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INFLUENCE OF POLYCYCLIC AROMATIC HYDROCARBON (PAH) CONCENTRATION ON MACROPHYTE ABUNDANCE AND DISTRIBUTION IN MANGROVE WETLANDS IN IBENO LGA, AKWA IBOM STATE

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ABSTRACT

There is abundant growth of invasive species against native species in PAH contaminated mangroves wetlands in Akwa Ibom State. This study is aimed at investigating the influence of PAH concentration on macrophyte abundance and distribution in mangrove wetlands in Ibeno LGA, Akwa Ibom State, Nigeria. Vegetation and soil samples were collected systematically using five 5 m × 5 m quadrats placed at 10 m intervals along belt transects. While soil samples were collected using a soil auger and transported for laboratory analysis. Plant species were identified, counted, and recorded to determine species frequency and density using standard ecological methods. Sediment samples were prepared for hydrocarbon analysis and digested and further Atomic Absorption Spectrophotometry (AAS) analysis was done. The results revealed that *Nypa fruticans* was the most dominant species (IVI = 49.84; density = 150), while *Acrostichum aureum* and *Avicennia africana* were the most frequently occurring species (100% frequency). Site 2 recorded the highest diversity (Shannon H = 1.735; Simpson 1−D = 0.7878; Equitability J = 0.8919), while Site 1 showed the highest dominance (D = 0.7437; Berger-Parker = 0.8571). Site 3 recorded the highest species richness (Menhinick = 0.6187; Margalef = 1.237; Fisher's alpha = 1.591). For PAHs, Site 3 recorded the highest concentrations, with peak values in benzo(k)fluoranthene (9.265 µg/g), anthracene (8.722 µg/g), and fluoranthene (6.940 µg/g). Significant correlations were observed for fluoranthene (r = 0.999; Margalef and Fisher's alpha) and pyrene (r = 0.983; Fisher's alpha), while dominance showed strong negative correlations with fluoranthene (r = −0.795) and pyrene (r = −0.659). The mangrove ecosystem is being degraded by hydrocarbon contamination and invasion of *Nypa fruticans*, resulting in reduced biodiversity and altered species composition, despite the persistence of native species such as *Avicennia africana, Acrostichum aureum,* and *Rhizophora mangle*, and therefore requires continuous monitoring, pollution control, habitat restoration, and management of invasive species for ecosystem sustainability.

Keywords: Polycyclic Aromatic Hydrocarbon (PAH), Contamination, Macrophyte Abundance, Mangrove Wetlands, Ibeno LGA and Akwa Ibom State

1.0. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are the persistent organic pollutants that are composed of multiple fused aromatic rings generated mainly through incomplete combustion of fossil fuels, petroleum exploration, crude oil spills, industrial discharges, biomass burning, urban runoff, and gas flaring activities (Honda and Suzuki, 2020). Due to their hydrophobic characteristics, PAHs have the ability to accumulate easily into aquatic sediments for long periods, especially in wetland ecosystems where oxygen availability is limited (Behera *et al*., 2018). Mangrove wetlands are among the most ecologically productive ecosystems in the tropical regions, and provides numerous ecosystem services such as nutrient recycling, shoreline stabilization, carbon sequestration, biodiversity conservation, erosion control, nursery habitats for fish and shellfish, and purification of water bodies (Alongi, 2015). However, mangrove ecosystems are highly susceptible to hydrocarbon contamination because their sediments serve as sinks for pollutants including PAHs, heavy metals, and petroleum residues.

Globally, mangrove sediments contaminated with PAHs have been associated with reduced vegetation density, poor regeneration capacity, altered nutrient cycling, and biodiversity loss (Nwankwegu *et al*., 2022). In Nigeria, particularly in the Niger Delta region and coastal areas of Akwa Ibom State, oil exploration and industrial activities hugely contributes to the environmental degradation and contamination of these wetlands. Oil spills, gas flaring, dredging, urbanization, transportation activities, industrial discharges and other anthropogenic activities have resulted in high concentration of hydrocarbons and toxic substances in mangrove ecosystems (Adeniji *et al*., 2018).

In Akwa Ibom State, studies have shown increasing anthropogenic perturbations in aquatic ecosystems (Akpabio *et al.,* 2024). They added that road construction and inorganic sedimentation significantly altered macroinvertebrate communities in Qua Iboe River, demonstrating the sensitivity of aquatic organisms to environmental disturbances. Such disturbances are also capable of influencing wetland vegetation structure and ecosystem functioning.

Aquatic macrophytes are important ecological components of wetlands because they contribute to primary productivity, nutrient cycling, sediment stabilization, oxygen production, habitat formation, and ecological balance (Bornette and Puijalon, 2011; Friess *et al*., 2019) and also serve as bioindicators of environmental pollution (Yuan *et al*., 2022). Some pollution-tolerant macrophytes also possess phytoremediation potential and can be utilized in ecological restoration of contaminated wetlands. Their abundance and distribution are strongly influenced by environmental conditions such as hydrology, salinity, nutrient availability, sediment quality, dissolved oxygen, pH, light penetration, and contaminant concentration.

Studies have shown that PAHs negatively affect aquatic plants by reducing chlorophyll concentration, inhibiting photosynthesis, suppressing root development, impairing nutrient uptake, and reducing biomass production (Behera *et al*., 2018). Long-term exposure to PAHs may also alter species composition by eliminating pollution-sensitive species while promoting the dominance of tolerant species. Udo *et al*. (2024) reported perturbations in physicochemical properties and heavy metal concentrations in soils of coastal areas in Akwa Ibom State due to anthropogenic activities. Substantial accumulation of heavy metals in tissues of *Acrostichum aureum* within coastal wetlands of Akwa Ibom State were also reported (Udo *et al*. 2025).

They are insufficient study on the relationship between PAH contamination and macrophyte abundance in mangrove wetlands. Also, existing Nigerian studies have concentrated more on coastal water pollution and sediment chemistry without integrating vegetation ecology with hydrocarbon contamination assessment and lack studies on identifying pollution-sensitive and pollution-tolerant macrophyte species in Ibeno mangrove wetlands. Identification of such species is important for ecological monitoring, biomonitoring, and phytoremediation programs. Recent studies in Akwa Ibom State by Udo *et al*. (2024, 2025) focused mainly on heavy metal contamination in soils and plant tissues, but there remains limited information on PAH contamination and its ecological implications on wetland vegetation. Akpabio *et al*. (2024) reported anthropogenic impacts on macroinvertebrate communities, yet similar ecological assessments involving wetland macrophytes are scarce. There is also inadequate baseline ecological data for mangrove wetlands in Ibeno Local Government Area. This limits effective environmental monitoring and ecological restoration planning.

This study contributes to existing knowledge on wetland ecology by providing empirical information on the influence of PAH concentration on macrophyte abundance and distribution in mangrove wetlands and also generate baseline ecological data for wetlands in Ibeno Local Government Area, thereby contributing to environmental monitoring and future ecological studies in Akwa Ibom State. Lastly, the research improves understanding of how hydrocarbon contamination influences the ecosystem, thereby identifying pollution-sensitive and pollution-tolerant macrophyte species that can serve as bioindicators of environmental pollution.

The study is important for environmental management agencies such as National Environmental Standards and Regulations Enforcement Agency (NASREA), Federal Ministry of Environment (FME), Niger Delta Development Commission (NDDC) and other Akwa Ibom State environmental agencies.

Hydrocarbon contamination threatens the ecological stability and sustainability of these ecosystems (Akpabio *et al.,* 2024). The problem is particularly severe in coastal Nigeria because petroleum exploration and exploitation activities occur extensively within wetland environments. Oil spills, gas flaring, industrial discharge, dredging activities, and transportation-related pollution continuously introduce PAHs into mangrove sediments and water bodies.

Loss of macrophytes can destabilize sediments, increase shoreline erosion, reduce habitat quality, and disrupt aquatic food webs. The degradation of wetland vegetation also reduces the natural purification capacity of wetlands, making ecosystems more vulnerable to pollution and climate-related disturbances. Hence, it is pertinent to investigate the influence of PAH concentration on macrophyte abundance and distribution in mangrove wetlands in Ibeno LGA, Akwa Ibom State, Nigeria.

2.0. METHODOLOGY

2.1. Study Area

Ibeno Local Government Area is located at the Southern, Akwa Ibom State map and occupies the largest coastline with general coordinates between 4º32’02”N, 4º36’02”N.36 and 7.48”E, 8º17’42”E. Ibeno is the host for oil producing companies. The area falls within the South-South region of Nigeria and records high number of oil exploration and oil servicing firms whose activities seriously impact indigenous wetlands.

2.2. Vegetation and Soil Sampling

Systematical sampling of vegetation (plant) and soil samples were carried out using five (5) 5 m x 5 m quadrant spaced 10 m along

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established belt transect. In each quadrant, vegetation components (plants) were identified to species level and their frequency and density were obtained by enumeration. Unknown plant species were collected for identification and confirmation from voucher specimens in Botany and Ecological studies Departmental Herbarium. At two different depths (0 – 15 cm and 15 – 30 cm), soil samples were collected from each of the quadrants using a soil auger. The two different samples were bulked into one composite sample, stored in labelled Ziploc bags and taken to the laboratory for physicochemical analyses.

2.3 Quantitative Determination of Vegetation Parameters

2.3.1 Frequency

The frequency of each species' occurrence was calculated thus:

$$\textbf{Frequency} = \frac{\textbf{Number of occupied quadrat for a species}}{\textbf{Total number of quadrats thrown}} \times \textbf{100}$$

2.3.2 Density

The density of each plant species was estimated by enumerating all plants present in each plot. The number of individuals of a species was taken as a proportion of the number of transects to give a mean of species. The mean was then taken as a proportion of the area of the quadrant to give density in m^2 which was multiplied by 10,000 m^2 to give density per hectare (Cochran, 1963).

2.4 Digestion of Sediment samples for GC-FID Analysis

The samples were oven dried at 100° C for 24 hours and blended to fineness for easy digestion with an electrical blender and then sieved through a 2 mm mesh sieve for easy digestion. 5 ml of 4:1 mixture of concentration HNO_3:$HClO_4$ was added to 1 g of weighed plant with an analytical weighing balance. It was heated at a temperature of 105° C for 1 hour to dryness. Then allowed to cool and made up to the mark of 50 ml volumetric flask with 1M HNO_3. The solution was centrifuged using a (HARRIER 15/80 model centrifuge) for 30 min then transferred into sampling bottles for analysis; all digested samples were analyzed using a Perk-Elmer Analyst AAS (Atomic Absorption Spectrophotometer).

3.0 RESULTS AND DISCUSSION

3.1. Results

A total of eight plant species were identified in the study area, spanning six families. The most dominant families were Arecaceae, represented by *Nypa fruticans*, *Elaeis guineensis*, and *Phoenix reclinata*, and Rhizophoraceae, represented by *Rhizophora mangle*. The most frequent and widely distributed species was *Avicennia africana*, occurring in all sampled plots with 100% frequency and a density of 50 individuals. Other commonly observed species include *Acrostichum aureum* and *Hibiscus tileaceus*. *Acrostichum aureum* had the highest density (85 individuals) and was also present in all three sites. On the other hand, *Phoenix reclinata* and *Elaeis guineensis* were more spatially restricted. The mean DBH values varied, with *Nypa fruticans* showing the largest average DBH (3.98 ± 1.56), followed by *Elaeis guineensis* (2.43 ± 0.57), as presented in Table 1.

In the species checklist (Table 2), *Nypa fruticans* recorded the highest abundance at Site 1 with 105 individuals, followed by *Acrostichum aureum* (55 individuals at Site 2) and *Hibiscus tiliaceus* (45 individuals at Site 2). *Avicennia africana* showed moderate distribution across the sites (5 individuals at Site 1, 39 at Site 2, and 6 at Site 3). *Rhizophora mangle* was consistently recorded low with uniform abundance across all sites (5 individuals each). While *Elaeis guineensis* occurred only at Site 3 (12 individuals), and *Phoenix reclinata* was present only at Site 2 (27 individuals). *Laguncularia racemosa* was recorded at Site 2 (16 individuals) and Site 3 (12 individuals), with absence at Site 1.

In terms of relative importance value (Table 3), *Nypa fruticans* recorded the highest IVI (49.84), followed by *Acrostichum aureum* (41.57) and *Avicennia africana* (33.27). *Hibiscus tiliaceus* had an IVI of 27.30, while *Rhizophora mangle* recorded 25.03. Lower IVI values were recorded for *Laguncularia racemosa* (20.90), *Phoenix reclinata* (13.44), and *Elaeis guineensis* (9.98).

Table 1: Species Floristic attributes in Mangrove ecosystem

Species	Frequency	Density	DBH
Nypa fruticans	66.70	150	3.98±1.56
Elaeis guineensis	33.30	12	2.43±0.57
Phoenix reclinata	33.30	27	1.86±0.14
Avicennia Africana	100	50	0.89±0.05
Acrostichum aureum	100	85	-
Rhizophora mangle	100	15	0.71±0.01
Hibiscus tileaceus	66.70	55	1.47±0.96
Laguncularia racemosa	66.70	28	0.82±0.02

Table 2: Species Checklist and Abundance in Mangrove ecosystem

Species	Family	Site 1	Site 2	Site 3
Nypa fruticans	Arecaceae	105	45	0
Elaeis guineensis	Arecaceae	0	0	12
Phoenix reclinata	Arecaceae	0	27	0
Avicennia Africana	Avicenniaceae	5	39	6
Acrostichum aureum	Pteridaceae	15	55	15
Rhizophora mangle	Rhizohoraceae	5	5	5
Hibiscus tileaceus	Malvaceae	0	45	10
Laguncularia racemosa	Combretaceae	0	16	12

Table 3: Relative importance value of species in Mangrove ecosystem

Species	Relative frequency	Relative density	Important value Index
Nypa fruticans	14.30	35.54	49.84
Elaeis guineensis	7.14	2.84	9.98
Phoenix reclinata	7.14	6.30	13.44
Avicennia Africana	21.43	11.84	33.27
Acrostichum aureum	21.43	20.14	41.57
Rhizophora mangle	21.43	3.60	25.03
Hibiscus tileaceus	14.30	13.00	27.30
Laguncularia racemosa	14.30	6.6	20.90

As presented in Table 4, Site 1 recorded 4 taxa (Taxa_S), while Sites 2 and 3 each recorded 7 taxa. Dominance (D) was highest at Site 1 (0.7437) and lowest at Site 2 (0.2122), with Site 3 recording 0.3772. Simpson's diversity index (1−D) showed the lowest value at Site 1 (0.2563) and higher values at Site 2 (0.7878) and Site 3 (0.6228). Shannon diversity (H) recorded lowest at Site 1 (0.5459), and highest at Site 2 (1.735). Brillouin index followed a similar pattern, with Site 1 recording 0.5134, Site 3 recording 1.292, and Site 2 recording 1.685. Evenness (e^H/S) was lowest at Site 1 (0.4315) and higher at Site 2 (0.8103). Equitability (J) followed the same trend, with Site 1 (0.3938) < Site 3 (0.7104) < Site 2 (0.8919). Species richness indices showed Site 3 with the highest Menhinick (0.6187) and Margalef (1.237) values and the least at Site 1

(Menhinick 0.3024, Margalef 0.5809). Fisher's alpha was lowest at Site 1 (0.7293) and highest at Site 3 (1.591), with Site 2 recording 1.282. Berger–Parker dominance was highest at Site 1 (0.8571) and lower at Site 3 (0.5859) and Site 2 (0.3667).

Table 4: Distribution of Species in Mangrove ecosystem

	Site 1	Site 2	Site 3
Taxa_S	4	7	7
Dominance_D	0.7437	0.2122	0.3772
Simpson_1-D	0.2563	0.7878	0.6228
Shannon_H	0.5459	1.735	1.382
Evenness_e^H/S	0.4315	0.8103	0.5692
Brillouin	0.5134	1.685	1.292
Menhinick	0.3024	0.4041	0.6187
Margalef	0.5809	1.052	1.237
Equitability_J	0.3938	0.8919	0.7104
Fisher_alpha	0.7293	1.282	1.591
Berger-Parker	0.8571	0.3667	0.5859

Table 5 presents the distribution of 12 PAH compounds in sediments from the three mangrove sites. The data show considerable spatial variation in PAH concentrations. Naphthalene was not detected in Site 1, recorded at 0.26172 µg/g in Site 2, and peaked at 5.194 µg/g in Site 3—the highest across all sites. Acenaphthylene was lowest in Site 2 (0.26549 µg/g), moderate in Site 1 (2.674 µg/g), and highest in Site 3 at 4.3763 µg/g. Acenaphthene followed a similar trend, with 0.24238 µg/g in Site 2 (lowest), 2.217 µg/g in Site 1, and 4.2174 µg/g in Site 3 (highest). Fluorene was undetected in Site 1, measured at 0.23052 µg/g in Site 2, and had its highest concentration in Site 3 (5.0058 µg/g). Anthracene recorded 0.43704 µg/g in Site 2 (lowest), 2.7329 µg/g in Site 1, and 8.722 µg/g in Site 3 (highest). Phenanthrene ranged from 1.28491 µg/g in Site 1 (lowest), 1.734 µg/g in Site 2, and peaked in Site 3 at 5.782 µg/g. Fluoranthene was lowest in Site 1 (0.26172 µg/g), increased significantly in Site 2 (4.64841 µg/g), and reached its maximum in Site 3 at 6.940 µg/g. Pyrene showed its lowest concentration in Site 1 (0.26549 µg/g), followed by Site 2 (0.823 µg/g), and highest in Site 3 (1.421 µg/g). Benzo(a)anthracene was lowest in Site 2 (0.413 µg/g), slightly higher in Site 1 (0.4281 µg/g), and greatest in Site 3 (3.421 µg/g). Chrysene varied from 0.23052 µg/g in Site 1 (lowest), 1.1172 µg/g in Site 2, to 4.261 µg/g in Site 3. Benzo(b)fluoranthene was lowest in Site 2 (0.2318 µg/g), slightly higher in Site 1 (0.43704 µg/g), and highest in Site 3 (3.218 µg/g). Benzo(k)fluoranthene had the lowest value in Site 1 (1.721 µg/g), moderate in Site 2 (1.1571 µg/g), and was highest in Site 3 at 9.265 µg/g, making it the single most concentrated PAH across the study. These results clearly identify Site 3 as the most contaminated, with significantly higher PAH concentrations than the other sites.

Table 5: Distribution of Species in Mangrove ecosystem

	Site 1	Site 2	Site 3
Naphthalene	-	0.26172	5.194
Acenaphthylene	2.674	0.26549	4.3763
Acenaphthene	2.217	0.24238	4.2174
Fluorene	-	0.23052	5.0058
Anthracene	2.7329	0.43704	8.722
Phenanthrene	1.28491	1.734	5.782
Fluoranthene	0.26172	4.64841	6.940
Pyrene	0.26549	0.823	1.421
Benzo(a)anthracene	0.4281	0.413	3.421
Chrysene	0.23052	1.1172	4.261
Benzo(b)fluoranthene	0.43704	0.2318	3.218
Benzo(k)fluoranthene	1.721	1.1571	9.265

Table 6 revealed that the species richness (Taxa) showed positive correlations with most contaminants, with relatively strong associations recorded for fluoranthene ($r = 0.941$), pyrene ($r = 0.856$), phenanthrene ($r = 0.576$), naphthalene ($r = 0.538$), chrysene ($r = 0.670$), and benzo(b)fluoranthene ($r = 0.446$), while weak or near-zero correlations were observed with acenaphthylene ($r = -0.099$) and acenaphthene ($r = 0.004$). Dominance showed negative correlations with most hydrocarbons, particularly fluoranthene ($r = -0.795$) and pyrene ($r = -0.659$), while positive associations were observed with acenaphthylene ($r = 0.396$) and acenaphthene ($r = 0.300$). In contrast, Simpson diversity, Shannon diversity, Brillouin index, and equitability generally showed positive correlations with most contaminants, with the strongest relationships observed with fluoranthene (Simpson r = 0.795; Shannon r = 0.804; Brillouin r = 0.777; Equitability r = 0.757) and pyrene (Simpson r = 0.659; Shannon r = 0.670; Brillouin r = 0.637; Equitability r = 0.612). Evenness showed mixed relationships, with negative correlations recorded for acenaphthylene (r = −0.702) and acenaphthene (r = −0.626), and positive correlations for fluoranthene (r = 0.520) and pyrene (r = 0.340). Species richness indices showed consistently strong positive correlations with all contaminants. Menhinick's index ranged from r = 0.588 to 0.994, with the highest value recorded for chrysene (r = 0.994). Margalef's index showed strong positive correlations, with the highest value recorded for fluoranthene (r = 0.998; $p < 0.05$) and pyrene (r = 0.965). Fisher's alpha similarly showed very strong positive correlations, reaching r = 0.999 ($p < 0.05$) for fluoranthene and r = 0.983 for pyrene. Berger–Parker dominance showed generally weak to moderate relationships, with both positive and negative values across contaminants, including a strong negative correlation with fluoranthene (r = −0.692) and pyrene (r = −0.535).

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Table 6: Correlation Matrix Showing Species Diversity Along Contaminants Gradient

	Naphtalene	Acenapthylene	Acenaphthene	Flourene	Anthracene	Phenanthrene	Flouranthene	Pyrene	Benzo(a) anthracene	Chrysene	Benzo(b) flouranthene	Benzo(k) flouranthene
Taxa	.538	-.099	.004	.535	.249	.576	.941	.856	.496	.670	.446	.445
Domina	-.257	.396	.300	-.253	.056	-.301	-.795	-.659	-.210	-.414	-.153	-.153
Simpso	.257	-.396	-.300	.253	-.056	.301	.795	.659	.210	.414	.153	.153
Shannon	.272	-.382	-.285	.268	-.041	.316	.804	.670	.224	.427	.168	.167
Evenn	-.111	-.702	-.626	-.115	-.415	-.065	.520	.340	-.160	.055	-.216	-.217
Brillouin	.230	-.421	-.326	.227	-.084	.275	.777	.637	.182	.388	.126	.125
Mehinni	.962	.588	.667	.961	.830	.974	.928	.983	.948	.994	.928	.928
Margal	.748	.177	.277	.746	.505	.778	.998*	.965	.715	.848	.674	.673
Equitab	.199	-.450	-.357	.195	-.116	.244	.757	.612	.150	.358	.094	.093
Fisher	.802	.260	.357	.799	.576	.828	0.999*	.983	.771	.889	.734	.733
Berger	-.106	.532	.443	-.102	.209	-.151	-.692	-.535	-.057	-.269	.000	.001

P < 0.05 = *; P< 0.001 = **

3.2 Discussion

The study evaluates the floristic composition, species diversity, and PAH contamination of the mangrove ecosystem in relation to ecological disturbance, species adaptation, and environmental quality. The floristic composition of the mangrove ecosystem revealed a relatively low species richness, with only eight plant species distributed across six families. This observation is consistent with the generally low floral diversity commonly reported in tropical mangrove ecosystems in places, such as in Akwa Ibom State (Anwana *et al.,* 2024), due to the harsh physicochemical conditions associated with tidal inundation, salinity fluctuations, and anoxic sediments (Akpabio *et al.,* 2024). The dominance of the family Arecaceae, particularly through the prevalence of *Nypa fruticans*, reflects the increasing ecological transformation occurring in many Niger Delta mangrove systems. Also, Numbere, 2019 and Ukpong, 2021 reported several coastal wetlands of southern Nigeria where *Nypa fruticans* to have been aggressively colonized disturbed mangrove habitats, often replacing indigenous mangrove species such as *Rhizophora racemosa* and *Avicennia africana*

The high abundance and Important Value Index (IVI) of *Nypa fruticans* observed in this study indicate its strong competitive advantage and invasive potential within the ecosystem. Its exceptionally high abundance at Site 1 suggests that the area may have experienced ecological disturbances that favored opportunistic colonization. Studies have shown that *Nypa fruticans* thrives in disturbed mangrove environments due to its rapid reproductive capacity, tolerance to fluctuating salinity, and efficient vegetative spread (Numbere, 2019; Osland *et al.*, 2021). The present findings corroborate reports from the Niger Delta, where *Nypa fruticans* invasion has been associated with anthropogenic activities (Akpabio *et al.,* 2024; Udo *et al.*, 2024; 2025), such as dredging, oil exploration, and shoreline modification. In contrast, indigenous mangrove species such as *Rhizophora mangle* recorded comparatively lower abundance and IVI values despite their ecological importance in shoreline stabilization and carbon sequestration.

The widespread occurrence of *Avicennia africana* across all sampling sites demonstrates its broad ecological tolerance and adaptability to varying environmental conditions. This finding agrees with the observations of Alongi (2020), who noted that *Avicennia* species exhibit high resilience to sediment instability, pollution stress, and salinity changes due to specialized physiological adaptations such as salt excretion and pneumatophore development. Similarly, the high density and broad distribution of *Acrostichum aureum* suggest that the species may be functioning as a secondary colonizer in disturbed mangrove zones. Previous studies have identified *Acrostichum aureum* as an indicator species for degraded or transitional mangrove environments, particularly where canopy opening and sediment alteration have occurred (Ellison *et al*., 2020).

The variation in DBH among species further reflects differences in age structure, growth performance, and habitat suitability within the ecosystem. The relatively larger DBH recorded for *Nypa fruticans* and *Elaeis guineensis* may indicate prolonged establishment and favorable nutrient availability in portions of the study area. Conversely, the lower DBH values observed in *Rhizophora mangle* and *Laguncularia racemosa* may reflect environmental stress or restricted regeneration. Similar structural patterns have been reported in polluted mangrove systems where hydrocarbon contamination negatively affects growth performance and stem development (Duke *et al*., 2020).

The diversity indices revealed substantial spatial variation among the sampling sites. Site 1 recorded the lowest taxa richness, Shannon diversity, Simpson diversity, and equitability values, while simultaneously exhibiting the highest dominance index and Berger–Parker dominance. These findings indicate that Site 1 was dominated by a few highly abundant species, particularly *Nypa fruticans*, resulting in reduced community evenness and lower ecological complexity. Such reduced diversity patterns are characteristic of disturbed mangrove systems experiencing biological invasion or environmental stress (Adesina *et al*., 2022). In contrast, Sites 2 and 3 exhibited comparatively higher diversity and evenness values, suggesting relatively improved habitat heterogeneity and species coexistence.

Interestingly, despite Site 3 recording the highest concentrations of PAHs, it also exhibited relatively high species richness indices such as Margalef, Menhinick, and Fisher's alpha. This somewhat contrasts with many studies reporting reduced vegetation diversity under hydrocarbon stress (Li *et al*., 2021). However, the result may indicate the proliferation of pollution-tolerant and opportunistic species capable of surviving under contaminated conditions. Mangrove ecosystems are known to possess species with varying tolerance capacities to petroleum hydrocarbons, and moderate contamination may sometimes facilitate shifts in species composition rather than outright vegetation loss (Alongi, 2020). Additionally, the positive correlations observed between several diversity indices

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and PAH compounds suggest that certain species within the study area may possess adaptive tolerance mechanisms to hydrocarbon contamination.

The distribution of PAHs showed clear spatial variability, with Site 3 consistently recording the highest concentrations for most compounds. Particularly high levels of anthracene, fluoranthene, phenanthrene, and benzo(k)fluoranthene suggest substantial hydrocarbon input into the area. These findings are consistent with reports from oil-producing coastal regions of the Niger Delta where petroleum exploration, artisanal refining, industrial discharges, and shipping activities contribute significantly to PAH accumulation in mangrove sediments (Benson *et al*., 2023; Chukwu *et al*., 2022). The predominance of high molecular weight PAHs such as benzo(k)fluoranthene and chrysene may further indicate pyrogenic sources associated with incomplete combustion processes, gas flaring, and industrial emissions.

The absence or low concentrations of certain PAHs in Sites 1 and 2 compared to Site 3 suggests varying degrees of anthropogenic influence and environmental exposure. Mangrove sediments function as effective sinks for hydrophobic contaminants due to their high organic matter content and fine sediment texture (Alongi, 2020). Consequently, contaminated sediments may retain PAHs for extended periods, thereby increasing ecological risks to mangrove vegetation and associated fauna.

The correlation analysis provided important ecological insights into the interaction between vegetation structure and hydrocarbon contamination. The strong positive relationships between species richness indices and compounds such as fluoranthene, pyrene, and chrysene may suggest that contamination did not completely suppress vegetation establishment but instead favored tolerant species assemblages. Similar observations have been reported in some contaminated wetlands where resistant species persist despite elevated pollutant concentrations (Li *et al*., 2021). Conversely, the negative correlations observed between dominance indices and several PAHs imply that increasing contamination may reduce the overwhelming dominance of individual species, thereby allowing more tolerant species to coexist.

The mixed relationships observed for evenness indicate that PAHs exert variable effects on species distribution patterns depending on contaminant type and concentration. The strong negative correlations between evenness and compounds such as acenaphthylene and acenaphthene suggest that some hydrocarbons may disproportionately affect sensitive species, leading to uneven community structure. In contrast, positive relationships between evenness and fluoranthene or pyrene may reflect adaptive restructuring of the plant community under chronic contamination stress.

4.1. CONCLUSION

The mangrove ecosystems are significantly affected by hydrocarbon contamination and the invasion of *Nypa fruticans*, resulting in altered species composition, reduced diversity, and ecological disturbance. indicate increasing environmental pressure on the mangrove habitat, although the continued presence of native species such as *Avicennia africana, Acrostichum aureum,* and *Rhizophora mangle* suggests some level of ecological resilience. To ensure the long-term sustainability of the ecosystem, there is a need for continuous environmental monitoring, stricter control of oil pollution and waste discharge, restoration of degraded mangrove areas using indigenous species, and effective management of *Nypa fruticans* invasion through sustainable conservation and community-based environmental practices.

Author's Contributions

Udo, E. D.: Conceptualization, investigation, methodology, data curation, formal analysis, data interpretation, writing; original draft preparation, writing; review & editing.

Archibong, I. J.: Investigation, methodology, writing; original draft preparation, writing; review & editing.

Odor, E. O.: Data curation, formal analysis, original draft preparation, writing; review & editing.

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