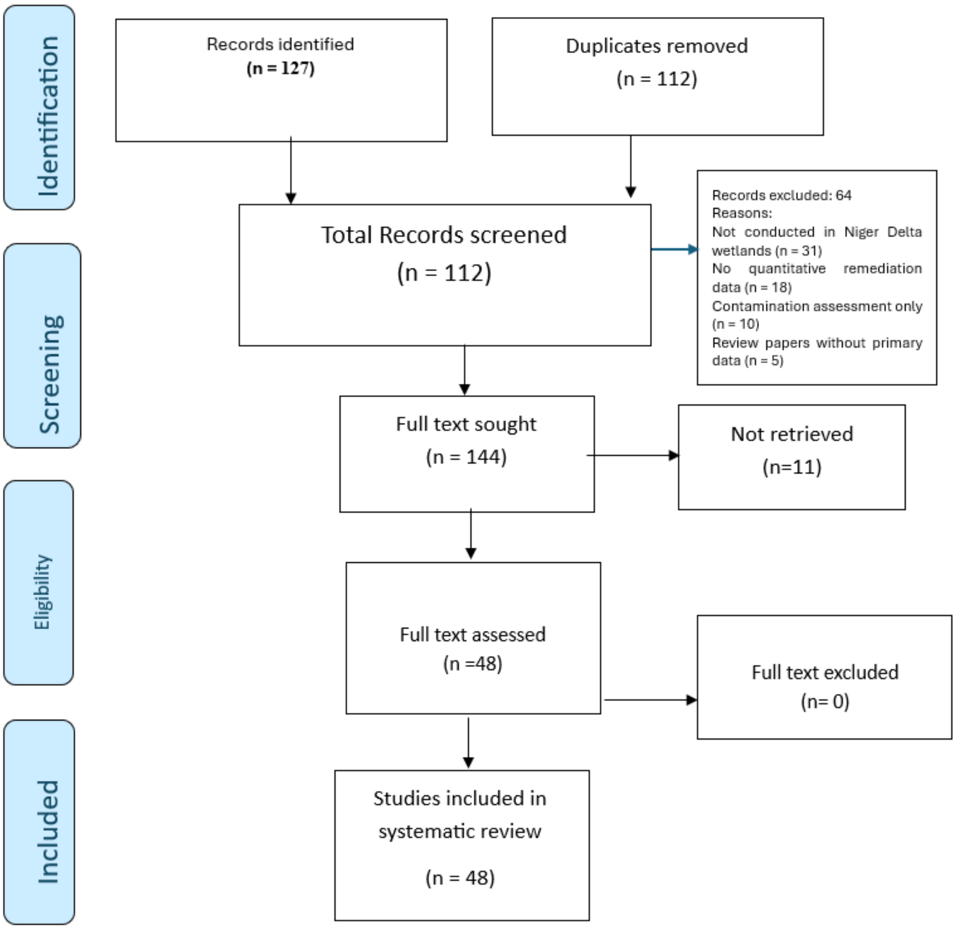

Fig 3: PRISMA 2020 flow diagram illustrating literature identification, screening, eligibility assessment, and inclusion for systematic review

This review was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A comprehensive literature search was performed across Web of Science, Scopus, PubMed, ScienceDirect, Google Scholar, and African Journals Online for publications between 1990 and 2023.
Search terms combined geographic identifiers (“Niger Delta”), ecosystem descriptors (“mangrove,” “freshwater swamp,” “wetland”), contaminants (“petroleum,” “oil spill,” “hydrocarbon”), and remediation techniques (“bioremediation,” “phytoremediation,” “bioaugmentation,” “biostimulation”). Studies were included if they reported quantitative remediation outcomes (TPH or PAH reduction) in Niger Delta wetland environments. Purely theoretical studies, contamination assessments without remediation data, and studies conducted outside the Niger Delta without soil translocation were excluded.
Of 127 records initially identified, 48 studies met all inclusion criteria and were included in the final synthesis.

2.1. Literature Search Strategy
A comprehensive literature search was conducted across Web of Science, Scopus, PubMed, Google Scholar, ScienceDirect, and African Journals Online (AJOL) for publications from 1990 to 2024. Search terms included combinations of: "Niger Delta," "petroleum," "oil spill," "hydrocarbon contamination," "mangrove," "swamp," "wetland," "remediation," "bioremediation," "phytoremediation," "bioaugmentation," and "biostimulation."

2.2. Inclusion and Exclusion Criteria
Inclusion Criteria:
1. Studies conducted in Niger Delta wetland ecosystems or using Niger Delta soils
2. Publications reporting quantitative remediation outcomes (TPH or PAH reduction)
3. Peer-reviewed articles, technical reports, and verified case studies
4. Publications in English from 1990-2024

5. Exclusion criteria: Studies from other regions without Niger Delta comparison
6. Purely theoretical models without empirical validation
7. Studies focusing solely on contamination assessment
8. Duplicate publications

2.3. Data Synthesis
From 127 initially identified studies, 48 met the inclusion criteria and were analyzed for remediation technology type, ecosystem characteristics, contaminant levels, treatment duration, removal efficiency, and implementation challenges.

3. Extent and Nature of Petroleum Contamination
3.1. Scale of Contamination
By 2008, oil-related activities had contaminated an estimated 2,000 sites across the Niger Delta (UNEP, 2011). In at least ten Ogoni communities, drinking water sources were found to contain hazardous levels of petroleum hydrocarbons, posing serious public health risks (UNEP, 2011). At one site in Nisisioken Ogale, UNEP scientists found an 8 cm layer of refined oil floating on groundwater serving community wells, with benzene contamination over 900 times WHO guidelines, linked to a spill from more than six years prior.

3.2. Contaminant Characteristics and Behavior
Reported TPH concentrations in contaminated Niger Delta wetland soils range from approximately 1,600 mg/kg to over 50,000 mg/kg, reflecting varying spill histories and degrees of weathering (Brown et al., 2017; Okere and Semple, 2019) [15, 2]. In mangrove sediments, hydrocarbons strongly adsorb to organic matter, reducing bioavailability and prolonging persistence (John et al., 2016; Ossai *et al.*, 2020) [9, 16]. The effects of petroleum spills on mangroves acidify soils, halt cellular respiration, and starve roots of vital oxygen, with areas destroyed by petroleum becoming susceptible to additional problems and unsuitable for native plant growth until microbial remediation occurs.

3.3. Environmental and Health Impacts
Petroleum hydrocarbon contamination in the Niger Delta has profound and long-lasting consequences for both human health and wetland ecosystems. Chronic exposure to petroleum-derived contaminants, particularly polycyclic aromatic hydrocar (PAHs) and volatile aromatic compounds such as benzene, has been associated with elevated risks of cancer, reproductive disorders, congenital abnormalities, genetic mutations, and endocrine disruption in exposed populations (Elum *et al.*, 2016; UNEP, 2011) [6]. Communities relying on contaminated surface water and shallow groundwater for drinking, fishing, and domestic use face heightened public health risks due to bioaccumulation of toxic hydrocarbons in aquatic organisms and food chains.
From an ecological perspective, oil contamination causes extensive degradation of mangrove and freshwater swamp ecosystems. Petroleum hydrocarbons coat aerial roots and sediments, impair gas exchange, inhibit photosynthesis, disrupt nutrient cycling, and induce widespread vegetation mortality. The loss of mangrove vegetation reduces habitat complexity, nursery grounds for fisheries, shoreline stability, and carbon sequestration capacity, thereby weakening ecosystem resilience (Zabbey and Uyi, 2014; Yavari *et al.*, 2015) [21-22]. Contaminated wetlands also experience declines in microbial diversity and benthic fauna, further slowing natural recovery processes.
Empirical studies indicate that ecosystem recovery following oil spills is strongly dependent on remediation intervention. Non-remediated mangrove ecosystems typically require approximately 13–14 years to regain structural and functional integrity after contamination events, reflecting slow natural attenuation under anaerobic, waterlogged conditions. In contrast, sites subjected to active remediation interventions including bioremediation and vegetation restoration have demonstrated substantially faster recovery, with observable ecological restoration occurring within approximately 7 years (Zabbey and Uyi, 2014; UNEP, 2011) [22]. These findings highlight the critical role of timely and effective remediation in reducing long-term ecological damage.
Landscape-level impacts further underscore the severity of petroleum pollution in the Niger Delta. Land-use change analyses employing satellite imagery and geospatial modeling have documented progressive conversion of mangrove forests to bare or degraded land in heavily impacted areas of Rivers State. Persistent contamination, coupled with inadequate remediation and recurrent spill events, continues to drive mangrove loss and fragmentation, threatening the long-term survival of remaining mangrove stands and associated ecosystem services (UNEP, 2011; Elum *et al*., 2016) [6]. Without substantial improvement in remediation effectiveness and spill prevention, ongoing environmental degradation poses a serious risk to the sustainability of the Niger Delta's wetland ecosystems and the livelihoods of communities that depend on them.

4. Bioremediation Technologies
4.1. Natural Attenuation
Natural attenuation refers to the intrinsic capacity of indigenous microbial communities to degrade petroleum hydrocarbons in contaminated environments without external intervention. This process depends on naturally occurring physical, chemical, and biological mechanisms, including microbial metabolism, volatilization, dispersion, and sorption. Although natural attenuation is attractive due to its low cost and minimal ecosystem disturbance, its effectiveness in Niger Delta wetland ecosystems is severely constrained.
In mangrove and freshwater swamp environments, persistent waterlogging creates predominantly anaerobic conditions that significantly limit aerobic microbial activity, which is responsible for the most efficient hydrocarbon degradation pathways. Oxygen diffusion is restricted by saturated sediments and high organic matter content, resulting in slow biodegradation rates and prolonged contaminant persistence.
Quantitative evidence demonstrates the limited effectiveness of natural attenuation under these conditions. Controlled tank studies have reported a maximum of approximately 35% reduction in total petroleum hydrocarbons (TPH) over a 63-day period. However, field-based investigations in Niger Delta wetlands indicate substantially lower degradation rates, typically ranging from 5–15% TPH reduction per year, reflecting the combined effects of anoxia, limited nutrient

availability, and reduced contaminant bioavailability (Brown *et al*., 2017; Chikere *et al.*, 2019) [2-3].
Given these constraints, natural attenuation alone is inadequate as a remediation strategy for petroleum-contaminated mangrove and freshwater swamp ecosystems. While it may contribute marginally to long-term contaminant reduction, particularly at low contamination levels, effective remediation in Niger Delta wetlands requires active intervention through enhanced biological or integrated remediation approaches.

Table 1: Comparative performance of remediation technologies in Niger Delta mangrove and freshwater swamp ecosystems

Remediation technology	TPH reduction (%)	Duration	Wetland suitability	Major constraints
Natural attenuation	5–15 annually	Years	Low	Anaerobic conditions severely limit degradation
Bioaugmentation	40–60	30–60 days	Moderate	Limited persistence of inoculated strains
Biostimulation	22–66	40–63 days	Moderate	Nutrient washout and eutrophication
Bioaugmentation + biostimulation	74–99	60–180 days	High	Requires optimized nutrient dosing
Phytoremediation (*Vetiveria zizanioides*)	~41	≥12 months	High	Long remediation time
Enhanced rhizoremediation	Higher than individual methods	6–24 months	Very high	Plant establishment challenges
Chemical oxidation	Rapid (lab scale)	Short-term	Low	Toxicity and high oxidant demand
Excavation	Near-complete (localized)	Immediate	Very low	High cost and habitat disruption

TPH = Total petroleum hydrocarbons.

Table 2: Recommended remediation strategies based on petroleum hydrocarbon contamination levels in Niger Delta wetlands

Contamination level (TPH, mg/kg)	Recommended remediation strategy	Expected removal efficiency (%)	Implementation considerations
< 5,000 (Light)	Biostimulation	40–66	Apply slow-release organic or inorganic nutrients
< 5,000 (Light)	Enhanced rhizoremediation	40–60	Prefer native or wetland-adapted plant species
5,000–15,000 (Moderate)	Bioaugmentation + biostimulation	65–85	Use locally isolated microbial consortia
5,000–15,000 (Moderate)	Sequential phytoremediation	Long-term stabilization	Applied after primary biological treatment
> 15,000 (Heavy)	Intensive combined biological treatment	70–95	Requires aeration and frequent monitoring
> 50,000 (Extreme hotspots)	Targeted excavation + bioremediation	Near-complete (localized)	Limit to small, discrete areas

4.2. Bioaugmentation

Bioaugmentation involves the deliberate introduction of hydrocarbon-degrading microorganisms into contaminated environments to accelerate petroleum hydrocarbon biodegradation beyond natural attenuation rates. This approach aims to supplement or reinforce indigenous microbial populations, particularly where native communities are insufficient in abundance or metabolic capacity to effectively degrade complex hydrocarbon mixtures.
Numerous studies in the Niger Delta have identified diverse bacterial and fungal taxa with demonstrated hydrocarbon-degrading potential. Nitrifying bacteria isolated from oil-impacted mangrove sediments, notably *Nitrosomonas* spp. and *Nitrobacter* spp., exhibited measurable crude oil degradation capabilities. Mixed cultures of these organisms achieved approximately 52% degradation of introduced crude oil, while monocultures of *Nitrosomonas* and *Nitrobacter* achieved degradation efficiencies of about 40% and 20%, respectively (Ubogu and Akporhonor, 2019). These findings suggest synergistic interactions among microbial consortia enhance degradation efficiency.
In addition to nitrifiers, a wide range of culturable aerobic mesophilic hydrocarbon-utilizing bacteria have been isolated from Niger Delta mangrove swamps, including *Actinobacillus*, *Bacillus*, *Klebsiella*, *Micrococcus*, and *Pseudomonas* species. Hydrocarbon-degrading fungi such as *Aspergillus*, *Mucor*, *Penicillium*, and *Trichoderma* species have also been reported, highlighting the functional diversity of indigenous microbial communities in contaminated wetlands (Nwankwegu and Onwosi, 2017) [14].
Quantitative assessments demonstrate moderate remediation performance when bioaugmentation is applied as a standalone treatment. Controlled studies reported approximately 41% total petroleum hydrocarbon (TPH) reduction over a 63-day period in bioaugmented systems without nutrient amendment. More rapid degradation has been observed when microbial consortia are used; for example, combined cultures of *Rhodococcus erythropolis* and *Pseudomonas* spp. achieved over 60% TPH removal within 15 days under controlled conditions (Nwankwegu and Onwosi, 2017) [14].
Fungal bioaugmentation has also shown high potential. A consortium of *Candida adriatica* and *Candida taoyuanica* achieved 84.6% total petroleum loss over 56 days in crude oil–contaminated Niger Delta soils, compared with only 28.7% removal in unamended control treatments, underscoring the importance of targeted microbial selection (Ubogu and Akporhonor, 2019).
Despite these promising results, the effectiveness of bioaugmentation in wetland environments is often constrained by environmental factors such as nutrient limitation, anaerobic conditions, and competition with indigenous microorganisms. Consequently, bioaugmentation alone rarely achieves complete remediation in Niger Delta wetlands and is most effective when integrated with

complementary strategies such as biostimulation or phytoremediation.

4.3. Biostimulation

Biostimulation involves enhancing the activity of indigenous hydrocarbon-degrading microorganisms through the addition of limiting nutrients, primarily nitrogen and phosphorus, to optimize microbial metabolism and accelerate petroleum hydrocarbon degradation. In petroleum-contaminated wetland environments, microbial growth is often constrained by nutrient imbalance, despite the abundance of carbon from spilled hydrocarbons. Nutrient supplementation therefore plays a critical role in stimulating microbial enzymatic activity and biodegradation potential.

Several studies conducted under Niger Delta conditions have demonstrated the effectiveness of biostimulation as a standalone remediation approach. Application of inorganic fertilizer formulations (NPK) resulted in approximately 66% reduction in total petroleum hydrocarbons (TPH) over a 63-day treatment period, indicating substantial enhancement of indigenous microbial degradation capacity (Brown *et al*., 2017) [2].

In a bioreactor-based treatment of hydrocarbon-polluted Niger Delta marine sediments, biostimulation using a range of nutrient sources including K_2HPO_4, NH_4NO_3, $(NH_4)_2SO_4$, NPK fertilizer, urea, and poultry droppings reduced initial TPH concentrations from 106.4–116 ppm to $\leq$14.9 ppm within 56 days. Concurrent reductions in polycyclic aromatic hydrocarbons (PAHs) to $\leq$6.8 ppm were also observed, demonstrating the effectiveness of nutrient amendment in promoting degradation of both aliphatic and aromatic hydrocarbon fractions (Chikere *et al*., 2019) [3].

However, biostimulation performance can vary depending on nutrient type, dosage, and environmental conditions. Soil microcosm experiments using inorganic nutrient amendments alone achieved only 22% removal of used lubricant oil after 40 days, highlighting limitations associated with nutrient washout, oxygen limitation, and reduced contaminant bioavailability in waterlogged soils (Ossai *et al*., 2020) [16]. Consequently, while biostimulation can significantly enhance biodegradation, its effectiveness as a standalone strategy in wetland systems is often moderate and site-specific.

4.4. Combined Bioaugmentation and Biostimulation

The combined application of bioaugmentation and biostimulation represents the most effective biological remediation strategy for petroleum-contaminated wetland environments, as it simultaneously addresses microbial population limitations and nutrient constraints. This integrated approach exploits synergistic interactions between introduced hydrocarbon-degrading microorganisms and optimized nutrient availability, leading to substantially enhanced degradation rates.

Empirical evidence from Niger Delta-related studies consistently demonstrates superior performance of combined treatments compared with individual approaches. The combined application of *Alcanivorax* spp. and NPK nutrient supplementation achieved 74% TPH reduction, decreasing concentrations from 1,674 mg/kg to 430 mg/kg within 63 days, significantly outperforming bioaugmentation or biostimulation applied independently (Brown et al., 2017) [2].

Similarly, consortium-based bioaugmentation combined with nutrient amendment achieved exceptionally high degradation efficiencies of 97.4–99.0% TPH removal within 60 days in diesel-contaminated aged soils, compared with only 11.7% reduction under untreated control conditions (Nwankwegu and Onwosi, 2017) [14]. These results highlight the importance of microbial diversity and functional complementarity in degrading complex hydrocarbon mixtures.

Further enhancement has been observed through the use of organic co-substrates. Synergistic bioaugmentation and biostimulation using keratinaceous materials as nutrient sources achieved TPH biodegradation efficiencies ranging from 70.5% to 91.5% over 180 days in used engine oil-polluted soils, compared with only 18.5–22.5% degradation attributable to natural bioattenuation (Ossai *et al*., 2020) [16].

In aqueous systems, combined bioaugmentation and biostimulation has also proven highly effective. Treatment of crude oil-polluted water using *Aspergillus niger* and *Pseudomonas aeruginosa*, supplemented with nutrients and periodic aeration, resulted in TPH reductions of 92.3–94.4% over an eight-week period, underscoring the versatility of integrated biological approaches across different contaminated media (Das and Chandran, 2011) [5].

Overall, the consistent superiority of combined bioaugmentation and biostimulation demonstrates its suitability as the primary remediation strategy for petroleum-contaminated mangrove and freshwater swamp ecosystems in the Niger Delta, particularly where rapid contaminant reduction and ecological recovery are required**.**

5. Phytoremediation

5.1. Plant Species and Applications

Phytoremediation involves the use of plants to remove, transform, stabilize, or enhance the degradation of petroleum hydrocarbons in contaminated environments. In the Niger Delta, this approach has gained attention due to its low cost, ecological compatibility, and potential to restore vegetation cover in degraded wetland landscapes. In Ogbogu, Niger Delta, a sequential phytoremediation strategy has been employed using *Hibiscus cannabinus* and *Vetiveria zizanioides. H. cannabinus*, an indigenous West African species, is applied during the initial remediation phase to absorb oil-saturated materials, which are subsequently removed for ex-situ microbial treatment. This is followed by the establishment of *V. zizanioides* (vetiver grass), a perennial species characterized by an extensive fibrous root system, high tolerance to soil contaminants, and minimal maintenance requirements (Nwaichi *et al*., 2015; Yavari *et al*., 2015) [13, 21].

In mangrove and freshwater swamp environments, enhanced rhizoremediation studies have successfully utilized wetland plant species such as Phragmites australis (common reed) and Eichhornia crassipes (water hyacinth). These species are well adapted to saturated conditions and have demonstrated effectiveness in supporting microbial degradation of crude oil in contaminated sediments (Okere and Semple, 2019) [15].

Field studies conducted under Niger Delta conditions indicate that *V. zizanioides* achieved total hydrocarbon removal efficiencies exceeding 41% in crude oil-contaminated soils, significantly outperforming non-wetland species such as sunflower, which achieved only 25.59% removal (Nwaichi *et al*., 2015) [13]. These findings highlight the importance of selecting site-appropriate, stress-tolerant plant species for successful phytoremediation in wetland environments.

5.2. Enhanced Rhizoremediation Effectiveness

Enhanced rhizoremediation integrates phytoremediation with microbial inoculation and nutrient supplementation to maximize hydrocarbon degradation within the rhizosphere. Comparative studies conducted in crude oil-contaminated mangrove swamp soils with initial TPH concentrations of approximately 7,190 mg/kg demonstrated that enhanced rhizoremediation produced substantially higher TPH removal rates than either biostimulation or bioaugmentation alone. Specifically, the combined application of hydrocarbon-utilizing bacteria and fungi, together with NPK fertilization in the rhizospheres of P. australis and E. crassipes, resulted in significantly accelerated hydrocarbon degradation under waterlogged conditions (Okere and Semple, 2019) [15]. Root systems enhanced oxygen diffusion, nutrient availability, and microbial colonization, creating favorable microenvironments for biodegradation.

These findings indicate that enhanced rhizoremediation represents a more efficient and ecologically integrated bioremediation strategy for crude oil-contaminated mangrove swamps in the Niger Delta, particularly where long-term ecosystem restoration is a priority.

5.3. Mechanisms and Advantages

Phytoremediation enhances petroleum hydrocarbon degradation primarily through rhizosphere-mediated processes. Root exudates supply organic substrates that stimulate microbial growth and enzymatic activity, thereby increasing populations of hydrocarbon-degrading microorganisms (Yavari *et al*., 2015) [21]. In the case of vetiver grass, deep and dense root networks also improve soil structure, reduce erosion, and facilitate gradual ecosystem recovery following oil contamination.

Phytoremediation offers several advantages for wetland restoration, including low environmental impact, cost-effectiveness, restoration of vegetation cover, and strong community acceptance. However, it is inherently time-intensive, typically requiring 12–24 months or longer, and is most effective for light to moderate contamination levels. Consequently, phytoremediation is best applied as a complementary or secondary remediation strategy rather than a standalone solution for heavily contaminated sites (Cunningham and Ow, 1996; Ossai *et al*., 2020) [4, 16].

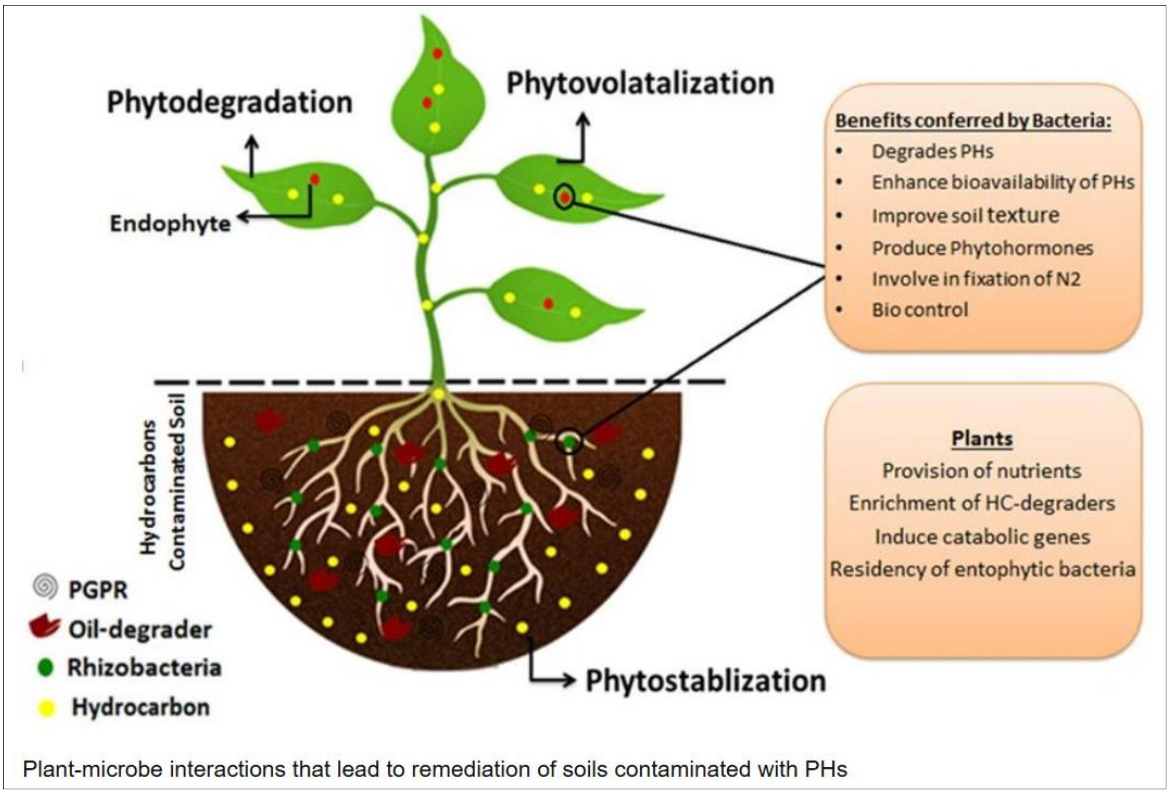

Fig 4: Rhizoremediation Mechanism Diagram (Afzal, *et al*., 2023) [23]

6. Chemical and Physical Remediation Methods

6.1. Chemical Oxidation

Chemical oxidation techniques, including the use of Fenton reagents and persulfate, are capable of rapidly degrading petroleum hydrocarbons under controlled conditions. However, their application in Niger Delta wetlands is severely constrained. High organic matter content in mangrove sediments consumes oxidants rapidly, reducing treatment efficiency, while maintaining effective oxidant concentrations in flowing or tidal waters is technically challenging (Prince and Parkerton, 2014) [17].

Advanced remediation options proposed for the Niger Delta include organoclay-based reactive materials for sediment remediation, permeable reactive barriers for groundwater treatment, and bioremediation for soils, representing a continuum from non-intrusive to moderately intrusive approaches (Ossai *et al*., 2020) [16]. Despite their potential, chemical oxidation methods pose risks of toxicity to aquatic organisms, high operational costs, and limited applicability in ecologically sensitive wetlands.

6.2. Physical Methods

Physical remediation methods such as excavation and dredging are typically reserved for small, discrete hotspots with extremely high contamination levels. In Niger Delta communities such as Bodo, remediation efforts funded by oil companies and government agencies have included physical interventions; however, local residents and environmental experts have reported that these efforts often fall short of achieving full ecological restoration (Zabbey and Uyi, 2014) [22].

Large-scale excavation in wetlands is associated with substantial ecosystem disruption, high logistical complexity, and costs ranging from approximately US$100–500 per cubic meter, making it impractical for widespread application. Disposal of contaminated sediments further complicates implementation in remote wetland locations (Vidonish *et al.*, 2016) [20].

7. Comparative Analysis of Remediation Effectiveness

7.1. Quantitative Performance Summary

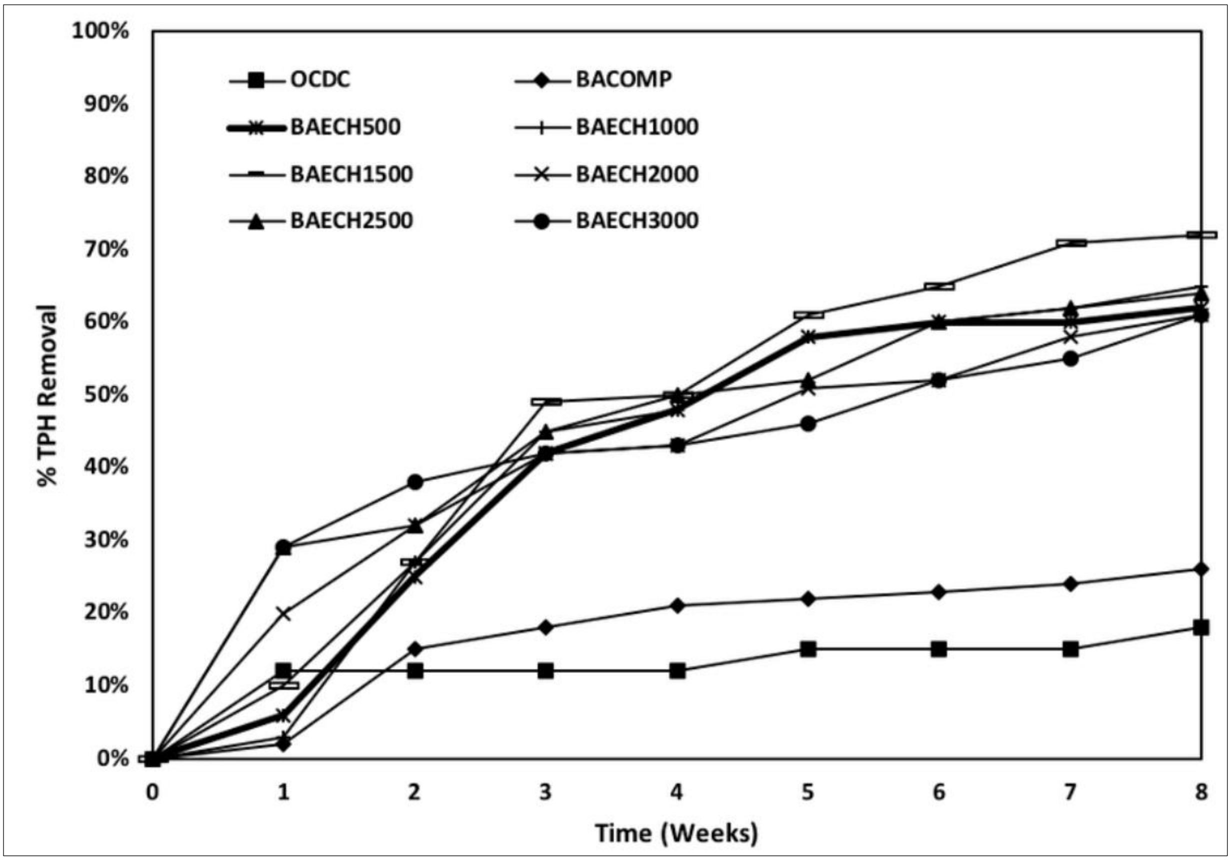

Fig 3: Comparative Effectiveness of Remediation Technologies

Across reviewed studies, remediation technologies demonstrated distinct effectiveness ranges:

- **Natural attenuation:** 5–15% annual TPH reduction; up to 35% over 63 days under controlled conditions; inadequate as a standalone approach (Brown *et al.*, 2017) [2].
- **Individual biological methods:** **Bioaugmentation:** 40–41% over ~60 days **Biostimulation:** 22–66% over 40–63 days **Phytoremediation (V. zizanioides):** ~41% removal efficiency (Nwaichi *et al.*, 2015) [13].
- **Combined biological methods:** Bioaugmentation + biostimulation: 74–99% over 60–63 days
  Enhanced rhizoremediation: consistently superior to individual methods
  Optimized integrated approaches: 91–95% degradation (Nwankwegu and Onwosi, 2017; Ossai *et al.*, 2020) [14, 16].

7.2. Time Requirements

Field evidence indicates that actively remediated mangrove sites recover within approximately 7 years, whereas non-remediated sites may require 13–14 years for ecological recovery. Active intervention therefore substantially accelerates restoration compared with natural recovery processes (UNEP, 2011; Zabbey and Uyi, 2014) [22].

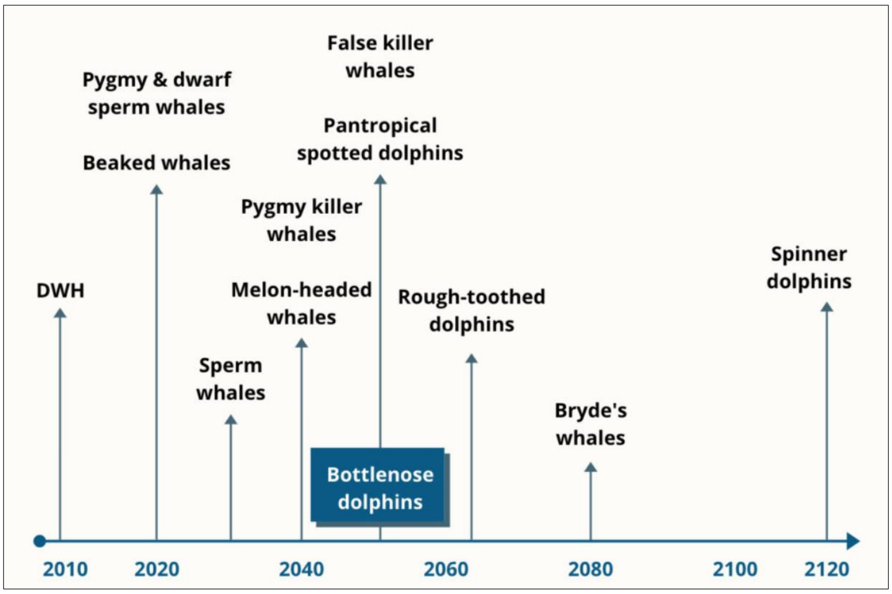

Fig 5: Ecosystem Recovery Timeline

A schematic comparison of ecosystem recovery timelines for remediated and non-remediated mangrove sites is shown in Figure 4.

7.3. Site-Specific Factors Affecting Effectiveness

Remediation success is strongly site dependent. Studies show that higher populations of TPH-degrading microorganisms correlate positively with removal efficiency, with bioaugmented systems exhibiting microbial populations up to two orders of magnitude greater than untreated controls (Nwankwegu and Onwosi, 2017) [14].

Key influencing factors include initial contaminant concentration and weathering, sediment organic matter and clay content, hydrological conditions, microbial community composition, nutrient availability, and implementation quality (Ossai *et al.*, 2020) [16].

8. Implementation Challenges and Considerations

8.1. Technical Challenges

Waterlogged wetland soils create predominantly anaerobic conditions that limit aerobic hydrocarbon degradation. While periodic aeration can enhance treatment efficiency, it may also cause physical disturbance to sensitive ecosystems. Limited accessibility and inadequate infrastructure further increase costs and logistical complexity, while aged contamination reduces bioavailability through strong sorption to organic matter (Brown *et al.*, 2017) [2].

8.2. Socio-Economic Factors

Divestment of major oil companies from Niger Delta assets has raised concerns regarding long-term responsibility for environmental remediation. Ongoing spills, artisanal refining, and delayed cleanup efforts continue to outpace remediation progress. Community engagement and local employment in remediation projects have been shown to improve acceptance and sustainability (Elum *et al.*, 2016; Zabbey and Uyi, 2014) [6, 22].

8.3. Monitoring and Verification

Integrated monitoring approaches combining chemical analysis, passive sampling, and ecological indicators provide more accurate assessments of remediation success and ecosystem recovery. Regular monitoring supports adaptive management and accountability to stakeholders and regulators (Prince and Parkerton, 2014) [17].

9. Knowledge Gaps and Research Needs

9.1. Fundamental Research Gaps

Despite identification of numerous hydrocarbon-degrading microorganisms, comprehensive metagenomic studies are needed to fully characterize indigenous microbial communities. Long-term field studies (3–5 years) are required to evaluate sustained remediation performance, and PAH-specific degradation remains under-studied in wetland contexts (Das and Chandran, 2011; Ossai *et al.*, 2020) [5, 16].

9.2. Technology Development Needs

Future research should focus on slow-release nutrient formulations, optimization of plant–microbe partnerships, and development of standardized scale-up protocols to bridge laboratory success and field application (Atlas, 1995; Okere and Semple, 2019) [1, 15].

9.3. Socio-Economic Research

Comprehensive cost–benefit analyses incorporating ecosystem service valuation and community-based remediation models are needed to inform policy and investment decisions (UNDP, 2006).

10. Recommendations

10.1. Technology Selection Guidance

- Light contamination (<5,000 mg/kg TPH): Biostimulation or enhanced rhizoremediation (12–24 months)
- Moderate contamination (5,000–15,000 mg/kg TPH): Combined bioaugmentation and biostimulation, followed by phytoremediation
- Heavy contamination (>15,000 mg/kg TPH): Sequential intensive biological treatment; targeted excavation for extreme hotspots

10.2. Implementation Best Practices

Priority should be given to locally adapted microbial consortia, slow-release nutrient formulations, and continuous monitoring. Community engagement and capacity building are critical for long-term success (UNEP, 2011).

10.3. Policy Recommendations

Clear wetland-specific remediation standards, dedicated environmental restoration funds, and regional centers of excellence are essential to sustain large-scale cleanup efforts in the Niger Delta.

11. Conclusions

Petroleum hydrocarbon contamination represents one of the most serious environmental challenges facing Niger Delta wetlands. This systematic review demonstrates that effective remediation technologies exist, with combined bioaugmentation and biostimulation showing the highest effectiveness (74-99% TPH reduction) in relatively short timeframes (60-180 days).

Enhanced rhizoremediation has emerged as particularly promising for mangrove swamp applications, demonstrating superior performance compared to individual biostimulation or bioaugmentation approaches. The integration of locally adapted microorganisms with appropriate wetland plant species offers both remediation effectiveness and ecosystem restoration benefits.

However, the scale of contamination across the Niger Delta, with environmental restoration projected to require 25-30 years and representing potentially the world's most extensive oil cleanup undertaking, demands sustained commitment from all stakeholders. Current cleanup efforts, while showing some progress, remain insufficient as ongoing oil spills continue to outpace remediation work.

Success requires:

1. Selection of appropriate technologies matched to site-specific conditions
2. Use of locally adapted microbial consortia and indigenous plant species
3. Adequate funding and long-term commitment
4. Community participation and capacity building
5. Rigorous monitoring and adaptive management
6. Addressing ongoing contamination sources

Recent advances in bioremediation technology combined with systematic selection of tailored technical solutions offer hope for addressing the unique challenges of the Niger Delta. With proper implementation of evidence-based remediation strategies, restoration of these critical wetland ecosystems is achievable, supporting both environmental recovery and the livelihoods of millions who depend on these ecosystems.

12. References

1. Atlas RM. Bioremediation of petroleum pollutants. Int Biodeterior Biodegrad. 1995;35(1-3):317-27. doi:10.1016/0964-8305(95)00030-9
2. Brown DM, Okoro S, Van Gils J, Van Spanning R, Bonte M, Hutchings T, et al. Comparison of landfarming amendments to improve bioremediation of petroleum hydrocarbons in Niger Delta soils. Sci Total Environ. 2017;596-597:284-92. doi:10.1016/j.scitotenv.2017.04.073
3. Chikere CB, Mordi IJ, Chikere BO, Selvarajan R, Ashafa TO, Obieze CC. Bioreactor-based bioremediation of hydrocarbon-polluted Niger Delta marine sediment, Nigeria. 3 Biotech. 2019;9:1-10. doi:10.1007/s13205-019-1603-5
4. Cunningham SD, Ow DW. Promises and prospects of phytoremediation. Plant Physiol. 1996;110(3):715-9. doi:10.1104/pp.110.3.715
5. Das N, Chandran P. Microbial degradation of petroleum hydrocarbon contaminants: an overview. Biotechnol Res Int. 2011;2011:941810. doi:10.4061/2011/941810
6. Elum ZA, Mopipi K, Henri-Ukoha A. Oil exploitation and its socioeconomic effects on the Niger Delta region of Nigeria. Environ Sci Pollut Res Int. 2016;23:12880-9. doi:10.1007/s11356-016-6864-1
7. Head IM, Jones DM, Röling WFM. Marine microorganisms make a meal of oil. Nat Rev Microbiol. 2006;4:173-82. doi:10.1038/nrmicro1348
8. Ite AE, Ibok UJ, Ite MU, Petters SW. Petroleum exploration and production: past and present environmental issues in Nigeria's Niger Delta. Am J Environ Prot. 2013;1(4):78-90.
9. John RC, Essien JP, Akpan SB, Okpokwasili GC. Polycyclic aromatic hydrocarbon-degrading bacteria from an aviation fuel spill site at Ibeno, Nigeria. Bull Environ Contam Toxicol. 2016;96:331-6. doi:10.1007/s00128-016-1734-1
10. Jørgensen KS, Puustinen J, Suortti AM. Bioremediation of petroleum hydrocarbon-contaminated soil by composting. Environ Pollut. 2000;107(2):245-54. doi:10.1016/S0269-7491(99)00144-X
11. Müller AK, Westergaard K, Christensen S, Sørensen SJ. The effect of long-term mercury pollution on the soil microbial community. FEMS Microbiol Ecol. 2001;36(1):11-9. doi:10.1111/j.1574-6941.2001.tb00824.x
12. National Research Council (US). An ecosystem services approach to assessing the impacts of the Deepwater Horizon oil spill in the Gulf of Mexico. Washington (DC): National Academies Press; 2013.
13. Nwaichi EO, Frac M, Nwoha PA, Eragbor P. Enhanced phytoremediation of crude oil-polluted soil by four plant species: effect of inorganic and organic bioaugmentation. Int J Phytoremediation. 2015;17(12):1253-61. doi:10.1080/15226514.2014.964843
14. Nwankwegu AS, Onwosi CO. Bioremediation of gasoline-contaminated agricultural soil by bioaugmentation. Environ Technol Innov. 2017;7:1-11. doi:10.1016/j.eti.2016.11.002
15. Okere UV, Semple KT. Enhanced rhizoremediation of crude oil-contaminated mangrove swamp soil using two wetland plants (Phragmites australis and Eichhornia crassipes). Environ Sci Pollut Res Int. 2019;26:15469-82. doi:10.1007/s11356-019-04998-8
16. Ossai IC, Ahmed A, Hassan A, Hamid FS. Remediation of soil and water contaminated with petroleum hydrocarbon: a review. Environ Technol Innov. 2020;17:100526. doi:10.1016/j.eti.2019.100526
17. Prince RC, Parkerton TF. The role of biodegradation in oil spill response. Environ Sci Technol. 2014;48:13562-9. doi:10.1021/es504265n
18. United Nations Development Programme. Niger Delta human development report. Abuja: United Nations Development Programme; 2006.
19. United Nations Environment Programme. Environmental assessment of Ogoniland. Nairobi: United Nations Environment Programme; 2011.
20. Vidonish JE, Zygourakis K, Masiello CA, Sabadell G,

Alvarez PJJ. Thermal treatment of hydrocarbon-impacted soils: a review of technology innovation for sustainable remediation. Environ Sci Technol. 2016;50:989-1002. doi:10.1021/acs.est.5b04072

21. Yavari S, Malakahmad A, Sapari NB. A review on phytoremediation of crude oil spills. Water Air Soil Pollut. 2015;226:279. doi:10.1007/s11270-015-2548-9
22. Zabbey N, Uyi H. Community responses and coping strategies in oil spill-impacted rivers in the Niger Delta, Nigeria. J Environ Sci Health A Tox Hazard Subst Environ Eng. 2014;49:1499-506. doi:10.1080/10934529.2014.910055
23. Afzal M, Li RYM, Shoaib M, Ayyub MF, Tagliabue LC, Bilal M, et al. Delving into the digital twin developments and applications in the construction industry: a PRISMA approach. Sustainability. 2023;15(23):16436. doi:10.3390/su152316436