



Development and Performance Evaluation of Indigenous Bioresource-Based Solid Biostimulant Technology for Petroleum Hydrocarbon Pollution Remediation in Bayelsa.

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ABSTRACT

Petroleum hydrocarbon contamination remains a significant environmental challenge in the Niger Delta, particularly in Bayelsa State, where recurrent oil spills, artisanal refining activities, and other anthropogenic disturbances have severely degraded soil quality and ecosystem health. In this study, an indigenous bioresource-based solid biostimulant for the remediation of hydrocarbon-contaminated soils was developed and evaluated. The biostimulant was formulated from locally sourced materials, including blended invasive aquatic plant biomass, and enriched with plant-derived biopolymers to enhance nutrient availability, improve soil structure, and stimulate microbial activity. The formulated product was characterized for its physicochemical properties and applied to hydrocarbon-contaminated soils collected from artisanal refining sites with Total Petroleum Hydrocarbon (TPH) concentrations ranging from 7,000 to 15,000 mg/kg. Remediation experiments were conducted under controlled conditions, and treatment performance was assessed through TPH quantification and gas chromatographic analysis of hydrocarbon fractions. The results demonstrated that the biostimulant significantly enhanced hydrocarbon degradation within three weeks compared with untreated controls, indicating effective stimulation of indigenous microbial communities. Petroleum hydrocarbon concentrations decreased substantially across all measured fractions, with most hydrocarbon homologous series exhibiting reductions exceeding 80% and a maximum reduction of 99.25%. TPH reduction ranged from 48% to 82%, corresponding to an average degradation efficiency of approximately 67%. Although residual TPH concentrations (3,709 mg/kg) remained above the target background threshold of 50 mg/kg, they were reduced below the intervention threshold of 5,000 mg/kg. These findings demonstrate the strong potential of locally derived, environmentally friendly biostimulant technologies as cost-effective and sustainable solutions for the remediation of petroleum hydrocarbon-contaminated soils in the Niger Delta.

Keywords: Bioresource-based biostimulant; Petroleum hydrocarbon; Bioremediation; Niger Delta; Circular bioeconomy, Biotechnology

Introduction

Petroleum pollution in Nigeria's oil-rich regions remains a persistent and complex environmental challenge, driven by decades of intensive exploration and production. The problem is further intensified by recurrent pipeline failures, crude oil spills, illegal bunkering, and artisanal refining, resulting in widespread contamination of soils, sediments, and water bodies. Petroleum hydrocarbons, composed of diverse aliphatic and aromatic fractions, are highly recalcitrant, toxic, and environmentally persistent, with significant implications for ecosystem integrity, agricultural productivity, and human health (Nestor et al., 2025 a and b; UNEP, 2011; Ite et al., 2013; Ogri, 2001).

The ecological vulnerability of Bayelsa State, defined by wetlands, mangrove forests, and interconnected creek systems, amplifies the dispersion and persistence of these pollutants. In soils, hydrocarbon contamination alters physicochemical properties, disrupts microbial communities, and impairs nutrient cycling, leading to reduced fertility and crop yields. In aquatic systems, it degrades water quality, threatens biodiversity, and promotes bioaccumulation and biomagnification across trophic levels. These impacts highlight the urgent need for effective, sustainable, and locally adaptable remediation strategies.

Despite extensive research, current bioremediation approaches in the Niger Delta remain fragmented and inadequately translated into scalable applications. Most studies focused on isolated microbial processes or conventional amendments, with limited integration into standardized, performance-driven biostimulant systems (Okerhi-Damisa & Izewbekhai, 2026; Ajayi et al., 2025; Nkereuwm et al., 2022; Ekpensi et al., 2020; Musa et al., 2020; Adekunle et al., 2020; Adekunle et al., 2017a and b; Ijah et al., 2017; Chikere et al., 2017; Adams et al., 2015; Ite et al., 2013; Adekunle et al., 2013; Adekunle et al., 2012 a to d; Kadafa, 2012; UNEP, 2011; Atlas 2011; Adekunle et al., 2009). Gaps persist in formulation optimization, product stability, dosage, shelf-life, and field validation, alongside insufficient exploration of synergistic interactions between indigenous bioresources and native microbial consortia. Moreover, existing remediation strategies are often poorly tailored to the unique ecological and edaphic conditions of Bayelsa State, limiting their effectiveness and adoption. High costs, limited accessibility, and operational constraints further restrict deployment, particularly in rural communities. At the same time, opportunities for waste-to-resource innovation such as the valorization of invasive aquatic species remain underutilized.

Against this backdrop, the development of an indigenous bioresource-based solid biostimulant technology represents a strategic and innovative intervention. By harnessing locally available biomass, particularly invasive aquatic plants, this approach enables the production of solid-phase amendments that enhance nutrient availability, improve soil structure, and stimulate microbial activity. Such systems not only accelerate hydrocarbon degradation but also support circular bioeconomy principles through resource valorization. This study was therefore designed to develop and evaluate a solid-phase biostimulant product formulated from blended invasive aquatic species sourced from Bayelsa waterways. It seeks to advance petroleum hydrocarbon remediation by integrating microbial efficiency, material innovation, and field applicability, while contributing to sustainable environmental restoration and livelihood support in the Niger Delta.

Materials And Methods

Blended invasive aquatic species harvested from Bayelsa waterways were processed into a petroleum hydrocarbon-degrading product using locally developed biotechnology. Plant-based biopolymers and biocatalysts were incorporated as functional additives to enhance performance. The resulting solid product was characterized for pH, electrical conductivity, and salinity, followed by maturation and curing. The biostimulant was applied to petroleum-impacted soils collected from artisanal refining sites in Bayelsa State at a soil-to-product ratio of 80:20 (v/v). A total of thirty-six (36) soil systems were established, comprising control soils from non-impacted environments, polluted soils from artisanal refining sites (PPS), and treated soils designated as eco-smart remediation systems (ERS).

Each treatment was replicated four times ($n = 4$). Composite soil samples were collected weekly for three weeks and analyzed for soil health indicators, including pH, electrical conductivity, and salinity, using standard methods reported by Isaac & Adekunle (2019). Baseline characterization of contaminated soils was conducted in certified laboratories in Port Harcourt. Total petroleum hydrocarbons (TPH) were determined using gas

chromatography-mass spectrometry (GC-MS), complemented by gas chromatography with flame ionization detection (GC-FID).

Results

Characteristics of the Formulated Bioresource-based Solid BioStimulant

The formulated bioresource-based solid biostimulant was characterized in terms of pH, electrical conductivity (EC), and salinity. The mean pH of the product was 8.44 ± 0.18 , indicating a mildly alkaline nature. This suggests that the biostimulant may exert a buffering or liming effect on acidic soil systems, such as those commonly found in Bayelsa State (Isaac and Adekunle, 2019), thereby improving soil conditions for microbial activity and plant growth. The electrical conductivity (EC) of the product indicated the presence of soluble bioactive components, nutrients, mineral salts, and buffering compounds. Such constituents are essential for enhancing soil biochemical processes. Moderate increases in soil EC can stimulate microbial activity by improving nutrient availability and facilitating microbial metabolism (Adekunle & Isaac, 2019; Adekunle et al., 2013; Adekunle, 2011), which is critical for effective hydrocarbon degradation.

The salinity of the formulated product reflected non-saline conditions. This is particularly important in ensuring that the biostimulant does not induce salt stress in plants or soil biota. Instead, the low-to-moderate ionic strength supports the proliferation and activity of hydrocarbon-degrading microorganisms, which typically thrive under such conditions. Altogether, these physicochemical characteristics indicate that the bioresource-based biostimulant product is well-suited for application in petroleum-contaminated soils. The product is expected to improve osmotic balance, support enzyme function, and enhance microbial metabolic processes involved in hydrocarbon degradation, thereby contributing to efficient and sustainable soil remediation.

Petroleum Hydrocarbon Concentration in Control Soil Environment

The Total Petroleum Hydrocarbon (TPH) concentration of the control soil collected from Otuoke (Golden Food Project Research Facility, Federal University Otuoke, Ogbia Local Government Area, Bayelsa State) was determined to be 27.75 ± 01 mg/kg. This value is below the stipulated background threshold of 50 mg/kg (DPR, 2022), indicating that the control soil was not contaminated, as it was obtained from a location with no known history of artisanal refining or petroleum contamination for at least ten years prior to the study period (2024 to 2025). The gas chromatographic (GC) profile of the control soil sample (Fig. 1) showed a relatively simple hydrocarbon distribution, with only four identifiable homologues. Distinct peaks were observed at n-C20 (1.37 mg/kg), n-C29 (3.11 mg/kg), n-C31 (20.51 mg/kg), and n-C34 (2.75 mg/kg), with the values in parentheses representing their respective TPH concentrations.

This limited hydrocarbon range and low concentration further confirm the relatively unimpacted nature of the control soil. The coexistence of n-C20 with higher homologues indicates a mixed source of both petrogenic (crude oil/diesel) and possible biogenic contributions. As earlier stated, at the time of this study between 2024 and 2025, there was no record of artisanal refining activity in this area since 2011, when the University was established. Based on TPH concentration of 27.75 ± 01 mg/kg for the carbon chains n-C20, n-C29, n-C31, and n-C34, which fell below the background threshold of 50 mg/kg (DPR, 2022); these chains indicate possible biogenic input attributed to terrestrial/mangrove plant wax input rather than petrogenic hydrocarbon inputs.

Pre-remediation Petroleum Hydrocarbon Concentration

The Total Petroleum Hydrocarbon (TPH) concentration of the control soil collected from Otuoke (Golden Food Project Research Facility, Federal University Otuoke, Ogbia Local

Government Area, Bayelsa State) was determined to be 27.75 ± 1.00 mg/kg. This value is below the stipulated background threshold of 50 mg/kg (DPR, 2022), indicating that the control soil was not contaminated. The sampling site had no known history of artisanal refining activities or petroleum contamination for at least ten years prior to the study period (2024 to 2025). The gas chromatographic (GC) profile of the control soil (Fig. 1) revealed a relatively simple hydrocarbon distribution, with only four identifiable n-alkane homologues. Distinct peaks were detected at n-C20 (1.37 mg/kg), n-C29 (3.11 mg/kg), n-C31 (20.51 mg/kg), and n-C34 (2.75 mg/kg), with the values in parentheses representing their respective hydrocarbon concentrations. The limited range of hydrocarbon homologues and the low overall TPH concentration further confirm the relatively unimpacted nature of the control soil.

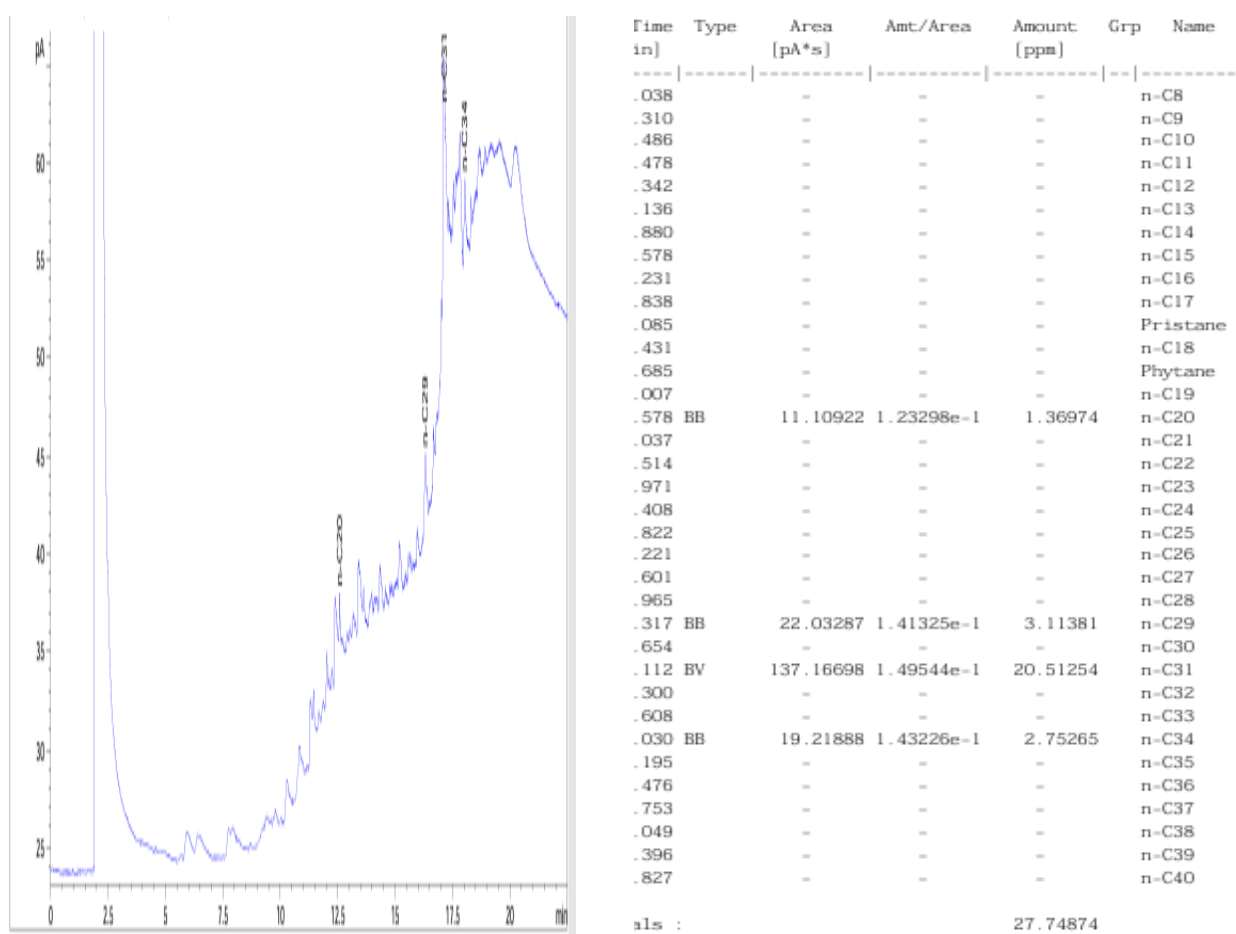


Fig.1: A typical gas chromatogram profile of a control soil sample collected from a site not characterized by artisanal refining activities in Federal University Otuoke, Ogbia, Bayelsa State

The occurrence of n-C20 alongside the higher molecular weight homologues (n-C29, n-C31, and n-C34) suggests a mixed hydrocarbon origin, comprising minor petrogenic contributions and more dominant biogenic inputs. However, considering the absence of documented artisanal refining or petroleum contamination in the study area since the establishment of the Federal University Otuoke in 2011, together with the low TPH concentration (27.75 ± 1.00 mg/kg), which is well below the DPR (2022) background threshold of 50 mg/kg, the detected hydrocarbons are more likely attributable to natural biogenic sources. Specifically, the predominance of the long-chain n-alkanes (n-C29, n-C31, and n-C34) is characteristic of terrestrial vegetation, particularly higher plant and mangrove waxes, rather than fresh petrogenic hydrocarbon contamination.

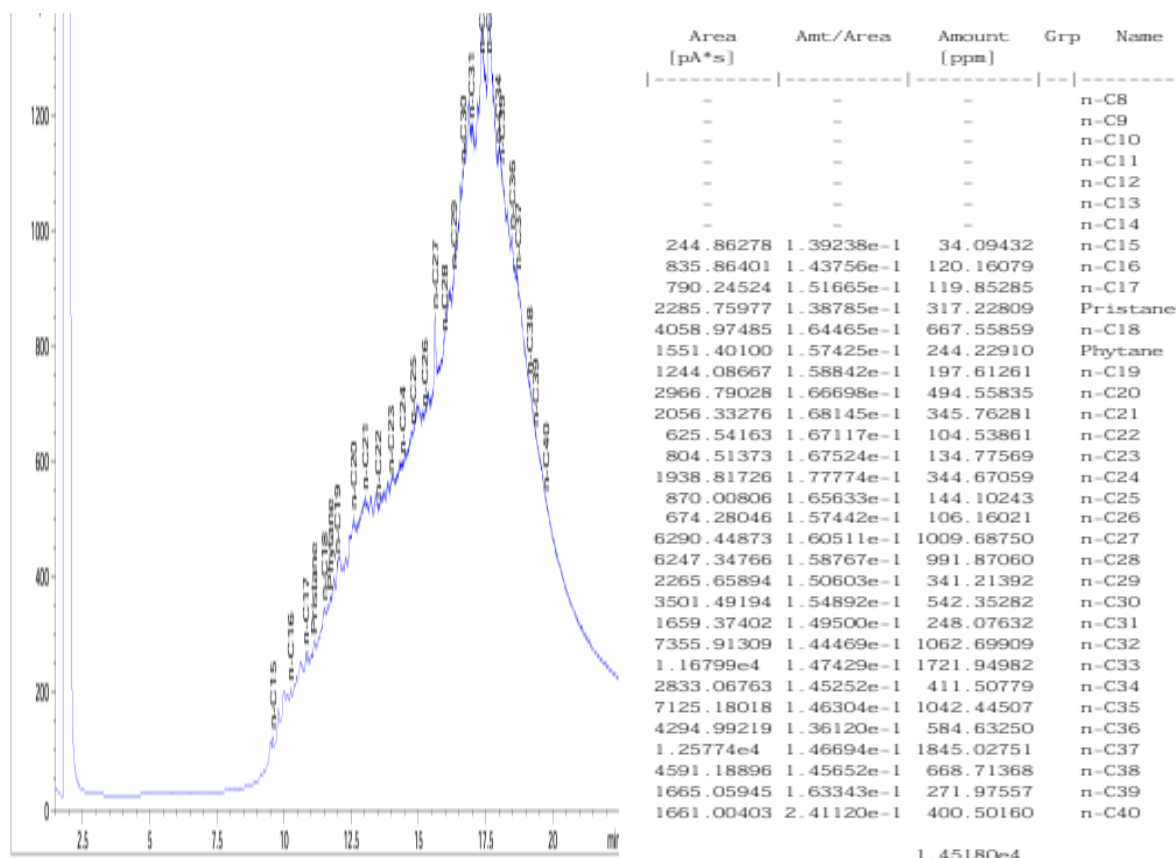


Fig.2: A typical gas chromatogram profile of a test soil sample collected from a site characterized by artisanal refining activities in a location in Southern Ijaw, Bayelsa State

Notably, the absence of hydrocarbons $\leq$ n-C15 indicates that the contamination is not recent but weathered. Lighter fractions are likely depleted through evaporation and microbial degradation, resulting in a chromatographic profile skewed toward heavier n-alkanes (n-C15 to n-C40). This compositional shift has important environmental implications. Lower carbon fractions are generally more toxic and mobile, posing immediate ecological risks, whereas higher molecular weight fractions are more persistent, less bioavailable, and resistant to biodegradation. The predominance of heavier hydrocarbons also reflects their hydrophobic nature, which promotes strong adsorption to soil particles, particularly organic matter and fine fractions. This reduces their mobility but prolongs their residence time in the environment, leading to the formation of chronic pollution hotspots rather than rapid contaminant dispersion. Although these higher fractions are less acutely toxic than lighter hydrocarbons, they can adversely affect soil structure by impairing aeration, reducing water infiltration, and disrupting soil microbial diversity and plant growth. In total, the dominance of n-C15 to n-C40 hydrocarbons indicates weathered petroleum contamination, confirming that the impacted sites are legacy artisanal refining locations, consistent with earlier reports (Nestor et al., 2025 a and b).

Performance of the Applied Bioresource-Based Solid Biostimulant for Petroleum Hydrocarbon Degradation Information from GC Chromatogram

A representative gas chromatographic (GC) profile of the remediated soil system is presented in Fig. 3, with the corresponding hydrocarbon peaks and their TPH concentrations indicated. Comparison of the pre-remediation (Fig. 2) and post-remediation (Fig. 3) chromatograms of the most heavily polluted soil system showed that the hydrocarbon carbon-number range remained essentially unchanged (n-C15 to n-C40) following remediation. However, the

principal difference between the two chromatograms was the marked reduction in the concentrations of the individual hydrocarbon homologues in the remediated soil. This decrease in peak intensities demonstrates that remediation substantially reduced the abundance of petroleum hydrocarbons.

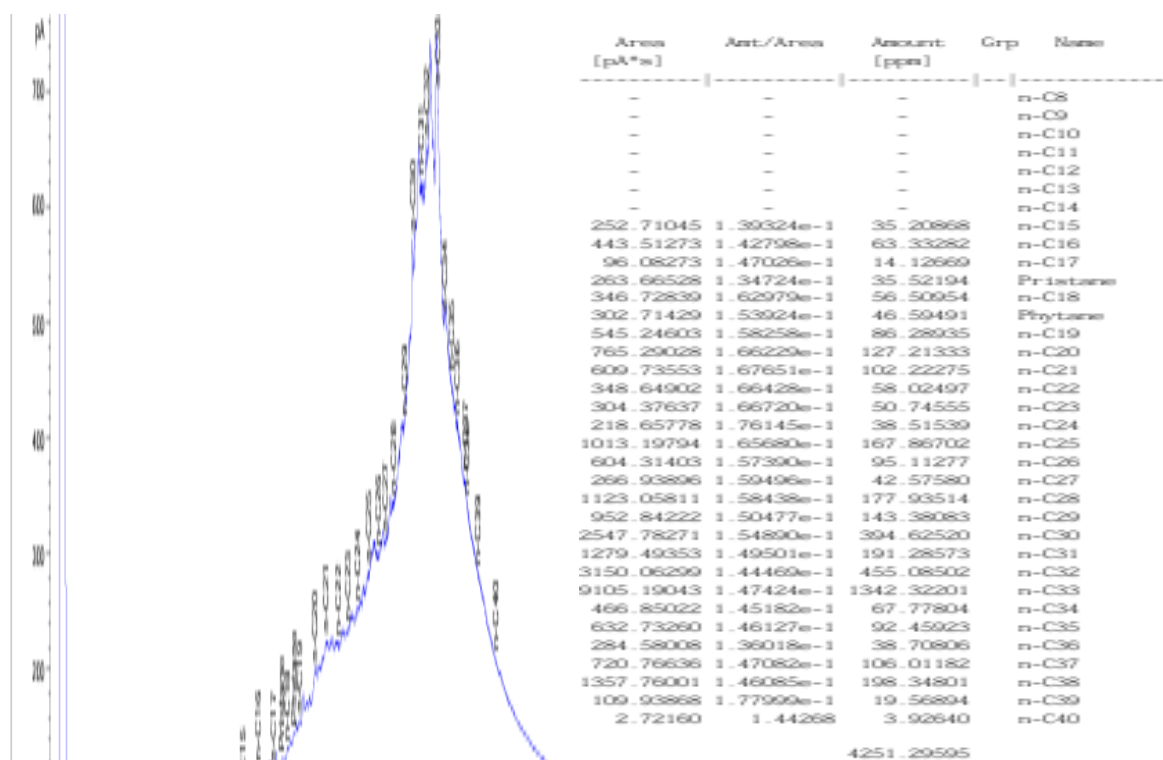


Fig.3: A typical gas chromatogram profile of the soil system after application of the biostimulant product formulated in this study

Degradation of Petroleum Hydrocarbon by the Applied Product

Performance Evaluation of the Applied Bioresource-Based Solid Biostimulant for Petroleum Hydrocarbon Fractions

The remediation process significantly reduced petroleum hydrocarbon concentrations across all measured hydrocarbon fractions (Table 1). Percentage reductions ranged from **57.06% to 99.25%**, demonstrating substantial degradation and removal of hydrocarbons from the contaminated soil. Most hydrocarbon homologues exhibited reductions exceeding **80%**, indicating the high efficiency of the remediation treatment over a broad range of hydrocarbon chain lengths.

Among the individual fractions, **n-C18** recorded a reduction of **91.47%**, while **n-C24** and **n-C28** decreased by **88.66%** and **90.42%**, respectively. Particularly high remediation efficiencies were observed for **n-C27 (95.74%)**, **n-C37 (93.08%)**, **n-C39 (92.65%)**, and **n-C40 (99.25%)**, indicating excellent removal of these hydrocarbon fractions. Notably, **n-C37**, which had the highest initial concentration (**1845 mg/kg**), was reduced to **106 mg/kg** after treatment, representing a **93.08%** reduction. This finding demonstrates that the remediation strategy remained highly effective even under elevated contamination levels. Similarly, **n-C38** exhibited a high reduction efficiency of **83.50%**. The highest remediation efficiency (**99.25%**) was achieved for **n-C40**, indicating near-complete removal of this hydrocarbon fraction. In contrast, **n-C32** showed the lowest reduction (**57.06%**), suggesting greater persistence and resistance to degradation than the other hydrocarbon fractions. This comparatively lower removal efficiency may be attributed to the reduced bioavailability and greater recalcitrance

of certain higher molecular weight hydrocarbons, which are generally less accessible to microbial degradation.

Table 1: Performance Evaluation of the Applied Bioresource-based Solid Biostimulant for Hydrocarbon Chain Fraction

S/N	Hydrocarbon Chain	TPH Before Remediation (mg/kg)	TPH After Remediation (mg/kg)	Percent Reduction (%)
1	n-C18	668	57	91.47
2	n-C20	494	127	74.29
3	n-C24	344	39	88.66
4	n-C27	1009	43	95.74
5	n-C28	992	95	90.42
6	n-C32	1062	456	57.06
7	n-C37	1845	106	93.08
8	n-C38	412	68	83.50
9	n-C39	272	20	92.65
10	n-C40	400	03	99.25

Performance Evaluation of the Applied Bioresource-Based Solid Biostimulant for Total Petroleum Hydrocarbon

The application of the bioresource-based solid biostimulant to the contaminated soils resulted in a substantial reduction in Total Petroleum Hydrocarbon (TPH) concentrations across all four samples within three weeks. As shown in Fig. 4, where PPS represents the polluted soil systems and ERS the remediated systems (Table 2), TPH levels declined markedly following treatment. The overall reduction ranged from 48.46% to 81.50%, with an average degradation efficiency of approximately 67%, demonstrating strong enhancement of petroleum hydrocarbon attenuation. Initial contamination levels confirmed severe pollution, with TPH concentrations ranging from 7,346 mg/kg (PPS01) to 14,518 mg/kg (PPS04), and a mean value of 11,234 mg/kg. These values reflect heavily impacted soils typical of artisanal refining environments. After treatment, concentrations decreased significantly to between 1,359 mg/kg and 5,422 mg/kg, with a reduced mean of 3,709 mg/kg, indicating a mean removal of about 7,526 mg/kg within the treatment period.

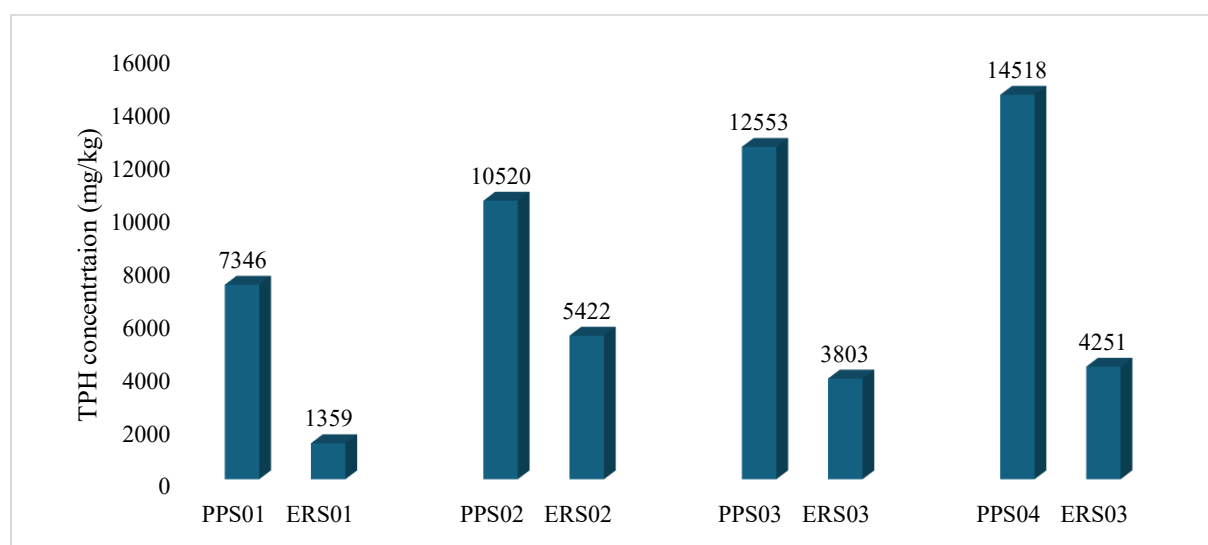


Fig.4: Comparative evaluation of the efficacy of the bioresource-based solid biostimulant across four petroleum-contaminated soil systems

The percentage degradation varied among samples, suggesting the influence of site-specific factors such as soil physicochemical properties, microbial activity, hydrocarbon composition, and nutrient availability. The lower efficiency observed in PPS04 may be associated with more recalcitrant hydrocarbon fractions or less favourable soil conditions. In all, the reduction from highly contaminated levels ($>10,000$ mg/kg) to substantially lower concentrations demonstrates meaningful progress toward soil recovery, although further treatment would be required to meet regulatory standards. These results highlight the effectiveness of locally sourced biostimulants as a cost-effective and sustainable approach for remediating petroleum-contaminated soils in the Niger Delta. A comparative overview against intervention and control values is presented in Fig. 5.

Table 2: Percent Petroleum Hydrocarbon Degradation by our Bioresource-based biostimulant product

S/N	Sample Code	TPH Before Remediation (mg/kg) (a)	Sample Code	TPH After 3 weeks of Remediation (mg/kg) (b)	TPH Removed (mg/kg) (a-b)	%TPH Degraded
1	PPS01	7,346 $\pm$ 02	ERS01	1,359 $\pm$ 02	5,987	82
2	PPS02	10,520 $\pm$ 05	ERS02	5,422 $\pm$ 05	5,098	48
2	PPS03	12,553 $\pm$ 05	ERS03	3,803 $\pm$ 05	8,750	70
4	PPS04	14,518 $\pm$ 03	ERS04	4,251 $\pm$ 03	10,267	71
Mean		11,234	Mean	3709	7525	67
Deviation		3063	Deviation	1709	2370	14
Minimum		7346	Minimum	1359	5098	48
Maximum		14518	Maximum	5422	10267	82

PPS = Petroleum Polluted Soil, ERS = Eco-Smart Remediated Soil

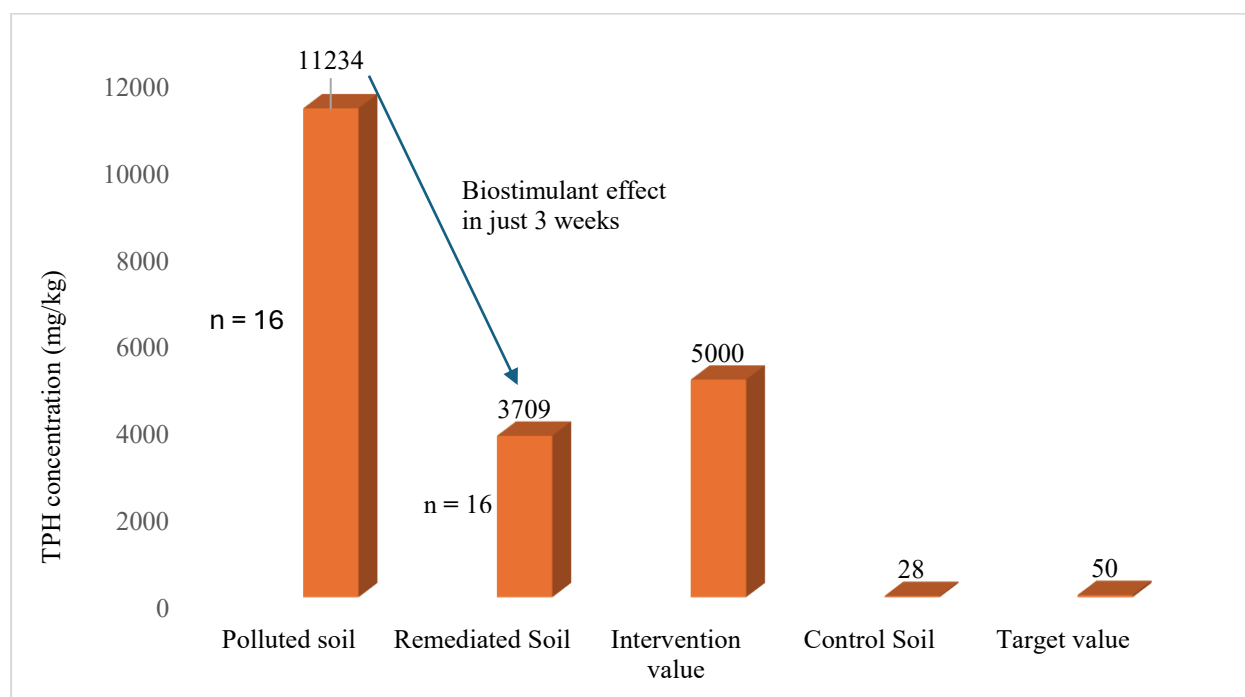


Fig.5: Efficacy of the bioresource-based solid biostimulant across petroleum-contaminated soil system in relation to established regulatory standards and background soil systems

Effect of Application on Soil Restoration

The graph (Fig.6) is an illustration of the effect of the applied bioresource-based biostimulant on plant height over three weeks (WK01-WK03) in soils with different levels of petroleum hydrocarbon contamination. The treatments include the uncontaminated background soil (28 mg/kg TPH), polluted soils (PPS), and remediated soils (ERS) with increasing initial TPH concentrations. Plant height increased progressively from Week 1 to Week 3 across all treatments, indicating that the bioresource-based biostimulant promoted continuous plant growth regardless of the contamination level. However, the magnitude of growth varied depending on the degree of soil contamination and remediation status.

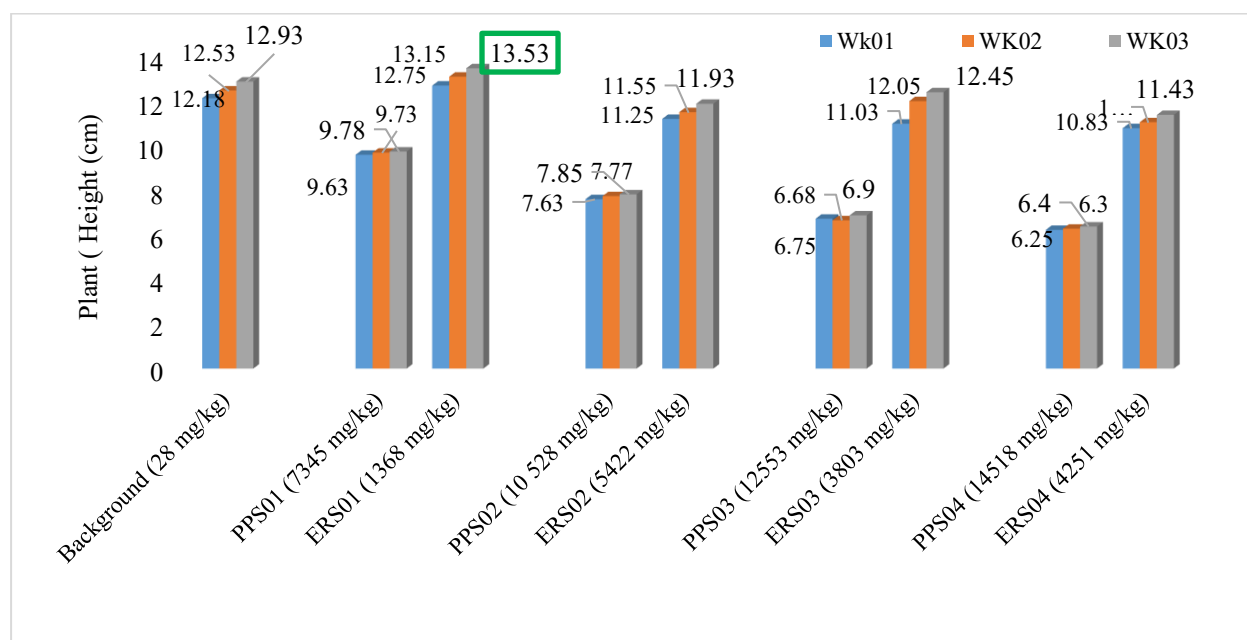


Fig.6a: Growth performance of crops in polluted soils against remediated soils and background soil, with TPH concentration in parenthesis

The **background (control) soil** consistently recorded high plant heights, increasing from **12.18 cm in Week 1 to 12.93 cm in Week 3**. This reflects normal growth under uncontaminated soil conditions and serves as the benchmark for evaluating the effectiveness of the biostimulant in contaminated soils. Among the remediated soils (ERS), ERS01 (1368 mg/kg TPH) produced the greatest plant growth throughout the study, with plant height increasing from 12.75 cm to 13.53 cm between Week 1 and Week 3. Remarkably, the Week 3 plant height (13.53 cm) exceeded that of the background soil (12.93 cm), suggesting that the bioresource-based biostimulant not only alleviated the adverse effects of petroleum contamination but also enhanced plant growth beyond the control. This superior performance may be attributed to improved nutrient availability, enhanced microbial activity, and stimulation of root development following remediation. The other remediated treatments also showed substantial growth improvements. ERS02 (5422 mg/kg) increased from 11.25 cm to 11.93 cm, ERS03 (3803 mg/kg) from 11.03 cm to 12.45 cm, and ERS04 (4251 mg/kg) from 10.83 cm to 11.43 cm over the three-week period. Although these values remained below those of the control and ERS01, they demonstrate that the biostimulant effectively supported plant growth even in soils with relatively high petroleum hydrocarbon concentrations.

In contrast, the polluted (unremediated) soils (PPS) consistently recorded the lowest plant heights. PPS01 (7345 mg/kg) increased only slightly from 9.63 cm to 9.73 cm, PPS02 (10,528 mg/kg) from 7.63 cm to 7.77 cm, PPS03 (12,553 mg/kg) from 6.75 cm to 6.90 cm, and PPS04 (14,518 mg/kg) from 6.25 cm to 6.30 cm. The limited growth observed in these treatments

indicates that petroleum hydrocarbon contamination severely inhibited plant development, even though minor increases occurred over time. A clear inverse relationship exists between petroleum hydrocarbon concentration and plant growth in the polluted soils. As TPH concentration increased from 7,345 mg/kg (PPS01) to 14,518 mg/kg (PPS04), plant height progressively declined, demonstrating the phytotoxic effects of increasing hydrocarbon contamination. Petroleum hydrocarbons are known to impair seed germination, inhibit root elongation, reduce nutrient uptake, and interfere with photosynthesis, thereby suppressing overall plant growth.

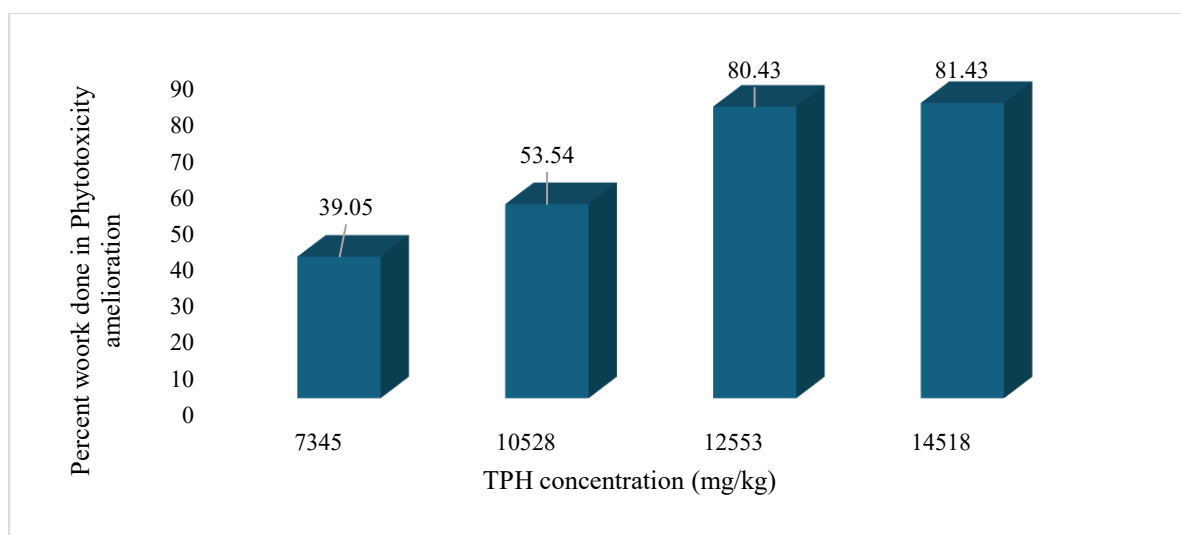


Fig.6b: Amelioration effect of the applied Eco-smart remediation tech on phytotoxicity

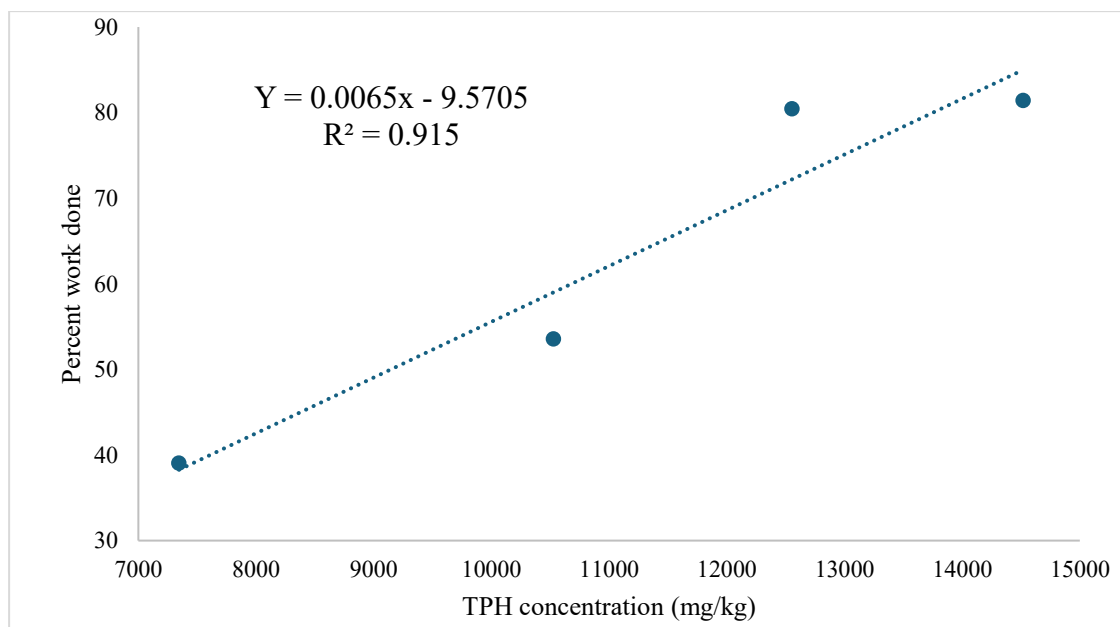


Fig.6c: Influence of the applied Eco-smart remediation tech on phytotoxicity amelioration

Comparison of the polluted and remediated soils at corresponding contamination levels clearly demonstrates the effectiveness of the bioresource-based biostimulant. For example, plants grown in ERS03 (3803 mg/kg) attained 12.45 cm by Week 3, compared with only 6.90 cm in the more heavily contaminated PPS03 (12,553 mg/kg). Similarly, ERS04 (11.43 cm) substantially outperformed PPS04 (6.30 cm). These differences indicate that remediation combined with biostimulant application significantly improved soil quality and restored

conditions favorable for plant growth. The results demonstrate that the applied bioresource-based biostimulant effectively enhanced plant growth by mitigating the adverse effects of petroleum hydrocarbon contamination. Plant height increased consistently over the three-week period in all treatments, but growth was markedly greater in the remediated soils than in the untreated polluted soils. The exceptional performance of ERS01, which exceeded even the uncontaminated control, suggests that the biostimulant not only restored soil fertility but also stimulated plant growth through improved nutrient availability, enhanced microbial activity, and better root development. In all, the findings provide strong evidence that the bioresource-based biostimulant is an effective amendment for promoting vegetation establishment and accelerating the restoration of petroleum-contaminated soils. The percent work done in phytotoxicity amelioration (Fig.6b) increased with increasing TPH concentration, rising from 39.05% at 7345 mg/kg to 81.43% at 14518 mg/kg. The greatest improvement was observed at the two highest TPH concentrations (12553 and 14518 mg/kg), indicating enhanced amelioration efficiency under higher contamination levels. The regression analysis in Fig.6c showed a strong positive linear relationship between TPH concentration and the percent work done in phytotoxicity amelioration ($R^2 = 0.915$). The positive slope (0.0065) indicates that amelioration increases with increasing TPH concentration, with approximately 91.5% of the variation explained by the regression model.

Discussion

The polluted soil system (PPS) recorded a very high mean Total Petroleum Hydrocarbon (TPH) concentration of 11,234 mg/kg, confirming severe petroleum contamination typical of impacted Niger Delta environments. Following application of the eco-smart remediation system (ERS), TPH levels decreased significantly to an average of 3,709 mg/kg, which was below the intervention threshold of 5,000 mg/kg (DPR, 2022). This substantial reduction demonstrated that the remediation strategy effectively enhanced hydrocarbon degradation processes. In contrast, the control soil recorded a negligible TPH concentration of 27.75 mg/kg, representing natural background conditions and providing a baseline for comparison. The sharp decline from PPS to ERS therefore reflected strong treatment efficiency and confirmed the capability of the bioresource-based formulation to reduce petroleum hydrocarbon loading within a short period.

Beyond the quantitative results, the study demonstrated strong scientific and practical relevance for the Niger Delta. It addressed a critical gap in existing remediation approaches by shifting from fragmented bioremediation methods to a structured, scalable biostimulant product. The integration of invasive aquatic biomass as feedstock strengthens sustainability outcomes while aligning with circular bioeconomy principles. The approach combined biostimulation, indigenous microbial activation, soil physicochemical improvement, and analytical validation through GC-based TPH assessment, thereby providing a multi-dimensional and credible remediation framework.

Importantly, the study maintained scientific rigor by acknowledging that post-treatment TPH levels, although significantly reduced, did not return to background conditions. This reflects realistic environmental outcomes and avoids overstatement of effectiveness. However, further strengthening could be achieved through quantitative benchmarking against existing remediation technologies, inclusion of degradation kinetics or half-life modelling, and detailed product standardisation (e.g., shelf-life, dosage consistency, and formulation stability). Field-scale validation in real contaminated sites and inclusion of basic cost-benefit analysis would also enhance scalability and policy relevance. In all, the study provided a promising foundation for environmental biotechnology development in Nigeria and demonstrated clear potential for translation into practical remediation solutions. With further optimisation, it could evolve into a deployable technology for large-scale oil-contaminated soil restoration.

Conclusion and Recommendation

The bioresource-based solid biostimulant demonstrated strong potential for petroleum hydrocarbon remediation, achieving substantial TPH reductions across all treated soils. Although performance varied with site conditions, overall efficiency was high, with concentrations reduced well below the intervention limit of 5,000 mg/kg. However, residual TPH levels remained above background value of 27.73 mg/kg, indicating that additional treatment cycles or extended remediation periods beyond 3 weeks may be required for full restoration. The findings confirm the effectiveness of eco-smart, bioresource-driven remediation as a sustainable approach for managing petroleum-contaminated soils. The results demonstrated that the percent work done in phytotoxicity amelioration increased with increasing TPH concentration and exhibited a strong positive linear relationship ($R^2 = 0.915$). This indicates that the amelioration process became more effective as the level of TPH contamination increased within the studied range. Ongoing research at the Federal University Otuoke, through the Environmental Remediation Research Group, is focused on improving formulation stability, process optimisation, and field-scale validation to consistently achieve near-background TPH levels under real environmental conditions.

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