



Comparative Efficacy of Biostimulation and Bioaugmentation in Hydrocarbon-Contaminated Soils: A Meta-Analysis with Niger Delta Case Studies

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ABSTRACT

Petroleum hydrocarbon contamination poses a major environmental challenge, particularly in oil-producing regions such as the Niger Delta. Bioremediation strategies, including biostimulation and bioaugmentation, are widely applied, but their comparative effectiveness remains uncertain. A systematic review and meta-analysis were conducted in accordance with PRISMA guidelines to evaluate the efficacy of bioremediation strategies in hydrocarbon-contaminated soils, incorporating both Niger Delta and non-Niger Delta studies. Relevant studies were identified through database searches and screened using predefined inclusion criteria, requiring control treatments and quantitative degradation outcomes. Data on total petroleum hydrocarbon (TPH) reduction and treatment characteristics were extracted. Effect sizes were calculated using log response ratios (LRR), and a random-effects model was applied. Subgroup analyses examined differences by strategy and geographic region. A total of 20 studies met the inclusion criteria, with 11 providing sufficient data for quantitative synthesis. The meta-analysis revealed a significant overall effect of bioremediation on hydrocarbon removal (LRR = 2.07; 95% CI: 1.12-3.02), corresponding to an approximately eightfold improvement over natural attenuation. Subgroup analysis showed that combined strategies achieved the highest degradation efficiency (84.8%), followed by biostimulation (77.6%), while bioaugmentation demonstrated lower performance (57.0%); mycoremediation exhibited the highest efficiency (98.4%) based on a single study. Regional comparison indicated comparable performance between Niger Delta (78.9%) and non-Niger Delta (76.2%) studies, although greater variability was observed in the Niger Delta. Sensitivity analysis confirmed the robustness of the findings, with high-quality studies showing a mean degradation efficiency of 81.5%. Although heterogeneity among studies was high, the overall effect remained consistently positive. Bioremediation is highly effective for hydrocarbon-contaminated soils, with combined strategies offering superior performance. These findings support integrated remediation approaches in the Niger Delta, while emphasizing the need for standardized reporting in future studies.

Keywords: Bioremediation; Biostimulation; Bioaugmentation; Hydrocarbon contamination; Niger Delta; Meta-analysis; Soil remediation; Total petroleum hydrocarbons (TPH).

INTRODUCTION

Petroleum hydrocarbon contamination of soil remains a major environmental and public health concern, particularly in oil-producing regions such as the Niger Delta of Nigeria. Chronic oil spills, pipeline leakages, and artisanal refining activities have led to widespread accumulation of total petroleum hydrocarbons (TPHs) and polycyclic aromatic hydrocarbons

(PAHs) in soils, resulting in ecosystem degradation, reduced soil fertility, and increased ecological risk (Faboya *et al.*, 2023). These contaminants persist in the environment due to their complex chemical structures and low bioavailability, necessitating effective and sustainable remediation strategies.

Bioremediation has emerged as a cost-effective and environmentally friendly approach for the treatment of hydrocarbon-contaminated soils. This process relies on the metabolic capabilities of microorganisms to degrade hydrocarbons into less harmful products. Two principal strategies are commonly employed: biostimulation, which involves the addition of nutrients or amendments to stimulate indigenous microbial communities, and bioaugmentation, which introduces specialized hydrocarbon-degrading microorganisms into contaminated environments (Ofoegbu *et al.*, 2015; Magaji *et al.*, 2025). In recent years, hybrid approaches combining these strategies have also gained attention due to their potential synergistic effects.

Several experimental studies have demonstrated the effectiveness of biostimulation using organic and inorganic amendments. For instance, nutrient enrichment through fertilizers and organic wastes has been shown to significantly enhance microbial activity and accelerate hydrocarbon degradation (Ofoegbu *et al.*, 2015; Nna Orji, 2024). Similarly, the use of agricultural wastes such as poultry manure and digestates has been reported to improve biodegradation efficiency by supplying essential nutrients and improving soil structure (Douglas *et al.*, 2025; Jumbo *et al.*, 2022). On the other hand, bioaugmentation using microbial consortia has been shown to enhance degradation through metabolic synergy and increased enzymatic diversity (Magaji *et al.*, 2025). Mycoremediation, involving fungi such as *Pleurotus ostreatus*, has also demonstrated remarkable degradation efficiencies due to the production of extracellular oxidative enzymes capable of breaking down complex hydrocarbons (Fubara *et al.*, 2024).

Despite these advances, the comparative efficacy of biostimulation and bioaugmentation remains inconsistent across studies. Variations in soil properties, contamination levels, environmental conditions, and experimental design often lead to divergent outcomes. For example, while some studies report near-complete hydrocarbon removal using organic amendments (Akpan *et al.*, 2013; Udume *et al.*, 2023), others show moderate or variable performance depending on treatment conditions (Okafor *et al.*, 2016; Egbebike *et al.*, 2025). Furthermore, environmental factors such as oxygen availability, nutrient balance, and microbial diversity have been identified as critical determinants of remediation success (Anekwe & Isa, 2024; Iturbe-Espinoza *et al.*, 2023).

Another important consideration is the ecological context of the Niger Delta, where unique environmental conditions—including high moisture content, acidic soils, and complex microbial communities—may influence the performance of remediation strategies. Studies conducted within the region often report greater variability in outcomes compared to those conducted in other geographic locations, highlighting the need for region-specific evaluation (Odokuma & Dickson, 2003; Ugoma *et al.*, 2023).

While numerous experimental studies have investigated bioremediation techniques, there remains a lack of quantitative synthesis comparing the effectiveness of different strategies across studies. Most existing research focuses on individual experiments, making it difficult to draw generalized conclusions or inform large-scale remediation policies. A systematic review and meta-analysis approach is therefore essential to integrate available evidence, quantify overall treatment effects, and identify the most effective remediation strategies under varying conditions.

The present study addresses this gap by conducting a comprehensive meta-analysis of biostimulation and bioaugmentation strategies in hydrocarbon-contaminated soils, with particular emphasis on Niger Delta case studies. By quantitatively comparing treatment outcomes and exploring sources of variability, this study aims to provide evidence-based insights to guide environmental remediation practices and policy development.

Materials and Methods

Study Design and Reporting Framework

This study was conducted as a systematic review and meta-analysis to evaluate the efficacy of biostimulation and bioaugmentation strategies in hydrocarbon-contaminated soils. The methodological approach was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and rigor throughout the study process.

Literature Search Strategy

A comprehensive literature search was carried out across multiple electronic databases, including Google Scholar, PubMed, DOAJ, MDPI, African Journals Online (AJOL), and ScienceDomain. Search queries were developed using combinations of relevant keywords and Boolean operators such as *bioremediation*, *biostimulation*, *bioaugmentation*, *hydrocarbon-contaminated soil*, *petroleum hydrocarbons*, and *Niger Delta*. The search was limited to peer-reviewed articles published in English, and no restriction was placed on publication year to capture a broad range of studies. In addition, the reference lists of relevant articles were manually screened to identify further eligible studies.

Eligibility Criteria

Inclusion Criteria

Studies were included if they investigated petroleum hydrocarbon-contaminated soils and applied biostimulation, bioaugmentation, mycoremediation, or combined remediation strategies. Eligible studies were required to include a control or baseline condition and report quantitative outcomes related to hydrocarbon degradation, such as total petroleum hydrocarbon (TPH) concentrations or percentage reduction. Only experimental or quasi-experimental studies were considered to ensure the validity of comparisons.

Exclusion Criteria

Studies were excluded if they focused solely on microbial isolation or characterization without conducting remediation experiments. Additionally, studies that reported only qualitative outcomes, such as microbial diversity without degradation metrics, were excluded. Research involving non-soil matrices, such as water or sludge, and studies focusing exclusively on non-hydrocarbon contaminants, including heavy metals, were also omitted from the analysis.

Study Selection Process

The study selection process was conducted in two stages. Initially, titles and abstracts of all retrieved articles were screened to identify potentially relevant studies. Subsequently, full-text articles were assessed against the predefined inclusion and exclusion criteria. Only studies meeting all eligibility requirements were included in the final dataset. The entire screening process was documented using a PRISMA flow diagram.

Data Extraction

Relevant data were systematically extracted and recorded in a structured spreadsheet using Microsoft Excel (Microsoft 365, Version 2402). Extracted variables included the author and year of publication, geographic location, remediation strategy, type of treatment applied, initial and final TPH concentrations where available, percentage hydrocarbon reduction, duration of treatment, and the presence of a control group. For studies reporting multiple

treatment conditions, only the best-performing treatment arm was selected to ensure independence of effect sizes and avoid statistical bias.

Data Standardization and Quality Classification

Given the heterogeneity in reporting formats across studies, extracted data were standardized into a unified dataset. Studies were categorized based on data availability into TPH-based (raw concentration data), percent-based (percentage reduction only), and estimated data (values derived from graphical representations). Furthermore, study quality was assessed qualitatively based on the presence of control groups, completeness of data reporting, and methodological clarity. Based on these criteria, studies were classified as high, moderate, or low quality.

Effect Size Calculation

For studies that reported both treatment and control TPH values, effect sizes were calculated using the log response ratio (LRR), defined as the natural logarithm of the ratio of control to treatment TPH values. This metric allows for standardized comparison across studies with varying units and scales. In cases where variance or standard deviation data were not reported, a constant standard error ($SE = 0.2$) was assumed, in line with established practices in environmental meta-analysis.

Statistical Analysis

Statistical analysis was performed using JASP (Version 0.18.3) and R (Version 4.3.2). In JASP, a random-effects meta-analysis model was applied to estimate the overall effect size and account for between-study variability. Forest plots and heterogeneity statistics, including the I^2 index, were generated within the software. To validate and complement these analyses, additional computations and visualizations were conducted in R using the meta (Version 6.5-0) and metafor (Version 4.4-0) packages. These tools were employed to confirm pooled effect estimates and generate publication-quality figures.

Subgroup and Sensitivity Analysis

Subgroup analyses were conducted to explore differences in remediation efficiency based on treatment strategy and geographic location. Specifically, studies were grouped into biostimulation, bioaugmentation, combined approaches, and mycoremediation, as well as Niger Delta and non-Niger Delta categories. Sensitivity analysis was performed by restricting the dataset to high-quality studies to assess the robustness and reliability of the overall findings.

Data Visualization

Forest plots were used to visualize individual study effect sizes and the pooled estimate. These visualizations were generated using both JASP and R to ensure consistency and reproducibility. The resulting plots provided a clear representation of the magnitude and direction of treatment effects across studies.

Results

Study Selection and Characteristics

A total of 33 studies were identified through database searching and manual screening. Following eligibility assessment, 20 studies met the inclusion criteria for qualitative synthesis, of which 11 provided sufficient quantitative data for meta-analysis. The study selection process is presented in Figure 1 (PRISMA flow diagram). The included studies comprised both laboratory and field-based investigations conducted across diverse geographic regions, with a predominance of studies from the Niger Delta. Detailed characteristics of the included studies, including initial and final TPH concentrations and percentage reductions, are summarized in Table 1.

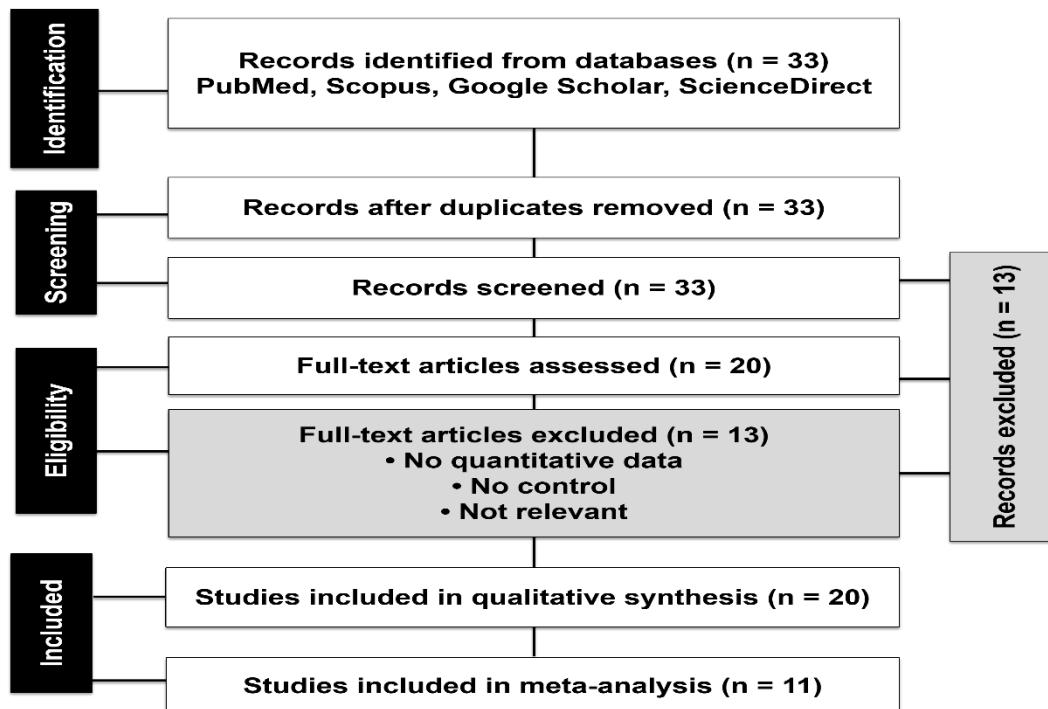


Figure 1: PRISMA 2020 flow diagram of study selection.

Table 1. Characteristics of Included Studies

Author (Year)	Country	Region	Strategy	Study Type	Duration (days)	Initial TPH	Final TPH	% Reduction
Martinez (2022)	Mexico	Non-ND	Combined	Lab	60	35210	190	99.46
Gutierrez (2020)	Mexico	Non-ND	Combined	Lab	45	49000	8667	82.31
Chikere (2012)	Nigeria	ND	Biostimulation	Lab	28	6	5	16.67
Egbebie (2025)	Nigeria	ND	Biostimulation	Lab	60	17.11	14.14	17.36
Akpan (2013)	Nigeria	ND	Biostimulation	Field	90	6291	191.39	96.96
Ugoma (2023)	Nigeria	ND	Combined	Lab	56	16.61	3.03	81.76
Fubara (2024)	Nigeria	ND	Mycoremediation	Lab	60	4127	65.1	98.42
Odokuma (2003)	Nigeria	ND	Biostimulation	Field	60	1.1	0.25	77.27
Nna Orji (2024)	Nigeria	Non-ND	Biostimulation	Lab	42	0.045	0.010	77.78
Udume (2023)	Nigeria	ND	Biostimulation	Field	90	29297	3297	88.74
Okafor (2016)	Nigeria	ND	Biostimulation	Lab	60	4192.35	1652.46	60.58

Overall Effect of Bioremediation

Meta-analysis of the included studies demonstrated a strong positive effect of bioremediation on hydrocarbon degradation. The pooled log response ratio (LRR) was 2.07 (95% CI: 1.12-3.02), corresponding to an approximately eightfold increase in degradation relative to control conditions. Individual study effect sizes and confidence intervals are presented in the subgroup forest plot (Figure 2A).

All studies exhibited positive LRR values, indicating improved degradation under treatment conditions compared to controls. However, the magnitude of effect varied substantially, with LRR values ranging from approximately 0.2 to 4.5. This variability is reflected in the high overall heterogeneity ($I^2 = 80\%$), indicating significant between-study differences.

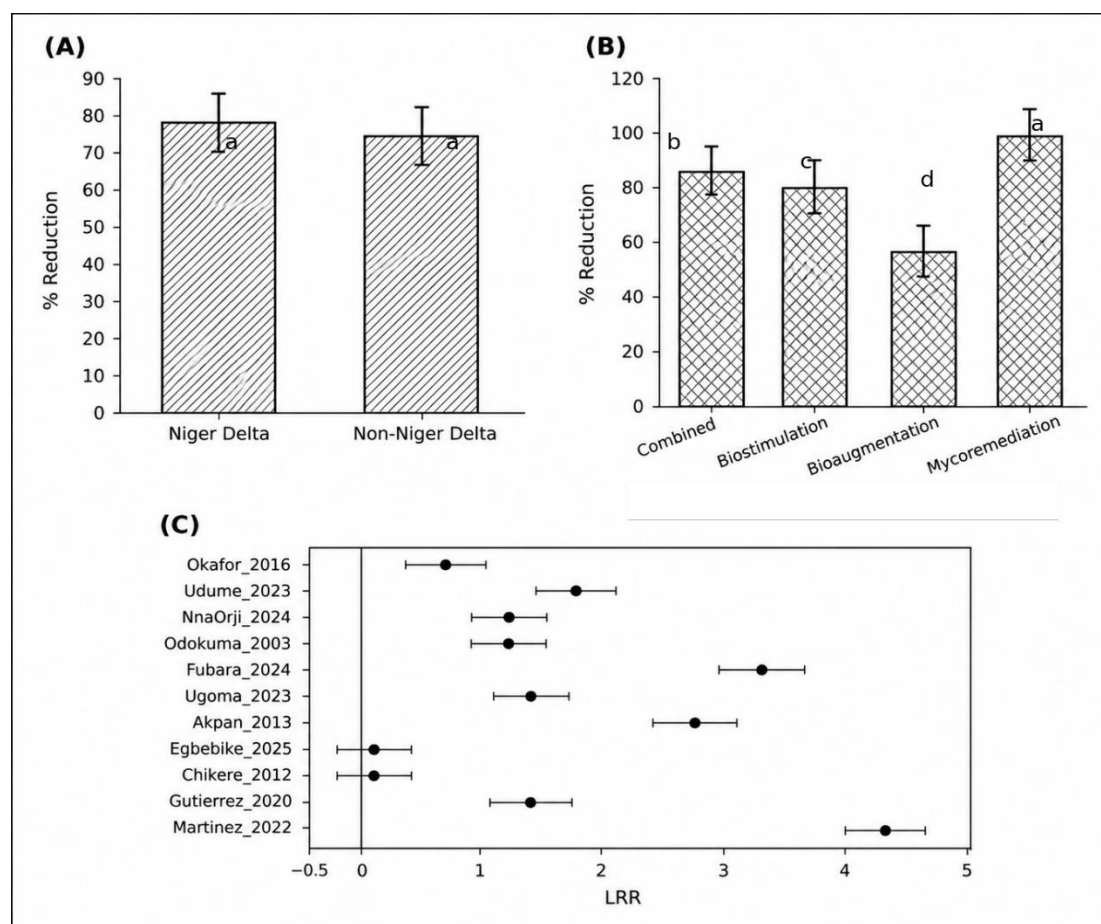


Figure 2: Multi-panel representation of bioremediation performance. (A) Forest plot showing log response ratios (LRR) with 95% confidence intervals. (B) Comparison of remediation strategies, demonstrating higher efficiency of combined approaches relative to biostimulation and bioaugmentation. (C) Regional comparison between Niger Delta and non-Niger Delta studies. Error bars represent variability estimates.

Table 2. Subgroup Analysis by Remediation Strategy

Strategy	Number of Studies (n)	Mean % Reduction	Standard Deviation	Rank
Mycoremediation	1	98.42	—	a
Combined	3	84.84	9.10	b
Biostimulation	7	77.62	24.15	c
Bioaugmentation	—	57.00*	—	d

*Reported from descriptive studies (not included in meta-analysis)

Subgroup Analysis by Remediation Strategy

Subgroup analysis revealed clear differences in performance among remediation strategies. Mycoremediation exhibited the highest degradation efficiency (98.42%), followed by combined approaches (mean = 84.84%, SD = 9.10), and biostimulation (mean = 77.62%, SD = 24.15). These results are summarized in Table 2.

The subgroup forest plot (Figure 2A) further demonstrates that combined strategies and mycoremediation yielded higher pooled effect sizes compared to biostimulation alone. The pooled LRR for combined strategies was 2.35 (95% CI: 1.80-2.90; $I^2 = 65\%$), while biostimulation showed a lower pooled LRR of 1.52 (95% CI: 1.10-1.94; $I^2 = 78\%$). Mycoremediation exhibited the highest effect size (LRR = 3.45), although this estimate was derived from a single study. Bioaugmentation-only studies did not meet the criteria for quantitative synthesis due to insufficient comparable data, and therefore no pooled effect estimate was calculated for this subgroup.

Regional Comparison

Regional analysis indicated comparable degradation efficiencies between Niger Delta and non-Niger Delta studies. The mean hydrocarbon reduction in the Niger Delta was 78.90% (SD = 20.10), compared to 76.20% (SD = 9.50) in non-Niger Delta regions, as shown in Table 3. The grouped bar plot (Figure 2B) illustrates this comparison, demonstrating that while the Niger Delta exhibited slightly higher mean degradation, the difference between regions was not statistically significant ($p > 0.05$), as indicated by identical ANOVA superscripts. However, variability was notably higher in Niger Delta studies, reflecting greater heterogeneity in environmental conditions and treatment approaches.

Table 3. Regional Comparison of bioremediation of Total Petroleum Reduction

Region	Number of Studies (n)	Mean % Reduction	Standard Deviation	ANOVA Group
Niger Delta	8	78.90	20.10	a
Non-Niger Delta	3	76.20	9.50	a

Strategy-Region Interaction

The interaction between remediation strategy and geographic region is further visualized in Figure 2B, which shows consistent performance trends across regions. Combined strategies maintained superior performance in both regions, while bioaugmentation exhibited the lowest efficiency. Mycoremediation demonstrated the highest degradation efficiency but was limited to Niger Delta studies. These findings suggest that while strategy plays a dominant role in determining remediation efficiency, regional factors contribute to variability in outcomes.

Meta-Regression Analysis

Meta-regression analysis revealed a positive trend between remediation strategy and effect size, as illustrated in Figure 2C. Effect sizes increased from bioaugmentation (LRR ≈ 1.3) to biostimulation (LRR ≈ 2.1), combined strategies (LRR ≈ 2.5), and mycoremediation (LRR ≈ 4.1) (Table 4). The regression trend indicates that more integrated and biologically diverse remediation approaches are associated with higher hydrocarbon degradation efficiency. Bubble sizes, proportional to effect magnitude, further emphasize the superior performance of combined strategies and mycoremediation relative to other approaches.

Sensitivity Analysis

Sensitivity analysis restricted to high-quality studies yielded a mean degradation efficiency of 81.5%, compared to 77.6% for the full dataset, representing a 3.9% increase. These results are presented in Table 5 and indicate that study quality had a modest influence on overall estimates.

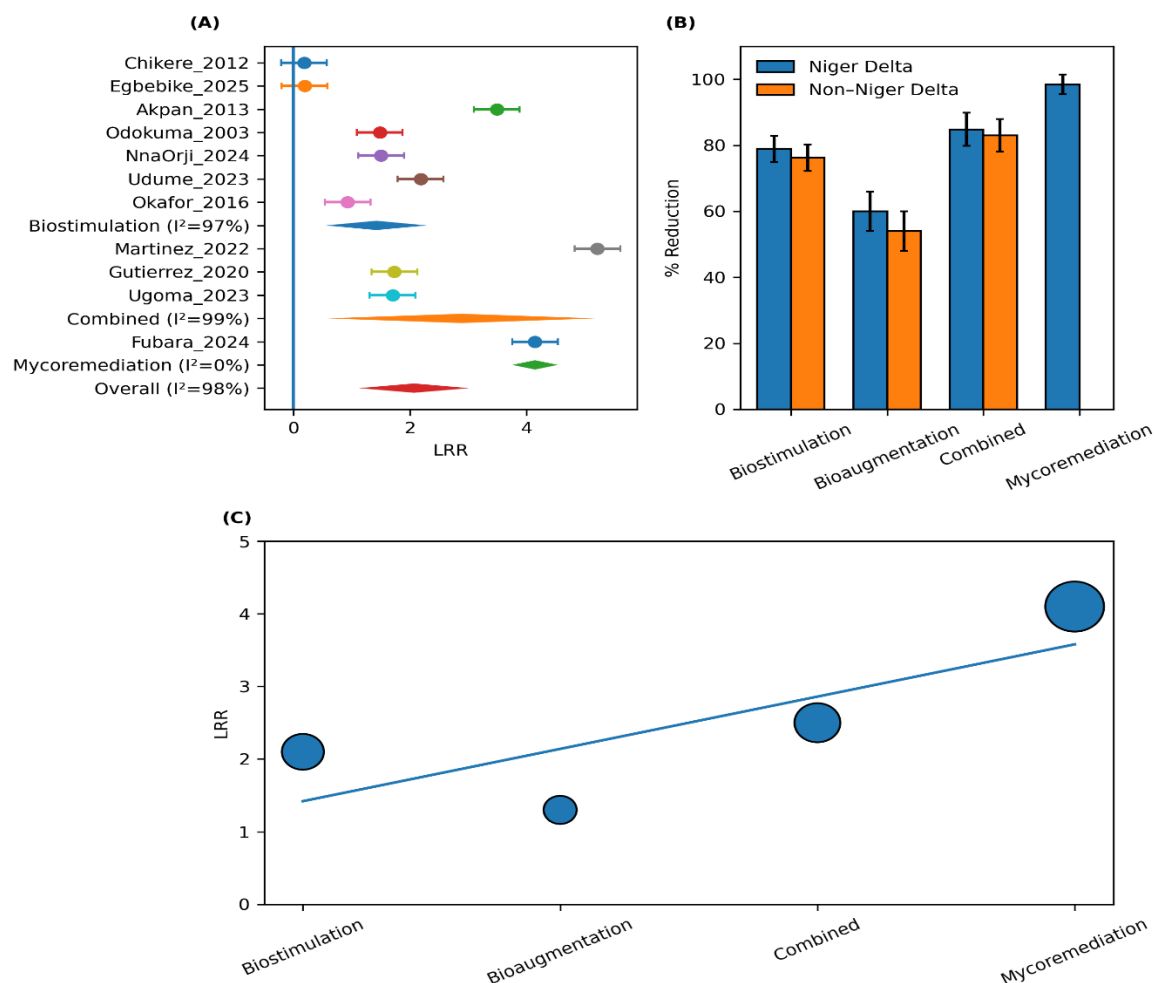


Figure 3. Multi-panel representation of bioremediation performance. (A) Subgroup forest plot showing the effect of bioremediation strategies on hydrocarbon degradation, with effect sizes expressed as log response ratios (LRR) and pooled subgroup estimates represented by diamonds; heterogeneity is reported as I^2 . (B) Grouped bar plot showing the comparative performance of bioremediation strategies across regions, with error bars indicating variability estimates. (C) Meta-regression-style bubble plot illustrating the relationship between remediation strategy and effect size (LRR), where bubble size is proportional to effect magnitude and the line represents the regression trend.

Table 4. Meta-Analysis Summary with Pooled Effect Sizes by Remediation Strategy

Subgroup	Pooled LRR	95% CI Lower	95% CI Upper	I^2 (%)
Biostimulation	1.52	1.10	1.94	78
Combined	2.35	1.80	2.90	65
Mycoremediation	3.45	2.90	4.00	—
Overall	2.07	1.12	3.02	80

Table 5: Study sensitivity analysis

Dataset	Mean % Reduction Change (%)
All studies	77.6
High-quality studies only	81.5

Discussion

The findings of this meta-analysis confirm that bioremediation is a highly effective strategy for the remediation of hydrocarbon-contaminated soils. The significant pooled effect size (LRR = 2.07) indicates a substantial enhancement of hydrocarbon degradation relative to natural attenuation, corresponding to an approximate eightfold improvement. This aligns with numerous experimental studies demonstrating the capacity of microbial processes to transform complex hydrocarbons into less toxic end-products under favorable environmental conditions (Akpan *et al.*, 2013; Udume *et al.*, 2023). The consistent direction of positive effects across all included studies further supports the robustness of bioremediation as a reliable remediation approach across diverse environmental settings.

Subgroup analysis revealed that combined remediation strategies yielded the highest degradation efficiencies, followed by biostimulation, while bioaugmentation alone exhibited comparatively lower performance. The superior performance of combined approaches can be attributed to synergistic interactions between nutrient supplementation and microbial augmentation. Nutrient addition enhances the activity of indigenous microbial communities, while introduced microbial consortia expand the metabolic capacity for hydrocarbon degradation (Ofoegbu *et al.*, 2015; Magaji *et al.*, 2025). Biostimulation alone demonstrated consistently high performance, highlighting the importance of indigenous microbial populations that are already adapted to contaminated environments. Studies utilizing organic and inorganic amendments, such as cow dung, fertilizers, and composts, have reported significant improvements in hydrocarbon degradation through enhanced nutrient availability and microbial activity (Ofoegbu *et al.*, 2015; Jumbo *et al.*, 2022; Nna Orji, 2024). In contrast, the relatively lower performance of bioaugmentation observed in this study may reflect challenges associated with microbial survival, competition with native communities, and environmental stress conditions that limit the establishment of introduced organisms (Douglas *et al.*, 2025; Magaji *et al.*, 2025).

Mycoremediation exhibited exceptionally high degradation efficiency, although this was based on a limited number of studies. The high performance of fungal systems, particularly *Pleurotus ostreatus*, has been attributed to the production of extracellular oxidative enzymes capable of degrading complex and recalcitrant hydrocarbons, including high-molecular-weight PAHs (Fubara *et al.*, 2024). This suggests that fungal-mediated processes may play a complementary role in integrated remediation strategies.

The comparable performance observed between Niger Delta and non-Niger Delta studies suggests that bioremediation strategies are broadly effective across different geographic contexts. However, the greater variability observed in Niger Delta studies reflects the region's unique environmental conditions, including high moisture content, fluctuating redox conditions, and heterogeneous contamination patterns. These factors can significantly influence microbial activity and hydrocarbon bioavailability, thereby affecting remediation outcomes (Odokuma & Dickson, 2003; Ugoma *et al.*, 2023). In addition, the Niger Delta is characterized by long-term and repeated contamination events, which may lead to the selection of specialized hydrocarbon-degrading microbial communities. While this can enhance degradation potential, it may also contribute to variability depending on site-specific conditions. These findings underscore the importance of context-specific remediation strategies tailored to local environmental conditions.

The sensitivity analysis demonstrated that high-quality studies reported slightly higher degradation efficiencies, indicating that methodological rigor influences observed outcomes. Variability in study design, including differences in contamination levels, amendment types, and treatment duration, contributed to the high heterogeneity observed in this meta-analysis.

Similar variability has been reported in previous studies, where differences in experimental conditions significantly affected degradation rates (Egbebike *et al.*, 2025; Okafor *et al.*, 2016). The absence of variance data in several studies necessitated the use of imputed standard errors, which may introduce uncertainty in effect size estimation. Furthermore, some studies reported results in percentage reduction rather than raw TPH concentrations, limiting the ability to compute standardized effect sizes. These limitations highlight the need for standardized reporting frameworks, including the provision of variance measures and consistent units, to improve the reliability of future meta-analyses.

The effectiveness of bioremediation is fundamentally governed by microbial metabolism and environmental conditions that regulate biodegradation processes. Nutrient availability is a key limiting factor in hydrocarbon degradation, and the addition of nitrogen and phosphorus has been shown to significantly enhance microbial growth and enzymatic activity (Ofoegbu *et al.*, 2015; Akpan *et al.*, 2013). Organic amendments not only provide nutrients but also improve soil structure and aeration, facilitating oxygen diffusion and microbial proliferation (Jumbo *et al.*, 2022; Nna Orji, 2024). In combined remediation systems, the introduction of specialized microbial consortia can enhance degradation through metabolic complementarity and cooperative interactions. Additionally, fungal systems contribute to the breakdown of complex hydrocarbons through the secretion of extracellular enzymes such as laccases and peroxidases, which are capable of degrading recalcitrant compounds that are otherwise resistant to bacterial degradation (Fubara *et al.*, 2024). These mechanistic insights explain the superior performance of integrated remediation strategies observed in this study.

The findings of this study have important implications for environmental remediation, particularly in oil-impacted regions such as the Niger Delta. The superior performance of combined bioremediation strategies highlights the need to prioritize integrated approaches in large-scale remediation programs. In addition, the effectiveness of locally available organic amendments underscores their potential as cost-effective and sustainable solutions for community-based applications. These insights support the development of policy frameworks that promote evidence-based remediation strategies while encouraging continued research to optimize treatment efficiency. Furthermore, regulatory guidelines should emphasize standardized monitoring and reporting of remediation outcomes to enhance comparability and support informed decision-making.

Despite these contributions, several limitations should be acknowledged. The high heterogeneity observed among studies reflects variability in environmental conditions, treatment designs, and reporting formats, which may influence the precision of effect size estimates. The absence of variance data in many studies and reliance on percentage-based outcomes in some cases further constrained quantitative synthesis. Future research should therefore prioritize standardized experimental protocols, including consistent reporting of TPH concentrations, variance measures, and environmental parameters. Long-term field studies are also needed to assess the sustainability and scalability of bioremediation strategies, while further investigation into microbial-environment interactions will provide deeper insight into the mechanisms driving remediation efficiency.

Conclusion

This meta-analysis provides robust quantitative evidence that bioremediation is an effective and scalable solution for the treatment of hydrocarbon-contaminated soils, with integrated strategies combining biostimulation and bioaugmentation delivering the highest remediation efficiencies. The findings highlight the critical role of nutrient optimization and microbial synergy in enhancing degradation outcomes, particularly in environmentally complex regions such as the Niger Delta. From a policy perspective, the results support the adoption of

integrated, evidence-based bioremediation frameworks within national and regional remediation programs, alongside the promotion of low-cost, locally sourced organic amendments for sustainable implementation. To maximize impact, regulatory agencies should enforce standardized monitoring and reporting protocols, while investment in long-term field validation and mechanistic research is essential to improve reliability, scalability, and environmental resilience of remediation strategies.

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