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(Research Article)

Bio-remediation of crude oil-contaminated soils in Eleme, Ogoni-land using CLOGEN, MicroSORB®, PRP® and a combination of Electro-Kinetic Action+KEEN®+Ors-SORB plus®

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Abstract

This study evaluated the efficiency, effectiveness and ecological impacts of bio-stimulation, bio-augmentation, and electro-bio-remediation interventions in phase-1 Ogoni-land remediated areas, focusing on the rate of Total Petroleum Hydrocarbon (TPH) degradation, soil health, soil physicochemical and biological properties across four selected locations in Eleme, using CLOGEN, MicroSORB®, Petroleum Remediation Product® and a combination of Electro-Kinetic Action plus KEEN® and Ors-SORB plus®. Nkeleoken Alode LOT 04 with the largest total area of 0.64Ha and remediated soil volume of 46,100m3 using Electro-Kinetic Action + Ors-SORB plus® + KEEN® had initial TPH value of 2,021 mg/kg reduced to 265 mg/kg, showing significant degradation with 86.89% efficiency with 13.11% residual hydrocarbons left in the soil, while Elelenwo Manifold, Akpajo LOT 46 with moderate total area of 0.3943Ha and soil volume of 12,100m3; a smaller area compared to LOT 04 had higher efficiency in TPH degradation, highlighting the effectiveness of CLOGEN® with 99.61% degradation leaving behind 0.39% residual contamination; where initial TPH value of 6,600 mg/kg was reduced to 26 mg/kg, showing the most efficient location, cleanest site, post-remediation, and high level of restoration. Ajeokpori Well 3, Okuluebu LOT 54 with smaller area of 0.0854Ha and moderate soil volume of 8,300m3 demonstrated a localized remediation effort with a focus on smaller-scale impact, where initial 4,550 mg-TPH/kg-Soil was reduced to 1,187.87 mg-TPH/kg-Soil, indicating 73.89% efficiency of MicroSORB®, with 26.11% residual contamination left in the soil after-remediation, while New Elelenwo Manifold, Akpajo LOT 56 with a medium area of 0.4139Ha and small soil volume of 9,600m3; balancing land coverage and soil volume for remediation, had initial TPH value of 5,600 mg/kg reduced to 402.29 mg/kg, highlighting degradation efficiency of 93.06% with 6.94% residual hydrocarbons still left in the soil after-remediation, showing a strong performance of PRP® and also representing a high level of restoration. Laboratory analyses of soil microbial count in bio-remediated locations show mean values for THB and THF of 417,000±0.9578622 and 36,000±0.5244044, and HUB and HUF of 4,125±0.5452446 and 2,800±0.1290994; while macronutrients of Nitrogen (N), Phosphorus (P), and Potassium (K) showed marked improvements in remediated areas post-bio-remediation; with N values of 1.091 – 4.299 mg/kg and 1.278 mg/kg for control, K values between 15.423 – 45.789 mg/kg and 0.652 mg/kg for control, and P values of 0.321 – 2.321 mg/kg and 0.639 mg/kg control, with specific locations displaying nutrient levels indicative of enhanced soil fertility. Nutrient distribution variability across the sites suggests that, while some areas have shown significant soil improvement, others may require site specific targeted interventions for uniform ecological restoration.

Keywords: Bio-stimulation; Bio-remediation; Electro-Kinetic Action+KEEN®+Ors-SORBplus®; Manifold; Restoration; Nutrients

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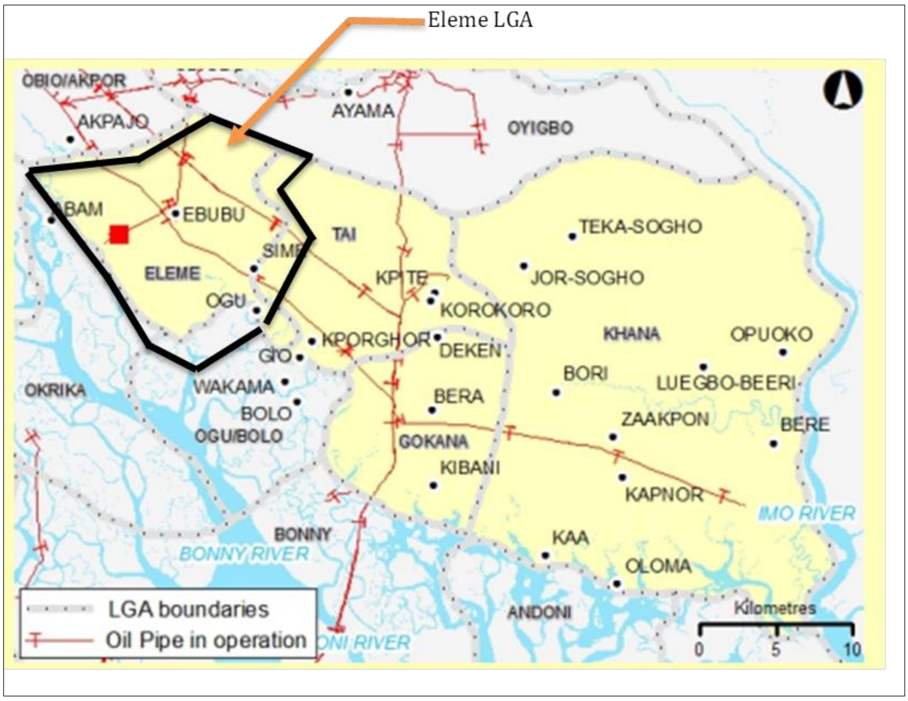
1. Introduction

The territory known as Eleme constitutes one of the Local Government Areas out of the four (4) in Ogoni-land of the Niger-delta and the twenty-three (23) that make up Rivers State. It is 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 120km^{2} (www.riversstateapps.ng-Eleme Local Government Council) (Fig.1), and projected population of 298,986 (Bodo & David, 2018 & National Population Commission (NPC), 2006). Oil exploration in the area began in the 1957s (www.riversstateapps.ng-Eleme Local Government Council), with the establishment of extensive oil production facilities and installations. However, like the rest of the Niger-delta, the presence of exploration facilities has led to multiple spill incidents arising from different causes like equipment failure, sabotage, artisanal refining and many others for over five decades, and in Ogoni-land where Eleme is located, many decades of oil activities have caused major pollution across a huge number of sites and soils. The Federal Government of Nigeria (FGN) created the Hydrocarbon Pollution Remediation Project (HYPREP) under the Federal Ministry of Environment (FMoEnv) to oversee the implementation of the recommendations in the UNEP report, and to coordinate the remediation and restoration of Ogoni-land, called the "UNEP Ogoni-land PROJECT". Remediation works in Eleme, as adopted by HYPREP were generally on-site, ex-situ soil treatment by bio-remediation technology; which entailed contaminated soil excavation, soil homogenization with bio-remediation products, setting and monitoring in engineered bio-cells until Total Petroleum Hydrocarbons (TPH) values are reduced to approved regulatory limits, and depending on the bio-remediation technique deployed, period of active soil treatment was within twelve (12) to eighteen (18) months.



(Source: UNEP, 2011).

Figure 1 Map of the Study Area - Eleme Local Government Area of Rivers State, Nigeria

The selected study locations in Eleme, as delineated by HYPREP; comprising of Phase 1, Batches 1 and 2 Ogoni-land restoration projects, encompassed twenty-three (23) locations (referred to as LOTs), which are unevenly distributed in the Local Government Area (LGA). Four (4) of the locations; Nkeleoken-Alode LOT 04, where a combination of Electro-Kinetic Action (Electro-bioremediation), Ors-SORB plus® and KEEN® were used, Elelenwo Manifold, Akpajo LOT 46, where Bio-stimulation and Bio- augmentation Techniques with the use of a locally formulated product, CLOGEN, Ajeokpori Well 3, Okuluebu 2, Ogale LOT 54, where Bio-stimulation and Bio-augmentation Techniques with the use of MicroSORB®, and Elelenwo Manifold, Akpajo LOT 56, where bio-stimulation with the use of Petroleum Remediation Product®(PRP®) were deployed as bio-remediation products were chosen for this study. The choice of these locations is informed by the efficiency of the different remediation-products deployed for TPH degradation and soil restoration; as evident in the base-line data gotten from the laboratory analysis for close-out of the LOTs, the physical state of the soil/environment, the nutrient levels and microbial counts, post-remediation. Environmental Guidelines and Standards for the Petroleum Industry (EGASPIN) section 2.11.2 - Oil Spill Contingency Planning on Remediation and Rehabilitation of affected areas; any restorative process to be embarked upon should adequately evaluate the biological sensitivities of the impacted environment, and a post spill impact assessment study conducted to determine the extent of damage before close-out, and the estimated duration for complete recovery of such an environment (EGASPIN, 2002).

Studies have shown varying depths and non-uniform layers of silty-clay, silty-sand, clay, and coarse sand in Niger-delta soils (United Nations Environment Program (UNEP), 2011 & Youdeowei & Nwankwoala, 2011). Just like Giadom & Tse (2015) and Bierrens & Geerts (2014) had stated: Abam *et al*. (2022) in their work; Post Close-out Evaluation of Hydrocarbon Impacted Soils in Idu-Ekpeye, Rivers State established that, soils are limited in their ability to absorb, degrade or attenuate the effects of degradation or contamination, so, the ultimate goal for soil remediation and contaminated land restoration is to ensure full elimination of the contaminants and restoration of soil quality to achieving complete functionality for human, animal and plant life. Once oil has come ashore or spilled on land, the options available and the problems are quite different. So, clean-up techniques to be deployed may be intrinsically quite damaging to the environment, and the benefits of cleaning that area must be balanced carefully against the dis-benefits of the damage to be caused by the clean-up activity. Soils impacted with crude oil require restoration to their natural state, so that, they can support plant growth and other ecosystem services (Egobueze *et al*., 2019), and the frame work to be adopted should harness all strategies that will guarantee complete restoration of the environment and guarantee the wellbeing of man and the biota. According to Cocârtă *et al*. (2017); "Remediation of polluted or contaminated soils can be achieved by physical, chemical or biological methods; however, the suitability of a site/soil for clean-up and bio-remediation depends not only on the contaminant's biodegradability but also on the soil/site's geological and chemical characteristics. Remediation is not an instantaneous event, rather, it is a scientific process that requires adequate time and strict observation of requisite processes and procedures, to achieving the set remediation goal and sustainable benefits to humans and the environment (Abam *et al*., 2022). The main purpose of remediation is to add value to the net environmental benefits of the area, and not to cause more harm to the environment post-remediation, by the wrong actions we take. If the reason for remediation is to remove risk to sensitive ecological receptors, enable redevelopment of the land, repair failed corrective actions and return the land to its natural state with all forms of life rejuvenated, then the remediation-products deployed in the restoration processes should be the ones that will enhance soil health and guarantee ecosystem restoration and biodiversity rejuvenation. Clean-up of spills in contaminated environments should be done in such a manner that, it should not cause additional damage to the already impacted environment, hence, clean-up methods should be designed to suit the environment within which the spill occurred, and careful examination and evaluation of socioeconomic and ecological sensitivity and behavior of the oil in the area need to be considered also.

2. Material and methods

The methodology deployed for the assessment was empirical. Soil samples were collected before commencement of remediation in the year 2019, following the provisions of Statutory Instrument (S.I.) 25 of the oil spill recovery, clean-up, remediation, and damage assessment regulations of the National Oil Spill Detection and Response Agency (NOSDRA, 2011) and initial TPH values were obtained (Table 1). These served as secondary data and baseline information for this study. Nkeleoken-Alode LOT 04, located at the Western flank of Eleme LGA of Rivers State, Nigeria with reference coordinates N04o46'3.7" and E007o06'55.7" is a sedimentary environment, made up of unconsolidated formation, with subsurface lithology of silty-sand, silty-clay, clay, sandy-clay, clayey-silt and sandy-silt down to about 8.6 mbgs depth, with groundwater table at 8 mbgs to 11.18 mbgs (Fig. 2a). Electro-bioremediation technique known as Electro-Kinetic Action was deployed to treat the contaminated soil. This technology entailed, electro-osmosis and electro-migration process, where external electrons were supplied through installed electrodes to the subsurface contaminated media (with crude oil); thereby aiding migration of anions and cations. This process was carried-out in-situ without the use of any engineered bio-cell. The excavated soil was homogenized with Ors-SORB®, and KEEN® for improved porosity and nutrient distribution, and the contaminants of concern (CoC) were desorbed from the soil surface. KEEN® is an ecologically biodegradable product from Thailand, composed of 94.2%(w/w) DI Water, 5%(w/w) Blends of Bacillus spores, and 0.8%(w/w) Micro-nutrients and Bio-accelerator, adjudged to be non-carcinogenic, non-flammable and completely soluble in water, no volatile organic compounds (VOCs), pH between 6.80-11.00 (alkaline), stable and has no adverse effects in the environment. Ors-SORB® on the other hand is an Absorbent for cleaning and recovery of oil produced from Finland; a biodegradable product composed of 40-45% Water, 20-30% Carbon, 20-30% Nitrogen, 1-5% Ammonium sulphate, and 0-1% Urea, with pH range of 4-6 (acidic), non-hazardous, non-toxic, not eco-toxic, chemically stable, not reactive under normal use, not classified as acutely toxic, not carcinogenic, not mutagenic, and not bio-accumulative. These products enhanced biodegradation in the presence of active hydrocarbon utilizing microbes and oxygen. Elelenwo Manifold (M/F), Akpajo LOT 46 also located at Northern flank of Eleme LGA with reference coordinates N04.8470o and E7.1117o (Fig. 2b) of same geologic terrain as LOT 04, covering a total area of 3,940m2 with soil volume of 12,100m2; soil treatment was in an engineered bio-cell through enhanced bio-remediation (Bio-stimulation and Bio-augmentation) which involved excavation and homogenization of the soil with CLOGEN, and the homogenized soil was piled in the lined bio-cell until residual TPH reduced below the risk-based screening levels

(RBSL). The product, CLOGEN, in liquid form, is manufactured in Nigeria by ANDELSTA LTD, a patent with the Federal Republic of Nigeria with Patent No.: R.16273, compose of Electro-Ionic Biopolymers (EIABP) 14% concentration, Polysaccharides cellulose 16%, Sodium Poly-Aromatic Alkylated Sulphonates 10%, Dispersants 0.999%, Hydrogen 14%, Sulphur 0.001%, and Carbon 45%; highly biodegradable, non-bio-persistent, non-bio-accumulative in the environment, with no eco-toxicological effects. The product has pH of 8.5-9.5 (acidic), relative density of 1.01124g/m3, highly soluble at 25oC, not flammable, non-hazardous, stable under normal conditions, non-carcinogenic, non-teratogenic, can be stored at ambient condition of (30±5.0oC), produces CO2, SO2, CH4, and Carbon as by-products at combustion, and does not decompose at low or high temperature, with good penetration and mobility in soils properties. The product contained cultured hydrocarbon degraders that were locally developed and patented to aid bio-augmentation in the remediation process and was diluted with water at the ratio of 1:6, while the application rate was 1 liter per cubic meter of soil. Ajeokpori Well 3, Okuluebu 2 LOT 54 is among the cluster of sites at Okuluebu 2, which is located at the North-eastern flank of Eleme LGA of Rivers State, Nigeria with reference coordinates N4.8279o and E7.1583o (Fig. 2c). Remediation was achieved ex-situ in a bio-cell covering an area of 854m2 and soil volume of 8,300 m3, which involved; excavation, homogenization with MicroSORB®, a bio-stimulation and bio-augmentation nutrient. MicroSORB 988S, a Product of MICRO Powders, INC of Tarrytown – New York are Micronized Polymers and Waxes, in powder form.; composed of Synthetic Wax, Calcium Silicate, and Silica. EC Regulation No. 1272/2008 classifies these Product as a non-hazardous substance or mixture, stable at normal conditions, incompatible with strong oxidizing agents and Amines, with relative density 1.31g/cc, and flash point > 450oF (232oC). It is a combustible solid, highly flammable, non-carcinogenic, not soluble in water, non-hazardous, and not considered a marine pollutant, but may emit oxides of carbon. This product, contained three components, which were mixed at varying proportions before being added to the soil.

Figure 2a Map of Nkeleoken Alode, Eleme LOT 04

Figure 2b Map of Elelenwo Manifold Akpajo LOT 46

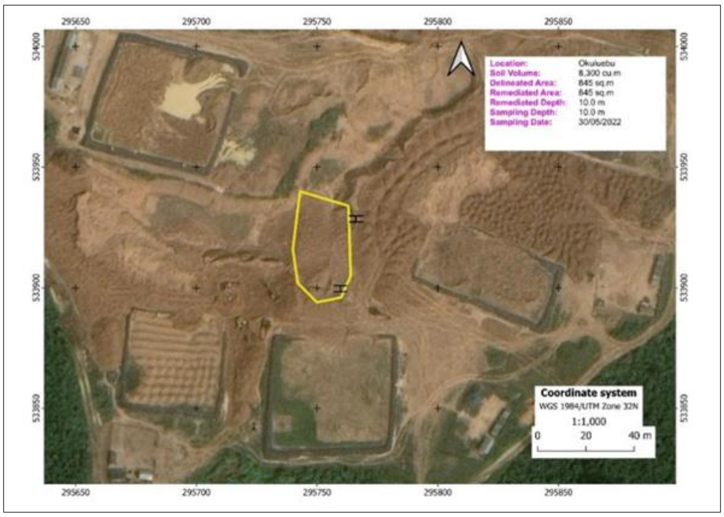


Figure 2c Map of Ajeokpori Well 3 Okuluebu 2, Ogale **-** Eleme

Figure 2d New Elelenwo Manifold Akpajo Eleme LOT 56 LOT

The components, AT-CAT (2.7L), AT-BOOST (0.006kg), and AT TRACE (0.003kg) were used per cubic meter of soil for bio-augmentation and bio-stimulation. New Elelenwo Manifold (M/F), Akpajo LOT 56 also located at the Northern flank of Eleme LGA of Rivers State, Nigeria with reference coordinates N4.8488° and E7.1101° (Fig. 2d) remediation of the silty-clay soil was achieved ex-situ in a bio-cell covering an area of 4,139m^2 with soil volume of 7,636m^3. The processes involved excavation, homogenization of the soil with Petroleum Remediation Product® (PRP®), an organic enhancer which activated microbial degradation of petroleum. PRP® is a Product of Universal Remediation, INC of Pittsburgh – USA, prepared in accordance with EC directive 91/155/eec. It is a Bioremediation nutrient and Sorbent granular product, supplied in the form of small particles or beads, incorporating microencapsulation and nanotechnology and used as a hydrocarbon remediation product. It is composed of 100% Cera Alba, which incorporates buoyant capsules that bind with the hydrocarbons on contact, and stimulates the naturally occurring oil degrading microorganisms to colonize. The Product is non-combustible, non-reactive, non-hazardous, with flash point > 200°C (392°F), specific gravity 0.97gm/cm^3 @ 20°C, stable at temperatures below 200°C (392°F), and viscosity 8 – 12cST @ 100°C, insoluble in water, incompatible with detergents, surfactants and strong oxidizing agents, and hazardous polymerization will not occur during use, though care needs to be taken to avoid sparks, flames and exposure to heat. A dilution ratio 1:20 was adopted, while application to the soil was at the rate of 1 liter per cubic meter of soil. Environmental soil samples (representative soil samples), after 12- to 18-months of bio-remediation for Nkeleoken-Alode LOT 04, Elelenwo Manifold Akpajo LOT 46, Ajeokpori Well 3, Okuluebu 2 LOT 54 and New Elelenwo Manifold Akpajo LOT 56, with the help of spiral hand auger at four (4) geo-referenced sampling points plus control, were collected and composites samples with the help of silver-plated basin and spatula obtained at each of the sampling points obtained. The soil samples were collected in sterile zip-top samples bags and stored in ice-packed containers maintained at 10°C in plastic coolers for safe handling to the laboratory for analysis, to determine the rate of degradation of HCs, measured as final TPH values (Table 1), and concentrations in the soil. The analytical methods deployed for this assessment were EPA – 1664: n-Hexane Extractable Materials (HEM; Oil and Grease) and Silica Gel Treated n-Hexane Extractable Materials (SGT-HEM; Non-polar Material), by extraction and gravimetry (EPA, 2010) and EPA – 8720: Selected Analytical Method for Environmental Remediation and Recovery (EPA, 2014) for TPH. Gas Chromatography (GC) Agilent 7890A was used for the separation and analysis of the Petroleum Hydrocarbons (PHCs) decanted into vials; to determine the relative amounts in the soil. Brucine (US-EPA 351.2) Method was used for Nitrogen (N) determination in a Jenway UV Spectrophotometer with a sensitivity of 0.001 ppm, and the nitrate-nitrogen forms in the Soil were extracted, using Morgan's reagent. The phosphorus (P) in the Soil was extracted with Brain P1 solution (NH_4F 0.03N + HCl 0.02 N) and analysed using the ascorbic acid- molybdenum blue colour method (US-EPA 365.3) in a UV-VIS spectrophotometer, while Potassium (K^+) was extracted and determined by a GBC Flame Atomic Absorption Spectrophotometer (FAAS) (US-EPA 7000B). Total Heterotrophic Bacteria (THB) and Total Heterotrophic Fungi (THF) samples were inoculated using pour plate Method. The colonies in the plate were counted and their values recorded (Table 2). Hydrocarbon Utilizing Bacteria (HUB) and Hydrocarbon utilizing Fungi (HUF) were determined according to APHA 9215C Method, the samples were inoculated using pour plate Method, and the Colony Forming Unit per gram of soil were determined (Table 2). Using Excel version 2016, descriptive statistics of the initial TPH values before-remediation and final TPH values after-remediation and close-out of the sites was used, to measure the significant difference in nutrients efficiency in the soils at the various locations in the study area. The mean, standard deviation (SD) which determines how much individual data points deviate from the mean value was also calculated, skewness and kurtosis of the locations, using paired samples statistics were computed. Samples test at 5% significance and confidence intervals were carried-out, and the standard mean errors, t-statistics value and z-test to measure the effectiveness of the remediation nutrients in the selected location were also determined. These values were referenced to the Hypothesis:

- H_o: There is no Significant Difference between the initial TPH values before remediation and finial TPH values after remediation and close-out of the sites,
- H_1: There is Significant Difference between the initial TPH values before remediation and finial TPH values after remediation and close-out of the sites.

The p-values at two-tailed significance test were also determined, and the number of degraded HCs and percentage (%) difference in degradation was also calculated

3. Results

At Nkeleoken-Alode LOT 04, the baseline soil TPH value of 2,021 mg/kg at the end of 12-months of electro-bioremediation reduced to 265.00mg/kg which is about 86.8877% degradation, while about 13.11123% was left in the soil un-degraded. This remediation approach and technology has proved to be efficient in degrading crude oil in the location. Also at Elelenwo Manifold (M/F), Akpajo LOT 46**,** the initial TPH value of 6,600mg/kg recorded in the area before bio-remediation, was reduced to 26.00mg/kg (about 99.606% degradation) after the process, while about 0.3939% was left in the soil un-degraded. This bio-remediation product had the highest degradation potency and effectiveness, as compared to other products used in the remediation process. Ajeokpori Well 3, Okuluebu 2 LOT 54 initial TPH value of 4,550mg/kg recorded before bio-remediation, was reduced to 1,187.87mg/kg (about 73.893% degradation) from the baseline values after 18-months, while about 26.107% was left in the soil un-degraded. New Elelenwo Manifold (M/F), Akpajo LOT 56 initial TPH of 5,800mg/kg recorded before remediation, was reduced to 402.29mg/kg (about 93.064% degradation) from the baseline values after remediation, while about 6.936% was left in the soil un-degraded. PRP® recorded very high efficiency at degradation of hydrocarbons. The results for the Nitrogen (N), Phosphorus (P), Potassium (K), Total Heterotrophic Bacteria (THB), Total Heterotrophic Fungi (THF), Hydrocarbon Utilizing Bacteria (HUB) and Hydrocarbon Utilizing Fungi (HUF) measured in the soil samples from Eleme are as shown in Table (2) below. Nkeleoken Alode LOT 04 with Nitrogen (N) concentration of 1.091 mg/kg is lower than Control location of 1.278 mg/kg, while Elelenwo Manifold-Akpajo LOT 46, Ajeokpori Well 3 Okuluebu 2-Ogale LOT 54 and New Elelenwo Manifold-Akpajo LOT 56 have Nitrogen (N) values of 2.139 mg/kg, 4.299 mg/kg, and 2.186 mg/kg respectively, which are higher than Control. Phosphorous (P) value of 0.321 mg/kg in Ajeokpori Well 3 Okuluebu 2-Ogale LOT 54 is as-well lower than control value of 0.639 mg/kg, while Nkeleoken Alode LOT 04, Elelenwo Manifold-Akpajo LOT 46, and Elelenwo Manifold-Akpajo LOT 56 have value of 2.321 mg/kg, 1.518 mg/kg and 1.242 mg/kg respectively, which are higher than Control. Also, Potassium (K) values for LOTs 04, 46, 54 and 56 are 25.011 mg/kg, 45.789 mg/kg, 39.429 mg/kg, and 15.423 mg/kg, are as-well higher than Control value of 0.652 mg/kg. The results from R-Studio Software analyzing four (4) samples for remediated soils and one (1) control, taken about ±100 from the site, and the data set subjected to One-way Analysis of Variance (ANOVA), to compare the parameters obtained in the LGA to the Control, and aggregate Mean (μ) and Standard Error (SE) for the LGA and Control being computed (Mean ± SE); at the control location in Eleme, the mean for Nitrogen (N) is 1.278 mg/kg, Phosphorous (P) 0.639 mg/kg and Potassium

(K) 0.652 mg/kg, while the bio-remediated areas showed mean of 2.4288±0.6726993 for Nitrogen (N), 1.3505±0.4124691 for Phosphorous (P) and 31.413±6.8774471 for Potassium (K). These values were compared with the Federal Ministry of Agriculture and Rural Development (FMARD), 2020 standards of Nitrogen (N) 1.5 – 1,000 mg/kg, Phosphorous (P) 3.0 – 8.0 mg/kg and Potassium (K) 100 – 200 mg/kg, and Nigerian Institute of Soil Science (NISS), 2019 standards of Nitrogen (N) 1,000 – 5,000 mg/kg.

Table 1 Total Petroleum Hydrocarbons (TPH) Degradation in considered locations in Eleme (Phase-1 Ogoni-land Remediated Areas)

S/No	Site Name and Community (L.G.A)	Coordinate (Degree Decimal)	Bio-remediation Products Used	Total Area (Ha)	Total Area (m^2)	Volume of Soil Remediated	Initial TPH Values before Remediation	Final TPH Values after Remediation	Percentage Degraded (%)	Percentage Un-degraded (%)
1.	Nkeleoken, Alode (Eleme) LOT 04	N 4.76715 E 7.116253	Electro-kinetic with Ors-SORB® & KEEN®	0.6200	6,200	46,100	2,021	265.00	86.89	13.11
2.	Elelenwo Manifold Akpajo (Eleme) LOT 46	N 4.8470 E 7.1117	CLOGEN®	0.3943	3,943	12,100	6,600	26.00	99.61	0.39
3.	Ajeokpori Well 3, Okuluebu 2 (Eleme) LOT 54	N 4.8279 E 7.1583	Micro-SORB®	0.0854	854	8,300	4,550	1,187.87	73.89	26.11
4.	New Elelenwo Manifold Akpajo (Eleme) LOT 56	N 4.8488 E 7.1101	Petroleum Remediation Product® (PRP)	0.4139	4,139	9,600	5,800	402.29	93.06	6.94

Table 2 Results for Physicochemical and Biological Parameters in Eleme Soils

Parameters								
S/No	**Sample ID**	**Nitrogen (mg/kg)**	**Phosphorous (mg/kg)**	**Potassium (mg/kg)**	**THB (cfu/g)**	**THF (cfu/g)**	**HUB (cfu/g)**	**HUF (cfu/g)**
1	IGEM/ELEME/LOT 04	1.091	2.321	25.011	3.2×10^5	2.7×10^4	5.7×10^3	3.1×10^3
2	IGEM/ELEME/LOT 46	2.139	1.518	45.789	7.0×10^5	4.9×10^4	3.5×10^3	2.7×10^3
3	IGEM/ELEME/LOT 54	4.299	0.321	39.429	3.5×10^5	2.8×10^4	3.3×10^3	2.5×10^3
4	IGEM/ELEME/LOT 56	2.186	1.242	15.423	2.9×10^5	4.0×10^4	4.0×10^3	2.9×10^3
5	IGEM/ELEME/Control	1.278	0.639	0.652	4.8×10^5	3.4×10^4	3.5×10^3	2.8×10^3

SOURCE: Author's Analyses (2024) [IGEM/ELEME/LOT 04 = Nkeleoken-Alode LOT 04, IGEM/ELEME/LOT 46 = Elelenwo Manifold -Akpajo LOT 46, IGEM/ELEME/LOT 54 = Ajeokpori Well 3-Okuluebu LOT 54, IGEM/ELEME/LOT 56 = New Elelenwo Manifold-Akpajo LOT 56. THB = Total Heterotrophic Bacteria, THF = Total Heterotrophic Fungi, HUB = Hydrocarbon Utilizing Bacteria and HUF = Hydrocarbon Utilizing Fungi]

Phosphorous (P) 8 – 20 mg/kg and Potassium (K) 78 – 195 mg/kg for fertile soils. Same R-Studio Software analysing for Total Heterotrophic Bacteria (THB) and Total Heterotrophic Fungi (THF) showed mean values of 480,000 and 3,400 and Hydrocarbon Utilizing Bacteria (HUB) and Hydrocarbon Utilizing Fungi (HUF) mean values of 3,500 and 2,800. The bio-remediated locations show means of 417,000±0.9578622 and 36,000±0.5244044 for THB and THF, and 4,125±0.5452446 and 2,800±0.1290994 for HUB and HUF. THB count of 3.2×10^5 cfu/g, 7.0×10^5 cfu/g, 3.5×10^5 cfu/g, and 2.9×10^5 cfu/g for LOTs 04, 46, 54, and 56 respectively, are lower than 4.8×10^5 cfu/g Control value. THF counts are 2.7×10^4 cfu/g, 4.9×10^4 cfu/g, 2.8×10^4 cfu/g, and 4.0×10^4 cfu/g, while 3.4×10^4 cfu/g is for Control.; where LOTs 04 and 54 are lower than Control, while LOTs 46 and 56 are higher than Control. These values were compared with the United Nations Environmental Protection (UNEP), 2011b microbial standards for fertile soils of, 1.0×10^5 – 1.0×10^7

cfu/g for THB, 1.0 x 10^3 – 1.0 x 10^4 cfu/g for THF. HUB count of LOTs 04 and 56 with values 5.7 x 10^3 cfu/g and 4.0 x 10^3 cfu/g are higher than Control value of 3.5 x 10^3 cfu/g, while LOT 46 of 3.5 x 10^3 cfu/g has the same value with Control, while LOT 54 of 3.3 x 10^3 cfu/g is lower than Control. HUF has count values of 3.1 x 10^3 cfu/g, 2.7 x 10^3 cfu/g, 2.5 x 10^3 cfu/g, and 2.9 x 10^3 cfu/g, and 2.8 x 10^3 cfu/g as Control. These were also compared with UNEP (2011b) standards for uncontaminated soils of <10^3 cfu/g. A descriptive statistic to ascertain the level, effectiveness of the remediation efforts, degree of TPH degradation and key variables, site characteristics in the four locations in Eleme bio-remediated soils, is as shown in Table (3) below. The sites, represented by the total area in hectares (Ha) and volume of soil remediated in m^3 vary considerably, with areas ranging from 0.085 to 0.62 Ha, and remediated soil volumes between 8,300 and 46,100 m^3. These variations reflect the diversity of the sites, indicating that the remediation efforts were applied to different scales of contamination. The mean TPH values before- and after-remediation are 4742.75 mg/kg and 470.29 mg/kg, and Standard Deviation (SD) before- and after-remediation and close-out are 2001.019 and 503.0184. The t-Test results comparing TPH values before and after bio-remediation, as shown in Table (4) below, gave t-statistic value of 3.995 and p-Value of 0.0281 at 5% significance level and 95% confidence interval. The trend of TPH degradation is as shown in Fig. (3) below.

Table 3 Descriptive Statistics of Total Petroleum Hydrocarbons (TPH) Degradation in Phase-1 Ogoni-Land Remediated Soils before- and after-Remediation in Eleme LGA

Descriptive Statistics							
	Count	**Mean**	**SD**	**Min**	**Max**	**Skewness**	**Kurtosis**
Total Area (Ha)	4	0.3784	0.220403	0.0854	0.62	-0.6851	1.725766
Total Area (m^2)	4	3784	2204.031	854	6200	-0.6851	1.725766
Volume of Soil Remediated (m^3)	4	19025	18118.75	8300	46100	1.955162	3.844728
Initial TPH Values before Remediation (mg/kg)	4	4742.75	2001.019	2021	6600	-0.6044	-1.1142
Final TPH Values after Remediation (mg/kg)	4	470.29	503.0184	26	1187.87	1.42906	2.426865
Percentage Degraded (%)	4	88.3625	10.95741	73.89	99.61	-0.76415	0.458572
Percentage Un-degraded (%)	4	11.6375	10.95741	0.39	26.11	0.764148	0.458572

Table 4 Paired sample T-test

T- Test						
	t	**df**	**Sig. (2-tailed)**	**Mean Difference**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
Coefficients	3.995	3	0.028	4272.46000	869.0100	7675.9100

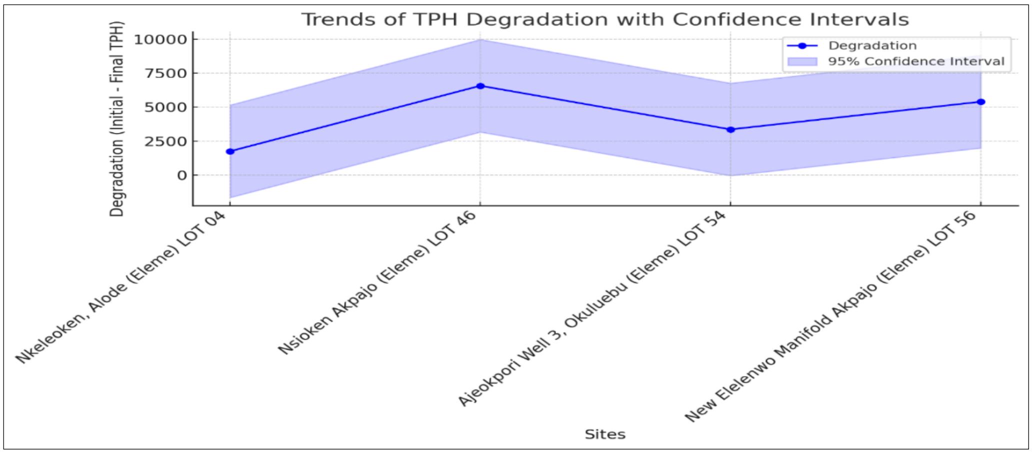


Figure 3 Trends of TPH Degradation in Eleme

4. Discussion

Generally speaking, the top soil in some places in Eleme is composed of lateritic sand to loamy- silt and is usually underlain by clayey-silt and/or fine sand intercalations. The four (4) LOTs assessed in Alode, Akpajo and Okuluebu are sedimentary environments with unconsolidated formations of silty-sand, silty-clay, clay, sandy-clay, clayey-silt and sandy-silt, and a difference in soil composition at Alode and Okuluebu. While Alode soil is loamy and rich in humus, that of Okuluebu is lateritic and plastic, and Akpajo is more of silty-clay. Soils in Alode, being also loamy, have an ideal balance of sand, silt and clay, which makes it suitable for bio-remediation and as-well gives room for aerobic respiration, and allows microbial activity to thrive; leading to increase in efficiency of TPH degradation. It also has ability for bio-remediation nutrients retention, without excessive leaching, efficient nutrient use, fast initial improvement in soil health and quick start to ecosystem recovery. Nkeleoken-Alode LOTs 04, using Electro-kinetic Action method in combination with Ors-SORB plus®; a nutrient-rich soil amendment and soil conditioner; composed of 40-45% water, 20-30% carbon, 20-30% nitrogen, 1-5% ammonium phosphate and 0-1% urea, to help support microbial activity and as-well function as absorbent and adsorbent, and KEEN®; a bio-stimulant and bio-fertilizer, composed of 94.2% DI water, which helped to hydrate the microorganisms in the remediation process, 5% blends of bacillus spores that functioned to promote plant growth, soil health and plant-disease suppression, and 0.8% micro-nutrients and bio-accelerator to help for nutrient circulation, microbial community development and plant-microbial interaction. These products achieved significant 86.89% TPH degradation from the initial 2,021 mg/kg after 12-months of bio-remediation. On the backdrop of the fact that this location achieved 86.89% TPH degradation with Electro-Kinetic Action and bio-stimulation with KEEN® and Ors-SORB plus®, the use of electric field in mobilizing the hydrocarbons and moving charged TPH particles together for the nutrients to act-on; the process will definitely alter the pH level of the soil, and by ion exchange, trace metals, accumulation of salts and ionized metals would be left in the soil as footprints. Elevated pH affected plant growth and reduced diversity of species that should colonize the area. Bacillus in KEEN® is a bacterial spore, which increases biological diversity, and over-time, the spores will decompose releasing carbon dioxide (CO_2) and organic acid, while soil fertility is enhanced by micro-nutrients release of zinc, manganese and iron. The Bio-accelerator, an organic compound produces decomposed organic matter and CO_2. Elevated CO_2 emissions contributed to carbon footprints of the bio-remediation process. The nutrients in Ors-SORB® increased residual ammonium and nitrates, and high levels of ammonium will acidify the soil over time, this will alter sensitive plant species, and as-well alter soil microbial community. Enhanced microbial activity from bacillus spores and organic compounds supported the continual decomposition of residual HCs and will improve soil structure through the production of soil-binding polysaccharides. This will help in plant regrowth, soil fertility, acceleration in the process of endemic species and native vegetation recolonization. So also will residual micro-nutrients enhance plant growth, with improved conditions for reestablishment of diverse plant communities that will enhance ecosystem restoration. Elelenwo Manifold – Akpajo LOT 46 soils achieved the most TPH degradation of 99.61% with the use of a made in Nigeria product, CLOGEN, a bio-stimulation and bio-augmentation formulation, composed of Electro-Ionic Biopolymers, Polysaccharides Cellulose, Sodium Poly-Aromatic Alkalated Sulphonates, Dispersants, Hydrogen, Sulphur and Carbon. The Electro-Ionic Biopolymer and Polysaccharide Cellulose components enhanced microbial activity and improved the soil physical structure; where the Biopolymers bind the soil particles together to reduce erosion and create more stable soil structure. The Polysaccharide Cellulose contributed to Organic Matter content in the soil and produced carbon compounds in the process of degradation, while the Polymers decomposed to release CO_2, simple sugars and organic acids; which can alter soil pH and microbial activity. The surfactant part, Sodium Poly-Aromatic Alkalated Sulphonates emulsified the HCs, making them more bioavailable for microbial degradation, with a release of residual sodium salts, which may pose challenges for plant regrowth and microbial activity in the soil; while the dispersants helped to breakup HCs, but trace amounts in the soil could influence hydrophobicity, which may affect the soil water retention ability. The microorganisms converted the Sulphur into Sulphates, which could also alter the soil pH. The bio-stimulation aspect of CLOGEN has enhanced microbial degradation rate, which is also beneficial for breakdown of the residual 26 mg-TPH/kg-soil (0.3939%) left in the soil after-remediation, and this will lead to cleaner soil over time. Also, achieving a significant 99.61% TPH degradation is critical for creating conditions suitable for plant growth and ecosystem restoration. The Bio-Polymers and Cellulose building organic matter in the soil will also create favorable environment for plant roots and soil organisms. The bio-augmentation aspect of the product has also produced additional species in the soil that has enhanced TPH degradation, but, this will have long-term impact on the native microbial populations. Therefore, a shift in microbial balance could impact soil nutrients cycle and organic matter breakdown. In Ajeokpori Well 3, Okuluebu 2, Ogale, Eleme LOT 54, MicroSORB®, the bio-stimulation and bio-augmentation product, composed of Micronized Polymers, Synthetic Wax, Calcium Silicate and Silica achieved 73.89% TPH degradation. The Micronized Polymers improved the adsorption of HCs in the soil, for easy accessibility by microorganisms, stabilized the soil structure, and their organic residue has improved soil organic matter, while the Synthetic Wax has helped to encapsulate the HCs, slow-released the nutrients and controlled the release of the HCs for degradation. The Calcium Silicate and Silica components of the product, acted as soil conditioner, which helped to neutralize the soil acidity and alkalinity, and maintained a stable pH conducive for microbial and plant growth; while, Silica has helped to stabilize the soil structure and contributed to the strengthening of the cells of the plants that regrow in the area, and as-well provided better resistance to environmental stresses. Generally, the use of MicroSORB® has enhanced the activity of microbes, provided a stable environment for HC degradation and nutrient recycling, and an improved overall cleanliness of the soil. Calcium Silicate has created a better environment for the establishment of plant roots, which is essential for revegetation and the restoration of native plant communities, while silica and calcium has contributed positively to the physical structure, long-term stability, and fertility of the soil. Okuluebu soils are more cohesive and less permeable (plastic), with restricted oxygen (O_2) flow; this on the other hand can provide stable conditions for longer-term bio-remediation, giving room for gradual and sustained recovery. New Elelenwo Manifold – Akpajo LOT 56, with still the same process of bio-stimulation, using Petroleum Remediation Product® (PRP®), a sorbent granular product composed of Cera Alba; a beewax consisting of long-chain HCs, esters, and fatty acids, which achieved 93.07% TPH degradation, supported microbial activity and maintained a diverse microbial ecosystem. The breakdown of the beewax has led to increase in microbial biomass, which has sustained the bio-remediation process and will still support it beyond the remediation phase, but, this could temporarily lower the soil pH; though the process has shown effectiveness in enhancing soil health and restoring balance to local ecosystem. From the R-Studio Software analyzing results for remediated soils and control, the One-way Analysis of Variance (ANOVA) showing mean Nitrogen (N) of 1.278 mg/kg, Phosphorous (P) 0.639 mg/kg and Potassium (K) 0.652 mg/kg for control locations, and bio-remediated areas mean of 2.4288±0.6726993 for Nitrogen (N), 1.3505±0.4124691 for Phosphorous (P) and 31.413±6.8774471 for Potassium (K); the mean Nitrogen (N) levels for bio-remediated and control locations are within the optimal range, as posited by FMARD (2020), FAO (2006) and FAO (2000). Mean Phosphorous (P) levels are below FMARD (2020), NISS (2019), FAO (2006), and FAO (2000) standards, while control level is suboptimal for plant growth. Potassium (K) is also below optimal range, while control is suboptimal; as all locations are deficient in Potassium (K), which is critical for plant growth and by extension, this will guarantee low soil fertility. Generally, bio-remediated soils in Eleme have higher Nitrogen (N) and Potassium (K) levels in comparison to control locations; this indicates partial recovery of basic soil nutrients post-remediation, though Phosphorous (P) levels are still suboptimal. Comparing soil physicochemical parameters (macro-nutrients) in Locations and Groups; Eleme remediated soils in comparison to control location have high Nitrogen (N) of 1.091 - 4.299 mg/kg compared to 1.278 mg/kg control, which are within range of FMARD (2020) for healthy soil and Potassium (K) value of between 15.423 – 45.789 mg/kg as compared to 0.652 mg/kg control, which are below the standard range of FMARD (2020) and NISS (2019), while Phosphorous (P) ranges between 0.321 – 2.321 mg/kg as compared to 0.639 mg/kg control, which is still suboptimal. This is suggestive of nutrient recovery after bio-remediation and close-out of the remediated sites, though Phosphorous (P) and Potassium (K) are low in concentration. Soil Microbial guidelines have Total Heterotrophic Bacteria (THB) for healthy soils optimal range of 1.0×10^5 – 1.0×10^7 cfu/g, Total Heterotrophic Fungi (THF) for healthy soils 1.0×10^3 – 1.0×10^4 cfu/g; according to United Nations Environmental Program (UNEP) (2011b), Microbial Standards for Fertile Agricultural Soils. Hydrocarbon Utilizing Bacteria (HUB) and Hydrocarbon Utilizing Fungi (HUF) for uncontaminated soils should be $<10^3$ cfu/g. Though these parameters vary, depending on the presence of hydrocarbons, according to UNEP Microbial Standards for Fertile Soils (United Nations Environmental Program (UNEP), 2011b). From the R-Studio Software analysing results and ANOVA, to compare the parameters obtained in the LGA to the Control, and aggregate Mean (μ) and Standard Error (SE) (Mean ± SE) for control; showing Total Heterotrophic Bacteria (THB) and Total Heterotrophic Fungi (THF) mean values of 480,000 and 3,400 and Hydrocarbon Utilizing Bacteria (HUB) and Hydrocarbon Utilizing Fungi (HUF) mean values of 3,500 and 2,800 and the bio-remediated locations showing means of 417,000±0.9578622 and 36,000±0.5244044 for THB and THF, and 4,125±0.5452446 and 2,800±0.1290994 for HUB and HUF; the THB values of between 2.9×10^5 cfu/g – 7.0×10^5 cfu/g for bio-remediated soils and 4.8×10^5 cfu/g for control are within the standard range of UNEP (2011b) of 1.0×10^5 – 1.0×10^7 cfu/g for healthy soils, while THF value ranging between 2.7×10^4 cfu/g – 4.9×10^4 cfu/g for bio-remediated soils and 3.4×10^4 cfu/g for control are also within the optimal ranges for healthy soils, as postulated by UNEP (2011b). The HUB and HUF values of 3.3×10^3 – 5.7×10^3 cfu/g and 2.5×10^3 – 3.1×10^3 cfu/g and their controls of 3.5×10^3 cfu/g and 2.8×10^3 cfu/g, respectively are above the value of $<10^3$ cfu/g for uncontaminated soils (UNEP, 2011b). This shows that, the Electro-bioremediation using Electro-Kinetic Action, Ors-SORB® and KEEN® at Nkeleoken Alode LOT 04, the combination of bio-stimulation and bio-augmentation using CLOGEN and MicroSORB® at Elelenwo Manifold Akpajo LOT 46 and Ajeokpori Well 3 Okuluebu 2, Ogale LOT 54, respectively and bio-stimulation at New Elelenwo Manifold Akpajo LOT 56 using Petroleum Remediation Product® has boosted THB and THF in the locations. Furthermore, HUB and HUF have been energized to continue with the breakdown of residual TPH in the locations, post-remediation. These findings align with Ajona & Vasanthi (2012), who posited that Carbon (C), Nitrogen (N) and Phosphorous (P) macronutrients were found to stimulate microbial growth, thus enhancing hydrocarbon degradation. It also agrees with Reddy *et al*. (2006) who worked on enhanced electro-kinetic remediation of a contaminated manufacturing gas plant (MGP) soil and demonstrated that, this process, when combined with chemical amendments like, citric acid and non-ionic surfactants can effectively remove PAHs and heavy metals from MGP-contaminated soils, highlighting a promising approach for the remediation of complex contaminant mixtures, and restoration of contaminated industrial land. The results achieved from the use of CLOGEN, a Nigerian-made cellulose based product, that achieved 99.61% TPH degradation, nutrient enrichment and microbial boost in LOT 46 lends credibility to the quest for nature-based solutions for contaminated land management, as-well underscores and gives credence to the work of Abioye *et al*. (2011); who highlighted the role of organic amendments like poultry manure, cow dung and water hyacinth in enhancing bio-remediation of crude oil-contaminated soils; offering a practical approach to soil restoration in oil-polluted environment, using local products and resources to achieve effective and sustainable remediation. Furthermore, the findings in Eleme bio-remediated soils also agrees with Solomon *et al*. (2018), who demonstrated that, using composted plant biomass as a bio-stimulant can significantly enhance bio-remediation of aged crude oil-contaminated soils in Yorla, Ogoni-land, and they observed that, the organic amendments boosted the activity of native hydrocarbon-degrading bacteria, leading to TPH reduction rates and improvement in soil quality. It underscores the potential of organic amendments to facilitating soil recovery and ecosystem restoration in contaminated areas and also, highlights the value of utilizing inherent microbial diversity for effective remediation efforts. Furthermore, the initial TPH values show a slight negative skew of -0.6044 and platykurtic distribution, indicating a fairly even spread of contamination levels with some lower values. In contrast, the final TPH values of 1.42906 are positively skewed and leptokurtic, indicating that the four sites have low levels of residual HCs. The t-statistic of 3.995 suggests that there is a substantial difference between the two sets of measurements. The degree of freedom (df) is 3, as the test was performed on four sites, with one pair of observations from each site. The p-value of 0.0281 is less than the commonly used significance level of 0.05, indicating that the difference between the initial and final TPH values is statistically significant, leading a rejection of the null hypothesis and accepting the alternate, which states that, there is significant difference between the TPH values before- and after-bio-remediation. This is further corroborated by the mean difference between the initial and final TPH values of 4,272.46 mg/kg, which shows that, on average, there was a reduction of this amount in the contamination levels across the sites after-remediation. The 95% confidence interval for the mean difference ranges from 869.01 mg/kg to 7,675.91 mg/kg, which provides a range within which we are 95% confident that the true mean difference lies. This interval suggests that, despite some variability, the remediation process consistently led to a significant reduction in TPH contamination. The result also shows moderate correlation between the four sites and level of TPH degradation, but the volume of soil remediated has little or no relationship with the percentages of TPH degradation, suggesting that; other factors, such as remediation methods, application ratios or site conditions, played a more significant role in determining the success of the clean-up efforts.

5. Conclusion and Recommendations

It is generally believed that remediation is a beneficial activity, almost regardless of how it is undertaken, but poorly considered or operated schemes may cause more detriment to the environment than they remedy (Sustainable Remediation Forum (SURF), 2009). The quality of soil remediated should not cover only the capacity of the soil for crop production, but food safety for microorganisms, animals, plants, and human beings (Abam *et al*., 2022). It should involve not just the removal of contaminants or pollutants from hydrocarbon contaminated soils, but about protecting the environment and everything that interacts in it, and hinged on removing risk to sensitive ecological receptors, enabling redevelopment of the land, repairing failed corrective actions and should be sustainable. 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 efficiency and effectiveness of the remediation strategies implemented across these LOTs in Eleme and the application of the various bio-remediation products is relatively uniform. Besides, these locations were chosen for more detailed study as a result of the high percentages (above 70%) in TPH reduction demonstrated by the various bio-remediation products, with a view to ascertaining the levels of ecosystem restoration after close-out. Greater than 70% TPH degradation is a significant reduction in soil contamination, with its attendant improvement in soil health, and creation of more favorable conditions for the return of biodiversity. Elelenwo Manifold, Akpajo LOT 46 showed higher efficiency in TPH degradation of 99.606%, highlighting the effectiveness of CLOGEN®, leading to high level of restoration and the cleanest site, post-remediation, followed by New Elelenwo Manifold, Akpajo LOT 56 with 93.064% degradation efficiency and high level of restoration, demonstrating strong performance of PRP® in the restoration process. Then followed by, Nkeleoken Alode LOT 04 with significant TPH degradation of 86.8877% using Electro-Kinetic Action + Ors-SORB plus® + KEEN®, and Ajeokpori Well 3, Okuluebu LOT 54 with 73.893% efficiency using MicroSORB®. Soil physicochemical parameters (macro-nutrients) have high Nitrogen (N) of 1.091 – 4.299 mg/kg compared to 1.278 mg/kg control and Potassium (K) value of between 15.423 – 45.789 mg/kg as compared to 0.652 mg/kg control, while Phosphorous (P) ranged between 0.321 – 2.321 mg/kg as compared to 0.639 mg/kg control, though, still suboptimal. This is suggestive of nutrient recovery after bioremediation and close-out of the remediated sites. THB values ranged between 2.9×10^5 cfu/g – 7.0×10^5 cfu/g for bio-remediated soils and 4.8×10^5 cfu/g for control, while THF values ranged between 2.7×10^4 cfu/g – 4.9×10^4 cfu/g for bio-remediated soils and 3.4×10^4 cfu/g for control. HUB and HUF values ranged between 3.3×10^3 – 5.7×10^3 cfu/g and 2.5×10^3 – 3.1×10^3 cfu/g and their controls of 3.5×10^3 cfu/g and 2.8×10^3 cfu/g, respectively. This shows that, the Electro-bioremediation using Electro-Kinetic Action + Ors-SORB® and KEEN® at Nkeleoken Alode LOT 04, the combination of bio-stimulation and bio-augmentation using CLOGEN at Elelenwo Manifold Akpajo LOT 46, the use of

MicroSORB® at Ajeokpori Well 3 Okuluebu 2, Ogale LOT 54 and bio-stimulation at New Elelenwo Manifold Akpajo LOT 56 using Petroleum Remediation Product® has boosted THB and THF in the locations. Furthermore, HUB and HUF have been energized to continue with the breakdown of residual TPH in the locations, post-remediation. These findings reflect several underlying factors, such as consistent environmental conditions, similar soil composition, or microbial activity levels that contributed to comparable degradation rates of petroleum hydrocarbons. While the absence of significant differences indicates effective remediation practices, and also highlights the need for further investigation into the specific conditions at each site. Future research could delve into more granular analyses of soil composition, site-specific nutrient amendments, microbial groups and populations, and other environmental factors that may influence TPH levels. Understanding these dynamics could provide valuable insights for stakeholders and inform ongoing efforts in environmental management and policy issues related to hydrocarbon-contaminated areas.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] 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): ISSN: 2630-6778.

[2] Abioye, O. P., Agamuthu, P., Abdul Aziz, A. R. (2011). Phytotreatment of soil contaminated with used lubricating oil using Hibiscus cannabinus. Biodegradation 23 (2): 277–286. https://doi.org/10.1007/s10532-011-9506-9 [Accessed 17 February 2020].

[3] Ajona, M. & Vasanthi, P. (2021). Bioremediation of petroleum contaminated soils: A review. Materials Today: Proceedings 45: 7117–7122.

[4] Bierrens, J. & Geerts, L. (2014). Environmental hazard and risk characterisation of petroleum substances: A guided ''Working Tour" of petroleum hydrocarbon. Environment International. 66: 182-193

[5] 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.

[6] EGASPIN (2002), Environmental Guidelines and Standards for the Petroleum Industry in Nigeria.

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

[8] Cocârtă, D. M., Stoian, M. A. & Karademir, A. (2017). Crude Oil Contaminated Sites: Evaluation by using Risk Assessment Approach. Sustainability MDPI. 9(1365): 1-17 doi: 10.3390/su9081365. www.mdpi.com/journal/sustainability.

[9] Federal Ministry of Agriculture and Rural Development (FMARD) (2020). Soil and Fertility Use. Recommendations for Crop Production in Nigeria. Abuja: FMARD.

[10] Food and Agriculture Organization (FAO) of the United Nations (2006). Guidelines for Soil Description (4th ed.). Rome; FAO.

[11] Food and Agriculture Organization (FAO) of the United Nations (2000). Fertilizer and their Efficient Use in Sustainable Agriculture. Rome; FAO.

[12] Giadom, F. D. & Tse A. C. (2015). Groundwater contamination and environmental risk assessment of a hydrocarbon contaminated site in Eastern Niger Delta, Nigeria. Journal of Environment and Earth Science. ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online). 5(14): 166-175.

[13] National Population Commission (NPC). (2006). National Population Census of Nigeria.

[14] Nigerian Institute of Soil Science (NISS) (2019). Soil Fertility Standards for Nigerian Agricultural Lands. Abuja: NISS.

[15] National Oil Spill Detection and Response Agency (NOSDRA) (2011). National Oil Spill Detection and Response Agency. Oil Spill Recovery, Clean-up, Remediation and Damage Assessment Regulations. Statutory Instrument (S.I) 25 of 2011. NOSDRA, Abuja – Nigeria.

[16] Reddy, K. R., Ala, P. R., Sharma, S. & Kumar, S. N. (2006). Enhanced electro-kinetic remediation of contaminated manufactured gas plant soil. Eng. Geol. 85 (1-2): 132–146. https://doi.org/10.1016/j.enggeo.2005.09.043.

[17] Solomon, L., Omokhomion, A. & George-West, O. (2018). Organic Wastes Utilization for Enhanced Biodegradability of Total Petroleum Hydrocarbon in a Crude Oil Polluted Soil Environment. New York Science Journal. 11(11): 20-30. ISSN 1554-0200 (print); ISSN 2375-723X (online). http://www.sciencepub.net/newyork. 3. doi:10.7537/marsnys111118.03.

[18] SURF. (2009). Integrating Sustainable Principles, Practices and Metrics into Remediation Projects. Sustainable Remediation Forum (SURF). Remediation Journal. 19(3): 5-114. (eds) P. Hadley and D. Ellis. DOI: 10.1002/rem.20210.

[19] United Nations Development Programme (UNDP) (2012). The Future We Want: Biodiversity and Ecosystems—Driving Sustainable Development. United Nations Development Programme Biodiversity and Ecosystems Global Framework 2012-2020. New York.

[20] United Nations Environment Program (UNEP) (2011). Environmental Assessment of Ogoni Land. Published by United Nations Environment Program. ISBN: 978-92-807-3130-9, Job No.: DEP/1337/GE. Available online at: www.unep.org/nigera.

[21] United Nations Environmental Program (UNEP) (2011b). Microbial Standards for Fertile Soils. www.riversstateapps.ng-ElemeLocal Government Council.

[22] Youdeowei, P., & Nwankwoala, H. (2011). Studies on sub-soil characteristics of sand deposits in some parts of Bayelsa State, Eastern Niger Delta, Nigeria. Journal of Soil Science and Environmental Management, 2(2): 34-38.