Normalized Difference Vegetation Index (NDVI) as an indicator of bio-remediation efficiency in crude oil-impacted soils in Ogoni-land: A case study of Eleme local government area, Rivers State, Nigeria

Komommo Omini Abam[1]
Tubonimi J. K. Ideriah[2]
Akuro Ephraim Gobo[3]
Francis Egobueze[4]

[1]komsabam@gmail.com (+234-8037878357)
[2]ideriah.tubonimi@ust.edu.ng
[3]gobo.akuro@ust.edu.ng
[4]francis.egobueze@gmail.com

[1]National Oil Spill Detection and Response Agency (NOSDRA), Federal Capital Territory, [2,3,4]Rivers State University, [1,2,3,4]Nigeria

https://doi.org/10.51867/ajernet.6.3.11

ABSTRACT

Eleme, a sub-region of Ogoni-land in Rivers State, Nigeria, has experienced decades of severe environmental degradation due to crude oil contamination, resulting in ecosystem disruption and reduced vegetation health. In line with the United Nations Decade on Ecosystem Restoration (2021–2030), this study assesses the ecological impact and bio-remediation efficiency of four remediated sites; Nkeleoken-Alode (LOT 04), Elelenwo Manifold-Akpajo (LOT 46 and LOT 56), and Ajeokpori Well 3-Okuluebu (LOT 54), under Phase I of the UNEP Ogoni-land Environmental Restoration Project. The study employed Normalized Difference Vegetation Index (NDVI) analysis to evaluate vegetation health and restoration trends across four historical epochs: 1994 (pre-contamination baseline), 2004 and 2014 (periods of high contamination), and 2024 (post-remediation). Satellite-derived NDVI data were processed using Landsat imagery (30 m resolution), and NDVI changes were analyzed to quantify vegetation vigor, variance, and ecosystem recovery. Results showed that NDVI values decreased sharply between 1994 and 2014, reaching negative thresholds in some LOTs, indicating severe ecological degradation due to crude oil pollution. For example, LOT 46 recorded an NDVI decline from 0.434 (1994) to –0.020 (2014), a 104.6% drop in vegetation vigor, Post-remediation in 2024, all LOTs demonstrated positive NDVI recovery, with LOT 54 rising from –0.0875 (2004) to 0.1275 (2024), representing a 164% increase, highlighting effective remediation outcomes. LOTs treated with bio-augmentation products such as Micro SOLUTION® and KEEN® exhibited stronger vegetation rebound than others, suggesting the effectiveness of tailored remediation strategies. The study finds that vegetation health improved significantly post-remediation, with gradual increases in NDVI values across sites indicating partial ecosystem restoration and enhanced vegetation vigor. However, residual hydrocarbon stress persists in some areas, warranting continued site-specific interventions. This research contributes valuable empirical evidence on the use of NDVI as a cost-effective monitoring tool for post-bioremediation assessment in crude oil-impacted regions. It underscores the need for integrated, location-specific bio-remediation and restoration strategies to enhance long-term ecological resilience in Ogoni-land and similar environments globally.

Keywords: Bio-Stimulation, Bio-Augmentation, Ecosystems, Electro-Bioremediation, Restoration

I. INTRODUCTION

The ultimate goal of soil remediation and contaminated land restoration is to eliminate contaminants and restore soil quality to support human, animal, and plant life (Abam *et al.*, 2023). Oil spills pose significant threats to the environment in oil-producing areas, often causing severe ecosystem destruction if not effectively managed (Anifowose, 2008; Onuoha, 2008). Hydrocarbon pollutants disrupt the fragile balance between living species and their habitats, leading to habitat alteration, community structure changes, and the proliferation of invasive species (Sam *et al.*, 2023). In crude oil-impacted soils, restoration to natural states is critical to support plant growth and ecosystem services (Egobueze *et al.*, 2019). However, environmental degradation in Ogoni-land has diminished biodiversity functioning, ecosystem resilience, and the sustainability of socio-ecological systems. The United Nations Development Program (UNDP, 2012) emphasizes that human well-being depends on biodiversity and healthy ecosystems, yet rapid demographic changes and environmentally damaging technologies are pushing the planet toward unprecedented biodiversity loss and ecosystem degradation. In response, global initiatives like the G20 Land Initiative 2040 focus on halting land degradation by promoting nature-based, sustainable restoration approaches tailored to local and regional contexts (Nigeria Extractive Industries Transparency Initiative [NEITI], 2021). Ecosystem revitalization must be systemic, emphasizing not only product certification but also process certification and comprehensive ecosystem restoration.

In Eleme Local Government Area of Ogoni-land, various soil amendment methods including; bio-stimulation, bio-augmentation, and electro-kinetic remediation have been applied as bioremediation strategies to restore soil and groundwater health and facilitate ecosystem recovery. This study evaluates the efficiency and ecological impacts of these methods across four selected sites during Phase 1 of the UNEP Ogoni-land Restoration Project. Products tested include CLOGEN™ (bio-stimulation and bio-augmentation), Micro SOLUTION® (bio-augmentation), Petroleum Remediation Product® (bio-stimulation), and an electro-bioremediation combination involving Electro-Kinetic Action with KEEN® and Ors-SORB plus®. Key findings show significant Total Petroleum Hydrocarbon (TPH) degradation: Nkeleoken Alode LOT 04 (0.64 ha) reduced TPH from 2,021 mg/kg to 265 mg/kg (86.89% efficiency). Elelenwo Manifold Akpajo LOT 46 (0.3943 ha) achieved 99.61% degradation, reducing TPH from 6,600 mg/kg to 26 mg/kg having the highest efficiency and the cleanest post-remediation site. Ajeokpori Well 3, Okuluebu LOT 54 (0.0854 ha) achieved 73.89% efficiency, reducing TPH from 4,550 mg/kg to 1,187.87 mg/kg. New Elelenwo Manifold Akpajo LOT 56 (0.4139 ha) showed 93.06% degradation, with TPH reduced from 5,600 mg/kg to 402.29 mg/kg. The central question remains: to what extent have these restoration efforts enhanced soil health, reversed biodiversity loss, improved ecosystem resilience, increased ecosystem services, reduced environmental risk, and contributed to human well-being? Restoration aims to return degraded ecosystems to their pre-disturbance conditions (Sam *et al*., 2023; Klaus & Kiehl, 2021; and Gann *et al*., 2019). The United Nations Decade on Ecosystem Restoration (2021–2030) calls for scaling up efforts to restore ecosystems, essential for securing a healthier future. Human survival depends on biodiversity and healthy ecosystems, yet these are increasingly threatened by environmental degradation (UNDP, 2012). Vegetation cover is a key indicator for sustainable soil health, biodiversity, ecosystem function, and productivity (Altieri *et al*., 2015). This study assesses the environmental impact of crude oil spills and remediation efforts in Eleme, Ogoni-land, by analyzing Normalized Difference Vegetation Index (NDVI) data for four LOTs across 1994, 2004, 2014, and 2024. NDVI, ranging from -1 to +1, effectively indicates vegetation health by measuring plant reflectance in infrared and visible spectra and correlates with photosynthetic activity, biomass, and ecosystem condition (Rouse *et al*., 1973). Complementary indices, Normalized Difference Vegetation Vigor Index ($NDVVI_{(vigor)}$) and Normalized Difference Vegetation Variance Index ($NDVVI_{(variance)}$) provide enhanced remote sensing methods for monitoring biodiversity and vegetation quality in crude oil-impacted and remediated areas (Onyia *et al*., 2018). Vegetation vigor reflects active, healthy plant growth, which is critical to environmental quality and ecosystem productivity (Vrieling, 2006).

1.1 Statement of the Problem

Despite decades of crude oil contamination and several remediation efforts in Ogoni-land, significant gaps remain in understanding the long-term ecological effectiveness of different bioremediation strategies, particularly their impact on vegetation recovery and soil health under real-world conditions. Existing studies have often focused on short-term pollutant degradation or laboratory-based assessments, with limited empirical data on ecosystem-level recovery over extended timeframes. Additionally, there is a lack of contextualized evaluation of how various bio-stimulation, bio-augmentation, and electro-bioremediation techniques perform across diverse sites within Eleme Local Government Area; a critical hotspot of contamination and restoration. This study addresses these gaps by providing a comprehensive, multi-epoch assessment of ecosystem restoration progress in Ogoni-land's Phase 1 UNEP remediation sites. It evaluates the efficiency and ecological impacts of bio-remediation products across four selected LOTs in Eleme, focusing on Total Petroleum Hydrocarbon (TPH) degradation, soil physicochemical and biological properties, and vegetation health indicators derived from satellite-based Normalized Difference Vegetation Index (NDVI) and related indices over a 30-year period (1994 to 2024).

1.2 Research Objective

To assess the effectiveness and ecological impact of various bio-remediation strategies; specifically bio-stimulation, bio-augmentation, and electro-bio-remediation on crude oil-contaminated soils in Eleme Local Government Area of Ogoni-land, by evaluating changes in soil health, Total Petroleum Hydrocarbon (TPH) degradation, and vegetation recovery using the Normalized Difference Vegetation Index (NDVI), Vegetation Vigor ($NDVVI_{(vigor)}$), and Vegetation Variance ($NDVVI_{(variance)}$) over a 30-year period (1994–2024), with the aim of determining the extent of ecosystem restoration achieved during Phase 1 of the UNEP Ogoni-land remediation program.

II. METHODOLOGY

Eleme, located between Longitudes 007^0 00'' and 007^0 15'' East of the Meridian and Latitudes 04^0 60'' and 04^0 35'' North of the Equator; covering about 120 km^2 (www.riversstateapps.ng - Eleme Local Government Council) (Fig.1), constitutes one of the four (4) Local Government Areas of Ogoni-land, in Rivers State of the Niger-delta region. It has a projected population of 298,986 (Bodo & David, 2018 & National Population Commission (NPC), 2006), and characterized by considerable amount of sunshine and high cloud cover, especially during the wet season, which may affect the quality of satellite data obtained at certain times of the year (Onyia *et al*., 2018; Omo-Irabor *et al*., 2011). Ecologically, Eleme, a subset of Ogoni-land has been classified as Coastal Plan and Freshwater Rain Forest Zone, populated by forest tree species, palms, shrubs, ferns, etc., (Onyia *et al*., 2018; Ugochukwu & Ertel, 2008 & World Bank, 1995). The legacy of exploration, exploitation and transportation of crude oil and gas resources in the Niger-delta region of Nigeria, with special mention to Ogoni-land without adequate environmental protection has resulted in the creation of one of the most polluted natural environments in the World (Sam *et al*., 2023). According to Abam (2001), the advantage of geographic information system (GIS) is that, spatial change detection analysis can be applied to time sequenced databases, to track environmental changes and trends in terms of land-use, coastline geometry, vegetation drift, pollution levels, etc., and studies have demonstrated the potential of combining satellite remote sensing and ground data (Ellis & Port-Bolland, 2008; Murdiyarso & Skutsch, 2006 and DeFries *et al*., 2005) to effectively determine the spatial extent of deforestation across tropical forest regions of the World.

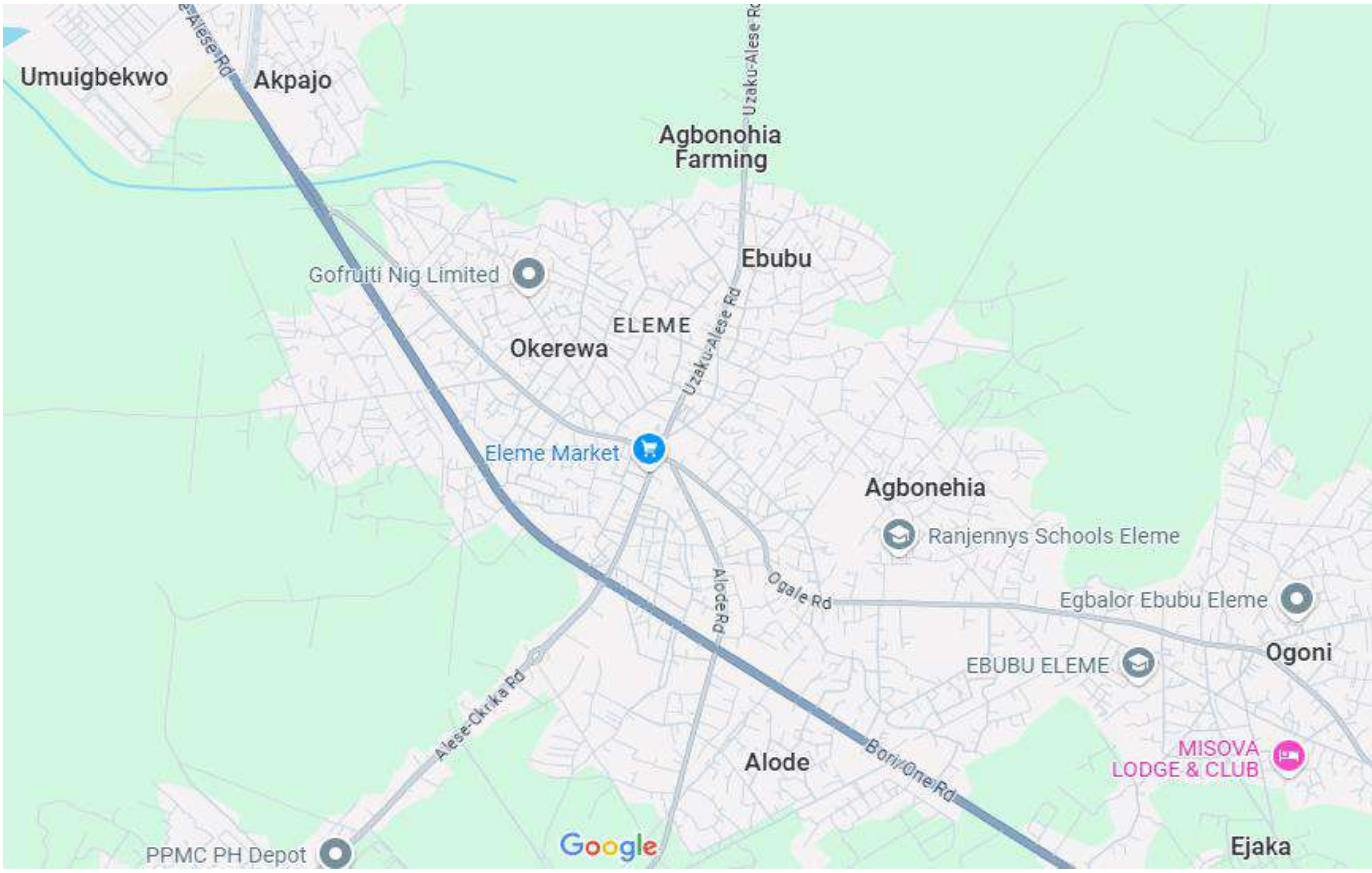


Figure 1

Map of the Study Area in Eleme Local Government Area of Rivers State

(Source: *Satellite Imagery from Google Earth date* ® 2025)

This study employed multi-temporal satellite remote sensing data spanning a 30-year period (1994–2024), with decadal intervals (1994, 2004, 2014, and 2024). The satellite imagery datasets used included; Landsat 5 TM (for 1994), Landsat 8 OLI/TIRS (for 2004 and 2014), and Landsat 9 OLI-2/TIRS-2 (for 2024). These datasets were selected for their consistency, global availability, and 30-meter spatial resolution, which is suitable for landscape-scale environmental assessments. Each dataset has a 16-day revisit cycle, allowing for regular monitoring, and provides 7 to 11 spectral bands, which include visible and near-infrared (NIR) wavelengths required for vegetation analysis. The Normalized Difference Vegetation Index (NDVI), introduced by Rouse *et al*. (1973), is one of the most widely used indices for mapping and monitoring vegetation health globally. It provides a quantitative measure of vegetation by comparing the reflectance in the red and near-infrared (NIR) portions of the spectrum. Healthy vegetation absorbs more red light (due to chlorophyll) and reflects more near-infrared light, while stressed or sparse vegetation reflects more red light and less NIR. All satellite images were imported into ERDAS Imagine 2011 for geometric and atmospheric corrections. This step ensured that geometric distortions, radiometric inconsistencies, and atmospheric interferences were minimized. Geo-referencing was performed using known ground control points (GCPs) to ensure spatial accuracy. The preprocessed imagery was further analyzed in ArcGIS 10.8, where the Normalized Difference Vegetation Index (NDVI) was calculated for each time period using the formula:

$$NDVI = (NIR + Red) / (NIR - Red)$$

NDVI values range from -1.0 to +1.0, where Values closer to +1.0 indicate healthy, dense vegetation, Values close to 0.0 suggest barren areas or sparse vegetation and Values below 0.0 typically indicate water bodies, built-up areas, or stressed vegetation, often the result of hydrocarbon pollution. The study locations, data extraction and vegetation analysis was conducted for four bio-remediated sites in Eleme Local Government Area, Ogoni-land: Nkeleoken-Alode (LOT 04), Elelenwo Manifold-Akpajo (LOT 46), Ajeokpori Well 3-Okuluebu (LOT 54), and New Elelenwo Manifold-Akpajo (LOT 56). Each location was spatially buffered and delineated using site-specific coordinates. NDVI values were extracted from the satellite imagery for each epoch (1994, 2004, 2014, and 2024), and results were summarized in Table (1) and visualized as NDVI raster maps (Figures 1a–d). To quantify the extent and direction of vegetation change across decades, Change Detection Analysis was performed by comparing NDVI values across epochs. The difference between pre- and post-remediation NDVI values allowed for the classification of vegetation change as: Positive Change - indicating vegetation recovery or regeneration and Negative Change - indicating vegetation loss or ongoing degradation. Two derived indices were employed to enrich the analysis; Normalized Difference Vegetation Vigor Index (NDVVI $_{(vigor)}$). This index measures the growth robustness and productivity of vegetation, particularly useful in tracking restoration in previously polluted sites; a superior and new Remote Sensing Approach to Biodiversity Monitoring in crude oil-polluted or crude oil-remediated regions (Onyia *et al*., 2018); defined as active, healthy, well-balanced and robust growth of plants; and recognized as an essential environmental quality index (Onyia *et al*., 2018), characterized by enhanced growth, extent, as-well-as increased productivity (Vrieling, 2006), was computed using the formula:

$$\text{NDVVI}_{\textbf{(vigor)}} = \frac{(\boldsymbol{NDVI}\ current\ year - \boldsymbol{NDVI}\ reference\ year)}{(\boldsymbol{NDVI}\ reference\ year)}$$

Where;

NDVI current year = NDVI value for a specific year (i.e., 2004, 2014, or 2024)

NDVI reference year = NDVI value for the baseline year (i.e., 1994)

Then Normalized Difference Vegetation Variation Index (NDVVI $_{(variance)}$), where the index quantifies the relative variability or change in vegetation cover between two time periods, especially useful in assessing spatial heterogeneity in ecosystem recovery, calculated using the formula:

$$\text{NDVVI}_{\textbf{(variance)}} = \frac{(\boldsymbol{NDVI}\ new - \boldsymbol{NDVI}\ old)}{(\boldsymbol{NDVI}\ old)}\ X\ 100$$

Where;

NDVI $_{new}$ = NDVI value for the later year – newer year (e.g., NDVI for 2004)

NDVI $_{old}$ = NDVI value for the earlier year – older year (e.g., NDVI for 1994)

NDVVI-based interpretations help assess the vitality, resilience, and variability of vegetation under remediation influence. The results for both indices are presented in Table (2).

As a mark of justification of the methodology deployed for this study, the use of NDVI and its derivative indices is well-established in environmental monitoring for evaluating vegetation health, land-use change, and ecosystem recovery. Previous studies (e.g., Ansah *et al.*, 2022; Onyia *et al.*, 2018; and Sonwalkar *et al.*, 2010) confirm the sensitivity of these indices in detecting vegetation stress due to hydrocarbon pollution, making them appropriate for assessing remediation outcomes and efficiency in the Niger Delta region; where products that contributed to an increase in NDVI in their specific locations are considered to be relatively more efficient and effective, and provides a comprehensive view of how soil and vegetation have responded over time to both crude oil-contamination and the relevant remedial actions, allowing for a better understanding of which product or strategy is more effective in achieving sustainable ecosystem recovery in the region. The United States Environmental Protection Agency (USEPA) (2012) and Organization for Economic Co-operation and Development (OECD) (2006) have recommended Normalized Difference Vegetation Vigor Index (NDVVI$_{(vigor)}$) in test, to evaluate the effect of chemical substances like pesticides on the growth of various plant species, so, in this study, we deployed this quality index to complement NDVI. This provided a measure of vegetation vigor and health, with higher values indicating healthier vegetation, and bringing it to bear on the NDVI of the study area over time, reflecting the vigor of vegetation in relation to reference periods.

III. FINDINGS

Generally, the NDVI Maximum values (Table 1 below) for Nkeleoken-Alode LOT 04 in 1994 is 0.5 (26.32%) while the subsequent years 2004, 2014 and 2024 are -0.595238 (12.50%), 0.000 (0%), and 0.10896 (27.27%) respectively, Elelenwo Manifold-Akpajo LOT 46 is 0.434343 (21.05%) in 1994, and -0.139241 (35%), -0.020979 (-66.67%), and 0.0974441 (22.73%) in 2004, 2014, and 2024 respectively, while Ajeokpori Well 3-Okuluebu LOT 54 are 0.527273 (26.32%), -0.0875 (22.50%), 0.0482759 (166.67%), and 0.127522 (29.55%) for 1994, 2004, 2014 and 2024 respectively, and New Elelenwo Manifold-Akpajo LOT 56 is 0.466667 (26.32%), -0.122581 (30%), 0.00699301 (0%), and 0.103144 (22.73%) for 1994, 2004, 2014, and 2024 respectively, while $NDVVI_{(vigour)}$ and $NDVVI_{(variance)}$ are as represented in Table (2) below.

Analysis of the vegetation trend from 1994 to 2024 using NDVI values across the four remediated locations in Eleme (LOT 04, LOT 46, LOT 54, and LOT 56) revealed a dynamic pattern of vegetation change over the 30-year period under study, where the total NDVI value across the four sites decreased from 1.928 in 1994 to -0.409 in 2004, indicating a severe decline in vegetation health shortly after major hydrocarbon contamination events. There was a modest recovery in 2014 (NDVI = 0.0343) and a more significant increase in 2024 (NDVI = 0.4371), suggesting the positive impact of bio-remediation efforts and natural regrowth processes over time. By 2024, the cumulative NDVI had slightly surpassed the 1994 baseline, showing a 102.28% relative gain, despite earlier dips. Site-Specific NDVI observations, shows that LOT 54 consistently exhibited the highest NDVI values in 1994 (0.527) and 2024 (0.1275), and the strongest percentage rebound (+166.67%) by 2014, reflecting a better response to remediation with Micro Solution® in terms of vegetative cover. LOT 46, which used CLOGEN™, showed the lowest 2004 NDVI (-0.139), and despite a partial recovery in 2024 (0.0974), vegetation remained comparatively weaker, while LOT 56 treated with PRP® demonstrated moderate initial vegetation loss but recorded a 1,374.96% increase in vegetation variance from 2014 to 2024, the most remarkable rebound among all locations. Vegetation Vigor and Variance ($NDVVI_{(vigor\ and\ variance)}$) values show that, all sites experienced negative vegetation vigor from 1994 to 2004, ranging from -116.59% to -219.05%, reflecting vegetation loss likely due to hydrocarbon pollution. Between 2004 and 2014, vegetation vigor remained negative, but LOT 54 and LOT 46 showed signs of moderate recovery. The most significant improvement occurred between 2014 and 2024, with LOT 54 showing a positive vegetation variance of +164.15%, and LOT 56 recording an exceptional +1,374.96%, indicating a strong resurgence in vegetative regeneration likely aided by the application of PRP® and favorable site conditions. Generally, the vegetation indices show an overall trend of initial environmental degradation post-contamination, followed by gradual but significant ecological recovery facilitated by tailored bio-remediation interventions. LOT 54, with Micro Solution® and LOT 56 with PRP® were particularly effective in restoring vegetation, making them promising models for scaling in other impacted areas. The positive vegetation variance from 2014 to 2024 serves as a key indicator of ecosystem restoration success, reinforcing the role of science-driven remediation strategies in improving land health in oil-polluted regions. The Spatial and Temporal Trends in Vegetation as shown in the NDVI Maps (Figures 1a–1d) for the four bio-remediated locations; Nkeleoken-Alode LOT 04, Elelenwo Manifold-Akpajo LOT 46, Ajeokpori-Okuluebu LOT 54, and New Elelenwo Manifold-Akpajo LOT 56 show distinct spatiotemporal vegetation patterns over the 30-year period (1994–2024), offering insights into the ecosystem response to hydrocarbon pollution and subsequent remediation. At Nkeleoken-Alode LOT 04 (1994–2024), the 1994 NDVI map reveals moderate vegetation health, with values peaking at 0.5, indicative of relatively dense green cover. However, by 2004, NDVI sharply declined to a negative value of -0.0595, suggesting severe vegetation stress or loss, likely due to hydrocarbon contamination. The zero NDVI in 2014 implies barren or disturbed land conditions, consistent with either ongoing pollution or insufficient recovery. By 2024, NDVI improves modestly to 0.10896, signifying early signs of regrowth or successful remediation, though vegetation health remains below pre-impact levels. The spatial distribution in this location shows significant loss of vegetative cover post-pollution, with limited but positive regeneration by 2024. This trend underscores the prolonged recovery time required in crude-oil heavily polluted areas. At Elelenwo Manifold-Akpajo LOT 46 (1994–2024), in 1994, NDVI was 0.434343, indicating healthy vegetation. This declines to -0.1392 in 2004 more severe than at LOT 04, highlighting intense degradation. The 2014 value of -0.0209 reflects continued degradation or stressed conditions. A moderate recovery is evident in 2024, with NDVI increasing to 0.0974. This location experienced persistent vegetative decline from 1994 to 2014, with only a modest rebound by 2024. Spatially, the maps show large areas transitioning from vegetated (green/yellow) to degraded (red/brown), with some greening reappearing in 2024. In Ajeokpori-Okuluebu LOT 54 (1994–2024), this site exhibited relatively strong NDVI values across time, with 1994 at 0.527273, followed by a drop in 2004 to -0.0875, still showing degradation but less severe than in LOT 46. By 2014, NDVI climbs to 0.0482, and further improves to 0.1275 in 2024, reflecting progressive recovery over time. Spatially speaking, this site shows a clear trajectory of ecological restoration, with NDVI maps shifting from degraded surfaces in 2004 to visibly greener zones by 2024. The site likely benefited from effective bioremediation and favorable natural recovery conditions. New Elelenwo Manifold-Akpajo LOT 56 (1994–2024) initial NDVI in 1994 was 0.466667, followed by a sharp drop to -0.1226 in 2004, confirming significant degradation.

Table 1

General Pattern of Vegetation Change in Eleme considered Locations (NDVI 1994-2024)

Locations	1994 NDVI Maximum Value	1994 NDVI Percentage Value (%)	2004 NDVI Maximum Value	2004 NDVI Percentage Value (%)	2014 NDVI Maximum Value	2014 NDVI Percentage Value (%)	2024 NDVI Maximum Value	2024 NDVI Percentage Value (%)
Eleme LOT 04	0.5	26.32	-0.0595238	12.50	0.0000	0.00	0.10896	27.27
Eleme LOT 46	0.434343	21.05	-0.139241	35.00	-0.020979	-66.67	0.0974441	22.73
Eleme LOT 54	0.527273	26.32	-0.0875	22.50	0.0482759	166.67	0.127522	29.55
Eleme LOT 56	0.466667	26.32	-0.122581	30.00	0.00699301	0.00	0.103144	22.73
Total	1.928283	100.01	-0.4088458	100	0.034289	100	0.43707041	102.28

Source: Researcher's Analysis and Compilation, 2024

Table 2

Normalized Difference Vegetation Vigor and Variance ($NDVVI_{(vigor)}$ and $NDVVI_{(variance)}$ 1994-2024)

Locations	2004 $NDVVI_{(vigor)}$ in Percentage (%)	2014 $NDVVI_{(vigor)}$ in Percentage (%)	2024 $NDVVI_{(vigor)}$ in Percentage (%)	1994-2004 $NDVVI_{(variance)}$ in Percentage (%)	2004-2014 $NDVVI_{(variance)}$ in Percentage (%)	2014-2024 $NDVVI_{(variance)}$ in Percentage (%)
Eleme LOT 04	-219.0476	-100	-78.208	-219.0476	-100	+10.896
Eleme LOT 46	-132.0578437	-104.8300537	-77.56517315	-132.0578437	-84.93331705	-564.4840078
Eleme LOT 54	-116.594819	-90.8442306	-75.81480561	-116.594819	-155.1724571	+164.1525067
Eleme LOT 56	-126.2673384	-98.501499	-77.89773007	-126.2673384	-105.7048074	+1,374.958566

Source: Researcher's Analysis and Compilation (2024)

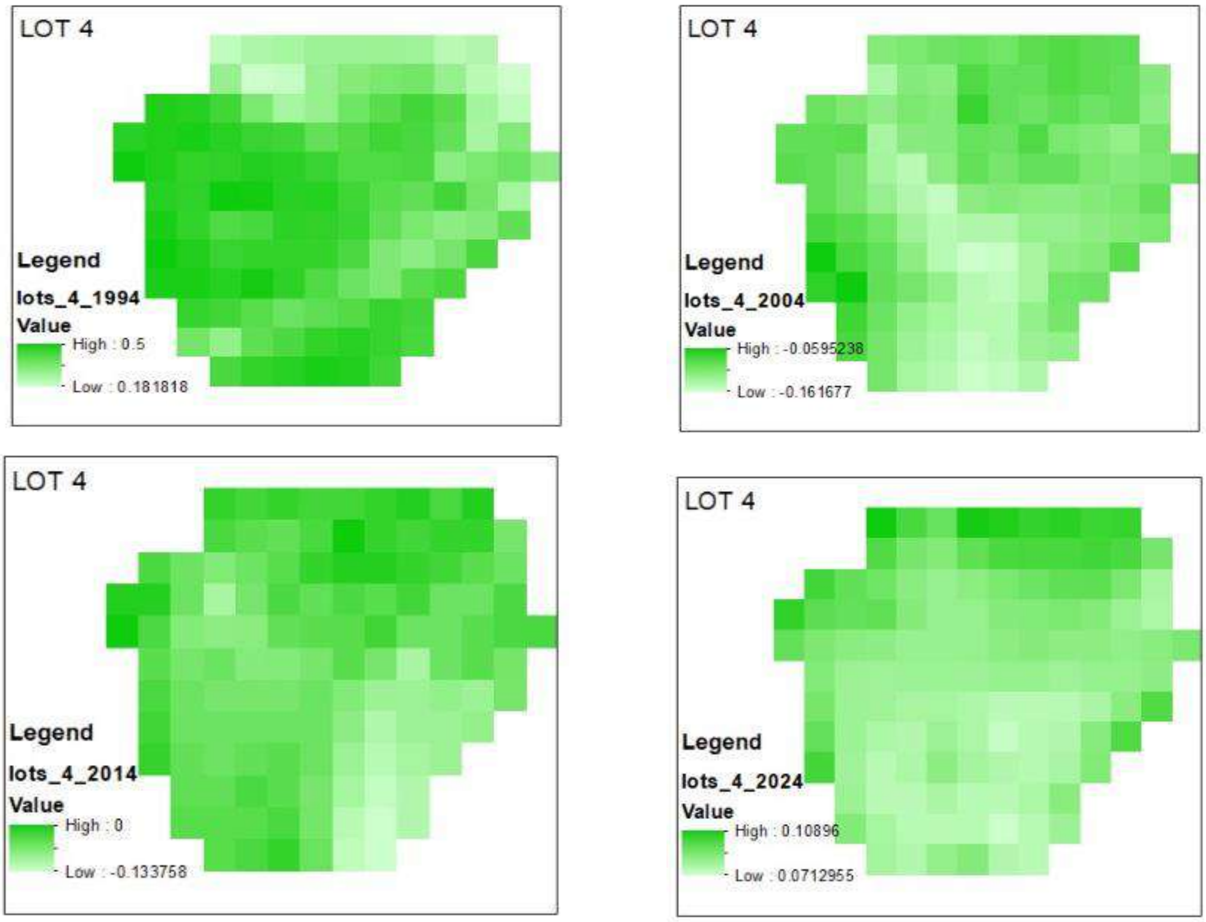


Figure 1a

Normalized Difference Vegetation Index (NDVI) for Nkeleoken-Alode LOT 04 Eleme (1994-2024)

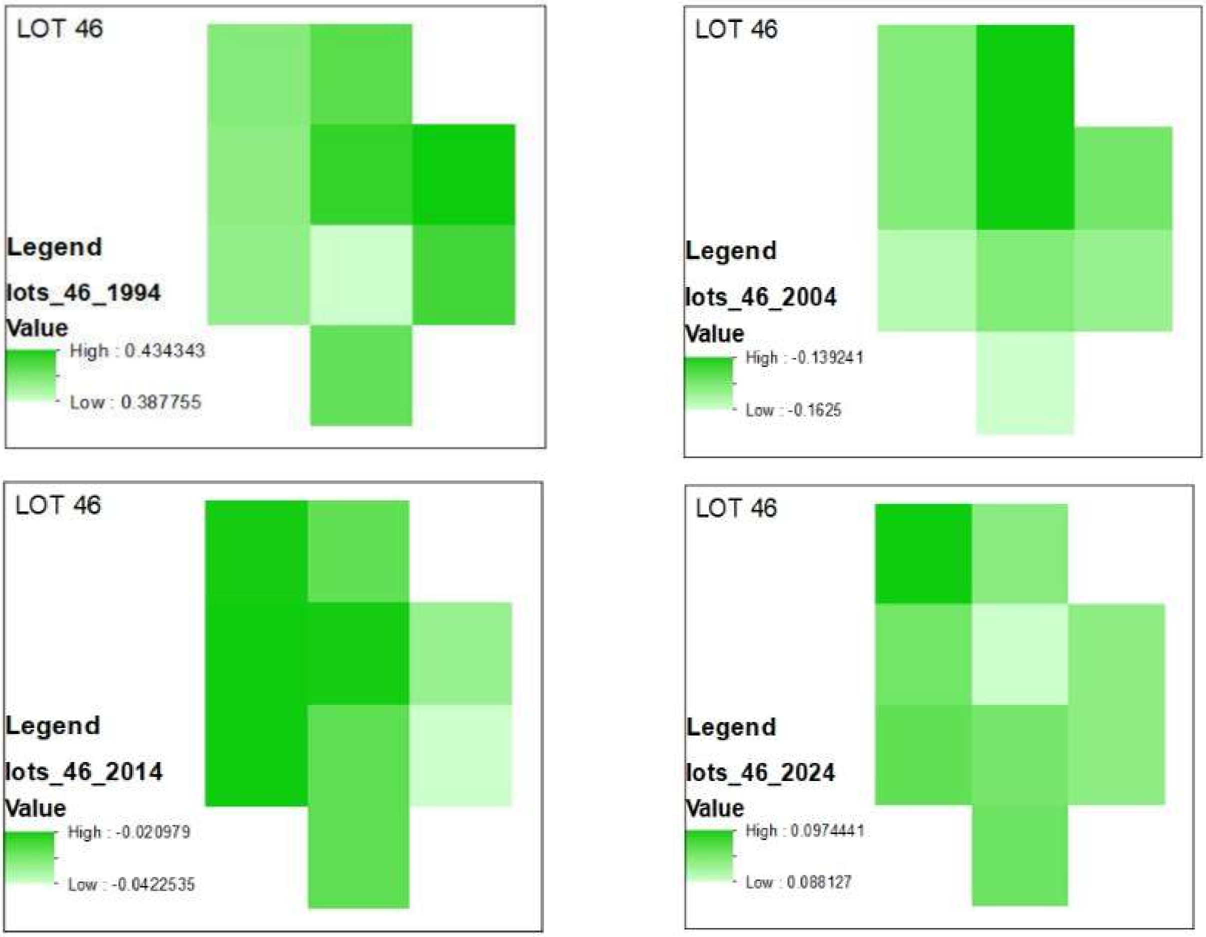
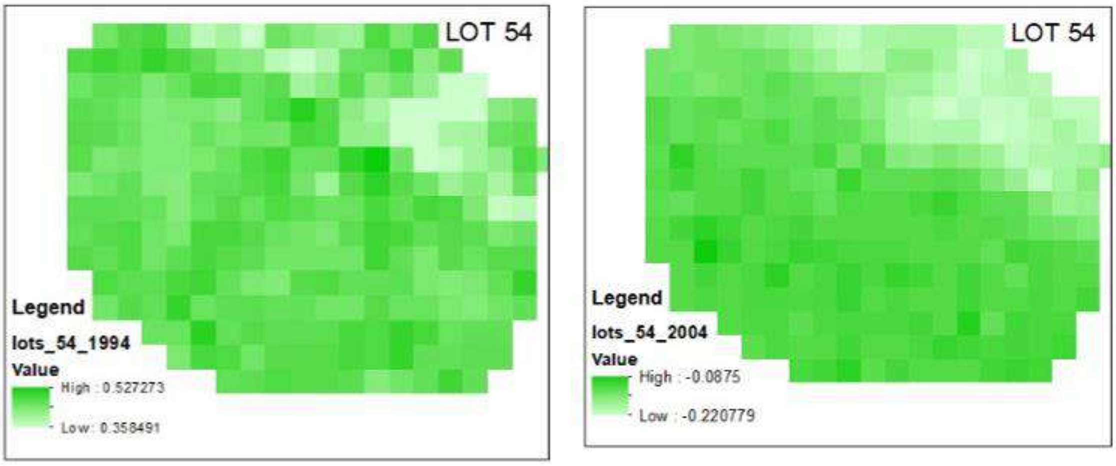


Figure 1b
Normalized Difference Vegetation Index (NDVI) for Elelenwo Manifold-Akpajo LOT 46 Eleme (1994-2024)



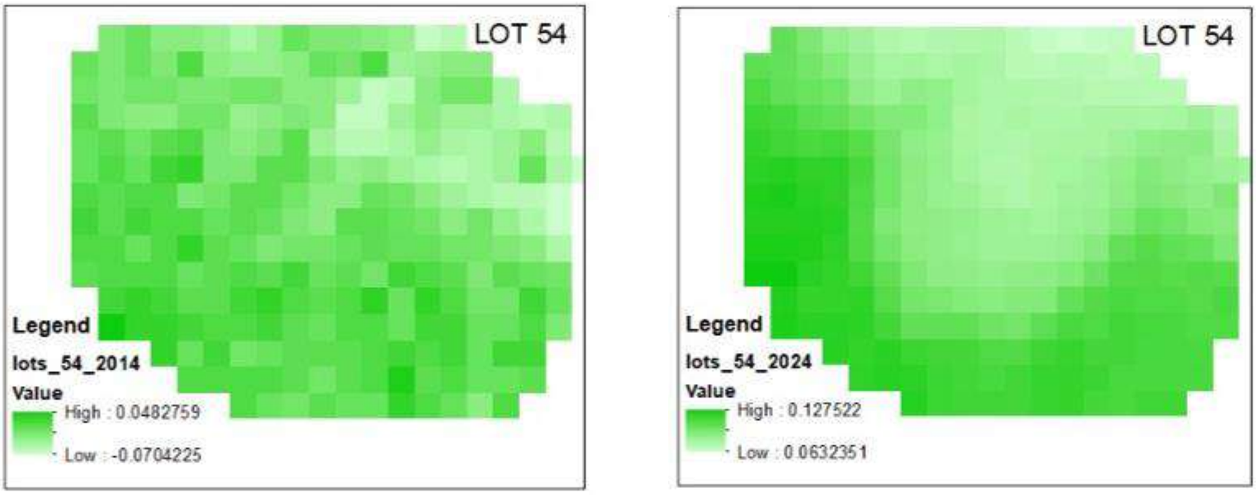


Figure 1c
Normalized Difference Vegetation Index for (NDVI) for Ajeokpori-Okuluebu LOT 54 Eleme (1994-2024)

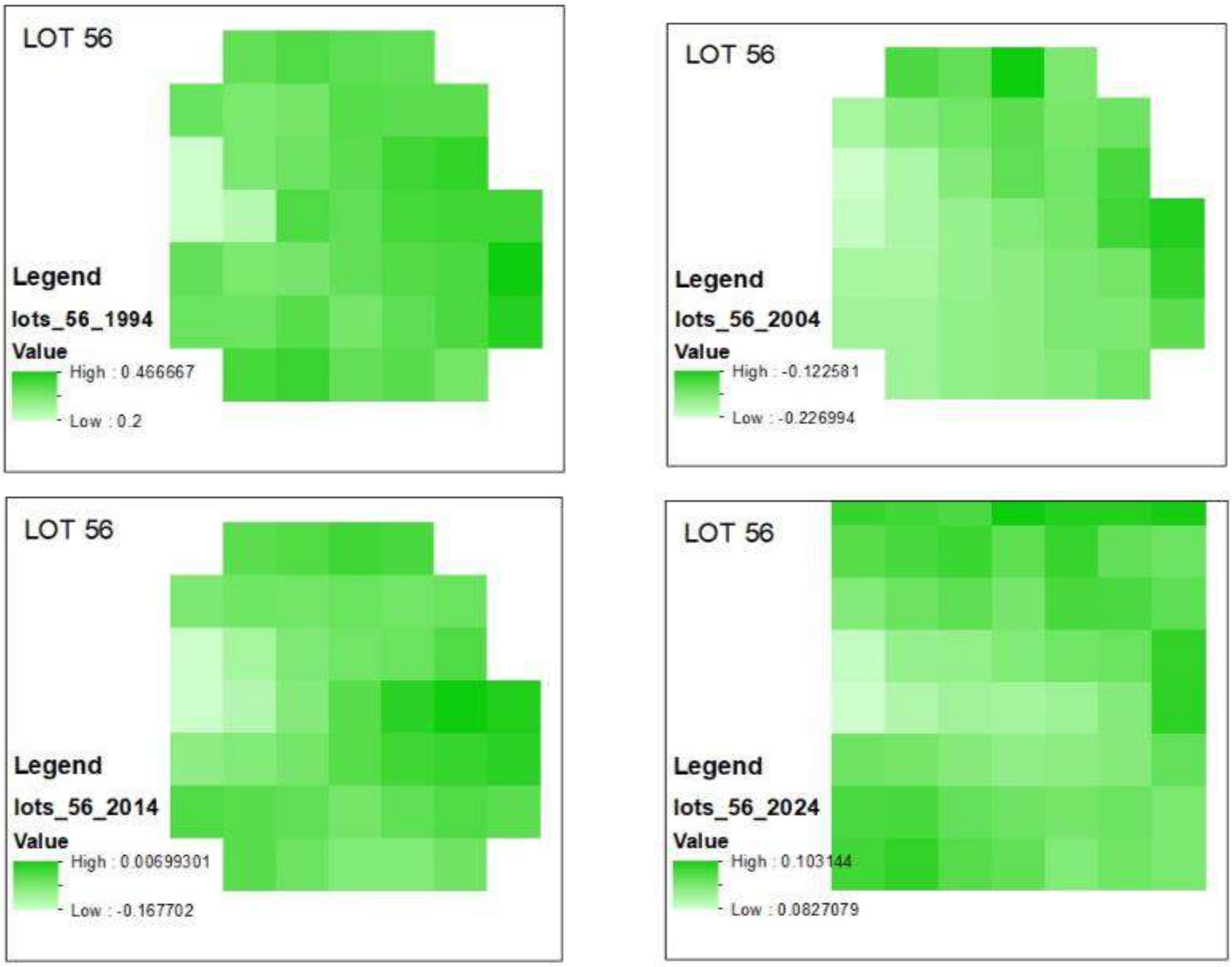


Figure 1d
Normalized Difference Vegetation Index (NDVI) for Elelenwo Manifold-Akpajo LOT 56 Eleme (1994-2024)

The 2014 value (0.0069) indicates minimal vegetation, yet by 2024, NDVI reaches 0.1031, suggesting partial restoration. The maps likely depict a spatial progression from degraded (dark tones) to partial regrowth (light green tones). The pattern is comparable to LOT 04, indicating similar degradation-recovery dynamics. Considering temporal patterns, general observations and ecological implications; all four locations experienced NDVI decline between 1994 and 2004, likely correlating with peak hydrocarbon pollution periods. However, NDVI values improved in all locations by 2024, suggesting ongoing vegetation recovery, albeit at varying rates. The spatial patterns of the NDVI maps reveal heterogeneous regrowth, with patches of vegetation recovery in 2024 more visible in LOT 54 and LOT 04 than in LOT

46. The Negative NDVI Values signifies non-vegetative surfaces, possibly oil-polluted soil, bare land, or built-up areas; particularly pronounced in the 2004 imagery for all locations. The $NDVVI_{(vigor)}$ and $NDVVI_{(variance)}$ (Table 2) corroborate these findings, showing that Ajeokpori-Okuluebu LOT 54 and New Elelenwo Manifold-Akpajo LOT 56 experienced the most significant positive changes in vegetation vigor between 2014 and 2024, whereas LOT 46 continues to lag. While all sites exhibit partial ecosystem recovery, differences in regrowth patterns highlight the need for location-specific remediation strategies and continued vegetation monitoring to achieve full restoration in Eleme's crude oil-impacted landscapes.

IV. DISCUSSION

The NDVI analysis was utilized to assess vegetation health and forest density in Eleme Local Government Area (L.G.A), Ogoni-land, serving as an indicator of overall flora ecosystem condition. The NDVI values, reflecting how vegetation absorbs and reflects light, showed significant environmental degradation due to crude oil-contamination from 1994 to 2004, with severe declines in vegetation vigor and variance across all sites. Full-scale bio-remediation efforts between 2014–2024 utilized products like Electro-Kinetic Action + KEEN® + Ors-SORB®, CLOGEN™, Micro SOLUTION®, and PRP®, which led to varying degrees of Total Petroleum Hydrocarbon (TPH) reduction, improvement in soil nutrient levels and vegetation health; where the NDVI analyses demonstrated positive trends in vegetation recovery, which reflects enhanced photosynthetic activity and improved plant cover with microbial diversity, indicating a continuous restored soil health and resilience. The analysis of the vegetation dynamics and patterns using NDVI Trends and NDVVI metrics across four remediated locations in Eleme (LOT 04, LOT 46, LOT 54, and LOT 56) over a 30-year period (1994–2024) revealed significant fluctuations in vegetation health and recovery. This analysis was deployed to assess forest density and the physical condition of vegetation within Eleme L.G.A.

This assessment also serves as an indicator of the overall health of the biodiversity (flora ecosystem), as established by previous studies of Ochege, (2014) and Eve *et al*. (1999). The analysis is grounded in the characteristic reflectance properties of vegetation as captured by satellite imagery, where the measure of the state of plant health is based on how the plant reflects light at certain frequencies; some waves are absorbed and others are reflected (Ugwu, 2022) and also considering chlorophyll, which is a health indicator, which strongly absorbs visible light from the Red Band, while the cellular structure of the leaves strongly reflect near-infrared light (NIR), which helps in characterizing vegetation condition, and a great potential for application in environmental monitoring (Ugwu, 2022). Healthy vegetation in the study area was found to absorb majority of the visible light emitted by the sun, while reflecting a substantial portion of near-infrared light. In contrast, unhealthy and degraded vegetation exhibited the opposite pattern, by reflecting more visible light and less near-infrared light (either, absorbing more near-infrared light) (Vermot *et al*., 2016 and Masek *et al*., 2006). The NDVI value of 0.5, corresponding to 26.32% for Nkeleoken Alode LOT 04 in 1994 suggest a healthy vegetation cover, which drastically dropped to -0.595238 (12.50%) in 2004, indicating severe vegetation loss and/or stress from crude oil-contamination in the area, while the 0.000 (0%) value in 2014 shows continuous vegetation stress with no significant recovery. The rise of NDVI in 2024 to 0.10896 (27.27%) after bio-remediation with a combination of Electro-Kinetic Action + Ors-SORB® and KEEN® (Electro-bioremediation), which gave an 86.89% TPH degradation, shows some level of positive vegetation response and recovery, post-remediation in LOT 04. This shows that, bio-remediation, not only aids in reducing contamination levels, but also plays a vital role in fostering conditions that allow vegetation regrowth, contributing to overall ecosystem recovery. In 1994, NDVI value of 0.434343 (21.05%) in Elelenwo Manifold Akpajo LOT 46 also indicates healthy vegetation. This, falling sharply to -0.139241 (35%) in 2004, reflects stress from crude oil-contamination and other environmental stressors, and in 2014 NDVI reaching -0.020978 (-66.67%) suggest further environmental degradation in the area, harsh environmental conditions inhibiting natural recovery or continuing struggle in the recovery process; but by 2024, the value increased to 0.0974441, corresponding to 22.73% and indicates gradual recovery following bio-remediation with CLOGEN™, which achieved 99.61% TPH reduction in the location.

Ajeokpori Well 3 Okuluebu LOT 54 showed a healthy vegetation state with NDVI value of 0.527273 (26.32%) in 1994, which declined to -0.0875 (22.50%) in 2004 as a result of crude oil-contamination stress, then the value rose again in 2014 to 0.0482759 (166.66%), showing significant improvement and rapid rebound in vegetation cover and health, in response to the pilot remediation project organized by UNEP in some locations in the area, prior to clean-up of Ogoni-land. This value further increased to 0.127522 (29.55%) after bio-remediation with Micro SOLUTION®, which reduced TPH concentration in the LOT to 73.89%, indicating sustained vegetation recovery, after bio-remediation. At New Elelenwo Manifold Akpajo LOT 56, the NDVI value of 0.466667, corresponding to 26.32% in 1994 also reflects good vegetation cover before crude oil-pollution. This decreased to -0.122581 (30%) in 2004, indicating the beginning of contamination in the area, then had a slow recovery in 2014 with NDVI value of 0.00699301 (0%). In 2024 after bio-remediation with Petroleum Remediation Product® (PRP®) which achieved 93.07% TPH reduction, NDVI value rose to 0.103144 (22.73%) signaling vegetation recovery. The environmental implication of this findings is that, the negative NDVI values in several locations in Eleme, between 2004 and 2014 indicate severe environmental degradation as a result of crude oil-contamination, and the positive shift in NDVI values in 2024 shows partial ecosystem restoration, following the application of the various bio-remediation products. The gradual increase in NDVI values across the various locations in Eleme, suggest that, the bio-remediation products have positively impacted vegetation recovery and ecosystem resilience. Nkeleoken Alode LOT 04, showing a significant NDVI increase in 2024, reaching 27.27% suggest a positive vegetation response after achieving 86.89% TPH reduction. Elelenwo Manifold Akpajo LOT 46, showing improvement in NDVI from 2004 to 2024, from a low of -0.139241 to 0.0974441 respectively, also suggest that, CLOGEN™ was effective not only in TPH reduction, but also in supporting vegetation recovery, but not as much as Ajeokpori Well 3 Okuluebu LOT 54, using Micro SOLUTION®. These variation indicates that, while some products are highly effective in TPH degradation, the degree of ecosystem recovery may vary due to other factors influencing vegetation regrowth. However, the NDVI values in 2024s are quite lower than the 1994s; indicating that, although there has been some environmental improvement after bio-remediation, we are yet to have their full return to pre-contamination era, and despite the recovery, the slower rates of improvement in certain locations like, Nkeleoken Alode LOT 04 and Elelenwo Manifold Akpajo LOT 46 indicate that, full ecosystem restoration needs time. This is in agreement with Principle-8 of Ecosystem Restoration, which state that "Ecological Restoration is part of a continuum of restorative activity" (Gann *et al.*, 2019), where it is seen as a journey and not a destination.

Besides, Ajeokpori Well 3 Okuluebu LOT 54, with a more significant increase in NDVI in 2024 demonstrates that, some products like Micro SOLUTION® may have shown more effectiveness in fostering quick vegetation growth than CLOGEN™ which had the highest TPH reduction and PRP®, which achieved second high TPH reduction in Eleme. It is therefore instructive that, high TPH reduction in any location does not always immediately correlate with rapid vegetation recovery or regrowth, indicating that, factors like soil type, product specificity, microbial diversity, time and duration of product application plays critical roles, and the positive NDVI trend in LOT 54 highlights the potential for successful bio-remediation to promoting significant vegetation restoration when the right products, after preliminary site characterization, location-specific strategies and site-specific factors are determined before remediation, and the right conditions and products are applied. The NDVI values when paired with TPH reduction results suggest that, locations with higher TPH reduction tend to show improved NDVI values over time, indicating better vegetation recovery, however, the rate of recovery varies, implying that, while bio-remediation is effective in reducing crude oil-contamination, achieving full ecosystem restoration is a more complex process influenced by multiple factors. The results generated from NDVI analysis helps in measuring forest density and vegetation physical condition in specific study locations in Eleme and Ogoni-land in general, which cumulatively represents a flora ecosystem health, as demonstrated by Ochege (2014), and a rejuvenating biodiversity in the Phase-1 Ogoni-land bio-remediated LOTs in Eleme. The data, drawn from satellite imagery and processed through standard remote sensing techniques, reflects both the extent of environmental degradation and the subsequent restoration response following bio-remediation. In Nkeleoken Alode LOT 04, both vegetation vigor and variance showing a significant decline of -219.0476% in 1994-2004, reflects severe vegetation stress from crude oil-contamination, while a -100% in vegetation vigor and variance in 2004-2014, indicates inability of ecosystem recovery in this epoch, and in 2014-2024, a vegetation vigor decline of -78.208% and variance slight increase of +10.896% suggest that, while overall vegetation health is still struggling, there are localized areas showing signs of improvement, which aligns with the slow recovery of NDVI value in the location. The drop in both vigor and variance in 1994-2004 for Elelenwo Manifold Akpajo LOT 46, also highlights severe vegetation decline, which is also consistent with impacts from initial contamination, while a further decrease in vigor of -104.83000537% and sharp decline in variance of -84.9331705% in 2004-2014, indicates continuous stress, but with more uniform degradation, and a further vigor decline of -77.56577315%, with a large negative variance of -564.4840078% in 2014-2024, shows that, the ecosystem is recovering in some patches and very unstable in vegetation distribution. Ajeokpori Well 3 Okuluebu LOT 54, showing decline in vigor and variance of -116.594819% in 1994-2004 also implies vegetation loss, and a further decline in vigor of -90.8442306% coupled with a more pronounced negative variance of -155.1724571% in 2004-2014, indicates that, although vegetation is still under stress, it is not uniformly affected across the entire location, while a decrease in vigor of -75.81480561% with a paired large positive variance of +164.1525067% in 2014-2024, suggest pockets of recovery where bio-remediation efforts by Micro SOLUTION® have been particularly effective. Finally, in New Elelenwo Manifold Akpajo LOT 56, the significant decline in both vigor and variance of -126.2673384% in 1994-2004, shows widespread vegetation stress. A further decrease in vigor of -98.501499% and variance decrease of -105.7048074% in 2004-2014, indicates continued stress with less variation in the remaining vegetation, while a slighter decline in vigor of -77.89773007% contrasted with a very high positive variance of +1,374.958566% in 2014-2024, shows that, the ecosystem is starting to show more variability, with some areas recovering well, while other areas are lagging behind. The cumulative NDVI values declined sharply between 1994 and 2004, falling from 1.928 to -0.409, indicative of extensive vegetative stress likely due to hydrocarbon pollution. Soil fertility and microbial populations suffered significantly, which resulted in diminished biodiversity and compromised ecosystem functions. A modest recovery was recorded in 2014 (NDVI = 0.0343), followed by a more substantial rebound in 2024 (NDVI = 0.4371). This progression suggests the effectiveness of site-specific remediation approaches and gradual ecosystem restoration. Specific Site-level analysis of LOT 54 treated with Micro Solution® recorded the highest NDVI values in both 1994 (0.5273) and 2024 (0.1275), with a strong positive rebound of +166.67% in 2014.

LOT 46 with CLOGEN™ experienced severe NDVI loss in 2004 (-0.1392) and lagged behind in recovery, although some positive trajectory was noted by 2024 (0.0974). LOT 56 PRP®-treated showed moderate vegetative stress initially, but achieved one of the best performances by 2024 (NDVI = 0.1031), supported by a sharp percentage increase in vegetation variance. The Vegetation Vigor and Variance ($NDVVI_{\text{(vigor and variance)}}$) data analysis further supports the trends observed. Between 1994 and 2004, all four sites recorded negative vegetation vigor and declining variance, ranging from -116.59% to -219.05%, reflecting severe vegetative damage. Between 2004 and 2014, recovery was marginal for most sites, with continued negative vigor, but between 2014 and 2024, a dramatic turnaround was recorded. The vegetation recovery and improved NDVI trends across multiple locations shows substantial recovery; where the positive trends from 2014 to 2024 demonstrates enhanced vegetation vigor and density, which are vital for soil stabilization and habitat restoration, but with reduced variability. LOT 54 registered a +164.15% increase in vegetation variance and LOT 56 recorded an outstanding +1,374.96% increase, representing the strongest vegetation recovery observed in the study area. The implications of this findings for Ecosystem Restoration is that, the NDVI and $NDVVI_{\text{(vigor and variance)}}$ trajectories underscore a clear pattern, where an initial period of ecosystem degradation driven by hydrocarbon contamination was followed by measurable ecological recovery post-remediation.

The observed gains, particularly in LOT 54 and LOT 56 highlights the role of effective bio-remediation strategies in accelerating vegetation regeneration and soil health recovery. These findings also validate the use of satellite-based indices in environmental monitoring and support the expansion of Micro Solution® and PRP®-based remediation protocols across similarly impacted landscapes in the Niger Delta. While all locations showed positive NDVI trends in 2024, recovery rates varied; for example, Micro SOLUTION® in LOT 54 fostered greater vegetation regrowth than PRP® in LOT 56, despite PRP® achieving a higher TPH reduction. This highlights that TPH reduction does not always directly correlate with rapid vegetation recovery, as factors like soil type, microbial diversity, and product suitability significantly influence outcomes. Vegetation Vigor and Variance Indices further revealed the spatial heterogeneity of recovery. Locations like New Elelenwo Manifold-Akpajo LOT 56 displayed high variance in 2014–2024, suggesting patchy recovery.

Meanwhile, Nkeleoken Alode LOT 04 and Elelenwo Manifold Akpajo LOT 46 showed slow but steady improvement, aligning with observed NDVI increases. Understanding these differences aids in refining the selection of bio-remediation approaches for various soil-types and contamination levels in Eleme and Ogoni-land in general, and the ultimate measure of success lies in the extent to which these efforts translates into visible ecological recovery, as evidenced by vegetation regrowth. Overall, while bio-remediation has initiated ecosystem restoration in Eleme, full recovery remains a gradual process requiring time, adaptive strategies, and continuous monitoring. The findings underscore the importance of tailored, site-specific remediation approaches to optimize vegetation regrowth and ecological resilience in Ogoni-land.

V. CONCLUSIONS

Remediation involves not just the removal of contaminants or pollutants from hydrocarbon contaminated soils, but about protecting the environment and everything that interacts in it. It is generally believed that remediation is a beneficial activity, almost regardless of how it is undertaken, but it is now apparent that most remediation activities are not sustainable per. Since remediation does not always result in complete mineralization of organic compounds, rather, they are transformed to metabolites of unknown persistence and toxicity, the target should be attaining a condition of the soil, in which, the functionality of the soil for human, animal, and plant life are not threatened. The environment around us; which constitutes a life support system for man and all other components of the ecosystems is where we get food to eat, water to drink, air to breathe and all necessities of day-to-day life. Environmental degradation is not inevitable; we have the power to reverse the harm it creates, and restore the earth. The key to resolving this issue lies with total environmental and ecological restoration. This study assessed the vegetation health and ecosystem recovery in crude oil-impacted sites within Eleme, Ogoni-land, through a 30-year NDVI change detection analysis (1994–2024), focusing on four key remediation locations. The NDVI analysis has offered critical insights into the impact of crude oil-contamination and subsequent bio-remediation efforts on the vegetation health of Eleme in Ogoni-land. The findings revealed a sharp decline in NDVI values in the early years following oil contamination, highlighting the devastating impact of hydrocarbon pollution on vegetative cover and environmental health. However, a gradual increase in NDVI values from 2014 to 2024 across all sites though at different rates indicates partial vegetation regeneration, corresponding with bio-remediation interventions. The incorporation of $NDVVI_{\text{(vigor)}}$ and $NDVVI_{\text{(variance)}}$ further enhanced the interpretation of vegetation recovery dynamics, providing insight into not only the extent of regrowth but also the variability and resilience of vegetative health across space and time. These indices demonstrate that, while bio-remediation has yielded tangible ecological benefits, the pace and completeness of recovery vary significantly by location, reflecting differences in contamination levels, remediation techniques, soil structure, and broader environmental interactions. The vegetation analysis validates the utility of remote sensing in long-term ecosystem monitoring. The progressive NDVI and NDVVI $_{\text{(vigor and variance)}}$ improvements from 2004 onward affirm the success of bio-remediation in Eleme, underscoring its potential replication in other impacted areas of Ogoni-land. These results support the argument for sustained remediation funding and the use of vegetation indices as critical tools for environmental assessment in oil-polluted regions. Importantly, this study underscores that remediation is not simply about pollutant removal, but about restoring ecosystem functionality, biodiversity, and environmental services critical for human and ecological wellbeing. Despite the visible gains, the incomplete restoration of pre-contamination NDVI levels suggests that current remediation approaches, while beneficial, may not be fully sustainable or sufficient for long-term ecological resilience. These insights advocate for more integrative and adaptive strategies, linking soil quality, microbial regeneration, vegetation health, and hydrological balance.

IV. RECOMMENDATIONS

There should be implementation of Post-Remediation Monitoring Programs, where all the bio-remediated sites under the Eleme Phase-1 (Batches 1 and 2) project undergo structured post-close-out monitoring to assess long-term ecosystem recovery. The key indicators should include NDVI trends, soil nutrient composition, microbial diversity, and plant community structure. Secondly, adopt Integrated Remediation Approaches where future strategies should move beyond contaminant reduction to embrace ecologically integrated bio-remediation techniques, which incorporate soil revitalization, native vegetation restoration, and microbial enhancement. More-so, routine satellite-based NDVI assessments should be institutionalized to track vegetation trends. This will enable low-cost, large-scale, and timely monitoring of environmental health, and incorporating NDVVI Tools into Environmental Audits, where the use of $NDVVI_{(vigor)}$ and $NDVVI_{(variance)}$ should be standardized in environmental recovery audits, offering quantitative benchmarks for measuring ecological stability and vegetation vitality. Besides, environmental regulators and project implementers should integrate findings from NDVI analyses into policy frameworks to enforce sustainability standards, monitor compliance, and improve remediation outcomes. Furthermore, academic and research institutions should be encouraged to undertake longitudinal ecological studies in Ogoni-land, building a body of knowledge that tracks recovery trajectories over multi-decadal scales. Finally, local communities should be engaged in ecosystem restoration efforts through awareness programs, co-monitoring initiatives, and capacity-building on sustainable land use practices. These recommendations, if implemented, can significantly improve the effectiveness and sustainability of remediation projects in Eleme and similar oil-impacted regions, ultimately contributing to the restoration of biodiversity, ecosystem services, and human wellbeing in the Niger Delta.

REFERENCES

Abam, K. O., Daka, E. R., & Egobueze, F. (2023). Degradation of total petroleum hydrocarbon (TPH) in a polluted site at Idu-Ekpeye, Rivers State. *Journal of Geosciences and Environmental Research (JOGER)*, *3*(1), 1–14.

Abam, T. K. S. (2001). Regional hydrological research perspective in the Niger Delta. *Hydrological Science Journal*, *46*(1), 13–25. https://doi.org/10.1080/02626660109492797

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, *35*, 869–890. https://doi.org/10.1007/s13593-015-0285-2

Anifowose, B. (2008). Assessing the impact of oil and gas transport on Nigeria's environment. *U21 Postgraduate Research Conference Proceedings*, *1*. University of Birmingham UK.

Ansah, C. E., Abu, I.-O., Kleemann, J., Mahmoud, M. I., & Thiel, M. (2022). Environmental contamination of a biodiversity hotspot—Action needed for nature conservation in the Niger Delta, Nigeria. *Sustainability*, *14*, 14256. https://doi.org/10.3390/su142114256

Bodo, T., & David, L. K. (2018). The petroleum exploitation and pollution in Ogoni, Rivers State, Nigeria: The community perspective. *European Scientific Journal*, *14*(32), 197–212.

DeFries, R., Hansen, A., Newton, A. C., & Hansen, M. C. (2005). Increasing isolation of protected areas in tropical forests over the past twenty years. *Ecological Applications*, *15*, 19–26. http://dx.doi.org/10.1890/03-5258

Egobueze, F. E., Ayotamuno, J. M., Iwegbue, C. M. A., Okparanma, R. N., & Isitekhale, H. H. E. (2019). Effects of organic amendment on some soil physicochemical characteristics and vegetative properties of *Zea mays* in wetland soils of the Niger Delta impacted with crude oil. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(Suppl 1), 423–435. https://doi.org/10.1007/s40093-019-00315-6

Ellis, E. A., & Porter-Bolland, L. (2008). Is community-based forest management more effective than protected areas? A comparison of land use/land cover change in two neighboring study areas of the central Yucatán Peninsula, Mexico. *Forest Ecology and Management*, *256*, 1971–1983. http://dx.doi.org/10.1016/j.foreco.2008.07.036

ERDAS. (2011). *Earth resource data analysis software*. ERDAS.

Eve, M. D., Havstadt, K. M., & Whitford, W. G. (1999). Applying satellite imagery to triage assessment of ecosystem health. *Environmental Monitoring & Assessment*, *54*(3), 205–227. http://dx.doi.org/10.1023/A:1005876220078

Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., et al. (2019). International principles and standards for the practice of ecological restoration. Second edition. *Restoration Ecology*, *27*, S1–S46.

Gayton, D. V. (2001). *Ground work: Basic concepts of ecological restoration in British Columbia*. Southern Interior Forest Extension and Research Partnership, Kamloops, B.C. SIFERP Series 3.

Klaus, V. H., & Kiehl, K. (2021). A conceptual framework for urban ecological restoration and rehabilitation. *Basic and Applied Ecology*, *52*, 82–94.

Masek, J. G., Vermote, E. F., Saleous, N., Wolfe, R., Hall, F. G., Huemmrich, F., Gao, F., Kutler, J., & Lim, T. K. (2006). A Landsat surface reflectance data set for North America, 1990–2000. *IEEE Geoscience and Remote Sensing Letters*, *3*, 68–72.

Murdiyarso, D., & Skutsch, M. (2006). Community forest management as a carbon mitigation option: Case studies. CIFOR.

NEITI. (2021). *Oil and gas industry report*. Nigeria Extractive Industries Transparency Initiative (NEITI). NEITI Secretariat, NEITI House, Abuja. https://www.neiti.gov.ng

NPC. (2006). *National Population Census of Nigeria*. National Population Commission.

Ochege, F. U. (2014). *Geospatial assessment of forest degradation in Sagbama, Niger Delta region of Nigeria* (MSc thesis). University of Edinburgh, Scotland.

Omo-Irabor, O. O., Olobaniyi, S. B., Akunna, J., Venus, V., Maina, J. M., & Paradzayi, C. (2011). Mangrove vulnerability modelling in parts of western Niger Delta, Nigeria using satellite images, GIS techniques, and spatial multi-criteria analysis (SMCA). *Environmental Monitoring and Assessment*, *178*, 39–51.

Onuoha, F. C. (2008). Oil pipeline sabotage in Nigeria: Dimensions, actors, and implementations for national security. *African Security Review*, *17*(3), 23–28.

Onyia, N., Balzter, H., & Berrio, J.-C. (2018). Normalized difference vegetation vigor index: A new remote sensing approach to biodiversity monitoring in oil-polluted regions. *Remote Sensing*, *10*, 897–900.

Organisation for Economic Co-operation and Development (OECD). (2006). *Test No. 227: Terrestrial plant test: Vegetative vigor test*. OECD.

Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. In *Third Earth Resources Technology Satellite-1 Symposium*, Volume I: Technical presentations (NASA SP-351, pp. 309–317).

Sam, K., Zabbey, N., Vincent-Akpu, I. F., Komi, G., Onyagbodor, P. O., & Babatunde, B. B. (2023b). Socio-economic baseline for oil-impacted communities in Ogoni-land: Towards a restoration framework in Niger Delta, Nigeria. *Research Square*, *5*, 1–32. https://doi.org/10.21203/rs.3.rs-2583759/v1

Sonwalkar, V. S., Reddy, A., & Carpenter, D. L. (2010). Magnetospherically reflected, specularly reflected, and backscattered whistler mode radio-sounder echoes observed on the IMAGE satellite: 2. Sounding of electron density, ion effective mass (meff), ion composition (H+, He+, O+), and density irregularities along the geomagnetic field line. *Journal of Geophysical Research: Space Physics*, *115*(A12), 610–615.

SURF. (2009). *Integrating sustainable principles, practices and metrics into remediation projects*. Sustainable Remediation Forum (SURF). *Remediation Journal*, *19*(3), 5–114. https://doi.org/10.1002/rem.20210

Ugochukwu, C. N. C., & Ertel, J. (2008). Negative impacts of oil exploration on biodiversity management in the Niger Delta area of Nigeria. *Impact Assessment and Project Appraisal*, *26*, 139–147.

Ugwu, O. L. (2022). GIS-based assessment of the thematic land cover dynamics and vegetation health in Warri South, Delta State. (Unpublished master's thesis). Department of Geography, Nasarawa State University, Keffi.

UNDP. (2012). *The future we want: Biodiversity and ecosystems—Driving sustainable development*. UNDP Biodiversity and Ecosystems Global Framework 2012–2020.

USEPA. (2012). *Ecological effects test guidelines OCSPP 850.4150: Vegetative vigor*. United States Environmental Protection Agency.

Vermot, E., Justice, C., Claverie, M., & Franch, B. (2016). Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sensing of Environment*, *185*, 46–56.

Vrieling, A. (2006). Satellite remote sensing for water erosion assessment: A review. *CATENA*, *65*, 2–18.

World Bank. (1995). *Defining an environmental development strategy for the Niger Delta*. The World Bank.