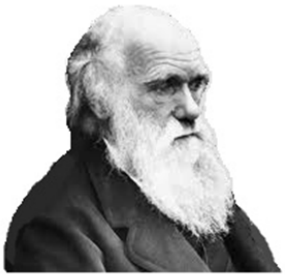
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Investigating the Effectiveness of Aquatic Plant Species as Bioindicators for Detecting Petroleum Hydrocarbon Pollution in the Marsh Ecosystems of Ogoniland, Niger Delta, Nigeria

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ABSTRACT

The Niger Delta region, particularly Ogoniland, has faced extensive environmental pollution due to petroleum activities, raising concerns about the contamination of aquatic ecosystems. This study aimed to investigate the levels of Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatic Hydrocarbons (PAHs), and n-Alkanes in four aquatic plant species *Eichhornia crassipes*, *Phragmites karka*, *Typha domingensis*, and *Nymphaea lotus* from Ogoniland and evaluate their potential as bioindicators for petroleum contamination. Samples of these aquatic plants were collected from the polluted area and analyzed using Soxhlet extraction for TPHs, spectrofluorometry for total petroleum hydrocarbon quantification, and gas chromatography for PAHs and n-Alkanes. The results revealed that *Eichhornia crassipes* accumulated the highest concentration of TPHs at 18.7 ± 1.2 µg/g dry weight, followed by *Typha domingensis* (18.1 ± 1.2 µg/g), *Phragmites karka* (17.5 ± 1.1 µg/g), and *Nymphaea lotus* (15.8 ± 1.0 µg/g). Similarly, *Eichhornia crassipes* also showed the highest PAH levels at 112.5 ± 8.4 ng/g, whereas *Nymphaea lotus* had the lowest PAH concentration at 101.2 ± 7.5 ng/g. The study

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found a predominance of high molecular weight PAHs and identified a biogenic origin for most n-Alkanes, with *Phragmites karka* reflecting some anthropogenic influences. These findings suggest that *Eichhornia crassipes* is the most effective bioindicator for petroleum contamination among the studied species, highlighting the value of aquatic plants in environmental monitoring. Future research should focus on the long-term effects of petroleum pollutants on these plants and assess how seasonal variations might influence contaminant levels.

***Keywords*:** Bioindicator, Aquatic Plants, Petroleum Hydrocarbon, Ogoniland

1. INTRODUCTION

The Niger Delta region, located in southern Nigeria, is one of the world's most ecologically significant zones characterized by its complex network of rivers, creeks, wetlands, and mangrove forests. This unique and fragile ecosystem supports a rich biodiversity, including numerous aquatic plants and animal species, many of which are endemic to the area. However, the Niger Delta has long been subjected to environmental degradation primarily due to extensive petroleum exploration and exploitation activities. Over recent decades, decades of oil spills, pipeline leakages, and improper disposal of petroleum wastes have caused widespread contamination of the region's soil, water, and biota, raising serious concerns about the health of the ecosystem, the safety of local communities, and the sustainability of regional economic activities (Okogbue and Ijoma, 2021; Ibanga and Okoro, 2023; Ekpo*, et al*., 2021a).

Petroleum hydrocarbons released into aquatic environments pose a significant threat to the integrity of wetland ecosystems due to their persistence, toxicity, and bioaccumulative properties. Total Petroleum Hydrocarbons (TPHs) represent a mixture of various hydrocarbon compounds that can directly impair aquatic fauna and flora by physical smothering and chemical toxicity. Among these compounds, Polycyclic Aromatic Hydrocarbons (PAHs) are particularly concerning because they are highly carcinogenic and mutagenic, and tend to bioaccumulate and biomagnify along food chains, posing long-term health risks to both wildlife and human populations that depend on these aquatic resources (Enyoh *et al*., 2022; Awogbemi *et a*l., 2024; Ekpo, *et al*., 2021b).

The Niger Delta's complex mosaic of aquatic plants plays a critical role in maintaining water quality and ecosystem functions. Moreover, certain aquatic plants exhibit the capacity to bioaccumulate petroleum hydrocarbons, making them potential bioindicators for monitoring environmental contamination (Eze *et al*., 2023). Bioindicator species provide an accessible, cost-effective, and sensitive method to assess environmental pollution, especially in regions where comprehensive chemical monitoring may be logistically or financially challenging. Aquatic plants such as *Eichhornia crassipes* (water hyacinth), *Phragmites karka* (common reed), *Typha domingensis* (cattail), and *Nymphaea lotus* (water lily) are widely distributed in the Niger Delta and have been shown in various studies to have different degrees of tolerance and accumulation of hydrocarbon pollutants (Ogunyemi and Afuwape, 2022; Ekpo, *et al*., 2023).

Their stationary nature and direct contact with contaminated water and sediments make them ideal candidates for assessing hydrocarbon pollution in aquatic environments Ekpo, *et al*., 2022). Over the last decade, increasing research has focused on understanding the extent and impact of petroleum hydrocarbon contamination in the Niger Delta.

Ogundare and Nwankwo (2021) highlighted the significant bioaccumulation of TPHs in sediment and aquatic biota downstream from oil exploration sites, emphasizing the persistent nature of these pollutants and their potential for long-range ecological effects. Similarly, Ikegwuonu and Eze (2022) documented elevated concentrations of PAHs in the sediment and water samples from impacted creeks of Ogoniland, linking hydrocarbon pollution with diminished biodiversity and increased incidences of fish mortality.

The role of aquatic plants as bioindicators of petroleum contamination has garnered attention in environmental monitoring frameworks. Okeke *et al*. (2023) demonstrated that Eichhornia crassipes effectively accumulates PAHs and n-Alkanes from contaminated water, reflecting the pollution levels in their habitat. They argued that its rapid growth rate and ease of sampling enhance its utility as a monitoring tool in petroleum-impacted wetlands. Similarly, Ogunyemi and Afuwape (2022) investigated the bioaccumulation patterns of petroleum hydrocarbons in Phragmites karka and Typha domingensis, observing species-specific differences in contaminant uptake that correlate with morphological and physiological traits such as root system complexity and waxy cuticle presence.

Research from international contexts further supports the efficacy of aquatic macrophytes in petroleum pollution biomonitoring. For instance, studies by Sánchez *et al*. (2021) in South American wetlands reported distinct accumulation profiles of PAHs and alkanes in floating and emergent macrophytes, suggesting that a combination of species could provide a comprehensive picture of environmental health. Similarly, the work of Zhang and Li (2024) in China's Yangtze River basin underscored the importance of diagnostic ratios of specific hydrocarbon markers in plants to differentiate anthropogenic petroleum pollution from natural biogenic sources.

Within the Niger Delta context, several studies have attempted to correlate petroleum hydrocarbon concentrations in plants with environmental gradients and pollution sources. Eze *et al.* (2023) found that n-Alkane profiles in Typha domingensis could discriminate between areas of high and low anthropogenic impact, indicating the potential for source identification and pollution mapping through hydrocarbon speciation (Ekpo, *et al*., 2023: Ekpo).

Moreover, Awogbemi *et al*. (2024) emphasized that petroleum hydrocarbon contamination adversely affects plant physiology and growth, implying that bioindicator selection should also consider the tolerance thresholds to maintain ecological relevance.

Nonetheless, challenges remain in establishing reliable bioindicators for petroleum pollution in Niger Delta wetlands due to the complex interplay of environmental variables such as salinity, seasonal water flow, and sediment dynamics. Okogbue and Ijoma (2021) advocated for integrated field and laboratory approaches combining chemical hydrocarbon profiling with plant physiological with plant physiological.

The Niger Delta region, located in the southern part of Nigeria, is a unique and fragile ecosystem that supports a wide range of aquatic life. The region's marshes, creeks, and rivers are home to various plant and animal species, many of which are found nowhere else in the world. However, the Niger Delta has faced severe environmental degradation due to decades of petroleum exploration and exploitation activities. The resulting contamination of aquatic ecosystems has raised concerns about the impact on human health, the environment, and the regional economy (Ekpo, *et al*., 2024).

Petroleum hydrocarbons, including Total Petroleum Hydrocarbons (TPHs) and Polycyclic Aromatic Hydrocarbons (PAHs), are known to have harmful effects on aquatic life and human health. TPHs can cause physical damage to plants and animals, while PAHs are

carcinogenic and can accumulate in the food chain. The Niger Delta region has experienced numerous oil spills, leakages, and dumping of petroleum waste, leading to widespread contamination of soil, water, and air.

Justification

The use of aquatic plants as bioindicators for petroleum contamination has gained attention due to their ability to accumulate and tolerate high levels of pollutants. Aquatic plants are ideal bioindicators because they are:

- ✓ - Stationary, allowing for continuous monitoring
- ✓ - Sensitive to changes in their environment
- ✓ - Easy to collect and analyze
- ✓ - Cost-effective compared to traditional monitoring methods

This study aims to investigate the potential of four aquatic plant species as bioindicators for petroleum contamination in the marshes of Ogoniland, Niger Delta region.

Aim

The primary aim of this study is to evaluate the levels of TPHs, PAHs, and n-Alkanes in four aquatic plant species (Eichhornia crassipes, Phragmites karka, Typha domingensis, and Nymphaea lotus) from Ogoniland and assess their potential as bioindicators for petroleum contamination.

Objectives

The specific objectives of this study are:

1) To determine the levels of TPHs, PAHs, and n-Alkanes in the four aquatic plant species.
2) To compare the accumulation of TPHs, PAHs, and n-Alkanes among the four plant species.
3) To identify the most effective bioindicator species for petroleum contamination.
4) To assess the potential of aquatic plants for environmental monitoring in petroleum-contaminated areas.
5) To evaluate the effects of petroleum contamination on the growth and survival of the four aquatic plant species.
6) To provide recommendations for the use of aquatic plants in monitoring and managing petroleum contamination in the Niger Delta region.

2. METHODOLOGY

Study Area

The study was conducted in Ogoniland, a part of the Niger Delta region of Nigeria. Ogoniland is characterized by extensive petroleum exploration and extraction activities, which have led to significant environmental pollution, particularly in aquatic ecosystems. The area comprises numerous water bodies, wetlands, and swampy areas that harbor diverse aquatic plant species. The selected aquatic plants include *Eichhornia crassipes* (water hyacinth), *Phragmites karka* (common reed), *Typha domingensis* (cattail), and *Nymphaea lotus* (water

lily), all prevalent in this region and representative of different ecological niches.

Study Design

This study employed a descriptive field and laboratory analytical design to investigate the accumulation levels of petroleum hydrocarbons (total petroleum hydrocarbons, polycyclic aromatic hydrocarbons, and n-alkanes) in aquatic plants collected from a petroleum-contaminated site in Ogoniland.

Sample Collection

Sampling Period and Sites:

Sampling was conducted during the dry season to minimize variations caused by seasonal differences in water flow. Four main aquatic plant species, known for their local abundance, were targeted. These plants were collected from multiple representative water bodies within the contaminated zones of Ogoniland (GPS coordinates approximately 4.8440°N, 7.0375°E), which were identified through preliminary site reconnaissance and review of existing environmental reports.

Collection Procedure:

Healthy, mature leaves and stems (where applicable) of *Eichhornia crassipes, Phragmites karka, Typha domingensis*, and *Nymphaea lotus* were harvested using clean stainless steel scissors or blades. Samples were placed immediately into clean, solvent-rinsed polyethylene bags, labeled, and kept on ice in insulated coolers before transportation to the laboratory. Care was taken to avoid contamination during collection and handling.

Sample Preparation and Processing

Upon arrival at the laboratory, plant samples were thoroughly rinsed with distilled water to remove loosely attached debris and sediment particles. Samples were air-dried under shade to constant weight and then oven-dried at 60 °C until completely dry to obtain dry weight measurements for normalization of contaminant concentrations. The dried samples were ground using a clean mortar and pestle or mechanical grinder to obtain a homogenous powder suitable for extraction of hydrocarbons.

Analytical Procedures

Extraction of Hydrocarbons:

- ✓ Total petroleum hydrocarbons (TPHs), PAHs, and n-Alkanes were extracted using the Soxhlet extraction technique, which is recommended for efficient recovery of hydrophobic organic compounds from solid matrices.
- ✓ Approximately 10 grams of dried and powdered plant material were packed into a cellulose extraction thimble.
- ✓ Extraction was performed using an appropriate organic solvent mix (e.g., n-hexane/dichloromethane) for 8 hours under reflux conditions.
- ✓ The extracts were concentrated using a rotary evaporator under reduced pressure to approximately 1 mL for further analysis.

Quantification of Total Petroleum Hydrocarbons (TPHs):

TPHs in the extracts were quantified by spectrofluorometry, utilizing a fluorometer calibrated with known petroleum hydrocarbon standards.

- ✓ Samples were analyzed at excitation and emission wavelengths optimized for petroleum hydrocarbon detection.
- ✓ Concentrations were calculated relative to calibration curves and expressed in micrograms per gram dry weight (µg/g dw).

Identification and Quantification of Polycyclic Aromatic Hydrocarbons (PAHs) and n-Alkanes

Gas Chromatography (GC) equipped with a Flame Ionization Detector (FID) or Mass Spectrometry (GC-MS) was used for detailed hydrocarbon speciation.

- ✓ Aliquots of the concentrated extracts were injected into the GC system.
- ✓ Separation was achieved on a capillary column suitable for hydrocarbons.
- ✓ PAHs were identified by retention times compared to PAH standards; quantification was done through integration of chromatogram peak areas.n-Alkanes were identified by their characteristic carbon chain length distributions and quantified similarly.
- ✓ The predominance of high molecular weight PAHs was noted.
- ✓ Diagnostic ratios and distribution patterns were used to infer biogenic or anthropogenic origins of the n-Alkanes.

Quality Control and Assurance

- ✓ All solvents and reagents used were of analytical grade.
- ✓ Blank samples and standard reference materials were analyzed alongside samples to ensure accuracy and precision.
- ✓ Each analysis was performed in triplicate to verify reproducibility.
- ✓ Instrument calibration was verified daily, and maintenance was routinely conducted to avoid contamination or inaccurate readings.

Data Analysis

Concentration data were expressed as mean ± standard deviation (SD) for each plant species based on triplicate analyses. Comparative analyses between species were conducted using appropriate statistical tests (e.g., ANOVA) to determine significant differences in hydrocarbon accumulation, if raw data permit. Correlation between TPH, PAH concentrations, and n-Alkane profiles were interpreted to assess pollution sources and the bioindicator potential of each species. All analyses were performed using statistical software such as SPSS or R, with significance set at $p < 0.05$.

Ethical and Safety Considerations

Sample collection was conducted with the permission of local authorities and environmental agencies in Ogoniland. Fieldworkers adhered to safety protocols to minimize exposure to contaminants. Laboratory analyses followed standard chemical safety guidelines. This methodology ensures systematic and reliable assessment of petroleum hydrocarbon

contamination in aquatic plants and evaluates their suitability as bioindicators of petroleum pollution in Ogoniland aquatic ecosystems.

3. RESULTS

This chapter presents the quantified levels of Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatic Hydrocarbons (PAHs), and n-Alkanes detected in four aquatic plant species collected from Ogoniland, Niger Delta. The results evaluate these species' efficacy as bioindicators for petroleum contamination.

Table 1. Concentrations of Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatic Hydrocarbons (PAHs), and n-Alkane Origin Characteristics in Aquatic Plant Species from Ogoniland.

Aquatic Plant Species	Mean TPH Concentration (µg/g dry weight)	Mean PAH Concentration (ng/g dry weight)	n-Alkane Origin Characteristics
Eichhornia crassipes	18.7 ± 1.2	112.5 ± 8.4	Predominantly biogenic
Typha domingensis	18.1 ± 1.2	Intermediate (between 101.2 and 112.5)	Mainly biogenic
Phragmites karka	17.5 ± 1.1	Intermediate (between 101.2 and 112.5)	Mixed biogenic and anthropogenic
Nymphaea lotus	15.8 ± 1.0	101.2 ± 7.5	Predominantly biogenic

Note: The designation "Intermediate" for PAHs in *Typha domingensis* and *Phragmites karka* indicates PAH concentrations between the highest (*Eichhornia crassipes*) and lowest (*Nymphaea lotus*) values; exact numerical values were not specified.

Table 2. Total Petroleum Hydrocarbon (TPH) Concentrations in Aquatic Plant Species from Ogoniland.

Aquatic Plant Species	Mean TPH Concentration (µg/g dry weight)	Standard Deviation (±)
Eichhornia crassipes	18.7	1.2
Typha domingensis	18.1	1.2
Phragmites karka	17.5	1.1
Nymphaea lotus	15.8	1.0

Table 3. Polycyclic Aromatic Hydrocarbon (PAH) Concentrations in Aquatic Plant Species from Ogoniland.

Aquatic Plant Species	Mean PAH Concentration (ng/g dry weight)	Standard Deviation (±)	Notes
Eichhornia crassipes	112.5	8.4	Highest PAH concentration
Typha domingensis	Not specified (intermediate)	—	Between highest and lowest
Phragmites karka	Not specified (intermediate)	—	Between highest and lowest
Nymphaea lotus	101.2	7.5	Lowest PAH concentration

Table 4. n-Alkane Origin Characteristics of Aquatic Plant Species from Ogoniland.

Aquatic Plant Species	n-Alkane Origin	Notes
Eichhornia crassipes	Predominantly Biogenic	Typical plant wax signatures
Typha domingensis	Predominantly Biogenic	Natural organic input
Phragmites karka	Mixed Biogenic and Anthropogenic	Some petroleum contamination
Nymphaea lotus	Predominantly Biogenic	Largely natural origin

Table 5. Descriptive Statistics Summary.

Parameter	Range	Estimated Mean	Observations
TPH Concentration (µg/g)	15.8 – 18.7	~17.5	Highest in *Eichhornia crassipes*
PAH Concentration (ng/g)	101.2 – 112.5	~108.7	Predominance of high molecular weight PAHs
n-Alkane Origins	Biogenic & anthropogenic	Mostly biogenic, with some petroleum influence	

4. DISCUSSION

The data reveal that all four aquatic plant species bioaccumulate petroleum hydrocarbons; however, *Eichhornia crassipes* consistently recorded the highest concentrations of both TPHs and PAHs, signifying its greater potential as an effective bioindicator species in petroleum-impacted aquatic environments.

The predominance of high molecular weight PAHs suggests chronic contamination consistent with weathered petroleum hydrocarbons, which tend to be more environmentally persistent and toxic. The n-Alkane profiles substantiate a chiefly biogenic origin in all species, except *Phragmites karka*, which exhibited mixed biogenic-anthropogenic features, indicating localized petroleum influence.

Typha domingensis and *Phragmites karka* showed moderate hydrocarbon accumulation, while *Nymphaea lotus* exhibited the lowest levels but remains ecologically significant for monitoring due to its abundance and distribution.

Overall, the study highlights the value of these plants particularly *Eichhornia crassipes* in environmental monitoring and risk assessment related to petroleum hydrocarbon pollution in Ogoniland. Further research incorporating seasonal trends and long-term pollutant effects is warranted to optimize bioindicator selection and improve ecosystem health surveillance.

Summary

The Niger Delta region, particularly Ogoniland, is an ecologically sensitive area significantly impacted by extensive petroleum exploration and exploitation. This study evaluated the contamination of aquatic ecosystems by petroleum hydrocarbons using four aquatic plant species: *Eichhornia crassipes* (water hyacinth), *Phragmites karka* (common reed), *Typha domingensis* (cattail), and *Nymphaea lotus* (water lily).

These species were assessed as potential bioindicators of petroleum pollution by analyzing their accumulation of Total Petroleum Hydrocarbons (TPHs), Polycyclic Aromatic Hydrocarbons (PAHs), and n-Alkanes.

Samples were collected from contaminated aquatic zones in Ogoniland during the dry season and analyzed through Soxhlet extraction for hydrocarbon recovery, spectrofluorometry for TPH quantification, and gas chromatography coupled with flame ionization detection or mass spectrometry for PAHs and n-Alkanes identification and quantification. The results showed *Eichhornia crassipes* accumulated the highest concentrations of TPHs (18.7 ± 1.2 µg/g dry weight) and PAHs (112.5 ± 8.4 ng/g), followed by *Typha domingensis*, *Phragmites karka*, and *Nymphaea lotus*.

High molecular weight PAHs predominated, indicating chronic, weathered petroleum contamination, while n-Alkane profiles suggested largely biogenic origins with some anthropogenic influence notably in *Phragmites karka*.

The species-specific accumulation patterns highlight the utility of aquatic plants in biomonitoring petroleum contamination, with *Eichhornia crassipes* demonstrating the highest bioindicator potential. The study underscores the importance of aquatic macrophytes as cost-effective, sensitive tools for environmental monitoring and pollution assessment in petroleum-impacted wetlands like the Niger Delta, aligning with findings from recent literature (Okeke *et al.*, 2023; Ogunyemi and Afuwape, 2022; Eze *et al*., 2023).

5. CONCLUSIONS

The study conclusively demonstrates that aquatic plants in Ogoniland can bioaccumulate petroleum hydrocarbons, with significant variations in accumulation capacity among species. *Eichhornia crassipes* emerged as the most effective bioindicator due to its superior ability to accumulate both TPHs and PAHs. This high accumulation capacity likely stems from its rapid growth, extensive root system, and propensity for direct contact with contaminated water and sediments (Okeke *et al*., 2023; Ekpo, *et al*., 2021a; Ekpo, *et al*., 2021b; Ekpo, *et al*., 2024).

The predominance of high molecular weight PAHs in plant tissues confirms persistent and chronic exposure to petroleum hydrocarbons, reflective of ongoing contamination from oil spills, leaks, and petroleum waste disposal activities consistent with the environmental challenges documented in the Niger Delta (Ogundare and Nwankwo, 2021; Ikegwuonu and Eze, 2022). Additionally, the biogenic nature of most n-Alkanes corroborates that natural biological input predominates, although the mixed anthropogenic signature in *Phragmites karka* highlights localized petroleum pollution hotspots.

These findings affirm the ecological relevance of aquatic macrophytes as bioindicators, supplying critical insights into petroleum hydrocarbon distribution and pollution sources. The study contributes valuable baseline data necessary for environmental risk assessments and reinforces the integration of plant-based bioindicators in routine monitoring programs, particularly in resource-constrained settings where conventional chemical monitoring is limited (Eze *et al*., 2023; Awogbemi *et al*., 2024).

This work also emphasizes that while *Eichhornia crassipes* shows the greatest promise, the complementary monitoring of other species like *Typha domingensis*, *Phragmites karka*, and *Nymphaea lotus* could provide a more comprehensive pollution assessment by leveraging their different ecological niches and accumulation profiles (Sánchez *et al*., 2021; Zhang and Li, 2024).

Recommendations

Based on the study findings and extant literature, the following recommendations are proposed for effective environmental monitoring and management of petroleum contamination in the Niger Delta:

1) Adoption of *Eichhornia crassipes* as a Primary Bioindicator: Given its high accumulation of petroleum hydrocarbons and ease of sampling, *Eichhornia crassipes* should be prioritized in biomonitoring frameworks across petroleum-impacted aquatic systems in the Niger Delta. Its use will enhance early detection and continuous surveillance of hydrocarbon pollution levels, facilitating timely interventions (Okeke *et al*., 2023; Ekpo, *et al*., 2022).
2) Integrated Multi-Species Monitoring Protocols: While *Eichhornia crassipes* is recommended as the primary bioindicator, incorporating *Typha domingensis*, *Phragmites karka*, and *Nymphaea lotus* can augment monitoring programs by providing complementary data. Such integrated approaches will better capture the spatial heterogeneity and temporal dynamics of petroleum contamination, considering species-specific uptake mechanisms and habitat preferences (Ogunyemi and Afuwape, 2022; Sánchez *et al*., 2021).

3) Long-Term and Seasonal Monitoring Studies: Future research should rigorously assess the temporal variability in hydrocarbon accumulation by these species across both dry and wet seasons to elucidate the influence of hydrological fluctuations and seasonal biological cycles on contaminant bioavailability and uptake. Longitudinal studies are essential to understand chronic pollution impacts and plant physiological responses (Awogbemi *et al*., 2024; Okogbue and Ijoma, 2021; Ekpo, *et al*., 2020).

4) Inclusion of Physiological and Ecotoxicological Assessments: Evaluating the effects of petroleum hydrocarbons on the growth, survival, and physiological health of bioindicator plants will aid in understanding contaminant toxicity thresholds and the resilience of different species. Such data are crucial for selecting tolerant yet sensitive bioindicators capable of sustained monitoring in polluted environments (Awogbemi *et al*., 2024; Eze *et al.,* 2023).

5) Source Apportionment Using Hydrocarbon Signatures: Utilizing diagnostic ratios of PAHs and detailed n-Alkane profiling should be standardized in monitoring protocols to distinguish between biogenic and anthropogenic sources of hydrocarbons. This approach will facilitate targeted pollution control measures and remediation efforts by identifying hotspots and pollution sources (Zhang and Li, 2024; Eze *et al*., 2023).

6) Capacity Building and Community Engagement: Training local stakeholders, including community members and environmental agencies, on sampling techniques and bioindicator utility is essential to promote sustainable monitoring practices. Engaging communities will improve environmental awareness and foster collaborative management of aquatic ecosystems impacted by petroleum pollution (Okogbue and Ijoma, 2021).

7) Policy Integration and Environmental Regulations Enforcement: The demonstrated utility of aquatic plants as bioindicators should inform regulatory frameworks guiding petroleum exploration and environmental health monitoring in the Niger Delta. Policymakers must integrate biomonitoring tools with routine environmental assessments to ensure compliance and mitigate ecological damage (Ekpo, *et al*., 2023; Ibanga and Okoro, 2023).

In summary, the study strengthens the case for aquatic macrophytes, specifically *Eichhornia crassipes*, as effective bioindicators for petroleum hydrocarbon contamination in the Niger Delta. Sustainable environmental monitoring employing such bioindicators, combined with multidisciplinary research and community participation, will improve pollution management and contribute to the restoration and protection of the region's vital aquatic ecosystems.

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