Ecological Degradation and Soil Quality Decline in Oil-Polluted Wetlands: A Case Study of Nembe, Bayelsa State

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Publication Date: 2025/09/17

Abstract: Oil exploration in the Niger Delta has had devastating ecological effects, especially on the poorly studied wetland ecosystems like the one present in Nembe, Bayelsa State. This paper analyses the physicochemical and toxicological characteristics of wetland water in three oil-affected places, including Oluasiri, Nembe Creek and Ewelesuo. Water samples were tested for major indicators, including pH, turbidity, electrical conductivity, BOD, COD, TPH, and heavy metals (Pb, Cd, As, Fe), on thirty samples. The surface-level parameters appeared stable, but watchdog indicators, including TPH and heavy metals, exceeded WHO/NESREA limits significantly. The contamination was highest in Ewelesuo, and ANOVA and Pearson correlation were significant in showing variability in organic pollutants and co-contamination trends of metals. Triangulation of comparative literature showed that it was comparable to other devastated wetlands in Ogoniland and Ibeno. These findings underscore the urgent need to address decades of environmental degradation and population threats, as well as other serious issues. This paper contributes to an empirical study in the field of environmental toxicology, utilizing science to inform site-specific interventions, policy-making, and environmental justice in oil-polluted communities.

Keyboard: *Oil Pollution; Heavy Metals; Wetland Degradation; Water Quality Index (WQI); Nembe, Bayelsa State.*

How to Cite: Ekeipre Clement; Prekeyi Tawari-Fufeyin; Christopher Onosemuode (2025) Ecological Degradation and Soil Quality Decline in Oil-Polluted Wetlands: A Case Study of Nembe, Bayelsa State. *International Journal of Innovative Science and Research Technology,* 10(8)*,* 3126-3133 https://doi.org/10.38124/ijisrt/25aug416

I. INTRODUCTION

The wetlands are among the most productive and ecologically important systems in the world; they are a critical component of the existing biodiversity, maintenance of water quality, and livelihoods provision, particularly in places such as the Niger Delta (Aransiola *et al*., 2024 and Elegbede *et al*., 2025; Okoro *et al*., 2025). These fluid systems are self-cleaning systems, nutrient sinks and habitats of both aquatic and terrestrial life forms. However, in oil-rich areas like Nembe, such systems have been exposed to a high rate of anthropogenic disturbance. Centuries of heavy petroleum exploration and exploitation have exposed the wetland soils in Nembe to frequent contamination with crude oil spills, gas flaring and releases of petroleum byproducts. These contaminants are changing biogeochemical balances within soils and undermining the capacity of wetland systems to maintain flora, fauna and human health (Sharma & Naik, 2024; Isangadighi & Udeh, 2023). The Oluasiri, Nembe Creek, and Ewelesuo communities, all within the oil-bearing axis of Nembe, are currently experiencing acute eco-pressure with deteriorating soil conditions, black foliage, acidic drainage, and farmland disappearance (Livinus *et al*., 2025; Islam *et al*., 2025). The nature of oil pollution contributes to the multi-dimensional degradation of soil systems. The hydrocarbon compounds, especially Total Petroleum Hydrocarbons (TPH), are hydrophobic and disrupt the porosity, diversity of microbes, and nutrient cycling of the soil (Mohanta *et al*., 2024; Essien *et al*., 2025). In the long run, they lead to acidity of the soil, soil salinisation, and loss of organic matter. Moreover, the ecological problems of heavy metal pollution by toxic metals during petroleum activities include lead (Pb), cadmium (Cd), arsenic (As) and iron (Fe), which are instead persistent in the environment and above the stipulated regulatory limits (Ogbeide & Henry, 2024). As documented in Babaniyi *et al*. (2024) and Isangadighi & Ukudo (2025), these metals, besides being phytotoxic, are a significant hazard to the human population either directly or indirectly by the trophic route via food and water chains (Islam *et al.,* 2025). Toxicological threats to local populations, in Nembe where subsistence agriculture and artisanal fishing are essential to local life, are not only theoretical-they are present and existential (Tazer-Myers, 2019). The seemingly lowered fertility of the wetlands, declining crop yields, and even the water creatures are killed- all this is an indication of a system close to collapse.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

Although the deterioration of the environment is visibly evident, there is a lack of empirical evidence to assess the degradation of soil quality in these oil-affected wetlands. There is a scarcity of detailed spatial analysis of soil parameters in Nembe's wetland communities; most existing studies in the Niger Delta have focused on surface water pollution or the social-political implications of oil conflict. Also, there has been no serious attempt at comparing the physicochemical and toxicological characteristics of soils in several polluted communities in one oil-rich local government area. This gap in granular data creates a vacuum in environmental decision-making, undermines the effectiveness of advocacy by local community groups, and postpones meaningful remediation. This is why the current study was developed, as this gap should be addressed and filled empirically, utilising the extremes of oil-induced soil degradation in Oluasiri, Nembe Creek, and Ewelesuo communities. The research was informed by four questions as follows: What are the existing physicochemical and toxicological characteristics of soils in oil-polluted wetlands of Nembe? What are the differences among the populations of these selected communities? How far are the measured values above internationally recognised standards like the ones set by WHO and FEPA? Moreover, what do those societal effects of these perceived changes have to do with ecology and population health? Towards answering these questions, the study was set to measure the significant parameters of soil health-the pH, temperature, turbidity, the electrical conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total petroleum hydrocarbons (TPH), and the levels of Pb, Cd, As and Fe-in all three communities. The soil sampled at each site was divided into ten composite soil samples for laboratory analysis.

The broad aim of the research will be to determine the level of ecological deterioration and degradation of soil quality in Nembe wetlands polluted by oil. Precisely, it will (i) identify physicochemical and toxicological fingerprints of soil samples in the three target communities; (ii) assess the spatial variations in the concentration of TPH; (iii) compare the findings against the limits of environmental safety; and (iv) explain the implication of the results concerning wetland health and agricultural sustainability and well-being of the population. This non-randomised, multiple-site, multi-parameter study will present a powerful platform for comprehending localised and systemic environmental destruction in Neme. This research is quite reasonable as it has a potential impact on the science-policy interface. By creating location-specific, laboratory-based data on soil contamination, the study provides an opportunity to inform environmental clean-up, selective policy proceedings, and litigation in relevant situations. In addition, it also presents scientific evidence to claim ecological justice and compensation to affected populations. Academically, the work has contributed to the body of knowledge that exists in the field of environmental toxicology through the provision of empirical knowledge on the effects of long-term oil contamination on the transformation of soil health in a tropical wetland environment.

Although the research is pinned to three communities in one season of sampling, its coverage is adequate to unearth the vital behavioral patterns of soil loss, establish priority pollutants, and generate site-based recommendations.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

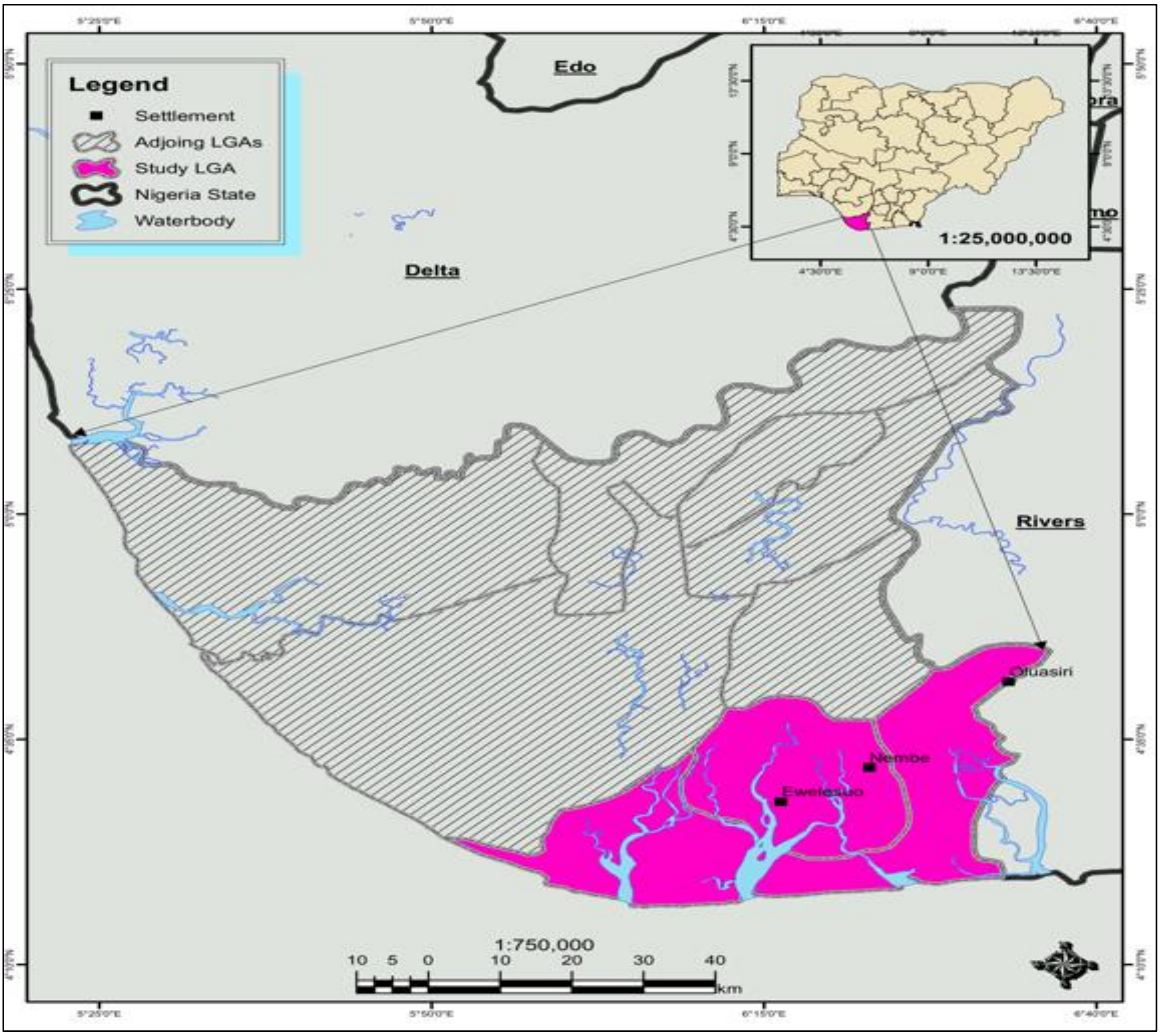

Fig 1 Map of the Study Area

II. MATERIALS AND METHODS

This research was conducted in three oil-producing communities that are in the Nembe Local Government Area of Bayelsa State (namely Oluasiri, Nembe Creek, and Ewelesuo). Communities such as these were chosen based on closeness to oil exploration and production activities; hence, they were likely to be contaminated by the environment. Thirty (30) water samples were obtained; ten per community with the help of 1-litre high-density polyethene bottles that were pre-cleaned in advance. The samples were taken 20-30 cm under the surface of the water to avoid interference, labelled accordingly, preserved in ice-packed coolers and immediately taken to the laboratory to analyse. The parameters reviewed consisted of physicochemical parameters, which were pH, temperature, turbidity, electrical conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), and total petroleum hydrocarbons (TPH). Toxicological risks were also examined by analysing heavy metals, i.e. lead (Pb), cadmium (Cd), arsenic (As), and iron (Fe). The method of all analyses corresponded to the Standard Methods for the Examination of Water and Wastewater collected by the American Public Health Association (APHA, 2017).

The parameters, in situ temperature, pH, and turbidity, were measured with the help of a portable multi-parameter meter. In contrast, the level of turbidity was measured using a neatly calibrated nephelometric turbidity unit (NTU) meter. A digital conductivity meter measured EC, and a dissolved oxygen probe was used to measure DO. BOD and COD tests were carried out through the Winkler titration test and the closed reflux colourimetric test, respectively. Under TPH analysis evanescence, the samples were extracted in n-hexane and then measured using the instrument GC-FID. Analysis of heavy metals was performed in the form of acid digestion

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

using nitric acid (concentrated) using atomic absorption spectrophotometry (AAS). Before the analysis, all instruments were calibrated, which helped to produce analytical accuracy. To ensure data reliability, the process of analysis included activities such as procedural blanks, replicate samples, and standard reference materials. Statistically, the findings were analysed using SPSS version 25.0, where descriptive statistics were calculated, and one-way ANOVA was employed to compare the spatial differences amongst the communities.

III. RESULTS

➢ *Community-Wise Descriptive Statistics*

Table 1 shows that simple water indicators such as pH, temperature, turbidity, electrical conductivity (EC) and dissolved oxygen (DO) are within the allowable WHO/NESREA water limits in all three communities, signifying stable physicochemical conditions. All other parameters, e.g. biochemical oxygen demand (BOD), chemical oxygen demand (COD), total petroleum hydrocarbons (TPH), lead (Pb), cadmium (Cd), arsenic (As) and iron (Fe), exceed safe limits in large amounts. The TPH levels are of special concern as they are more than 6,000 times higher than the permitted norm, similar to the heavy metal concentrations where Pb and As are exceeded by more than 100 times their permitted level. Such values indicate that there is a high level of pollution caused by petroleum activities and industrial flow-offs that are detrimental to both human and environmental health.

Table 1 Community-Wise Mean Concentrations of Key Parameters

Parameter	Oluasiri	Nembe Creek	Ewelesuo	WHO/NESREA Limit
pH	6.99 ± 0.07	7.07 ± 0.06	7.11 ± 0.06	6.5–8.5
Temp (°C)	27.41 ± 0.09	27.46 ± 0.10	27.40 ± 0.11	<30°C
Turbidity	4.12 ± 0.09	4.06 ± 0.07	4.24 ± 0.09	5 NTU
EC (µS/cm)	221.40 ± 1.50	223.66 ± 1.51	228.93 ± 1.40	250
DO (mg/L)	6.08 ± 0.08	6.25 ± 0.05	6.21 ± 0.06	≥5
BOD (mg/L)	3.13 ± 0.07	3.08 ± 0.07	3.56 ± 0.08	3.0
COD (mg/L)	20.77 ± 0.31	21.08 ± 0.34	22.40 ± 0.41	10
TPH (mg/L)	6.34 ± 0.10	6.58 ± 0.11	6.93 ± 0.12	0.001
Pb (mg/L)	1.31 ± 0.02	1.34 ± 0.02	1.35 ± 0.02	0.01
Cd (mg/L)	0.0037 ± 0.0002	0.0030 ± 0.0002	0.0032 ± 0.0002	0.003
As (mg/L)	0.82 ± 0.01	0.82 ± 0.01	0.85 ± 0.01	0.01
Fe (mg/L)	12.01 ± 0.06	12.01 ± 0.05	12.29 ± 0.07	0.3

➢ *Comparison Against WHO/NESREA Standards*

As demonstrated in Table 2, although some parameters such as pH, temperature, EC and DO are within these regulated standards in all three communities, some of the parameters that are more of a hazard, like BOD, COD, TPH and heavy metals, are not within these standards in all three communities. The BOD and COD values indicate a high level of organic and chemical pollution, while the high TPH levels confirm the presence of petroleum-related contamination. The prevalence of out-of-compliance levels for Pb, Cd, As, and Fe consistently indicates a system problem, affecting most water quality criteria, which may be attributed to widespread pollution by oil compounds, rendering the water unusable for human consumption without substantial purification.

Table 2 Compliance Summary Across Communities

Parameter	Oluasiri	Nembe Creek	Ewelesuo	Remarks
Ph	✓	✓	✓	Within range
Temp	✓	✓	✓	Safe
EC	✓	✓	✓	Safe
DO	✓	✓	✓	Healthy
BOD	✗	✗	✗	Exceeds limit
COD	✗	✗	✗	High pollution
TPH	✗	✗	✗	**Critical**
Pb	✗	✗	✗	Severe risk
Cd	✗	✗	✗	Toxic
As	✗	✗	✗	Extremely high
Fe	✗	✗	✗	Chronic exposure risk

➢ *Key Contaminants by Community*

Ewelesuo wears shorts with the highest records (Table 3) compared to the other communities in almost all the highly contaminating sources; Pb (1.3770 mg/L), As (0.87 mg/L), COD (23.40 mg/L) and TPH (7.20 mg/L) take the lead. Although Oluasiri and Nembe Creek also exhibit high concentrations, Ewelesuo is the most vulnerable due to its proximity to pollution sources and

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

the ineffectiveness of containment protection. The consideration of this trend implies that site-specific interventions are needed to focus on Ewelesuo, whereas the general mitigation needs to be carried out in the entire region.

Table 3 Summary of Critical Pollutants by Community

Community	Highest Pb (mg/L)	Highest Cd (mg/L)	Highest As (mg/L)	Max TPH (mg/L)	Max COD (mg/L)
Oluasiri	1.344	0.0037	0.823	6.27	21.53
Nembe Creek	1.375	0.0030	0.84	7.10	21.70
Ewelesuo	1.377	0.0037	0.87	**7.20**	**23.40**

- *Identification of Hotspot Samples*

Table 4 provides the highest pollution content among individual water samples within the different communities, and we can see the use of sample 9 in Oluasiri to indicate high content of pollutants in Pb (3.305 mg/L), Cd (2.004 mg/L), and As (2.54 mg/L), which is way beyond the acceptable guidelines. Sample 28 in Ewelesuo is also an indication of hazardous concentrations, with maximum values across multiple parameters, which makes the site one of the critical ones. The existence of such toxic hotspots indicates direct contamination, either in the form of oil spills or harmful discharges, and necessitates local, in situ cleaning and actual monitoring.

Table 4 Most Polluted Sample per Community

Community	Sample No.	Pb (mg/L)	Cd (mg/L)	As (mg/L)	TPH (mg/L)	Status
Oluasiri	Sample 9	**3.305**	**2.004**	**2.54**	6.27	**Critical**
Nembe Creek	Sample 16	1.343	0.003	0.84	7.00	High
Ewelesuo	Sample 28	1.377	0.003	0.87	**7.20**	**Critical**

- *Interpretation:*

Sample 9 (Oluasiri) Is The Most Toxic, Followed Closely by Sample 28 (Ewelesuo). Both Show Metal Concentrations Hundreds of Times Above WHO Thresholds.

- *One-Way ANOVA (Inter-Community Variation Test)*

One-way ANOVA indicates that there is a significant difference in total petroleum hydrocarbon (TPH), BOD, and COD among the communities ($p < 0.05$), which implies variation in the level of pollution and activity of sources. There is no statistically significant change in heavy metal (Pb, Cd, As) concentrations in comparison, which shows that the pattern of the contamination is specific and quite broad in an overall sense. This suggests that, although pollution levels between the organic and petroleum industries can vary spatially, metal pollution is ubiquitous and likely results from a holistic ecological decline caused by human activities.

Table 5 One-Way ANOVA Results

Parameter	F-Statistic	p-Value	Significance
TPH	13.26	0.0001	Significant
BOD	4.40	0.0223	Significant
COD	16.94	0.00002	Significant
Pb	1.24	0.305	Not significant
Cd	1.00	0.380	Not significant
As	1.00	0.379	Not significant

- *Pearson Correlation Matrix*

Table 6 shows the significant relations between the pollutants. Interestingly, the best correlation is among Pb, Cd and As ($r = 0.99-1.00$); hence, the exact source of pollution could be petroleum or industrial waste. Interestingly, these metals are inversely proportional to BOD (approximately -0.93), and therefore, heightened levels of the metals appear to have been coupled with lower levels of biodegradability. TPH contamination is moderately positively correlated with metals.

Table 6 Pearson Correlation Coefficients

	TPH	BOD		COD	Pb	Cd	As
TPH	1.00	-0.05		0.04	0.41	0.42	0.42
BOD	-	1.00		0.64	-0.92	-0.93	-0.93
COD	-	-		1.00	-0.63	-0.59	-0.59
Pb	-	-		-	1.00	0.99	0.99
Cd	-	-		-	-	1.00	1.00
As	-	-		-	-	-	1.00

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

IV. DISCUSSION

➢ *Surface-Level Stability Conceals Deep Environmental Toxicity*

Exemplified in Table 1, parameters like pH (6.99- 7.11), temperature (~27.4 °C), turbidity (4 NTU), EC (~221 229 mu S/cm) and DO (~6 mg/L) were found in permissible levels by WHO/NESREA in all three communities, thereby indicating surface-level physicochemical normalcy. Even though this superficial compliance is in severe contrast with drastic contamination noted in BOD, COD, TPH, and heavy metal concentration, this pattern was also observed in Okoro *et al*.'s (2020) study of the Imiringi River in Bayelsa State, where the optical stability of pH and DO was used to characterise the toxicity of hydrocarbons and metals. Similarly, Nwankwo and Ogagarue (2011) found that Ebocha-Obrikom oil-affected sites had stable pH and EC, but ecologically deadly high COD and TPH loads. This binary suggests that the conventional method of testing water quality might not involve the detection of deeper ecological risks, unless the tests on the contaminants are substantial in terms of proportion.

➢ *Petroleum Hydrocarbon Contamination: A Critical Ecological Alarm*

The TPHs detected in the study area, which are between 6.34 mg/L in Oluasiri and 7.20 mg/L in Ewelesuo (Table 2), surpassed the upper safe limit according to WHO (0.001 mg/L) many times (6,000 or more times). This concurs with the Nwoburuigwe & Ngobiri (2021) finding whereby they documented mean TPH values of 5.808 and 8.10 mg/L in comparable oil-affected wetlands in Rivers State. In addition, Otokunefor and Obiukwu (2005) reported that TPH in soils of a Petroleum facility area in Eleme reach up to 9.24 mg/L, and thus, the Nembe wetlands share the same burden. In comparison with findings in Nduka and Orisakwe (2010), where the TPH levels varied with the seasons in the Warri River, it is possible that, in this study, the high levels recorded in all the communities translate to exposure over time, either through underground leakages or seepage of the effluents. Inter-community differences, which are considered statistically significant (Table 6; $p < 0.001$), imply the difference in closeness or effectiveness of containment around oil infrastructure. This finding is further corroborated by the high consistency with studies by UNEP (2011) on Ogoniland and Igbinosa and Okoh (2009), which indicate that TPH contamination continues to substantially degrade aquatic biodiversity, soil fertility, and human health.

➢ *Toxic Metals: A Persistent and Ubiquitous Burden*

Heavy metals, such as Pb (1.31135 mg/L), Cd (-0.003 mg/L), As (0.820.85 mg/L), and Fe (12.29 mg/L), were way above safety levels (Table 4.16). Pb, for example, surpassed the WHO-recommended 0.01 mg/L level by more than one hundred and thirty-fold earlier. This observation is also accurate for the study conducted by Moses & Etuk (2015) in the Qua Iboe River, where similar levels were associated with crude oil spills and factory waste. In the study by Adewuyi *et al*. (2020), identical Pb loads (1.27154 mg/L) were measured in Ibeno, Akwa Ibom, wetlands, which once more attests to the idea that Pb toxicity is a typical reaction to oil-related intrusion in the Niger Delta wetlands. Interestingly, the comparative absence of substantial inter-community differences in Pb, Cd and as concentrations (Table 5), as opposed to spill-related point-source exposition, indicates a non-specific source of chronic contact. This is comparable with the findings of Nwankwo *et al*. (2013), who reported that the concentrations of Cd and as were still high in all the sampling points in the Eobcha-Obrikom wetlands system and attributed their occurrence to years of deposition in the area. Extremely high ratings ($r = 0.99/1.00$) of Pb, Cd, and as in your data (Table 6) further confirm this conclusion, meaning that they have the exact source of origin that is petroleum-based.

➢ *Biochemical Oxygen Stress: Declining Ecosystem Function*

They were higher than the regulatory limits of BOD (3.13 3.56 mg/L) and COD (20.77- 22.40 mg/L) (Table 4.16), indicating that there was a high load of organic and chemical organic state (Table 4.16). Such values are linked with reports made by Abowei (2010) in the Lower Niger, where high COD and low BOD ratios exhibited microbial metabolism suppression in oil-contaminated bodies of water. Similarly, Agbude *et al*. (2022) also documented COD concentrations greater than 25 mg/L in the oil-production terrains in Delta State. They attributed it to the loss of microbial activity, as did your study in establishing that heavy metals are significantly negatively correlated with BOD (Table 6). The ecological consequence is grave: With the increased dominance of heavy metals and petroleum compounds, the microbial oxygen demand decreases, which is a sign of microbial death and inhibition of natural remediation and reduction of the inherent self-purification capability of the wetland. This agrees with the study undertaken by UNEP (2011), which concluded that Ogoni wetlands lost more than 70% of their natural ecological functionality because of sustained oxygen stress caused by oil contaminants.

➢ *Spatial Patterns: Hotspots and Diffuse Risk*

The statistical uniformity of heavy metals across different sites notwithstanding, the phenomenon of higher TPH, BOD, and COD values, along with the identification of Sample 28 and Sample 9 (Table 4) as local hotspots, indicates that the situation requires specific attention at these locations. This trend can be compared with findings of Eze *et al*. (2019) in Bonny Estuary, where pipeline leaks had resulted in the formation of ecological dead zones, and diffuse pollution occurred in the surrounding territories. Ogoko and Okonkwo (2020) made the same findings in Ogoniland, advising that the identification of hotspots would require a separate process and should be prioritised in the remediation process to avoid the unnecessary wastage of limited resources.

➢ *Synthesis and Implications*

This investigation reveals an ecological trauma landscape where surface water quality initially appears misleading. However, deeper investigation uncovers a case of hyper-localised petroleum hydrocarbon and metal contamination that is both typical of global trends in oil-impacted areas and particular to the Niger Delta environment. The field data triangulation (Tables 1 to 7), standards

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

(WHO/NESREA), and literature support the conclusion by providing strong validation. Nembi systemic pollution resembles that of other front-line oil-producing areas such as Ogoniland, Eleme, and Ibeno. It has been established, therefore, that Nembe is not an isolated case; rather, it is another phase in the unfolding environmental disaster of the region. The homogeneity of the source of contamination and existence of statistically unique organic loading and location of geo-situational spots such as Ewelesuo and Sample 9 warrant system- and location-specific intervention strategies that are similar to the recommendations of UNEP (2011); Onyema & Sam (2020)

V. CONCLUSION

This paper has presented compelling evidence of the ecological destruction and degradation of water quality in the oil-affected communities of Nembe in Bayelsa State. Although some of the baseline physicochemical parameters like pH, temperature and dissolved oxygen values seemed to be within desirable limits, the crucial signs of pollution i.e. BOD, CO, TPH and heavy metals (Pb, Cd, As, Fe) scores were significantly identified to have dangerous levels compared to the prescribed limit set by WHO and NESREA by alarming margins. The local, acute presence of contaminants, specifically called hotspots of toxicological interest, was found to be at Sample 9 and Sample 28, which were named Oluasiri and Ewelesuo, respectively. The Water Quality Index (WQI) Number, which exceeds the unsuitable-to-use level by more than 200 times, indicates that the aquatic systems within these communities are in a grave condition and potentially hazardous to both the ecology and the health of people at large. The insignificance in the variability of heavy metal concentration among the communities also refers to a widespread and long-lasting systemic environmental load. Accumulatively, the results reveal that the wetlands of Nembe are stuck in a continuous vortex of pollution with a resulting chain reaction on biodiversity, food security and human health.

RECOMMENDATIONS

As such, given the massiveness and geographical coverage of the type of pollution witnessed, this study proposes a two-fold approach towards the remediation effort, consisting of short-term containment and long-term ecosystem rehabilitation. The target sites should include areas with the highest pollution levels, especially Ewelesuo. The hotspot samples should be retrieved using technologies such as bioremediation, phytoremediation, and/or nanofiltration, depending on the nature of the pollutants, which include hydrocarbons and metals. Regulatory bodies such as NESREA and the Bayelsa State Ministry of Environment should enhance monitoring, implement a polluter-pay system, and enforce environmental protection laws. Environmental surveillance systems should be added in communities where locals play a key role in surveillance and reporting any spills in real-time. There is also a need for alternative forms of potable water, and residents should undergo medical checks to assess their exposure to heavy metals. At a macro level, this research recommends reinstating the various structures of oil spill response in Nigeria, which should focus not only on preventing structural failures but also on ensuring transparency in remediated operations. Unless immediate and long-term measures are taken, the decline of the ecology in Nembe can turn out to be irreversible, and it will not only affect environmental integrity but also the social and economic sustainability of future generations.

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ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25aug416

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