



Post-Remediation Soil Quality Dynamics: The Role of Indigenous Bio-Resource Materials in Regulating pH in Petroleum Hydrocarbon-Impacted Soils.

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ABSTRACT

Petroleum hydrocarbon contamination remains a persistent environmental challenge in oil-producing regions, particularly in the Niger Delta of Nigeria, where soil quality and ecosystem functionality have been severely compromised. In this study an indigenous bioresource-based solid biostimulant was developed and evaluated for the remediation of petroleum-contaminated soils. The biostimulant, formulated from locally sourced organic materials, was applied to soils with varying Total Petroleum Hydrocarbon (TPH) concentrations (7,346 to 14,518 mg/kg), and remediation performance was monitored over a three-week period using soil pH as a key indicator of recovery. Results showed a consistent, time-dependent increase in soil pH across all treatment systems, reflecting progressive restoration of soil chemical balance. The magnitude of pH change increased with contamination level, ranging from 1.40 to 3.89% at the lowest TPH and 17.60 to 21.79% at the highest. Strong linear relationships between pH change and time ($R^2 = 0.804$ to 0.968 , $p \leq 0.05$) confirmed the reliability of the remediation process. Optimal performance was observed at moderate to high contamination levels (10,520 to 12,553 mg/kg), where both efficiency and predictability were highest. At the highest contamination level, although pH improvement was greatest, reduced linearity suggested possible system stress due to excessive hydrocarbon load. The findings demonstrate that the bioresource-based biostimulant effectively enhanced and accelerated hydrocarbon degradation, leading to measurable soil recovery. This approach offers a sustainable, low-cost alternative to conventional remediation technologies and holds significant potential for large-scale application in petroleum-impacted environments. Further field validation and process optimization are recommended to support its adoption and commercialization.

Keywords: Hydrocarbon-contaminated soils, Bioremediation, Indigenous bio-resources, Soil pH dynamics, Soil quality restoration

Introduction

Petroleum hydrocarbon contamination remains a major environmental challenge in oil-producing regions, particularly in the Niger Delta of Nigeria, where artisanal refining activities have intensified soil degradation. These activities release large quantities of crude oil and its derivatives into terrestrial ecosystems, leading to the accumulation of Total Petroleum Hydrocarbons (TPH) in soils. The persistence of these hydrocarbons significantly alters soil physicochemical properties, disrupts microbial communities, and impairs ecological functions essential for sustainable land use (Osuji & Onojake, 2004; Ekundayo et al., 2001). One of the most critical impacts of hydrocarbon contamination is its effect on soil pH, a key determinant of nutrient availability, microbial activity, and overall soil fertility. Hydrocarbon-polluted soils are often characterized by increased acidity due to the formation of organic acids during partial degradation, oxidation processes, and the disruption of natural buffering systems (Atlas & Bartha, 1998; Wang et al., 2010). A decline in soil pH adversely affects plant growth,

reduces enzymatic activities, and limits the bioavailability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), thereby compromising agricultural productivity (Brady & Weil, 2016).

In response to these environmental challenges, bioremediation has emerged as a sustainable and cost-effective approach for restoring contaminated soils. Bioremediation leverages the metabolic capabilities of microorganisms to degrade petroleum hydrocarbons into less harmful products, often resulting in improved soil quality parameters. However, the effectiveness of this approach depends largely on the availability of nutrients, suitable environmental conditions, and the presence of amendments that can stimulate microbial activity and enhance soil recovery. Recent research has increasingly focused on the use of indigenous bio-resource materials, locally available organic substances such as plant residues, agricultural wastes and composts, and bio-based formulations, as eco-friendly remediation agents. Importantly, their use aligns with circular economy principles and promotes sustainable environmental management in resource-constrained settings (Adenipekun et al., 2013; Adekunle et al., 2013; Vidali, 2001; Adekunle, 2007; Ayotamuno et al., 2006).

Despite growing interest in bioresource-driven remediation, there remains a need for a deeper understanding of post-remediation soil quality dynamics, particularly with respect to soil pH regulation over time and across varying contamination levels. While several studies have reported reductions in TPH following remediation, fewer have systematically evaluated how these interventions influence soil pH trajectories and the extent to which indigenous materials contribute to the restoration of soil chemical balance. Most of these studies emphasized reduction of total petroleum hydrocarbons (TPH) without adequately addressing post-remediation soil health indicators such as pH balance, nutrient recovery, and agricultural usability.

This study therefore evaluated the post-remediation dynamics of soil pH in hydrocarbon-impacted soils, with a specific focus on the role of indigenous bio-resource materials in regulating pH under varying TPH concentrations. By integrating regression analysis and temporal assessment, the study aims to elucidate the relationship between contamination intensity, remediation duration, and soil pH recovery. The findings are expected to provide valuable insights into the design of sustainable, locally adaptable remediation strategies that enhance soil quality restoration and support agricultural resilience in hydrocarbon-impacted environments.

Materials And Methods

Determination of Soil Petroleum Hydrocarbons and pH: Following application of the solid biostimulant to petroleum hydrocarbon-contaminated soil at the Federal University Otuoke, Bayelsa State (Niger Delta, Nigeria), surface soil samples (0-15 cm) were randomly collected using a stainless-steel auger. Samples from each site were homogenized to form composites, air-dried, and sieved (2 mm) to remove debris and ensure uniformity. A laboratory-controlled remediation experiment was conducted using a completely randomized design. Soils were grouped by initial total petroleum hydrocarbon (TPH) concentrations (7346, 10520, 12553, and 14,518 mg/kg), with four replicates per treatment. Untreated contaminated soils served as controls, while clean soil from Otuoke served as a primary control. The study spanned three weeks, with sampling at Weeks 1, 2, and 3. TPH was determined by solvent extraction and gas chromatography, while soil pH was measured in a 1:2.5 soil-water suspension using a calibrated pH meter. Measurements were taken at baseline and weekly thereafter. Quality assurance included the use of analytical-grade reagents, instrument calibration, and triplicate analyses with blanks and standards. All

determinations followed standard procedures. Data were analyzed using descriptive statistics, regression, and correlation, with significance at $p \leq 0.05$ (IBM SPSS 25). Results were presented in tables and graphs.

Results and Discussion

Results

In this study, quantitative data on Total Petroleum Hydrocarbon (TPH) concentration, pre-remediation soil pH values, post-remediation soil pH values, and percentage change in soil pH after remediation, for three weeks of study at weekly interval of time, are presented in Table 1.

Table 1: Pre- and post- remediation soil pH values in relation to TPH Concentrations with time

Remediation Period/Sample Code	TPH concentration (mg/kg)	Pre-remediation pH Value	Post remediation pH Value	Percent increase in soil pH after remediation
Week1				
PPS01	7346	6.42±0.04	6.51±0.03	1.40
PPS02	10 520	6.45±0.10	6.74±0.09	4.50
PPS03	12553	5.94±0.12	6.51±0/09	9.60
PPS04	14518	5.34±0.04	6.28±0.08	17.60
Week 2				
PPS01	7346	6.39±0.01	6.53±0.03	2.19
PPS02	10 520	6.40±0.20	6.75±0.02	5.47
PPS03	12553	5.80±0.14	6.59±0.03	13.62
PPS04	14518	5.35±0.04	6.31±0.11	17.94
Week 3				
PPS01	7346	6.42±0.02	6.67±0.24	3.89
PPS02	10 520	6.41±0.05	7.00±0.04	9.20
PPS03	12553	5.79±0.14	6.70±0.26	15.72
PPS04	14518	5.37±0.35	6.54±0.12	21.79

Soil TPH in test systems varied from 7346 to 14518 mg/kg. Soil pH ranged from 5.34 to 6.45 before remediation and 6.28 to 7.00 after remediation. Generally, application of bioresource-based remediation product resulted in soil pH modifications that varied with soil TPH concentration and remediation time.

The data from this study showed a clear and consistent improvement in soil pH following remediation across all contamination levels and time points. First, **pre-remediation pH values decreased as TPH concentration increased**, indicating that higher petroleum hydrocarbon contamination is associated with more acidic soils.

For example, soils with 14,518 mg/kg TPH consistently exhibited the lowest initial pH (~5.3 to 5.4), while less contaminated soils (~7,346 mg/kg) were closer to neutral (~6.4). Following remediation, **soil pH increased in all cases**, demonstrating the effectiveness of the treatment in restoring soil chemical balance. The **magnitude of pH improvement was directly proportional to TPH concentration**; more heavily polluted soils showed greater percentage increases in pH. For instance, at 14,518 mg/kg, pH increases reached up to approximately 21.79% by Week 3, compared to minimal increases (0.14 to 3.89%) at the lowest contamination level. There was also a **time-dependent trend**, with pH values progressively improving from Week 1 to Week 3 across all samples. This suggests that the remediation process is cumulative and becomes more effective over time. In total, there was a **strong inverse relationship between TPH and initial pH**, and a **positive correlation between**

remediation duration and pH recovery, highlighting the biostimulant's capacity to neutralize acidity and enhance soil quality, particularly in highly contaminated systems.

Pre-Remediation Soil pH Across Petroleum Hydrocarbon-Polluted Soil Systems (Weeks 1 to 3)

Pre-remediation data across Weeks 1 to 3 consistently showed a strong inverse relationship between total petroleum hydrocarbon (TPH) concentration and soil pH (Figs. 1 to 3). In Week 1, the regression model ($Y = -0.0001x + 7.714$; $R^2 = 0.7716$) indicated that increasing TPH levels were associated with declining pH. Approximately 77% of the variation in soil pH was explained by TPH concentration, highlighting hydrocarbons as a major driver of soil acidification. At lower contamination ($\sim 7,300$ mg/kg), soils remained near neutral (pH 6.4 to 6.6), whereas higher concentrations ($\sim 14,500$ mg/kg) corresponded to more acidic conditions (pH ~ 5.3).

This pattern became slightly stronger in Week 2, with a regression equation of $Y = -0.0001x + 7.6612$ and $R^2 = 0.81$. About 81% of pH variation was explained by TPH, confirming a robust and stable relationship. The data showed a clear gradient: lower TPH ($\sim 7,300$ mg/kg) corresponded to higher pH (~ 6.3 to 6.5), while higher TPH ($\sim 14,500$ mg/kg) results in lower pH (~ 5.3 to 5.4). This progressive acidification reflects hydrocarbon-induced disruption of soil buffering capacity and ongoing biochemical transformations.

By Week 3, the inverse relationship persists, with pH declining from ~ 6.4 to ~ 5.4 as TPH increased ($\sim 7,500$ to $14,500$ mg/kg). Soils with lower contamination ($7,000$ to $10,500$ mg/kg) remained slightly acidic to near neutral, conditions generally favorable for microbial activity. In contrast, highly contaminated soils ($>12,000$ mg/kg) exhibited increased acidity (pH 5.4 to 5.8), likely due to the accumulation of acidic intermediates, oxygen limitation, and microbial stress under high pollutant loads.

In all, the results demonstrated consistent and progressive soil acidification with increasing hydrocarbon concentration across all weeks. While natural attenuation may contribute to gradual TPH reduction, it also appeared to promote acidification as a secondary effect. This trend may limit microbial degradation efficiency over time, particularly in highly contaminated soils. Therefore, effective remediation strategies should integrate both TPH reduction and pH adjustment such as liming or buffering to optimize biodegradation and restore soil health.

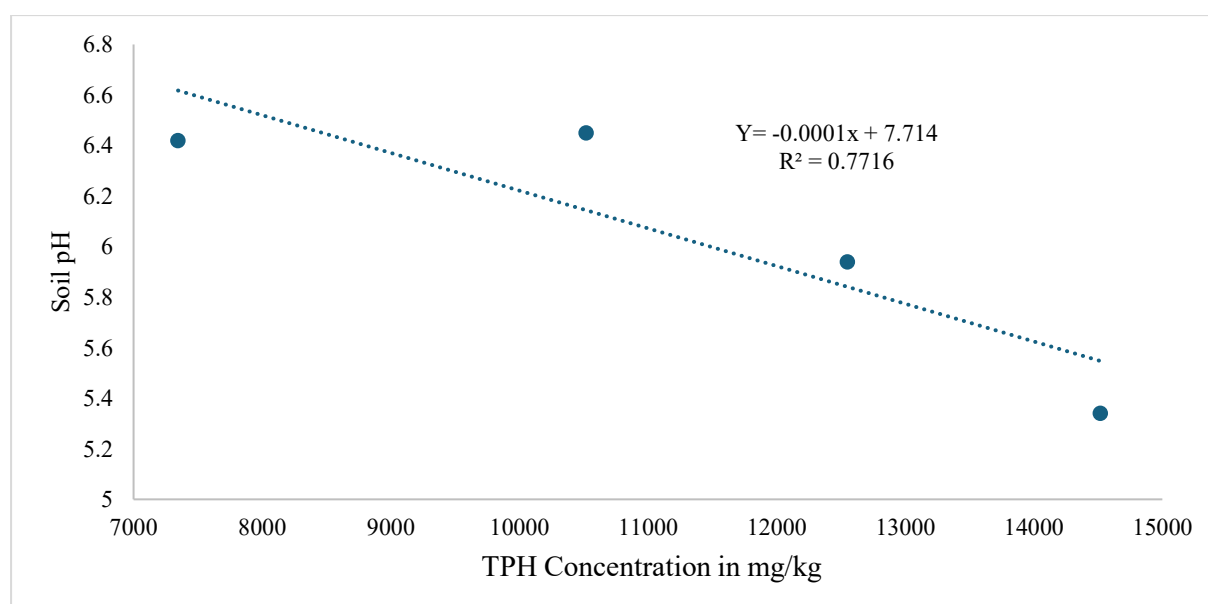


Fig.1: Soil pH values in pre-remediation Week 1

Post-Remediation Soil pH Across Petroleum Hydrocarbon-Polluted Soil Systems (Weeks 1 to 3)

Post-remediation results (Figs. 4 to 6) showed a progressive stabilization of soil pH and a weakening influence of total petroleum hydrocarbon (TPH) on acidity compared to pre-remediation conditions. In Week 1, a slight negative relationship between TPH and pH was observed ($Y = -3 \times 10^{-5}x + 6.877$; $R^2 \approx 0.28$). However, the low coefficient of determination was an indication that TPH was not yet the dominant factor influencing pH. Soil pH ranged from 6.3 to 6.7, reflecting slightly acidic to near-neutral conditions favorable for microbial activity. The scattered distribution of data points suggested a transitional phase in which the soil system was adjusting to treatment, with microbial populations becoming established and biodegradation processes just beginning. By Week 2, the inverse relationship persisted but remained weak ($Y = -3 \times 10^{-5}x + 6.8644$; $R^2 \approx 0.23$). A subtle downward shift in pH, particularly at higher TPH levels, indicated the onset of mild acidification, likely due to microbial degradation and the formation of intermediate organic acids. Despite this, pH values (6.3 to 6.75) remained within a range conducive to biodegradation. Compared to Week 1, the data showed slightly improved alignment with the regression trend, suggesting increasing system organization and microbial activity. This stage represented a transition from initial stabilization to active biodegradation, with TPH exerting a gradually increasing influence on soil chemistry.

In Week 3, soil pH stabilized within a narrow range (6.54 to 7.00) despite varying TPH concentrations (7,346 to 14,518 mg/kg). A mild inverse trend persisted, with higher TPH associated with slightly lower pH. However, the limited variation and low dispersion indicate effective buffering by the biostimulant. Near-neutral pH conditions, particularly at moderate contamination levels, reflected an optimal environment for microbial degradation. At this stage, the system appears to have reached a quasi-equilibrium, where acid-generating and buffering processes are balanced. Together, post-remediation results demonstrated improved pH stability and reduced acidification compared to pre-remediation conditions. While residual hydrocarbons exert a minor acidifying effect, the biostimulant effectively maintained favourable conditions for sustained biodegradation. Continued monitoring is recommended to ensure long-term pH balance and remediation efficiency.

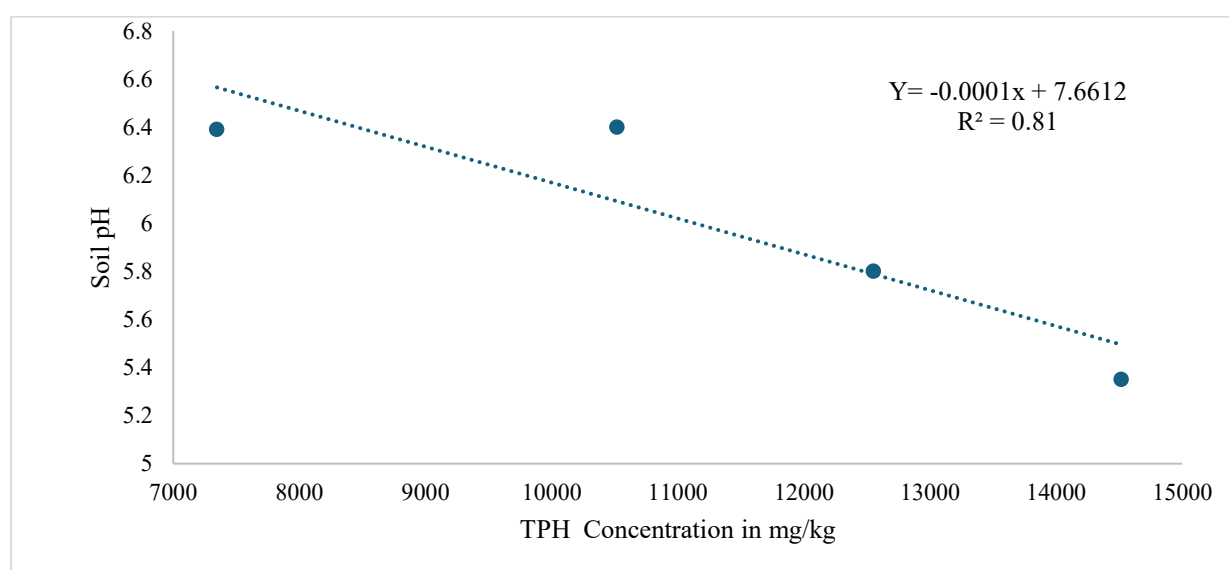


Fig.2: Soil pH values in pre-remediation Week 2

Post-Remediation Soil pH Dynamics Across Progressive Time Intervals

Post-remediation changes in soil pH over time (Table 2 and Fig.7) revealed a clear and consistent trend across all Total Petroleum Hydrocarbon (TPH) levels. Soil pH increased

progressively with time (Week 1 < Week 2 < Week 3), indicating a sustained recovery process. Moreover, the magnitude of pH change increased with rising TPH concentration, suggesting that more contaminated soils respond more strongly to remediation and that the biostimulant is particularly effective under elevated hydrocarbon stress. This reflects a time-dependent and concentration-enhanced amelioration of hydrocarbon-induced soil acidity. At the lowest contamination level (7346 mg/kg), pH change was modest but steady, increasing from 1.40% to 3.89%, with a strong linear relationship ($R^2 = 0.9574$), indicating predictable recovery. At 10,520 mg/kg, pH improvement was more pronounced (4.50% to 9.20%), although with slightly lower linearity ($R^2 = 0.8969$), suggesting minor system variability. The 12,553 mg/kg treatment exhibited substantial pH increases (9.60% to 15.72%) and the strongest linear fit ($R^2 = 0.9682$), indicating optimal microbial activity and biostimulant performance. The highest contamination level (14,518 mg/kg) showed the greatest overall pH change (17.60% to 21.79%), confirming strong remediation impact. However, reduced linearity ($R^2 = 0.804$) suggests decreased system stability, possibly due to toxicity effects or microbial limitations at extreme hydrocarbon loads. Overall, soil pH recovery was both time-dependent and positively correlated with TPH concentration. The results confirm that the biostimulant effectively restored soil pH across all treatments, with optimal performance at moderate to high contamination levels, while very high TPH introduced some variability in response dynamics.

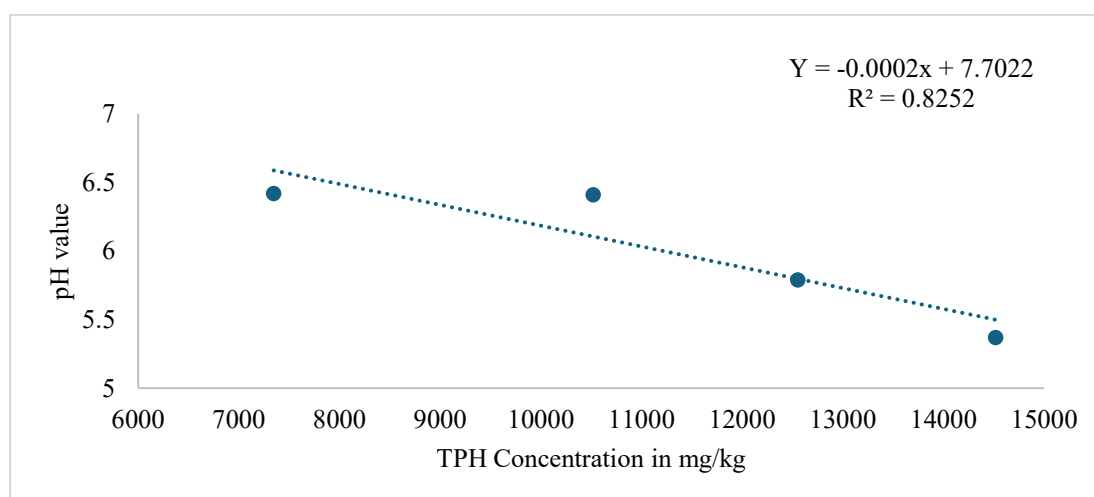


Fig.3: Soil pH values in pre-remediation Week 3

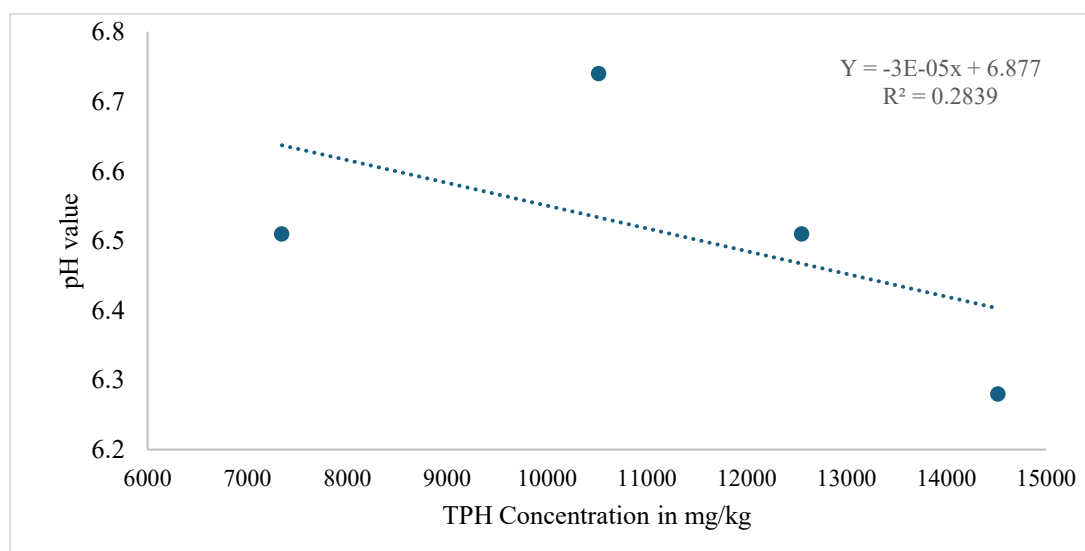


Fig.4: Soil pH values in post-remediation Week 1

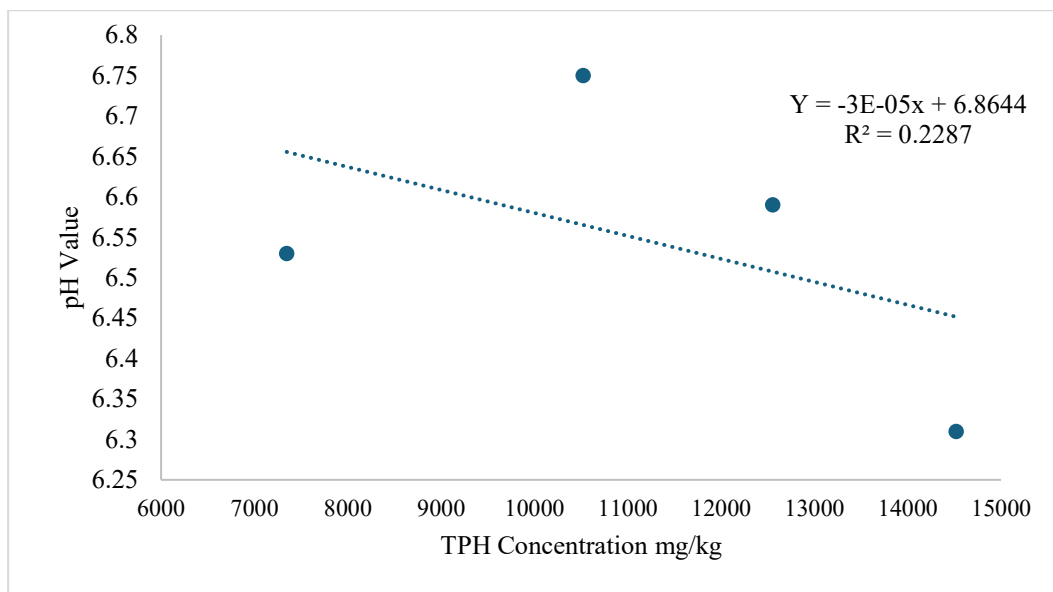


Fig.5: Soil pH values in post-remediation Week 2

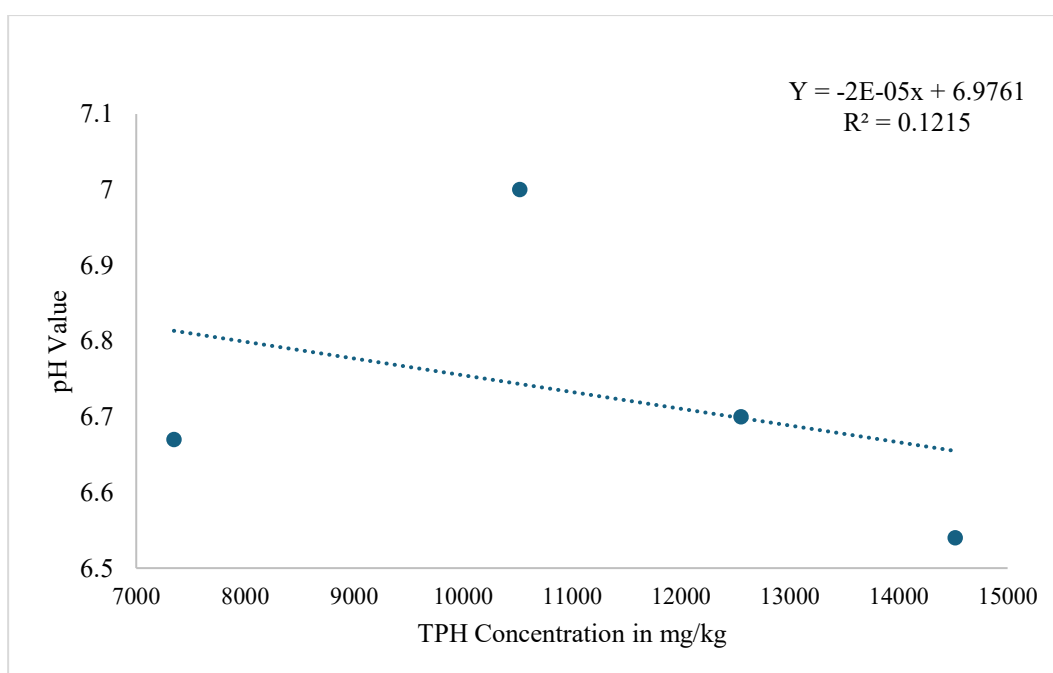


Fig.6: Soil pH values in post-remediation Week 3

Table 2: Post-Remediation Soil pH Changes Across Increasing Time Intervals

S/No	TPH (mg/kg)	Change in Soil pH with Time		
		Week 1	Week 2	Week 3
1	7346	1.40%	2.19 %	3.89 %
2	10 520	4.50 %	5.47%	9.20 %
3	12553	9.60 %	13.62 %	15.72
4	14518	17.60%	17.94 %	21.79 %

Regression equations for Week 2 data points (from Figure 5):

- For S/No 1: $Y = 0.1779x + 0.0033$; $R^2 = 0.9574$
- For S/No 2: $Y = 0.3357x + 1.69$; $R^2 = 0.8969$
- For S/No 3: $Y = 0.4371x + 6.86$; $R^2 = 0.9682$
- For S/No 4: $Y = 0.2993x + 14.92$; $R^2 = 0.804$

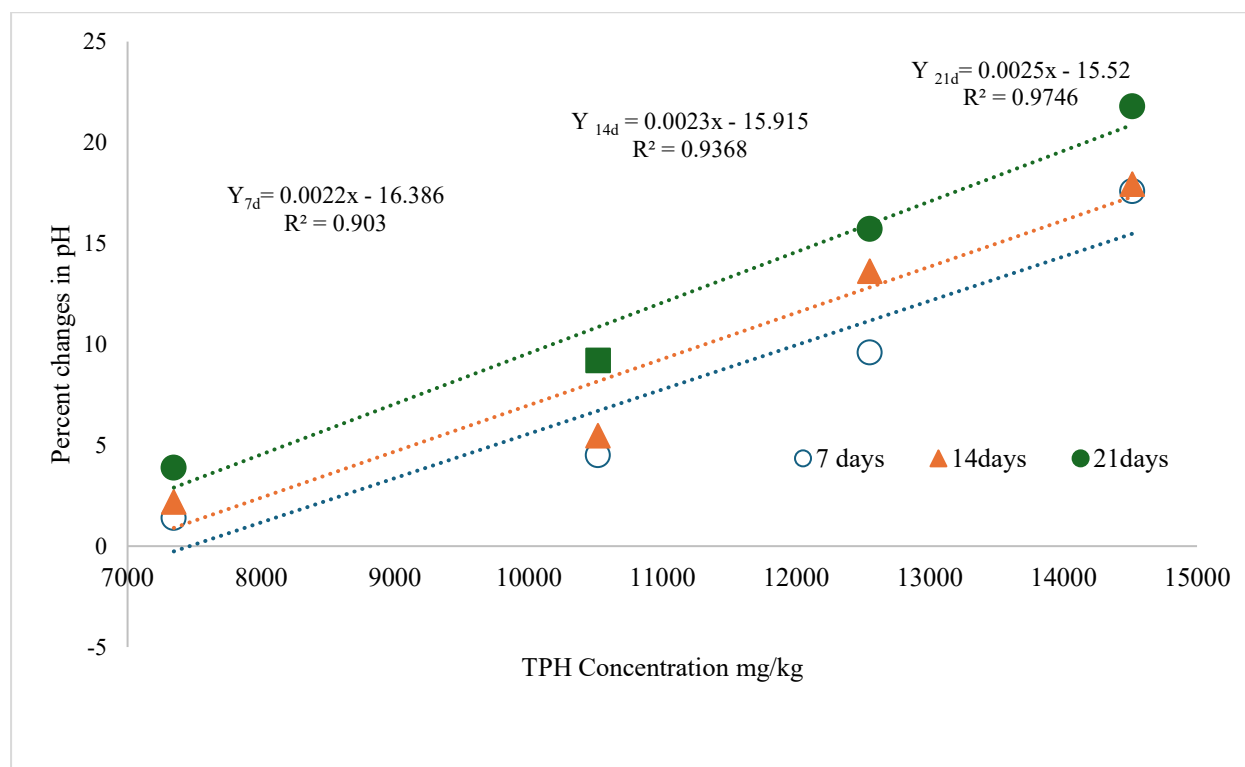


Fig.7: Post-Remediation Soil pH Dynamics Across Progressive TPH Concentration

Discussion

The temporal variation in soil pH across the six experimental subsets provides critical insight into the biogeochemical dynamics governing petroleum hydrocarbon-contaminated soils and their response to biostimulant-driven remediation. Altogether, the data demonstrated a transition from initial hydrocarbon-induced perturbation toward progressive stabilization, reflecting enhanced microbial activity and ecosystem recovery. During the pre-remediation phase (Weeks 1 to 3), soil pH values fluctuated within slightly acidic to near-neutral ranges, consistent with hydrocarbon-impacted soils in the Niger Delta. The observed variability can be attributed to the heterogeneous composition of petroleum hydrocarbons and their differential degradation pathways. Crude oil contamination often leads to acidification due to the accumulation of intermediate metabolites such as organic acids during partial oxidation (Atlas & Bartha, 1998). However, in some cases, alkaline shifts may occur due to ammonification and the release of basic cations (Adams et al., 2015). The lack of a stable pH trend during this phase suggests limited intrinsic bioremediation, likely constrained by nutrient deficiency and suboptimal microbial activity.

The early post-remediation phase (Week 1) showed modest pH adjustments across all treatment systems, indicating the onset of microbial activation following biostimulant application. This aligns with reports that nutrient amendment enhances microbial metabolism, leading to increased mineralization of hydrocarbons and buffering of soil pH (Vidali, 2001). The application of the bioresource-based solid biostimulant likely stimulated heterotrophic microbial populations, initiating the breakdown of labile hydrocarbon fractions (Adekunle et al., 2013). By post-remediation Week 2, a more pronounced stabilization trend emerged, with pH values converging toward neutrality across varying TPH concentrations. This suggests improved buffering capacity of the soil system, possibly due to the formation of humic substances and the release of mineral nutrients from the biostimulant matrix. Neutral pH conditions are widely recognized as optimal for hydrocarbon-degrading microorganisms, enhancing enzymatic efficiency and biodegradation rates (Bento et al., 2005). The reduced variability at this stage indicates that the remediation process is overcoming initial hydrocarbon toxicity constraints.

In post-remediation Week 3, the pH values (6.5 to 7.0) across all contamination levels further confirmed system stabilization and ecological recovery. Notably, even at higher TPH concentrations, the soil maintained near-neutral pH, reflecting the robustness of the biostimulant formulation. This suggests that the remediation strategy effectively mitigated the inhibitory effects of hydrocarbons while promoting microbial resilience. The slight decrease in pH observed at higher TPH levels may be linked to sustained microbial degradation and the continued production of low-molecular-weight organic acids, a typical feature of active biodegradation (Margesin & Schinner, 2001). Importantly, the convergence of pH values across all contaminated systems toward those typical of uncontaminated soils highlights the restoration of soil functional integrity. Soil pH is a master variable influencing nutrient availability, microbial diversity, and enzymatic activity; thus, its normalization is a strong indicator of successful remediation (Rousk et al., 2010). The findings corroborate previous studies demonstrating that bioresource-based amendments can significantly enhance the physicochemical and biological recovery of hydrocarbon-polluted soils (Ayotamuno et al., 2006; Bento et al., 2005).

Collectively, the six datasets revealed a clear trajectory: initial disturbance → transitional microbial activation → progressive stabilization → functional recovery. The consistency of this pattern across varying contamination levels demonstrates the effectiveness of the indigenous biostimulant technology. It further supports the concept that locally sourced, organic-based amendments can provide sustainable and context-specific solutions for petroleum hydrocarbon remediation in the Niger Delta and Bayelsa in particular. The bioresource-based remediation product induced significant, time-dependent recovery of soil pH. The effect was more pronounced at higher contamination levels, highlighting its efficacy in severely degraded soils. The strong regression fits validate the predictability and reliability of the remediation process.

Conclusion and Recommendations

This study demonstrated the effectiveness of an indigenous bioresource-based solid biostimulant in remediating petroleum hydrocarbon-contaminated soils. A consistent, time-dependent increase in soil pH across all treatments indicated progressive restoration of soil chemical quality and enhanced conditions for microbial activity. The magnitude of pH recovery increased with Total Petroleum Hydrocarbon (TPH) concentration, with optimal performance observed at moderate to high levels (10,520 to 12,553 mg/kg), where both efficiency and response linearity were highest. Although the highest contamination level (14,518 mg/kg) showed the greatest pH improvement, reduced linearity suggests possible system instability under excessive hydrocarbon stress. These findings confirm the potential of locally derived biostimulants to stimulate biodegradation and restore degraded soils. Further field validation, process optimization, and integration with complementary approaches are recommended, alongside standardization and regulatory support, to enable large-scale application of this sustainable remediation technology.

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