

Comparative Effectiveness of Nitrogen Sources for Nutrient Amendment in Bioremediation of Petroleum-Contaminated Soils in Nigeria's Niger Delta Region

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ABSTRACT

Oil spills are a recurrent environmental challenge in Nigeria's Niger Delta, leading to significant ecological and socio-economic impacts. Bioremediation, particularly nutrient amendment via biostimulation, has emerged as a viable approach for enhancing the natural degradation of petroleum hydrocarbons by indigenous microbes. This study investigates the comparative effectiveness of three nitrogen sources-ammonium (NH_4^+), nitrate (NO_3^-), and organic nitrogen-on the degradation of petroleum hydrocarbons in oil-contaminated soils. Using a mesocosm experimental setup with composite soil samples from three communities (Batan, Ajuju, and Umusia), treatments were applied across varying oil concentrations. Results showed that nutrient amendment generally increased total nitrogen (%), enhanced microbial population, and significantly reduced both total petroleum hydrocarbon (TPH) and polyaromatic hydrocarbon (PAH) levels. Ammonium-nitrogen was more effective in stimulating hydrocarbon degradation than nitrate, while organic nitrogen produced the highest microbial proliferation. Regression analysis revealed a strong positive correlation between nitrogen concentration and microbial population growth ($r = 0.95$). These findings support nitrogen-based biostimulation as a practical, low-impact strategy for accelerating oil spill remediation in tropical environments like the Niger Delta.

Keywords: Bioremediation, Hydrocarbon Contamination, Total Petroleum Hydrocarbon, Polyaromatic Hydrocarbon, Nutrient Amendment, Niger Delta, Microbial Activity

INTRODUCTION

The Niger Delta region of Nigeria is among the most ecologically diverse and economically important areas in West Africa, hosting over 30 million people and extensive oil and gas infrastructure. Despite its vast natural wealth, the region has suffered chronic and severe environmental degradation due to decades of oil exploration, pipeline leaks, sabotage, and spills. According to the United Nations Environment Programme (UNEP, 2011), oil pollution in the region has compromised agricultural land, aquatic habitats, and drinking

water sources, with many affected communities experiencing long-term exposure to toxic compounds such as benzene, polycyclic aromatic hydrocarbons (PAHs), and heavy metals. Oil contamination has significant long-term effects on soil structure, microbial dynamics, and ecosystem health (Renoux et al., 2000; Römbke et al., 2005).

Oil spills in the Niger Delta are not only a local ecological crisis but also a major public health and socio-economic concern. Contaminated soils and waters have led to declines in farm productivity, destruction of fisheries, and disruption of livelihoods, especially in rural communities dependent on natural resources. Despite global pressure and environmental justice campaigns, remediation efforts in the Niger Delta remain limited, expensive, and often unsustainable. Conventional remediation methods-such as physical containment, incineration, and chemical dispersants-are not always suitable due to their high costs, risk of secondary pollution, and inability to restore soil health or support ecological recovery in tropical environments (Das & Chandran, 2011; Obayori et al., 2009). This is particularly critical in tropical and wetland environments like the Niger Delta, where bioavailability, ecological compatibility, and long-term soil health must be considered (Renoux et al., 2000)."

As a result, bioremediation-using microbial communities to naturally degrade pollutants-has gained considerable attention as an eco-friendly, cost-effective alternative. Bioremediation is particularly suitable for large-scale, in-situ cleanups in regions like the Niger Delta, where widespread contamination persists across vast and often remote terrains (Margesin & Schinner, 2001; Bento et al., 2005). This technique relies on the metabolic capabilities of indigenous or introduced microorganisms to break down petroleum hydrocarbons into less harmful substances, such as carbon dioxide and water. Płaza et al. (2005) emphasized the utility of bioassays in tracking soil remediation success, complementing microbial population metrics used in this study.

However, successful bioremediation depends on the availability of essential nutrients, particularly nitrogen and phosphorus, which are often lacking in contaminated soils. The biodegradation of hydrocarbons is a nitrogen-intensive process, as microbial metabolism requires nitrogen for the synthesis of proteins, nucleic acids, and enzymes. Numerous studies have shown that hydrocarbon-degrading microbes thrive in nitrogen-rich environments and that nitrogen amendment significantly accelerates the rate of degradation (Leahy & Colwell, 1990; Seymour et al., 1996; Atlas & Hazen, 2011).

Nitrogen can be supplemented through various forms-such as ammonium (NH_4^+), nitrate (NO_3^-), or organic nitrogen sources like urea or compost. Each nitrogen form presents different dynamics in terms of solubility, bioavailability, soil retention, and microbial uptake. For example, ammonium is rapidly assimilable but may acidify soils and be lost through volatilization or leaching. Nitrate, while also bioavailable, is more prone to leaching and can pose risks to groundwater. Organic nitrogen releases slowly through microbial

decomposition and may support long-term fertility but with delayed effects on hydrocarbon degradation (Singh et al., 2007; Macaulay, 2015).

While international studies have explored nitrogen-enhanced bioremediation in diverse environments—from alpine soils to marine shorelines—relatively few have addressed the specific context of the Niger Delta. The region's acidic, humid tropical soils, combined with frequent flooding and diverse microbial populations, demand locally adapted remediation strategies. Moreover, the lack of comparative studies on the performance of different nitrogen sources under field-representative conditions presents a significant research gap. Without such insights, efforts to scale up bioremediation in the Niger Delta remain uncertain and inconsistent.

This study seeks to fill that gap by evaluating the relative effectiveness of ammonium, nitrate, and organic nitrogen sources in promoting bioremediation of petroleum-contaminated soils from three communities in the Niger Delta. Through a mesocosm simulation experiment, this research examines the impact of each nitrogen source on microbial activity, nitrogen availability, and the degradation of total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAHs). The goal is to identify the most efficient and ecologically sound nitrogen amendment approach suited to the environmental conditions of the Niger Delta.

By generating empirical data and insights on nitrogen-amended bioremediation, this study aims to inform evidence-based environmental management practices and policy development. Ultimately, enhancing remediation capacity can contribute to ecological recovery, food security, and health improvements for communities grappling with decades of oil pollution.

LITERATURE REVIEW

2.1 Bioremediation: Principles and Relevance to the Niger Delta

Bioremediation is a natural attenuation process that employs microbial metabolism to degrade and detoxify environmental pollutants, especially hydrocarbons. Microorganisms use hydrocarbons as a carbon and energy source, converting complex organic compounds into simpler, non-toxic substances like carbon dioxide, water, and biomass (Leahy & Colwell, 1990). As an environmentally sustainable and cost-effective alternative to conventional remediation techniques, bioremediation has gained widespread application for managing soil and groundwater pollution from petroleum products (Das & Chandran, 2011).

The relevance of bioremediation in the Niger Delta is particularly compelling due to the scale and persistence of oil pollution in the region. Traditional clean-up methods, such as mechanical skimming or the use of dispersants, are either ineffective in wetland environments or introduce additional toxicants into fragile ecosystems (UNEP, 2011). Bioremediation, especially in-situ approaches, is better suited for large, inaccessible areas and can enhance ecological recovery by restoring soil microbial communities and improving fertility (Margesin et al., 2005).

2.2 Biostimulation and the Role of Nitrogen

Bioremediation can be achieved through two major strategies: bioaugmentation and biostimulation. While bioaugmentation involves introducing exogenous microbial strains, biostimulation enhances the growth and metabolic activity of indigenous microbial populations through the addition of nutrients, moisture, or oxygen

(Atlas & Hazen, 2011). In nutrient-limited environments like oil-contaminated soils, biostimulation using nitrogen and phosphorus amendments is often critical to accelerate hydrocarbon degradation. Salanitro et al. (1997) observed that nitrogen-supplemented soils exhibited higher hydrocarbon breakdown and lower ecotoxicity levels, especially when monitored over a sustained remediation period.”

Nitrogen is essential for microbial cell growth, enzyme production, and hydrocarbon catabolism. Microbial metabolism of hydrocarbons requires a balanced carbon-to-nitrogen (C:N) ratio, ideally around 10:1 to 20:1 (Bossert & Bartha, 1984). However, oil-contaminated soils usually have an abundance of carbon (from hydrocarbons) but are severely deficient in nitrogen and phosphorus, which limits microbial degradation capacity. Numerous studies have demonstrated that nitrogen amendments significantly increase the rate of hydrocarbon biodegradation in both temperate and tropical settings (Venosa et al., 2002; Bento et al., 2005). In addition to nutrient augmentation, bioassays have been used to monitor microbial response and remediation success under petroleum stress (Płaza et al., 2005).

2.3 Comparative Analysis of Nitrogen Sources

The effectiveness of biostimulation varies depending on the form of nitrogen applied. Common nitrogen sources include:

Ammonium Nitrogen (NH_4^+):

Ammonium sulfate $[(NH_4)_2SO_4]$ or ammonium nitrate are frequently used due to their low cost and high nitrogen content. Ammonium is readily available to microbes, promoting rapid growth and hydrocarbon degradation. However, excessive ammonium can lower soil pH, affect microbial diversity, and contribute to nitrogen loss through volatilization or leaching in sandy or acidic soils (Roling & van Bodegom, 2014). Jackson and Pardue (1999) found that ammonium-nitrogen was more effective than nitrate in salt marshes because it adsorbed more strongly to organic matter, reducing washout losses.

Nitrate Nitrogen (NO_3^-):

Nitrate-based fertilizers, such as potassium nitrate (KNO_3), are also effective in aerobic conditions. Nitrate is more stable in well-aerated soils and supports sustained microbial activity. However, it is more prone to leaching, particularly in tropical regions with high rainfall like the Niger Delta. Additionally, nitrate application may pose risks to groundwater contamination if not carefully managed (Singh et al., 2007).

Organic Nitrogen:

Organic sources, including compost, poultry manure, biosolids, and urea, decompose slowly, releasing nitrogen over time. This gradual release helps maintain long-term microbial activity and improves soil structure and fertility. Organic nitrogen also supplies additional micronutrients and organic carbon that may benefit microbial consortia. However, the slow release limits their effectiveness in scenarios requiring rapid remediation (Das & Chandran, 2011; Macaulay, 2015). Despite this limitation, organic nitrogen is often more environmentally benign and suitable for sustainable land restoration.

This supports a dual-parameter approach combining TPH/PAH degradation and microbial assays, as highlighted in ecological risk models by Saterbak et al. (1999).

2.4 Field Studies and Regional Research Gaps

Several studies have investigated nitrogen-enhanced bioremediation globally, but only a few have focused specifically on the Niger Delta. Obayori et al. (2009) demonstrated the effectiveness of mixed inorganic fertilizers in reducing TPH in Nigerian soils. Okoh (2006) emphasized the importance of understanding local microbial communities and soil conditions for successful bioremediation. Similarly, Zabbey and Uyi (2014)

stressed that regional variability in soil properties and microbial ecology necessitates site-specific nutrient management strategies.

What remains lacking is a comparative evaluation of different nitrogen sources under controlled conditions that simulate the Niger Delta's acidic, waterlogged, and nutrient-poor soils. Without such evidence, environmental managers risk applying inappropriate or suboptimal remediation strategies. Moreover, the long-term effects of various amendments on microbial diversity, soil health, and pollutant transformation pathways remain underexplored in the region.

2.5 Microbial Dynamics in Petroleum Degradation

Hydrocarbon degradation in soil typically involves a microbial succession process, beginning with rapidly growing opportunistic species and followed by slower, more specialized degraders. Over 200 bacterial genera, including *Pseudomonas*, *Bacillus*, *Acinetobacter*, and *Rhodococcus*, have been implicated in petroleum biodegradation (Atlas, 1981; Zobel, 1973). Fungal species such as *Aspergillus* and *Penicillium* also contribute, particularly in organic-rich or slightly acidic soils (Rahman et al., 2003).

The microbial response to nutrient amendment varies based on both the nitrogen source and the physicochemical characteristics of the contaminated site. In soils with low cation-exchange capacities, such as sandy loams common in the Niger Delta, ammonium may be lost more quickly than nitrate or organic nitrogen, affecting nutrient availability (Jackson & Pardue, 1999). Therefore, assessing both microbial activity and soil nutrient dynamics under different treatments is essential to determine the most effective bioremediation strategy.

MATERIALS AND METHODS

3.1 Study Area Description

The study focused on three oil spill-impacted communities in the Niger Delta region of Nigeria: Batan and Ajuju in Bayelsa State and Umusia in Oyigbo LGA of Rivers State. The Niger Delta is a low-lying, wetland-rich area situated between latitudes 4°N and 6°N and longitudes 5°E and 8°E. The region experiences high annual rainfall ranging from 2,000 mm to 3,800 mm, with relative humidity between 80% and 90% and mean annual temperature around 25°C. These climatic conditions contribute to frequent flooding and high organic matter accumulation, but also pose challenges for petroleum hydrocarbon degradation due to nutrient depletion, poor aeration, and acidification.

The soils in the selected communities were predominantly sandy loam and sandy clay loam, with acidic pH and low cation exchange capacities (CEC). These characteristics affect nutrient retention, microbial proliferation, and hydrocarbon mobility, making them suitable for evaluating bioremediation interventions under challenging field conditions.

3.2 Soil Sampling and Pre-treatment

A stratified random sampling technique was used to select representative plots from each of the three oil-contaminated communities. Each site was divided into three sections to act as biological replicates. Composite soil samples were collected at a depth of 0-15 cm using a soil auger and were air-dried, sieved, and stored in sterile containers.

Baseline analyses were conducted to determine:

- Soil texture (via Bouyoucos hydrometer method)
- Soil pH (1:1 soil-water ratio using a glass electrode pH meter)
- Total organic carbon (Walkley-Black method)
- Total nitrogen (Kjeldahl method)
- Ammonium and nitrate nitrogen (colorimetric and ion-selective electrode methods)
- Total phosphorus (persulfate digestion and photometric analysis)
- Hydrocarbon content (TPH and PAH via GC-MS and gravimetry)
- Microbial counts (total heterotrophic and hydrocarbon-degrading bacteria using colony forming units [CFUs])

Meteorological and environmental data, including rainfall, temperature, and humidity, were obtained from the Nigerian Meteorological Agency.

3.3 Experimental Design and Simulation Setup

A mesocosm experiment was conducted under controlled outdoor conditions in Enugu, Southeast Nigeria. This location was chosen for logistical reasons and regional security concerns. The study simulated real-world oil spill conditions using intentionally contaminated soils.

A 4×3 factorial randomized complete block design (RCBD) with three replicates was employed. The two main factors were:

- Nitrogen source (4 levels):
 - N0 = No nutrient amendment (control)
 - N1 = Potassium Nitrate (KNO_3)
 - N2 = Ammonium Sulfate ($(\text{NH}_4)_2\text{SO}_4$)
 - N3 = Organic fertilizer (biosolids)
- Oil contamination level (3 levels):
 - P0 = No oil (control)
 - P1 = 20 g/kg of soil (moderate contamination)
 - P2 = 80 g/kg of soil (severe contamination)

A total of 12 treatment combinations were established (table 1), with 3 replicates each, totaling 36 experimental plots.

Table 1: Treatment Combinations

Concentration of oil spill	Levels of Nutrients			
	N0	N1	N2	N3
P0	N0P0	N1P0	N2P0	N3P0
P1	N0P1	N1P1	N2P1	N3P1
P2	N0P2	N1P2	N2P2	N3P2

N0P0 = No nutrient amendment and no oil spilled/released

N0P1 = No nutrient amendment and 20 gm/kg of oil released

N0P2 = No nutrient amendment and 80 gm / kg oil released

N1P0 = Amendment with KNO₃ and no oil spilled/released

N1P1 = Amendment with KNO₃ and 20 gm/kg oil spilled/released

N1P2 = Amendment with KNO₃ and 80 gm/kg oil spilled/released

N2P0 = Amendment with (NH₄)₂SO₄ and no oil spilled/released

N2P1 = Amendment with (NH₄)₂SO₄ and 20 gm/kg oil spilled/released

N2P2 = Amendment with (NH₄)₂SO₄ and 80 gm/kg oil spilled/released

N3P0 = Amendment with Organic fertilizer and no oil spilled/released

N3P1 = Amendment with Organic fertilizer and 20 gm/kg oil spilled/released

N3P2 = Amendment with Organic fertilizer and 80 gm/kg oil spilled/released

3.4 Treatment Application and Monitoring

Each treatment plot was artificially contaminated with refined petroleum diesel (AGO) to simulate oil spills. One week after contamination, nitrogen sources were applied based on their nitrogen equivalency.

- Inorganic fertilizers (N1 and N2) were dissolved and applied via spraying.
- Organic biosolids (N3) were analyzed for nitrogen content prior to application to ensure dosing equivalence.

- Nutrient amendments were monitored to ensure uniform distribution and avoid nutrient losses from leaching or volatilization.

Soil samples were collected on Days 0, 7, 49, and 108 post-treatment to assess changes in:

- Total nitrogen (%)
- Microbial population (log CFUs)
- Total petroleum hydrocarbons (TPH, mg/kg)
- Polyaromatic hydrocarbons (PAH, %)

3.5 Laboratory Analysis

- Microbial Enumeration: Performed using plate count methods and expressed as logarithmic CFUs/g soil. Selective media were used for total heterotrophs and hydrocarbon-degrading bacteria.
- Hydrocarbon Analysis: TPH was determined via gravimetric techniques, while PAH fractions were quantified using gas chromatography-mass spectrometry (GC-MS) in accordance with USEPA protocols.
- Nitrogen Concentration: Total N, NH_4^+ , and NO_3^- levels were measured using Kjeldahl digestion, salicylate-hypochlorite colorimetry, and nitrate-specific electrodes respectively.

3.6 Statistical Analysis

Data were statistically analyzed using SPSS (v22) and ANOVA to determine significant differences among treatment means. Fisher's Least Significant Difference (FLSD) test at $P \leq 0.05$ was used for post-hoc comparisons.

Regression and correlation analyses were performed to determine the relationships between:

- Nitrogen concentration (independent variable) and
 - Microbial population
 - TPH
 - PAH

This analysis provided insight into the biostimulatory effectiveness of each nitrogen source.

RESULTS AND DISCUSSIONS

4.1 Baseline Soil Characteristics

The physicochemical analysis of soils from Batan, Ajuju, and Umusia (table 2) revealed that all three locations had acidic soils (pH 4.5–4.7), low organic carbon (<2%), and low total nitrogen (<0.05%), consistent with typical post-spill tropical soils. Soils were either sandy loam or sandy clay loam, indicating

low cation exchange capacity and a high likelihood of nutrient leaching. These properties justify the need for nutrient amendment to stimulate microbial degradation of petroleum hydrocarbons.

Table 2: Initial Physicochemical Properties of Soils from Selected Sites

Property	Batan	Ajuju	Umusia
pH (1:1 soil:water)	4.61	4.55	4.70
Texture	Sandy Loam	Sandy Clay Loam	Sandy Loam
Organic Carbon (%)	1.81	1.57	1.43
Total Nitrogen (%)	0.045	0.038	0.042
Available Phosphorus (mg/kg)	7.4	6.1	6.8

4.2 Effects of Nitrogen Amendment on Total Nitrogen Content

Across all oil concentrations (P0, P1, P2), total nitrogen content (%) increased in amended soils relative to the unamended control (N0). The highest total nitrogen values were recorded in soils treated with organic nitrogen (N3), especially after 49 and 108 days, suggesting gradual release and sustained nutrient availability (table 3).

- In P2 (80 g/kg) plots, total N in N3 rose from 0.062% on Day 0 to 0.110% by Day 108.
- N2 (ammonium) and N1 (nitrate) treatments showed sharp early increases but began plateauing by Day 49.

Table 3: Total Nitrogen (%) Over Time in Soils Treated with Different Nitrogen Sources (P2 Level)

Treatment	Day 0	Day 7	Day 49	Day 108
N0 (Control)	0.045	0.048	0.051	0.053
N1 (Nitrate)	0.045	0.072	0.084	0.089
N2 (Ammonium)	0.045	0.080	0.092	0.098
N3 (Organic)	0.045	0.077	0.101	0.110

This confirms literature assertions that organic sources provide long-term nutrient support (Singh et al., 2007; Das & Chandran, 2011), while inorganic sources may be prone to leaching or volatilization in acidic soils.

4.3 Microbial Population Dynamics

Microbial counts (expressed in log CFUs/g) showed significant increases in all amended plots compared to control, with organic nitrogen (N3) again producing the highest microbial stimulation as illustrated in table 4 and figure 1 below.

Table 4: Microbial Population (log CFUs/g) Over Time at P2 Level

Treatment	Day 0	Day 7	Day 49	Day 108
N0 (Control)	5.52	5.67	5.80	5.94
N1 (Nitrate)	5.81	5.96	6.09	6.22
N2 (Ammonium)	6.15	6.30	6.43	6.56
N3 (Organic)	6.33	6.48	6.61	6.74

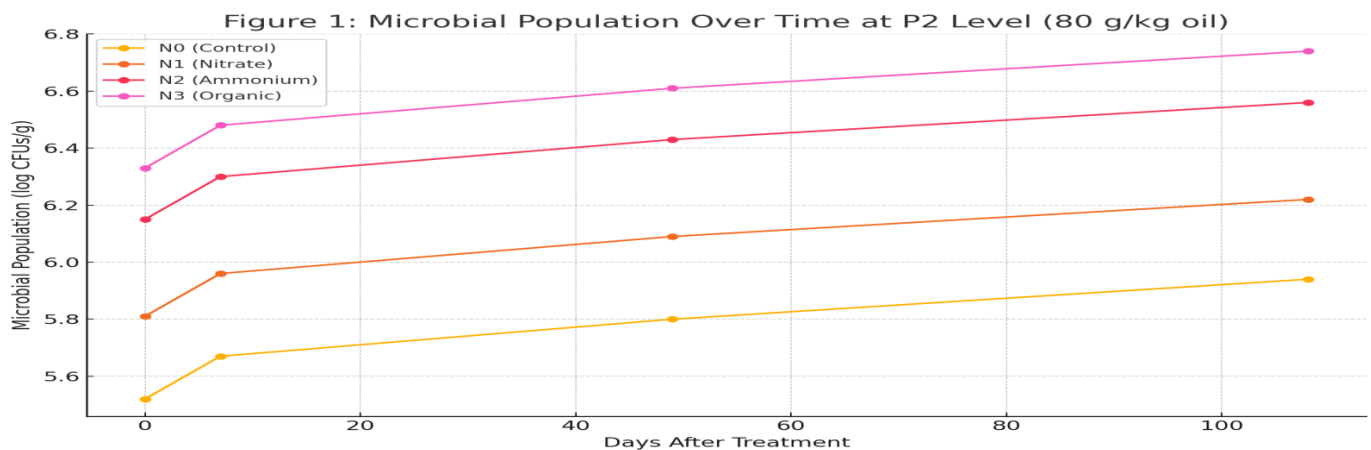


Figure 1: Microbial Population Over Time at P2 Level

- On Day 108, microbial population in N3 reached 6.74 log CFUs/g, compared to 5.94 log CFUs/g in N0.
- N2 (ammonium) followed closely with 6.56 log CFUs/g, while nitrate (N1) peaked at 6.22.

These results affirm that nitrogen availability, especially from organic sources, enhances indigenous microbial proliferation, a key driver of hydrocarbon biodegradation (Atlas & Bartha, 1973; Rahman et al., 2003).

4.4 TPH Degradation Performance

Total Petroleum Hydrocarbon (TPH) concentration decreased steadily over the 108-day period in all amended plots, particularly in soils treated with ammonium and organic nitrogen. This is illustrated in table 5 and figure 2 below.

Table 5: Total Petroleum Hydrocarbon (TPH) Concentration (mg/kg) Over Time at P2 Level

Treatment	Day 0	Day 7	Day 49	Day 108
N0 (Control)	18.81	18.00	17.19	17.11
N1 (Nitrate)	17.76	17.00	16.24	16.07
N2 (Ammonium)	16.77	16.05	15.33	15.08
N3 (Organic)	15.83	15.15	14.47	14.14

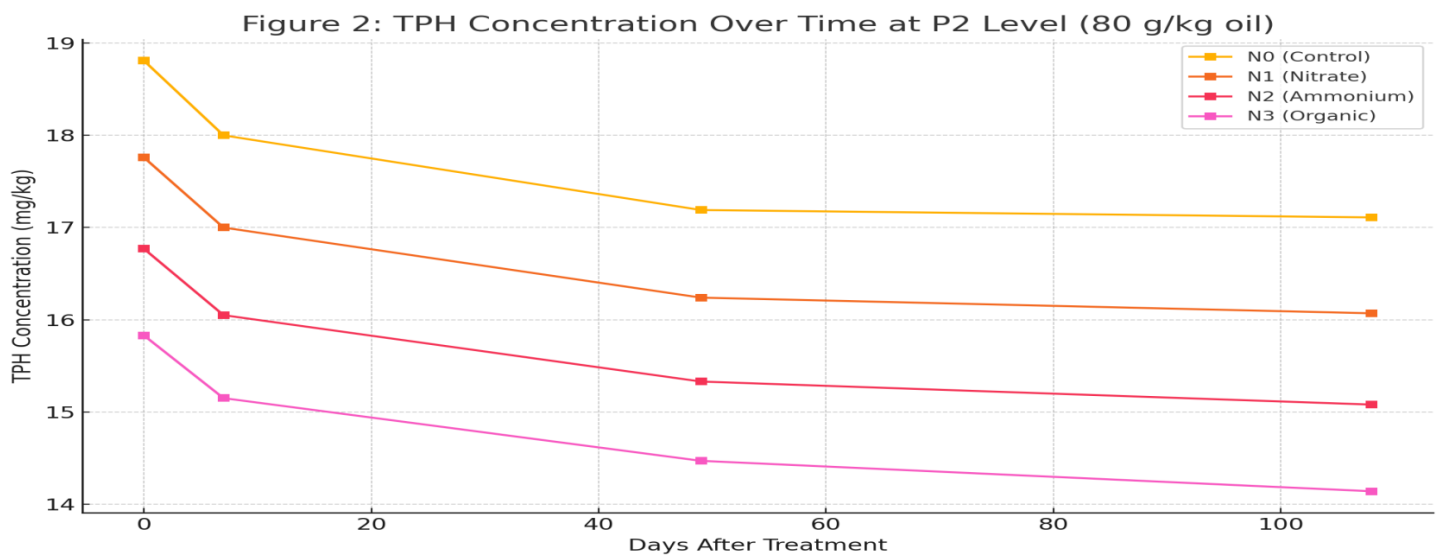


Figure 2: TPH Concentration Over Time at P2 Level

- N3 reduced TPH from 15.83 mg/kg (Day 0) to 14.14 mg/kg (Day 108).
- N2 followed with a final TPH of 15.08 mg/kg, while the control (N0) showed minimal reduction (17.11 mg/kg at Day 108).

The faster reduction in N2 (ammonium-treated) soils suggests rapid microbial response due to bioavailable nitrogen, consistent with other tropical soil studies (Roling & van Bodegom, 2014; Bento et al., 2005).

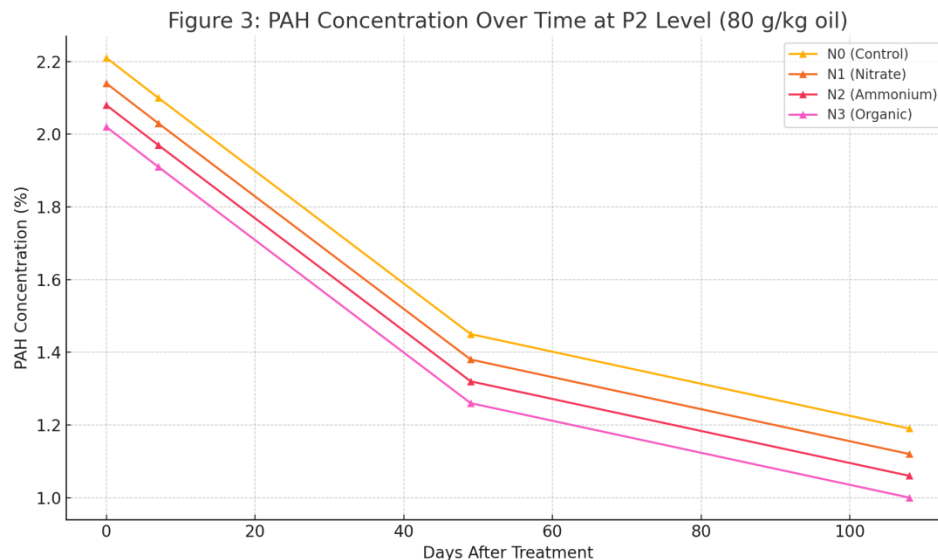
4.5 PAH Degradation

PAH degradation data visualization is shown in figure 3 below. As illustrated in table 6 and figure 3, PAH concentrations decreased steadily across all treatments. Organic nitrogen (N3) demonstrated the most consistent reduction, reaching 1.00% by Day 108, compared to 1.06% for ammonium (N2), 1.12% for nitrate (N1), and 1.19% for the control (N0). These trends reflect a strong response to nutrient-stimulated microbial activity

Table 6: PAH Concentration (%) Over Time at P2 Level

Treatment	Day 0	Day 7	Day 49	Day 108
N0 (Control)	2.21	2.10	1.45	1.19
N1 (Nitrate)	2.14	2.03	1.38	1.12
N2 (Ammonium)	2.08	1.97	1.32	1.06
N3 (Organic)	2.02	1.91	1.26	1.00

Figure 3: PAH Concentration Over Time at P2 Level (80 g/kg oil)



These trends are in line with other findings where nitrogen supports microbial catabolism of PAHs, particularly those with medium molecular weight fractions (Das & Chandran, 2011).

4.6 Regression and Correlation Analysis

Regression analysis demonstrated strong positive correlations between nitrogen concentration and microbial proliferation (see table 7 below):

Table 7: Regression Models Between Nitrogen Concentration and Microbial Population at P2 Level

Treatment	Regression Equation	r-value	Slope (b)	Interpretation
N3P2	$Y = 1.28x + 6.21$	0.93	1.28	Strong effect of organic N
N2P2	$Y = 0.61x + 5.86$	0.96	0.61	Highest correlation

N1P2	$Y = 0.38x + 5.58$	0.95	0.38	Moderate stimulation
N0P2	$Y = 0.21x + 5.46$	0.90	0.21	Weakest effect

These results support the hypothesis that organic nitrogen is most effective in enhancing microbial populations, although ammonium accelerates hydrocarbon reduction more effectively. Therefore, the choice of nitrogen source may depend on whether the remediation goal is long-term soil fertility recovery (organic) or rapid hydrocarbon breakdown (ammonium).

INTEGRATED DISCUSSION

This study reveals that nutrient amendment is vital to effective bioremediation in oil-impacted soils of the Niger Delta. Inorganic nitrogen (especially ammonium) enabled fast-acting hydrocarbon degradation, while organic nitrogen supported superior microbial proliferation and more stable nitrogen profiles over time.

Our findings support the conclusions of Salanitro et al. (1997), who demonstrated that nitrogen availability significantly enhances microbial degradation of hydrocarbons in contaminated soils. These findings also align with those of Macaulay (2015), who concluded that a combination of fast-release and slow-release nitrogen sources may provide the best outcomes in complex contaminated environments. Moreover, the use of indigenous microbial populations without bioaugmentation further supports biostimulation as a sustainable remediation option in rural and resource-limited settings.

CONCLUSION

This study comprehensively examined the comparative effectiveness of three nitrogen sources-ammonium (NH_4^+), nitrate (NO_3^-), and organic nitrogen-in enhancing the bioremediation of petroleum-contaminated soils in Nigeria's Niger Delta region. Through a mesocosm simulation mimicking real-world oil spill conditions, it was shown that nitrogen supplementation significantly improved microbial proliferation, total nitrogen content, and the degradation of total petroleum hydrocarbons (TPH) and polyaromatic hydrocarbons (PAH). Such outcomes reinforce the potential to incorporate microbial and hydrocarbon parameters into broader ecological quality frameworks (Römbke et al., 2005).

Among the nitrogen treatments:

- Ammonium nitrogen proved most effective in rapid hydrocarbon degradation, due to its immediate bioavailability to microorganisms.
- Organic nitrogen, while slower in action, supported the highest microbial population growth and long-term nutrient sustainability, likely due to its gradual nutrient release and improved soil organic matter content.
- Nitrate nitrogen was moderately effective but less stable under the acidic, leaching-prone soil conditions characteristic of the Niger Delta.

Regression and correlation analyses revealed a strong positive relationship between nitrogen concentration

and microbial activity, especially in the organic nitrogen-amended plots ($r = 0.93-0.96$). These findings reaffirm the critical role of nutrient limitation in controlling the efficacy of bioremediation and highlight the importance of site-specific selection of nutrient sources.

Overall, the study demonstrates that biostimulation using nitrogen amendment is a viable, low-cost, and ecologically sound strategy for oil spill remediation in tropical wetland environments. Moreover, the results advocate for integrated remediation approaches that balance short-term contaminant reduction with long-term ecological recovery.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

1. Adopt site-specific nutrient amendment strategies:

Soil type, oil concentration, and environmental conditions should guide the selection of nitrogen sources. Ammonium nitrogen may be suitable for rapid clean-up efforts, while organic nitrogen is better for sustained soil health recovery.

2. Combine nitrogen sources for synergistic effects:

A blend of fast-acting (e.g., ammonium sulfate) and slow-release (e.g., compost or biosolids) nitrogen may optimize both biodegradation efficiency and long-term microbial stability.

3. Promote the use of indigenous microbial populations:

Bioaugmentation may not be necessary in all cases, especially where indigenous degraders respond positively to nutrient enrichment. Further profiling of native microbes is encouraged to enhance biostimulation protocols.

4. Implement field-scale trials:

The mesocosm results should be validated through in-situ trials in various Niger Delta environments, including swampy, flood-prone, and upland zones, to evaluate operational feasibility.

5. Integrate bioremediation into environmental policy and spill response plans:

National agencies and oil operators should consider biostimulation protocols as part of approved remediation frameworks, especially for low-income rural communities affected by chronic oil pollution.

6. Monitor long-term soil recovery:

In addition to contaminant removal, future studies should monitor changes in soil fertility, structure, and microbial diversity post-remediation to assess ecological resilience.

7. Evaluate nutrient interactions:

Subsequent research should investigate the role of phosphorus, potassium, and micronutrients in combination with nitrogen to develop more holistic nutrient amendment formulations.

By addressing both scientific and implementation challenges, these recommendations aim to improve the sustainability and effectiveness of bioremediation strategies for petroleum pollution in the Niger Delta and similar tropical regions.

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