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Polycyclic Aromatic Hydrocarbon (PAH) Contents in Plant Tissues in Selected Mangrove Communities

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Abstract **Original Research Article**

This study was aimed to investigate the Polycyclic Aromatic Hydrocarbon contents in plant tissues in selected mangrove communities. The study was conducted in three mangrove communities in Akwa Ibom State: Iko Town (Eastern Obolo LGA), Okoroutip (Ibeno LGA), and Uta Ewa (Ikot Abasi LGA). Vegetation and soil sampling involved four randomly selected plots per site, each containing three belt transects. A systematic sampling approach was used. The vegetation parameters of *Acrostichum aureum* plant tissues (roots, stems, and leaves) were taken to laboratory for PAH analysis. Seventeen priority PAHs were analyzed in plant tissues using standard chromatography methods. The study revealed that in the dry season, *Acrostichum aureum* leaves in Okoroutip had the highest PAHs (24.53 mg/kg), dominated by benzo[j]fluoranthene and 3-methylcholanthrene, while roots were lowest (1.42 mg/kg). In Iko Town, stems accumulated the most PAHs (1.89 mg/kg), and in Uta Ewa, stems were highest (1.95 mg/kg) with lower root levels. During the wet season, PAHs increased, especially in Iko Town leaves (34.26 mg/kg, mainly indeno [1,2,3-cd]pyrene) and Okoroutip leaves (12.35 mg/kg, benzo[j]fluoranthene). Uta Ewa roots showed higher PAHs (5.77 mg/kg) than other tissues. Overall, high-molecular-weight PAHs (4–6 rings) predominated, with leaves and stems as major accumulation sites, showing clear seasonal and site variations. *Acrostichum aureum* accumulates high levels of PAHs, with tissue-specific and seasonal variations influenced by pollution sources and plant physiology. The species has potential as a bioindicator and accumulator of PAHs, though its effectiveness in active remediation likely depends on microbial associations. Recommendations include continuous monitoring of PAHs in mangrove ecosystems, stronger regulation of petroleum-related activities, use of A. aureum as a bioindicator, exploration of integrated phytoremediation strategies, and public health awareness to reduce exposure through contaminated seafood.

Keywords: Polycyclic Aromatic Hydrocarbon, bioaccumulation, plant tissues, mangrove.

1.0 Introduction

Mangrove ecosystems provide vital ecological services but are increasingly threatened by contamination from polycyclic aromatic hydrocarbons (PAHs) in oil-producing and industrial coastal regions. PAHs originate mainly from petroleum spills, fossil fuel combustion, biomass burning, and industrial discharges (ATSDR, 2005;

Wang *et al.*, 2019). Due to their persistence, toxicity, and bioaccumulative properties, PAHs pose serious environmental risks (Boström *et al.*, 2002). Mangrove soils act as long-term sinks for PAHs because of their high organic matter content and low redox conditions (Tam *et al.*, 2001), while seasonal variations influence their distribution through runoff, leaching, and sediment resuspension (Oyo-Ita *et al.*, 2013). In the Niger Delta, mangrove communities such as Iko Town, Okoroutip, and Uta Ewa are highly vulnerable to hydrocarbon pollution, yet site-specific seasonal data on PAH occurrence remain limited, necessitating detailed seasonal assessment for effective environmental management.

Despite widespread reports of Polycyclic Aromatic Hydrocarbon (PAH) contamination in coastal and mangrove environments of the Niger Delta, season-specific data on PAH concentrations, compositional profiles, and spatial variability in mangrove soils of communities such as Iko Town, Okoroutip, and Uta Ewa remain limited. Most recent studies emphasize water and sediment matrices, with comparatively little attention given to mangrove soils which is further accumulated by the plant tissues, which serve as long-term storage for hydrophobic contaminants due to their ability to hold matters together (Nikolaou *et al.*, 2022; Zhang *et al.*, 2023). Emerging evidence from the Niger Delta indicates that seasonal variations significantly influence PAH accumulation and ecological risk in plant tissues, yet these assessments rarely focus specifically on mangrove plants or community-scale spatial heterogeneity (Adeniji *et al.*, 2024; Okoro *et al.*, 2025). This lack of plant-focused, seasonally resolved data represents a critical gap in understanding long-term ecological exposure and pollution risk in mangrove ecosystems of the Niger Delta. Anwana *et al.*, (2024) recently reported that *Acrostichum aureum* is one of the most abundant mangrove flora species in the communities of concern. *A. aureum* is a typical example of medical important plant species of the mangrove ecosystem (Essien *et al.*, 2007). It is a member of the Pteridaceae family which is commonly known to the locals as the Swamp Fern or Mangrove Fern. It is an evergreen shrub, found in a hostile environment. It thrives in a hostile environment replete with bacteria, fungi or virus synthesize defensive natural products against these pathogens, which may also exhibit bactericidal, fungicidal or virucidal activity in the human system (Chikezie *et al.*, 2015). However, anthropogenic activities such as mining, road construction, industrial waste release has posed threats to the mangrove species in abundance and usage (Akpabio *et al.*, 2024).

Observed results revealed clear spatial and seasonal variations, which ranges from non-detection during the dry season in some locations to elevated levels of high-molecular-weight and carcinogenic PAHs in others. The dominance of 4–6 ring PAHs indicates petroleum and pyrogenic sources, yet the influence of seasonal hydrological processes on their distribution remains poorly understood. This data gap limits comprehensive environmental risk assessment and public health evaluation, emphasizing the need for systematic seasonal assessment of PAHs in mangrove plants. Consistent with Udo *et al.*, (2024), who reported high heavy metal concentrations in *Acrostichum aureum* tissues across the same mangrove communities, this study highlights the importance of assessing PAHs, as co-contamination can occur and their bioaccumulation patterns are often correlated. Understanding contaminant classes improves insights into pollutant sources, ecological behavior, and cumulative risks to mangrove ecosystems and associated food webs. The presence of toxic PAHs underscores the need for integrated ecological risk assessments and supports targeted remediation and management strategies, with implications for public health protection and the sustainable livelihoods of communities in oil-impacted mangrove areas.

2.0. Material and Methodology

2.1. Study Area

This study was carried out at three mangrove locations in Akwa Ibom State. These were Iko Town in Eastern Obolo Local Government Area, Okoroutip community in Ibeno Local Government Area and Uta Ewa community in Ikot Abasi Local Government Area. The coordinates of the Mangrove locations were Latitudes and Longitudes 4° 33' N to 23 ^{o}02' N and 7° 44' E to 50 ^{o}60' E and 4° 33' N to 06^{o} 74' N and 7° 32' E to 48 ^{o}64' E and 4° 32' N to 48

^{o}50' N and 7°32' E to 4 ^{o}83' E Iko Town, Okoroutip and Uta Ewa respectively (Field data, 2021).

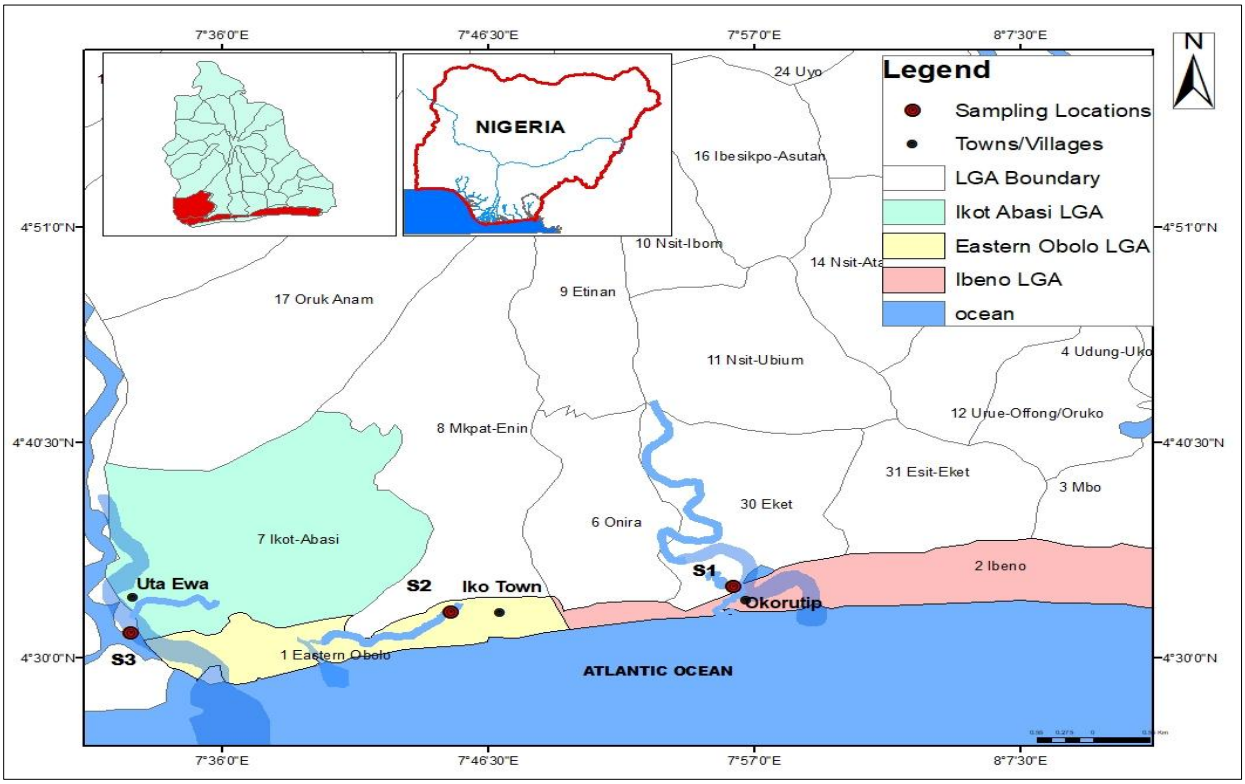

Figure 1: Map of the study areas showing sampling location (Field data, 2021)

2.2. Sample Collection

Four vegetation plots were randomly selected, and within each plot, three belt transects were established. Systematic sampling was conducted in each sampling plot to collect data on vegetation and soil. This involved sampling a 10 m x 10 m quadrat at regular intervals of 20 m along the established transects. Two samples were collected within each quadrat. The individual samples were combined to create a composite sample, which was then placed in ziploc bags that were appropriately labeled. The vegetative components, namely the root, stem, and leaf, of *A. aureum* were gathered within each quadrat and subsequently preserved in appropriately labeled ziploc bags and were transported to the laboratory for analysis of polycyclic aromatic hydrocarbons (PAHs) level.

2.3. Determination of Polycyclic Aromatic Hydrocarbon (PAHs) in Plant Tissue

The analysis of plant tissue samples involved the examination of seventeen polycyclic aromatic hydrocarbons (PAHs), namely phenanthrene, fluoranthene, pyrene, benz[c]phenanthrene, benz[a]anthracene, chrysene, Benzo[k]fluoranthene, Benzo[j]fluoranthene, 3 methylcholanthrene, Indeno [1,2,3-cd] pyrene, Dibenzo[a,h]anthracene, Benzo[ghi]perylene, Dibenzo[a,h]pyrene, Dibenzo[a,i]pyrene, Acenaphthylene, Benzo[e]pyrene, and Benzo(a)pyrene. The plant samples (stems, leaves and roots) were subjected to analysis using an Agilent 7890B Gas chromatograph that was equipped with a flame ionization detector (FID). The chromatograph was fitted with an HP-5 capillary column, which was coated with 5 % Phenyl

Methyl Siloxane and had dimensions of 30m length, 0.32mm diameter, and a 0.25µm film thickness. This equipment was provided by Agilent Technologies. A volume of one microlitre (µL) of the samples was introduced into the system using a splitless injection mode, with an injection temperature of 220 °C, a pressure of 14.861 psi, and a total flow rate of 21.364 mL/minute. The flow rate for the purge flow to split vent was adjusted to 15 mL/min at a time of 0.75 minutes. The oven was initially set to operate at a temperature of 100 °C for a duration of 2 minutes. Subsequently, the temperature was increased at a rate of 10 °C per minute until it reached 280°C, which took 4 minutes. Finally, the temperature was further increased to 300 °C at a rate of 10 °C per minute. The FID temperature was maintained at 300°C in the presence of hydrogen. The air flow rate of 30 mL/minute was increased to 300 mL/minute. Additionally, nitrogen was introduced as a makeup gas with a flow rate of 18 mL/minute. Following the calibration process, the samples underwent analysis, resulting in the determination of their respective concentrations. The chromatograms that were labeled were also extracted and subsequently reported.

3.0 Results

3.1. Dry Season Characterization of PAHs in *A. aureum* across the Mangrove Communities

The dry season characterization of PAHS in *A. aureum* across the mangrove communities is presented in Table 1. In Okoroutip mangrove, benzo[j]fluoranthene (7.69±1.16 mg/kg) and benzo (a) pyrene (0.07±0.01 mg/kg) had the highest and lowest PAH concentrations in the leaf respectively. PAHs such as phenanthrene and acenaphthylene were not detected in the leaf. In the stem, benzo[k]fluoranthene (1.74±0.02 mg/kg) and benz[a]anthracene (0.02±0.01 mg/kg) had the highest and lowest concentrations respectively while PAHs such as phenanthrene, chrysene, indeno[1,2,3-cd] pyrene, benzo[ghi]perylene, acenaphthylene, benzo[e]pyrene and benzo(a)pyrene were not detected in the stem. In the root, benzo[k]fluoranthene (0.96±0.01 mg/kg) had the highest concentration while dibenzo[a,h]anthracene (0.03±0.01 mg/kg) and benzo[ghi]perylene (0.03±0.02 mg/kg) were not detected in the root. Phenanthrene, benz[c]phenanthrene, benz[a]anthracene, chrysene, benzo[j]fluoranthene, indeno[1,2,3-cd]pyrene, dibenzo[a,i]pyrene, acenaphthylene, benzo[e]pyrene and benzo(a)pyrene were not detected in the root. The total concentrations of PAHs in the tissues of *A.aureum* followed this decreasing order: leaf (24.53 mg/kg) > stem (2.41 mg/kg) > root (1.42 mg/kg).

In Iko Town mangrove, benzo[k]fluoranthene (0.64±0.02 mg/kg) and dibenzo[a,h]pyrene (0.04±0.01 mg/kg) had the highest and lowest concentrations in the leaf, respectively. Phenanthrene, fluoranthene, benz[a]anthracene, chrysene, 3 methylcholanthrene, indeno[1,2,3-cd]pyrene, benzo[ghi]perylene, acenaphthylene, benzo[e]pyrene and benzo(a)pyrene were not detected in the leaf. In the stem, benzo[k]fluoranthene (1.73±0.06 mg/kg) and Dibenzo[a,h]anthracene (0.03±0.01 mg/kg) had the highest and lowest concentrations, respectively while PAHs such as phenanthrene, fluoranthene, benz[c]phenanthrene, benz[a]anthracene, chrysene, benzo[j]fluoranthene, 3 methylcholanthrene, indeno[1,2,3-cd]pyrene, benzo[ghi]perylene, dibenzo[a,h]pyrene, acenaphthylene, benzo[e]pyrene and benzo(a)pyrene were not detected in the stem. In the root, benzo[k]fluoranthene (0.53±0.02 mg/kg) and benzo [ghi]perylene (0.02±0.05 mg/kg) had the highest and lowest concentrations in the root respectively while phenanthrene, fluoranthene, pyrene, benz[c]phenanthrene, benz[a]anthracene, chrysene, benzo[j]fluoranthene, 3 methylcholanthrene, dibenzo[a,h]pyrene, acenaphthylene, benzo[e]pyrene and benzo(a)pyrene were not detected in the root. The total PAH accumulation in these plant tissues followed this decreasing order: stem (1.89 mg/kg) > leaf (1.37 mg/kg) > root (0.76 mg/kg).

In Uta Ewa mangrove, 3 methylcholanthrene (0.32±0.06 mg/kg) and benzo[ghi]perylene (0.01±0.00 mg/kg) had the highest and least concentrations in leaf respectively while phenanthrene, chrysene, acenaphthylene and benzo[e]pyrene were not detected in the leaf. In the stem, 3 methylcholanthrene (0.55±0.06 mg/kg) had the highest concentration while

benzo[k]fluoranthene (0.03±0.02 mg/kg) and dibenzo [a.h] pyrene (0.03±0.00 mg/kg) had the lowest concentrations. Phenanthrene and acenaphthylene were not detected in the stem. In the root, benzo[k]fluoranthene (0.65±0.03 mg/kg) and benzo[ghi]perylene (0.03±0.02 mg/kg) had the highest and lowest concentrations respectively. PAHs like phenanthrene, benz[c]phenanthrene, benz[a]anthracene, chrysene, benzo[j]fluoranthene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, , acenaphthylene, benzo[e]pyrene and benzo(a)pyrene were not detected in the root. The total PAH concentration followed this decreasing order: stem (1.95 mg/kg) leaf (1.22 mg/kg) and root (1.07 mg/kg).

Table 1: Mean values of dry season PAHS in *A.aureum* across the mangrove communities

PAHs	Okoroutip			Iko Town			Uta Ewa		
(mg/kg)	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root
Phenanthrene	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fluoranthene	0.21±0.01	0.03±0.00	0.12±0.01	ND	ND	ND	0.05±0.01	0.07±0.04	0.07±0.01
Pyrene	0.28±0.05	0.05±0.12	0.09±0.01	0.05±0.03	0.04±0.02	ND	0.04±0.01	0.04±0.00	0.05±0.02
Benz[c] phenanthrene	3.06±0.02	0.13±0.02	ND	0.14±0.01	ND	ND	0.12±0.02	0.15±0.03	ND
Benz[a] anthracene	1.17±0.58	0.02±0.01	ND	ND	ND	ND	0.07±0.01	0.20±0.12	ND
Chrysene	0.95±0.03	ND	ND	ND	ND	ND	ND	0.09±0.01	ND
Benzo[k] fluoranthene	1.19±0.58	1.74±0.02	0.96±0.01	0.64±0.02	1.73±0.06	0.53±0.02	0.02±0.00	0.03±0.02	0.65±0.03
Benzo[j] fluoranthene	7.69±1.16	0.15±0.03	ND	0.18±0.01	ND	ND	0.13±0.02	0.13±0.03	ND
3 methylcholanthrene	6.36±0.02	0.03±0.01	0.15±0.03	ND	ND	ND	0.32±0.06	0.55±0.06	0.23±0.02
Indeno[1,2,3-cd] pyrene	0.34±0.02	ND	ND	ND	ND	0.04±0.01	0.09±0.01	0.12±0.01	ND
Dibenzo[a,h] anthracene	0.56±0.01	0.04±0.02	0.03±0.01	0.06±0.01	0.03±0.01	0.11±0.01	0.13±0.06	0.08±0.01	0.04±0.01
Benzo[ghi] perylene	0.91±0.01	ND	0.03±0.02	ND	ND	0.02±0.05	0.01±0.00	0.04±0.00	0.03±0.02
Dibenzo[a,h]pyrene	0.66±0.38	0.04±0.01	0.04±0.02	0.04±0.01	ND	ND	0.07±0.02	0.03±0.00	ND
Dibenzo[a,i]pyrene	0.99±0.57	0.18±0.01	ND	0.26±0.01	0.09±0.01	0.06±0.02	0.12±0.03	0.29±0.05	ND
Acenaphthylene	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzo[e]pyrene	0.09±0.01	ND	ND	ND	ND	ND	ND	0.06±0.02	ND
Benzo(a)pyrene	0.07±0.01	ND	ND	ND	ND	ND	0.05±0.02	0.07±0.01	ND
Total	**24.53**	**2.41**	**1.42**	**1.37**	**1.89**	**0.76**	**1.22**	**1.95**	**1.07**

Mean ± Standard error; ND – Not Detected

3.2. Wet Season Characterization of PAHs in *A. aureum* across the Mangrove Communities

The wet season characterization of PAHs in *A. aureum* across the mangrove communities is presented in in Table 2. In Okoroutip mangrove, benzo[k]fluoranthene (5.36±0.02 mg/kg) and dibenzo[a,h] anthracene (0.00±0.00 mg/kg) had the highest and lowest concentrations in the leaf respectively.

PAHs such as chrysene, 3 methylcholanthrene, indeno[1,2,3-cd]pyrene, benzo[ghi]perylene and dibenzo[a,h]pyrene were not detected in the leaf. In the stem, benzo[k]fluoranthene (3.20±0.03 mg/kg) and benzo[e]pyrene (0.04±0.01 mg/kg) and had the highest and lowest concentrations respectively while chrysene, 3 methylcholanthrene, indeno[1,2,3-cd] pyrene, dibenzo[a,h]anthracene, benzo[ghi] perylene and dibenzo[a,h]pyrene were not detected in the stem. In the root, benz[a]anthracene (1.25±0.01 mg/kg) had the highest concentration while pyrene (0.60±0.12 mg/kg) had the lowest. Benzo[k]fluoranthene, benzo[j]fluoranthene, 3 methylcholanthrene, indeno[1,2,3-cd] pyrene, dibenzo[a,h]anthracene, benzo[ghi]perylene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, benzo[e[pyrene and benzo(a)pyrene were not

detected in the root. In Iko Town mangrove, indeno[1,2,3-cd]pyrene (21.13±0.18 mg/kg) and dibenzo[a,i]pyrene (0.20±0.12 mg/kg) had the highest and lowest concentrations in the leaf, respectively, while chrysene, 3 methylcholanthrene, benzo[ghi]perylene, dibenzo[a,h]pyrene, benzo[e]pyrene and benzo(a)pyrene were not detected in the leaf. In the stem, indeno[1,2,3-cd] pyrene (7.62±0.06 mg/kg) and dibenzo[a,i]pyrene (0.18±0.01 mg/kg) had the highest and lowest concentrations respectively while 3 methylcholanthrene, benzo[ghi]perylene, dibenzo[a,h], benzo[e]pyrene and benzo(a)pyrene were not detected in the stem. In the root, benzo (a) pyrene (2.94±0.02 mg/kg) and benzo [j]fluoranthe (0.09±0.02 mg/kg) had the highest and lowest concentrations in the root, respectively. PAHs like 3 methylcholanthrene, indeno[1,2,3-cd] pyrene, dibenzo[a,h]anthracene, benzo[ghi]perylene, dibenzo[a,h]pryrene, dibenzo[a,i]pyrene and benzo[e]pyrene were not detected in the root. In Uta Ewa mangrove, acenaphthylene (0.79±0.01 mg/kg) and benzo[j]fluoranthene (0.08±0.02 mg/kg) had the highest and lowest concentrations in the leaf respectively while benz[c]phenanthrene, benz[a]anthracene, chrysene, methylcholanthrene, indeno[1,2,3-cd]pyrene, dibenzo[a,h]anthracene, benzo[ghi]perylene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, benzo[e]pyrene and benzo(a)pyrene were not detected in the leaf. In the stem, phenanthrene (0.71±0.01 mg/kg) had the highest concentration while benz[c]phenanthrene (0.04±0.01 mg/kg) and benzo[j]fluoranthene (0.04±0.01mg/kg) had the lowest concentrations. PAHs such as benz[a]anthracene, chrysene, methylcholanthrene, indeno[1,2,3-cd] pyrene, dibenzo[a,h]anthracene, benzo[ghi]perylene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, benzo[e]pyrene and benzo(a)pyrene were not detected in the stem. In the root, benz[a]anthracene (1.18±0.58 mg/kg) and benz[j]fluoranthene (0.05±0.01 mg/kg) had the highest and lowest concentrations respectively. Benz[k]fluoranthene, 3 methylcholanthrene, indeno[1,2,3-cd] pyrene, dibenzo[a,h]anthracene, benzo[ghi]perylene, dibenzo[a,h]pyrene, dibenzo[a,i]pyrene, benzo[e]pyrene and benzo(a)pyrene were not detected in the root.

Table 2: Mean values of wet season PAHS in A.*aureum* across the mangrove communities

PAHs (mg/kg)	Okoroutip			Iko Town			Uta Ewa		
	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root
Phenanthrene	0.69±0.01	0.65±0.03	0.68±0.06	0.75±0.03	0.68±0.01	0.64±0.02	0.69±0.06	0.71±0.01	0.80±0.06
Fluoranthene	0.58±0.02	0.64±0.01	0.63±0.01	0.68±0.06	0.52±0.01	0.80±0.06	0.59±0.05	0.63±0.06	0.83±0.05
Pyrene	0.61±0.06	0.63±0.06	0.60±0.12	0.79±0.01	0.71±0.06	0.56±0.01	0.69±0.01	0.52±0.02	0.57±0.02
Benz[c]phenanthrene	0.88±0.01	0.67±0.01	0.65±0.03	0.64±0.01	0.62±0.12	0.60±0.01	ND	0.04±0.01	0.76±0.01
Benz[a]anthracene	1.21±0.01	1.19±0.58	1.25±0.01	1.43±0.12	1.42±0.01	1.41±0.01	ND	ND	1.18±0.58
Chrysene	ND	ND	0.65±0.01	ND	0.69±0.01	0.77±0.04	ND	ND	1.01±0.58
Benzo[k]fluoranthene	1.08±0.01	1.09±0.02	ND	0.58±0.12	0.47±0.02	0.79±0.06	0.43±0.01	0.25±0.03	ND
Benzo[j]fluoranthene	5.36±0.02	3.20±0.03	ND	0.21±0.01	0.14±0.04	0.09±0.02	0.08±0.02	0.04±0.01	0.05±0.01
3 methylcholanthrene	ND	ND	ND	ND	ND	ND	ND	ND	ND
Indeno[1,2,3-cd]pyrene	ND	ND	ND	21.13±0.18	7.62±0.06	ND	ND	ND	ND
Dibenzo[a,h]anthracene	0.00±0.00	ND	ND	7.27±0.01	4.21±0.04	ND	ND	ND	ND
Benzo[ghi]perylene	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dibenzo[a,h]pyrene	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dibenzo[a,i]pyrene	1.02±0.02	0.92±0.01	ND	0.20±0.12	0.18±0.01	ND	ND	ND	ND
Acenaphthylene	0.79±0.04	0.56±0.06	0.62±0.01	0.58±0.06	0.71±0.06	0.65±0.06	0.79±0.01	0.61±0.01	0.57±0.02
Benzo[e]pyrene	0.06±0.01	0.04±0.01	ND	ND	ND	ND	ND	ND	ND
Benzo(a)pyrene	0.07±0.03	0.05±0.02	ND	ND	ND	2.94±0.02	ND	ND	ND
Total	**12.35**	**9.64**	**5.08**	**34.26**	**17.97**	**9.25**	**3.27**	**2.80**	**5.77**

Mean ± Standard error; ND – Not Detected

4.0. Discussion, Conclusion and Recommendation

4.1. Discussion

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic pollutants of global concern due to their toxicity, mutagenicity, and carcinogenicity. Mangrove ecosystems, particularly those located in oil-producing regions, are highly vulnerable to PAH contamination. This study revealed substantial accumulation of PAHs in different tissues (roots, stems, and leaves) of *Acrostichum aureum* across three mangrove communities, with marked spatial and seasonal variations. These findings are discussed in relation to studies conducted globally within the last decade, with emphasis on environmental implications, human health risks, and the bioaccumulation capacity of mangrove plants.

The high concentrations of PAHs recorded in *A. aureum*, especially during the dry season at Okoroutip where leaf tissues accumulated up to 24.53 mg/kg, far exceed values reported for many mangrove-associated plants globally. Billah and Bhuiyan (2022) reported that PAH concentrations in mangrove vegetation across Asia and the Middle East are generally within the µg/kg range, which rarely exceeds 1 mg/kg. Similarly, Simbi-Wellington and Ideriah (2022) documented PAH concentrations between 0.02 and 0.06 mg/kg in mangrove leaves around gas-flaring sites in the Niger Delta, Nigeria. The substantially higher concentrations observed in the present study indicate intense and prolonged hydrocarbon inputs, likely linked to petroleum exploration, artisanal refining, and urban runoff.

The distribution pattern of PAHs among plant tissues showed that leaves generally accumulated higher concentrations than stems and roots, particularly in Okoroutip and Iko Town during both seasons. This observation aligns with previous studies suggesting that foliar deposition from atmospheric PAHs is a major pathway of contamination in mangrove plants (Billah and Bhuiyan, 2022; Meng *et al.*, 2024). Leaves possess large surface areas and waxy cuticles capable of adsorbing airborne PAHs, especially high-molecular-weight compounds. However, deviations from this trend were also observed, such as higher stem accumulation in Iko Town and increased root concentrations during the wet season in Uta Ewa. These variations suggest that both atmospheric deposition and root uptake from contaminated sediments contribute to PAH accumulation, depending on site-specific environmental conditions.

Seasonal variation played a significant role in PAH accumulation. Wet-season samples, particularly from Iko Town, recorded remarkably high total PAHs in leaves (34.26 mg/kg), far exceeding dry-season values. This seasonal increase may be attributed to enhanced runoff, flooding, and resuspension of contaminated sediments during heavy rainfall, which increases PAH bioavailability (Keshavarzifard *et al.*, 2018). Similar seasonal trends have been reported in tropical estuaries and mangrove sediments in India and Southeast Asia, where monsoon rainfall significantly elevated PAH concentrations (Borah *et al.*, 2019). Conversely, reduced concentrations observed in some tissues during the wet season may reflect dilution effects or enhanced microbial degradation under wetter conditions.

The PAH profiles observed in *A. aureum* were dominated by high-molecular-weight compounds such as benzo[j]fluoranthene, benzo[k]fluoranthene, 3-methylcholanthrene, and indeno[1,2,3-cd]pyrene. These compounds are characteristic of pyrogenic and petrogenic sources which are of particular concern due to their carcinogenic properties (USEPA, 2017). In contrast, studies on *Avicennia marina* and *Rhizophora mucronata* have reported dominance of low- to medium-molecular-weight PAHs such as phenanthrene and fluoranthene, particularly in roots (Naidoo and Naidoo, 2018). The predominance of heavier PAHs in *A. aureum* suggests exposure to chronic petroleum pollution rather than short-term combustion sources.

The exceptionally high PAH accumulation observed in *A. aureum* highlights its potential role as a bioindicator species in contaminated mangrove environments. Mangrove plants have long been recognized as effective biomonitors due to their sedentary nature and close association with

sediments (Billah and Bhuiyan, 2022). The strong accumulation of PAHs in *A. aureum* leaves supports its use in monitoring atmospheric PAH pollution in coastal regions. However, variability in tissue-specific accumulation patterns suggests that whole-plant assessments may provide a more comprehensive indication of environmental contamination.

For phytoremediation, *A. aureum* demonstrates a high capacity to absorb PAH but limited evidence of active degradation. Previous studies have shown that mangrove plants alone may not significantly enhance PAH removal from sediments unless supported by microbial activity (Tam and Wong, 2008). Nonetheless, plants like *A. aureum* can contribute to phytostabilization by immobilizing contaminants and reducing their mobility. Kafle *et al*. (2022) emphasized that effective phytoremediation of PAHs often requires synergistic interactions between plants, rhizosphere microbes, and environmental management practices such as nutrient amendment and aeration.

The environmental and public health implications of high PAH concentrations in mangrove vegetation are profound. Mangroves serve as feeding and breeding grounds for fish, crustaceans, and mollusks, which can bioaccumulate PAHs and transfer them through the food web (Billah and Bhuiyan, 2022) and affect man via egestion. Chronic exposure to PAHs has been associated with cancer, endocrine disruption, and developmental disorders in humans (USEPA, 2017). Therefore, the elevated PAH levels detected in *A. aureum* raise concerns regarding seafood safety and ecosystem health in the studied mangrove communities.

4.3. Conclusion

This study demonstrates that *Acrostichum aureum* accumulates PAHs at concentrations significantly higher than those reported for many mangrove species globally over the past decade. The observed tissue-specific and seasonal variations reflect complex interactions between pollution sources, hydrological processes, and plant physiology. While *A. aureum* shows promise as a bioindicator and accumulator of PAHs, its role in active remediation remains uncertain and likely dependent on microbial associations. These findings underscore the urgent need for pollution control, continuous monitoring, and integrated remediation strategies in oil-impacted mangrove ecosystems.

4.4. Recommendation

Based on the high concentrations of polycyclic aromatic hydrocarbons (PAHs) detected in *Acrostichum aureum* across the studied mangrove communities, it is recommended that continuous monitoring of PAHs in mangrove vegetation, sediments, and aquatic organisms is recommended due to the high levels detected in *Acrostichum aureum*. Regulatory authorities should strengthen controls on petroleum-related activities and waste discharge in coastal areas. Given its strong bioaccumulation capacity, *A. aureum* can be used as a bioindicator of hydrocarbon pollution. Integrated remediation approaches combining phytoremediation and microbial enhancement should be explored, alongside public health awareness to limit consumption of seafood from contaminated mangrove environments.

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