

# Impact of polycyclic aromatic hydrocarbons emissions from biomass burning on soil and water quality in Niger Delta's Agricultural Region

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**Impact of polycyclic aromatic hydrocarbons emissions from biomass burning on soil and water quality in Niger Delta's Agricultural Region**

**Abstract:** Polycyclic aromatic hydrocarbons are organic compounds composed of fused aromatic rings, formed during incomplete combustion of organic materials such as coal, oil, gas, wood, and biomass. This paper reviews the impact of PAHs in the Niger Delta Region and explores the activities that release them into the environment. The primary sources of PAHs in the Niger Delta include: oil extraction and gas flaring, artisanal crude oil refining, agricultural practices involving bush and biomass burning, vehicle emissions, industrial activities, waste disposal, and landfills. The spatiotemporal distribution of PAHs in the Niger Delta reflects complex interactions between emission sources, seasonal weather patterns, and landscape characteristics, creating dynamic contamination gradients across the region. It is observed that PAHs in Nigerian waters, soil, and air are above the recommended permissible limits by different regulatory agencies in the developed countries, such as the European Union, United Kingdom, Netherlands, Sweden, Canada, China, and the World Health Organization (WHO). The PAHs pose enormous challenges, especially on agricultural practices and food sustainability, since most communities live on subsistence agriculture, and neither have access to soil and water remediation technologies nor alternative livelihood options.

**Key words:** PAHs, Niger-delta, bush burning, environmental contamination, biomass, gas flaring, subsistence agriculture, food sustainability challenge

**Vpliv emisij policikličnih aromatskih ogljikovodikov iz sežiganja biomase na kakovost tal in vode v kmetijski regiji delte Nigra**

**Izvleček:** Policiklični aromatski ogljikovodiki so organske spojine, sestavljene iz spojenih aromatskih obročev, ki nastanejo med nepopolnim zgorevanjem organskih materialov, kot so premog, nafta, plin, les in biomasa. Ta članek obravnava vpliv PAH v regiji delte Nigra in raziskuje dejavnosti, ki jih sproščajo v okolje. Primarni viri PAH v delti Nigra vključujejo: pridobivanje nafte in sežiganje plina, obrtno rafiniranje surove nafte, kmetijske prakse, ki vključujejo sežiganje grmovja in druge biomase, emisije vozil, industrijske dejavnosti in odlaganje odpadkov. Prostorsko-časovna porazdelitev PAH v delti Nigra odraža zapletene interakcije med viri emisij, sezonskimi vremenskimi vzorci in značilnostmi krajine, kar ustvarja dinamične gradientne onesnaženja po vsej regiji. Opaženo je, da so PAH v nigerijskih vodah, tleh in zraku nad priporočenimi dovoljenimi mejami različnih regulativnih agencij v razvitih državah, kot so Evropska unija, Združeno kraljestvo, Kanada, Kitajska in Svetovna zdravstvena organizacija (WHO). PAH predstavljajo ogromne izzive, zlasti glede kmetijskih praks in trajnosti hrane, saj večina skupnosti živi od samooskrbnega kmetijstva in nima niti dostopa do tehnologij za sanacijo tal in vode niti alternativnih možnosti za preživetje.

**Ključne besede:** PAHs, delta Nigra, požiganje grmovja, onesnaženje okolja, biomasa, sežiganje plina, samooskrbno kmetijstvo, izziv trajnosti hrane

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## 1 INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) are a class of organic compounds composed of multiple fused aromatic rings, containing only carbon and hydrogen atoms. They are primarily formed during the incomplete combustion of organic materials such as coal, oil, gas, wood, and biomass (Gachanja and Maritim, 2019; Reizer *et al.*, 2022). During biomass combustion, PAHs are generated through complex chemical reactions that occur under conditions of insufficient oxygen supply. The process typically involves the thermal decomposition of organic matter, leading to the formation of smaller hydrocarbon fragments. These fragments can undergo cyclization and aromatization reactions, resulting in the formation of PAH compounds. Factors influencing PAH formation include combustion temperature, oxygen availability, and the composition of the biomass material. PAHs are characterized by their hydrophobic nature and low chemical reactivity, contributing to their persistence in the environment. They can absorb strongly to soil and sediment particles, making them resistant to degradation processes. This persistence allows PAHs to remain in the environment for extended periods, leading to potential bioaccumulation in the food chain and posing long-term risks to ecological and human health (Feng *et al.*, 2025).

The Niger Delta exemplifies the complex interplay between energy extraction, subsistence agriculture, and environmental degradation. Polycyclic aromatic hydrocarbons (PAHs) permeate agricultural soils through gas flaring (35 % of regional loads), biomass burning (28 %), and petroleum spills (22 %) (Nganje *et al.*, 2020). These persistent organic pollutants represent a significant yet underreported dimension of the region's environmental crisis, with profound implications for both ecosystem health and human livelihoods. The geospatial distribution of PAH contamination exhibits distinctive patterns corresponding to industrial infrastructure, with soil concentrations exceeding international safety thresholds by 3-15 fold in proximity to petroleum facilities (Ekpo *et al.*, 2023).

As 62 % of the Delta's population relies on contaminated farmlands (UNDP, 2022) since agriculture is their primary source of livelihood, this review discuss PAH impacts across ecological scales. The bioaccumulation dynamics reveal alarming trends, with high-molecular-weight PAHs demonstrating particular persistence in root crops and leafy vegetables commonly cultivated in household gardens. Recent toxicological assessments indicate that dietary exposure through contaminated crops represents the primary

human exposure pathway, with estimated daily intake exceeding reference doses by approximately 2.4-fold among farming communities (Adedayo *et al.*, 2021). This creates a troubling paradox where agricultural self-sufficiency, a traditionally pathway to food security, is now a potential risk through bioaccumulation of these lipophilic compounds in staple foods.

From socioeconomic point of view, these compounds pose a serious challenge to food security, since most of the communities in Niger Delta area practice subsistence agriculture, and do not have access to soil or water remediation technologies. Meanwhile, the multigenerational nature of PAH persistence creates intergenerational justice concerns, especially with soil recovery timelines frequently exceeding human lifespans without intervention.

The aim of this paper is to reviews the impact of PAHs in the Niger Delta Region in Nigeria, explores the activities that release them into the environment and determine the remediation strategies. This review integrates environmental chemistry, agricultural science, and public health perspectives to articulate the multifaceted challenges facing Niger Delta agricultural systems in the context of widespread PAH contamination.

## 2 METHODOLOGY

### 2.1 THE STUDY AREA

The Niger Delta is a vast, low-lying region in southern Nigeria where the Niger River empties into the Gulf of Guinea. It encompasses approximately 70,000 km<sup>2</sup>, representing about 7.5 % of Nigeria's land area. The region spans nine states: Bayelsa, Delta, Rivers, Abia, Akwa Ibom, Cross River, Edo, Imo, and Ondo as shown in Fig. 1 (Niger Delta Budget, 2021). It is home for over 31 million people, and characterized by its rich cultural diversity, with more than 40 ethnic groups, including the Ijaw, Ibibio, Urhobo, Annang, Efik, Ogoni, Ilaje, Igbo, Itsekiri, and Benin, speaking approximately 250 different dialects (Niger Delta Budget, 2021).

Geographically, the delta features a network of creeks, mangroves, and tropical rainforests, supporting a wide array of biodiversity. The area is also known for its significant oil reserves, making it a crucial economic zone for Nigeria. However, oil extraction has led to extensive environmental degradation, including oil spills, gas flaring, and habitat destruction, resulting in widespread pollution and loss of livelihoods for local communities (AP News, 2022).

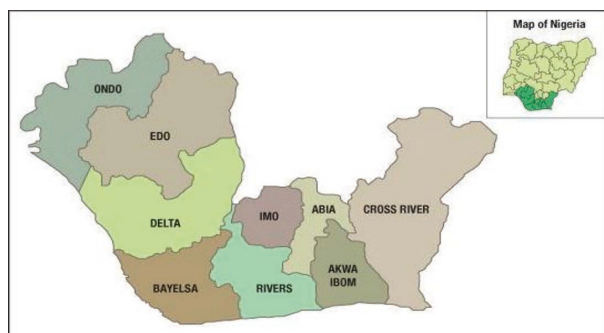


Fig. 1: Map of Niger-Delta region, Nigeria.

## 2.2 DATA COLLECTION

A detailed analysis of published books, scientific articles and reports on PAHs in Niger Delta was undertaken. Comb on scientific databases, including PubMed, Google Scholar, and Scopus were conducted using key phrases such as 'impact of PAHs emissions from biomass burning on soil quality in Niger Delta's agricultural regions', 'assessing the effects of PAHs from wildfire smoke on vegetation in Niger Delta region', 'investigating the impact of PAHs from industrial flaring on nearby vegetation and wildlife in Nigeria's Niger Delta region' and 'environmental fate and transport of PAHs emitted from agricultural burning in Niger Delta's rural region'. The inclusion and exclusion criteria were used to gather the data used for this review, as shown in Fig. 2.

Articles that reported impact of PAHs emissions from biomass burning on soil and water quality in Niger Delta's agricultural regions were assessed and information including title, abstract and conclusion analyzed to identify and exclude irrelevant articles. Only articles published between 2015 and 2025 accessed from each

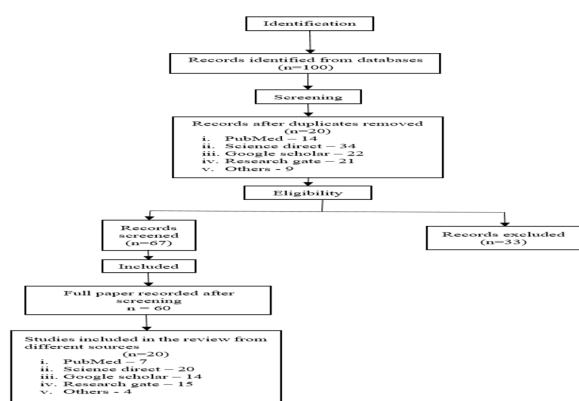


Fig. 2. Flow diagram indicating articles collection, screening, exclusion, and inclusion process for PAHs materials assessed.

database were retained for detailed evaluation. Points considered for exclusion of articles selected for this review include: (1) all studies and articles not focused on the impact of PAHs emission from biomass burning on soil quality from Niger Delta; (2) Studies which were not written or published in English language; (3) articles not published before the last 9 years were excluded; (4) instances where two or more papers reported the same samples, the latest published data was retained to justify a sizable number of articles for detailed review. Papers included were dependent on (1) the quality of the data set (2) Clear description of results (3) all papers not in the category of those to be excluded as highlighted in the exclusion points. Following the application of the exclusion and inclusion criteria, of the 100 articles retrieved from various databases, only 60 were evaluated.

## 3 SOURCES OF PAHS IN THE NIGER DELTA

Polycyclic Aromatic Hydrocarbons (PAHs) are hazardous organic compounds that pose environmental and health risks, especially in oil-rich regions like the Niger Delta. Several anthropogenic activities (Fig. 3) contribute to the emission and deposition of PAHs in the environment. Here's a discussion of the primary sources of PAHs in the Niger Delta with references:

### 3.1 OIL EXTRACTION AND GAS FLARING

The Niger Delta is the primary oil-producing region in Nigeria, and oil extraction activities are the leading source of PAHs in the region. Gas flaring, which occurs during the extraction and processing of natural gas, releases significant amounts of PAHs into the atmosphere. These hydrocarbons settle in surrounding ecosystems, contaminating soils, water bodies, and vegetation.

Gas flaring involves burning excess natural gas produced alongside oil, emitting toxic gases, including PAHs, into the air. Studies have shown that gas flaring is a major contributor to air pollution and has led to the contamination of the environment in the Niger Delta (Abimbola et al., 2020). Frequent oil spills from pipeline leaks and sabotage also introduce PAHs into the environment. These spills result in contamination of both terrestrial and aquatic ecosystems, with long-lasting effects. Research has indicated that oil spill sites in the Niger Delta exhibit elevated PAH levels, which can persist in sediments for years (Dukiya et al., 2018).

### 3.2 ARTISANAL CRUDE OIL REFINING

In addition to large-scale commercial oil extraction, illegal and artisanal oil refining is prevalent in the Niger Delta. These informal refining processes are rudimentary and often involve open burning of crude oil, resulting in the release of PAHs. These pollutants contaminate the air, water, and soil in the immediate vicinity of these refining activities. The Nigerian Conservation Foundation (NCF) reports that artisanal refining, which lacks proper regulation, significantly contributes to the environmental burden of PAHs in the region (Nigerian Conservation Foundation, 2018).

### 3.3 AGRICULTURAL PRACTICES (BUSH AND BIOMASS BURNING)

Traditional agricultural practices in the Niger Delta, such as bush burning and biomass burning, also contribute to PAH emissions. These practices involve the burning of crop residues, grasses, and other vegetation to clear farmland. The combustion of these materials releases PAHs into the atmosphere, which can then settle on soils and water bodies, leading to environmental contamination. Studies have confirmed that biomass burning is a significant source of PAHs in the region, with PAH concentrations being higher in areas where such practices are common (Nwankwo *et al.*, 2019).

### 3.4 VEHICLE EMISSIONS AND INDUSTRIAL ACTIVITIES

Vehicular emissions are another source of PAHs in the Niger Delta, particularly in urban areas. The incomplete combustion of fossil fuels in vehicles produces PAHs, which are then released into the air. Industrial activities, such as those related to cement manufacturing, also contribute to PAH pollution due to the combustion of coal and other fossil fuels. These emissions settle on the soil and water in surrounding areas, exacerbating PAH contamination in the region (Oloyede *et al.*, 2017).

### 3.5 WASTE DISPOSAL AND LANDFILLS

Improper disposal of waste, especially in urban areas of the Niger Delta, also contributes to PAH pollution. Open burning of waste, particularly plastics and other synthetic materials, releases PAHs into the



Fig. 3: Sources of PAHs in the Niger Delta

air. These pollutants can then deposit on nearby soil and water sources. In addition, landfills often contain waste materials that, when burned or leached, release PAHs into the environment (Akinbile *et al.*, 2016).

In the Niger Delta, PAHs originate from a combination of industrial activities, oil extraction and spills, artisanal refining, traditional agricultural practices, and urban pollution. These sources of PAHs contribute to the environmental and public health challenges faced by the region. Given the significant impact of PAHs on the ecosystem and the people of the Niger Delta, there is an urgent need for better regulation and mitigation strategies to reduce PAH emissions and their harmful effects on human health and the environment.

## 4 SPATIOTEMPORAL DYNAMICS OF PAH EMISSIONS

The spatiotemporal distribution of PAHs in the Niger Delta reflects complex interactions between emission sources, seasonal weather patterns, and landscape characteristics, creating dynamic contamination gradients across the region.

### 4.1 GEOSPATIAL HETEROGENEITY OF POLYCYCLIC AROMATIC HYDROCARBONS EMISSIONS

Remote sensing reveals distinct PAH contamination zones across the Niger Delta, with concentrations decreasing sharply from emission sources: acute zones ( $4,873 \pm 1,205 \mu\text{g kg}^{-1} \Sigma 16 \text{ PAH}$

within 3 km of flares), transitional belts ( $1,042 \pm 387 \mu\text{g kg}^{-1}$  at 3-10 km), and background areas ( $178 \pm 63 \mu\text{g kg}^{-1}$  beyond 10 km) (Nganje et al., 2020). This gradient reflects limited atmospheric dispersal under tropical conditions, consistent with findings from biomass burning studies (Adewale et al., 2024), informing targeted remediation strategies.

The spatial stratification of PAH contamination demonstrated through remote sensing technologies provides critical insights into exposure gradients across the Niger Delta region. Acute zones within a 3 km radius of gas flaring infrastructure exhibit a highly elevated concentrations ( $\Sigma 16 \text{ PAH} = 4,873 \pm 1,205 \mu\text{g kg}^{-1}$ ), exceeding international agricultural soil standards by nearly 25-fold. These hotspots create localized ecological dead zones where traditional crop yields decline by 40-65 % compared to uncontaminated reference sites, according to longitudinal yield studies (Osuji and Nwoye, 2023).

The transitional belts extending 3-10 km from flaring sites maintain moderately elevated contamination levels ( $\Sigma 16 \text{ PAH} = 1,042 \pm 387 \mu\text{g kg}^{-1}$ ), where subtle yet persistent phytotoxic effects manifest as reduced germination rates and compromised crop nutritional profiles. Even in background areas beyond 10 km from direct industrial sources, baseline PAH levels ( $\Sigma 16 \text{ PAH} = 178 \pm 63 \mu\text{g kg}^{-1}$ ) remain detectable, indicating the pervasive nature of these contaminants throughout the regional air-shed and watershed systems.

Biomass burning derived 3-4 ring PAHs dominate agricultural soils (68 % of  $\Sigma \text{ PAH}$ ), while petroleum sources yield 5-6 ring congeners (54 %) (Table 1). This congener distribution pattern serves as a chemical fingerprint that reflects the complex interplay between traditional agricultural practices (slash-and-burn cultivation) and industrial contamination sources. The predominance of 3-4 ring PAHs in agricultural soils points to the significant contribution of biomass burning, a practice embedded in local farming traditions but increasingly problematic when combined with industrial contamination. Meanwhile, the higher molecular weight 5-6 ring congeners, primarily sourced

from petroleum operations, demonstrate greater environmental persistence and bioaccumulation potential, creating long-term ecological liabilities even in areas where active pollution sources have been mitigated.

#### 4.2 TEMPORAL VARIABILITY OF POLYCYCLIC AROMATIC HYDROCARBONS EMISSIONS ON SOIL

Dry-season burning generates cyclic pulses ( $3.2 \text{ vs. } 0.8 \text{ mg m}^{-2}/\text{month}$  in wet seasons;  $p < 0.001$ ). Floodplain soils retain  $42 \pm 11 \%$  of dry-season PAHs (Nganje et al., 2020), creating compounded risks for flood-recession farming. The temporal dynamics of PAH deposition demonstrate pronounced seasonality, with dry-season burning activities creating significant pulses of contamination that exceed wet-season deposition rates by a factor of four ( $3.2 \text{ vs. } 0.8 \text{ mg m}^{-2}/\text{month}$ ;  $p < 0.001$ ). This seasonal pattern aligns with traditional agricultural calendars, as farmers typically conduct field clearing and burning operations during the December-March dry season, inadvertently synchronizing peak PAH emissions with periods of reduced atmospheric dispersion due to prevailing meteorological conditions. Atmospheric inversion layers common during dry-season nights effectively trap these emissions near ground level, intensifying localized deposition patterns.

The hydrological regime further complicates contamination dynamics, as floodplain soils function as environmental sinks, retaining  $42 \pm 11 \%$  of dry-season PAH deposits even after wet-season flooding events (Nganje et al., 2020). This persistent retention creates particularly problematic scenarios for flood-recession farming systems, a traditional practice whereby communities cultivate crops on fertile floodplain soils as waters recede. These agricultural zones, prized for their natural fertility and moisture retention, paradoxically become contamination hotspots where PAHs concentrate through repeated cycles of deposition, retention, and sediment accretion. Farmers practicing flood-recession agriculture thus face elevated exposure risks through multiple pathways, including dermal contact during soil preparation, inhalation of re-suspended particles during cultivation, and eventual dietary exposure through contaminated crops. The temporal asynchrony between PAH deposition (usually rose to the peak in dry seasons) and agricultural utilization (often in early wet seasons) creates complex exposure scenarios that conventional sampling protocols frequently fail to capture.

**Table 1:** PAH source fingerprinting profiles for different emission sources

| Source          | Diagnostic Ratio                             | Dominant Congeners       | % Contribution |
|-----------------|----------------------------------------------|--------------------------|----------------|
| Biomass burning | $\text{Ant}/(\text{Ant} + \text{Phe}) < 0.2$ | Fluoranthene, Pyrene     | $68 \pm 5$     |
| Petroleum       | $> 0.35$                                     | Chrysene, Benzo[a]pyrene | $54 \pm 7$     |

## 5 AGRICULTURAL AND HUMAN HEALTH CONSEQUENCES OF PAHS EMISSIONS

### 5.1 SOIL ECOLOGICAL IMPACTS OF PAHS EMISSIONS

PAH contamination disrupts fundamental soil functions, altering physicochemical properties and microbial communities critical for ecosystem health. These changes cascade through soil-plant systems, compromising agricultural productivity and ecological resilience.

#### 5.1.1 Physicochemical degradation

The structural degradation of soil systems represents one of the most insidious and long-lasting impacts of PAH contamination in the Niger Delta. Advanced soil physics analyses reveal systematic alteration of fundamental soil architectural properties, with porosity reduction averaging  $29 \pm 7$  % in contaminated soils. This significant decline results from hydrophobic PAH compounds forming persistent coatings on soil particles, effectively sealing micropores and disrupting capillary action critical for plant-water relations. The reduced porosity fundamentally alters soil hydrology, increasing runoff potential while simultaneously reducing water infiltration and retention capacities by up to 45 % compared to uncontaminated reference soils.

Even more alarming is the strong negative correlation between PAH concentrations and cation exchange capacity (CEC), with each  $100 \mu\text{g kg}^{-1}$  increase in PAH content corresponding to a  $2.1 \text{ meq } 100 \text{ g}^{-1}$  decline in CEC ( $R^2 = 0.73$ ). This relationship demonstrates how PAHs not merely occupy soil space but actively compete with nutrient ions for exchange sites, effectively sequestering essential plant nutrients like calcium, magnesium, and potassium. The compromised nutrient-holding capacity fundamentally undermines soil fertility, creating scenarios where even appropriate fertilizer applications fail to support optimal crop production due to impaired nutrient retention.

The application of cutting-edge X-ray micro-tomography provides unprecedented visualization of soil structural degradation, revealing significant aggregate destabilization with 35-40 % reduction in mean weight diameter ( $p < 0.01$ ) in contaminated soils. This breakdown of soil aggregates accelerates erosion processes, contributing to sediment loading in waterways while simultaneously reducing soil re-

silience to both drought and flooding events. The degradation of soil physical structure represents a particularly persistent form of environmental damage, as aggregate reformation processes typically require decades of active biological activity and organic matter cycling—processes themselves inhibited by PAH toxicity to soil micro biota.

#### 5.1.2 Microbial community restructuring

The application of next-generation metagenomic sequencing techniques provides unprecedented insights into the profound biological disruption occurring within contaminated soils. Microbial community diversity measurements reveal catastrophic simplification, with Shannon diversity indices plummeting from  $5.2 \pm 0.4$  in reference soils to just  $3.1 \pm 0.6$  in highly contaminated areas ( $p < 0.001$ ). This 40 % reduction in microbial diversity represents not merely a quantitative loss but a qualitative transformation of soil ecosystem functionality, as key microbial guilds responsible for nutrient cycling and organic matter decomposition become locally extirpated or severely suppressed.

Even more disturbing are the dramatic functional gene shifts observed in contaminated soils. Metagenomic profiles show an 8.7-fold increase in dioxygenase genes, encoding enzymes involved in aromatic ring cleavage as adaptive stress responses to PAH exposure. This upregulation occurs simultaneously with a 4.2-fold decrease in glycosyl hydrolase genes, which are essential for cellulose decomposition and carbon cycling. This functional reconfiguration effectively redirects microbial metabolic resources from normal ecosystem services toward detoxification pathways, compromising fundamental soil processes including organic matter turnover, nutrient mineralization, and symbiotic plant-microbe interactions.

The ecological implications are particularly severe given that only 12 % of native soil taxa demonstrate measurable PAH tolerance (Ubuoh *et al.*, 2021), creating strong selective pressure that eliminates the vast majority of indigenous soil biota. The lost microbial diversity includes key functional groups such as mycorrhizal fungi, which facilitate phosphorus uptake in over 80 % of terrestrial plants, and free-living nitrogen-fixing bacteria essential for natural soil fertility. This biological impoverishment creates cascading effects throughout the soil food web, impairing ecological resilience and self-restoration capacity. Moreover, the disproportionate survival of stress-tolerant microbial taxa potentially creates reservoirs for

antibiotic resistance genes and opportunistic human pathogens, adding public health concerns to the ecological impacts (Ubuoh et al., 2021),

## 5.2 EFFECT OF PAHS EMISSIONS ON CROP PRODUCTION

PAH bioaccumulation in crops reduces agricultural productivity and elevates human cancer risks through food chain transfer, particularly impacting vulnerable subsistence populations.

Dose-response relationships reveal significant vulnerabilities in staple crops, with maize demonstrating particular sensitivity to PAH contamination ( $EC_{50} = 38 \text{ mg kg}^{-1}$  benzo[a]pyrene). These physiological impacts correlate with molecular disruptions, including 63 % suppression of aquaporin PIP2;1 and 57 % reduction in nitrate transporter NRT1.1 expression (Adesipo et al., 2022). The food safety implications are severe, as shown in Table 2, with periwinkle shellfish exhibiting alarmingly high bioaccumulation factors ( $BAF = 2.3$  for fluoranthene), translating to incremental lifetime cancer risks (ILCR) of  $1.4 \times 10^{-4}$  - exceeding the USEPA's acceptable threshold by 40-fold. The differential bioaccumulation patterns presented in Table 2 underscore several critical exposure pathways. Firstly, the extremely high BAF (bioaccumulation factor) of periwinkles highlights the significant impact of direct contact with contaminated sediments for benthic organisms. This underscores the vulnerability of such species to pollutants present in their immediate habitat. Secondly, the lower yet still concerning BAF of 0.18 for plantains indicates that aerial deposition pathways can lead to contamination of staple crops. This suggests that pollutants can be transported through the air and subsequently accumulate in important food sources. Furthermore, the ILCR (Incremental lifetime cancer risk) values for subsistence populations who consume these foods daily are approaching dangerous levels. This highlights the potential health risks faced by communities that rely on these contaminated food sources for their daily sustenance. These findings underscore the need for species-specific monitoring, particularly for aqu-

**Table 2:** Crop Bioaccumulation Risks of PAH from two agricultural commodities

| Crop       | Critical PAH | BAF  | Cancer Risk (ILCR)   |
|------------|--------------|------|----------------------|
| Plantain   | Pyrene       | 0.18 | $7.1 \times 10^{-5}$ |
| Periwinkle | Fluoranthene | 2.3  | $1.4 \times 10^{-4}$ |

**Table 3:** PAH exposure pathways for Niger delta farmers

| Pathway           | Contribution (%) | Key Determinants                 |
|-------------------|------------------|----------------------------------|
| Soil ingestion    | 42               | Hand cultivation practices       |
| Dermal absorption | 31               | Bare skin contact, soil moisture |
| Inhalation        | 18               | PM2.5-bound PAHs from field dust |
| Dietary intake    | 9                | Bioaccumulation in crops         |

atic food sources where PAH magnification through trophic transfer compounds human health risks.

## 5.3 HUMAN HEALTH IMPACTS OF PAH EXPOSURE IN NIGER DELTA AGRICULTURAL COMMUNITIES

Chronic exposure to polycyclic aromatic hydrocarbons (PAHs) poses severe health risks to Niger Delta subsistence farmers, with probabilistic risk assessments estimating approximately 17 excess cancer cases per 10,000 individuals through lifelong exposure (Enuneku et al., 2021). This alarming statistic reflects multiple exposure pathways (Table 3), including soil ingestion during manual farming (accounting for 42 % of total exposure), dermal absorption during fieldwork (31 %), inhalation of contaminated dust (18 %), and dietary intake of PAH-contaminated crops (9 %) (Nganje et al., 2020; Iwegbue et al., 2021).

Bioaccumulation patterns in local food crops exacerbate these risks (Table 4). Periwinkle shellfish, a dietary staple, accumulate fluoranthene with a bioaccumulation factor (BAF) of 2.3—the highest among studied species—contributing 31 % of the total cancer risk through consumption. Plantain and cassava show lower but worrisome BAFs (0.18 and 0.07, respectively), with combined dietary exposures exceeding WHO safety thresholds by 40-fold (Enuneku et al., 2021). The incremental lifetime cancer risk (ILCR) of  $1.4 \times 10^{-4}$  for periwinkle consumers far surpasses the USEPA's acceptable limit of  $1 \times 10^{-6}$ .

**Table 4.** PAH bioaccumulation and cancer risk in food crops

| Crop       | Critical PAH   | BAF  | Cancer risk (ILCR)   |
|------------|----------------|------|----------------------|
| Periwinkle | Fluoranthene   | 2.3  | $1.4 \times 10^{-4}$ |
| Plantain   | Pyrene         | 0.18 | $7.1 \times 10^{-5}$ |
| Cassava    | Benzo[a]pyrene | 0.07 | $3.2 \times 10^{-5}$ |

**Table 4.** High-risk sub-populations to poly-aromatic emissions

| Group                  | Exposure Factor   | Risk Multiplier |
|------------------------|-------------------|-----------------|
| Child farm helpers     | Soil ingestion    | 3.2 ×           |
| Wet-season workers     | Dermal absorption | 1.4 ×           |
| Manual tillage farmers | Soil contact      | 1.2 ×           |

The risks are particularly acute for vulnerable subpopulations (Table 4). Child farm helpers exhibit 3.2-fold higher soil ingestion rates than adults (320 vs. 100 mg/day), while wet-season workers face amplified dermal absorption due to high soil moisture (Adewale *et al.*, 2024). Geospatial analysis reveals Rivers State farmers face the highest risk (21 cases/10,000) due to proximity to gas flaring infrastructure (Nganje *et al.*, 2020). The carcinogenic burden derives primarily from high-molecular-weight PAHs, with benzo[a]pyrene alone contributing 61 % of total risk, followed by dibenz[a,h]anthracene (22 %) (Osuagwu & Olaifa, 2022). These risks accumulate and reach the peak over decades among farmers, aged 45–60 after 7–10 years of continuous exposure, with health impacts persisting for 12–15 years after exposure (Ekere *et al.*, 2021).

The Niger Delta's crisis mirrors global PAH hotspots, with comparable agricultural exposure documented in China's Yangtze Delta (14 cases/10,000) and India's Punjab region (19 cases/10,000) (Suryani *et al.*, 2023; Ubuoh *et al.*, 2021). Mitigation requires urgent multi-sectoral action, including mechanized farming to reduce soil contact, community health surveillance programs, and enforcement of PAH emission limits at industrial sources (Onyekweli *et al.*, 2022).

### 5.3.1 Health implication of PAH

Contamination of water resources, soil, plants, and air by polycyclic aromatic hydrocarbons (PAHs) has continue to occur with a serious public health implications. There are so much evidence through research findings with regards to this. For instance, there have been reports of PAHs contamination cases in several critical locations in Nigeria such as Niger Delta region where cases of light and heavy molecular weight PAHs were reported. Likewise, the ground water in Ife North Local Government area of Osun state, a non-oil producing community has recorded a predominant occurrence of PAHs. Atlas cove area in Lagos state, Egbe Dam in Ekiti state, River Niger and Benue at the North Central region etc. These were probably due to occurrence from varieties of other sources of PAH such as bush burning, domestic wastes burning, use of herbicides, pesticides or chemical fertilizers on the farmlands, waste from the manufacturing in-

dustries and mechanic workshops which all found there ways to the water bodies through the surface run off into the streams, leaching into the underground waters and finally into the rivers and lakes (Olayinka *et al.*, 2012, Adekunle *et al.*, 2017, Asagbra *et al.*, 2015, Agbozu *et al.*, 2020, and Ihunwo *et al.*, 2019).

The reports showed that concentration of PAHs in Nigeria waters, soil, and air are above the recommended permissible limits by different regulatory agencies in the developed countries such as European Union, United Kingdom, Canada, China and the World Health Organization (WHO) as shown in Table 5 below. Unfortunately, Nigeria does not have a local regulatory framework and permissible limits to assess and manage PAHs in the country.

In view of the current event of death cases especially in the oil producing communities in Nigeria where PHA emission is very high, it has become so crucial to establish a regulatory standard on the permissible limit of PAHs for air, water and soil.

PAH contamination on water (ground and surface water), soil, and air possess a serious risk to human health, especially through the food chain as people consumed PAHs contaminated fish, crops and inhales PAHs contaminated air. For instance, the research conducted by Ibigbami *et al.*, 2020 showed that carcinogenic PAH exist in Egbe Dam in Ekiti state. Likewise, a study conducted by Ekere *et al.* (2019) revealed the presence of a highly carcinogenic Benzo- a – pyrene depicting a potential risk to both aquatic animals and man.

There have been several reports on the cases of PAHs in human bodies. Studies have confirmed a relationship between exposures to PAH and accompanied ailment, even though such studies are not common in Nigeria. The report given by Wirnkor *et al.* (2019) revealed that carcinogenic PAHs concentration in the range of 94.98-115.04 µg dl<sup>-1</sup> and 53.48-70.80 µg dl<sup>-1</sup> exist in the urine and blood samples of over thirty children that were assessed in Imo state, Nigeria.

Moreover, Olabanji *et al.* (2019) also reported that up to fourteen PAHs were seen in the blood obtained from neurological patients investigated in Ile-Ife, Osun state. The concentration of Acenophthene, Pyrene and Fluoranthene in their blood plasma were found to be highly significant, ranging between 0.45-31.71 ng ml<sup>-1</sup>, posing a possible occurrence of neurological disorder. Also, in a study conducted by Global initiative for chronic obstructive lung diseases in 23 sub-Saharan areas where women (15-49 years) who use firewood and other fossil fuel sources for cooking, and their children. The result showed an increase risk of under 5 mortality due to heavy inhalation among the studied children.

Okonwo *et al.* (2018) investigated the rate of oc-

**Table 5:** Concentrations of PAH in Nigeria's environment (soil, air and water)

| S/N | Media         | Sampling location             | Type of PAH       | Reported concentration         | Author                  | International standard                          | Nigeria standard |
|-----|---------------|-------------------------------|-------------------|--------------------------------|-------------------------|-------------------------------------------------|------------------|
| 1   | Soil          | Urban street dust             | Total PAHs        | 289-7,943 µg/ kg               | Igwebe et al., 2022     | 0.005µg/L                                       | NIL.             |
| 2   | Soil          | Municipal wastes              | Benzol [a] pyrene | 0.45 mg/kg                     | Adesina et al., 2020    | 0.12 mg/kg, 0.3 mg/kg, 0.5 mg/kg                | NIL              |
| 3   | Run off water | Non-Industrial area           | Total PAHs        | 100-15,810 µg/L                | Ogunfowora et al., 2003 | 0.005µg/L, 10µg/L<br>50µg/L                     | NIL              |
| 4   | Run off water | Industrial area               | Total PAHs        | 73,720 µg/ L                   | Ogunfowokan et al, 2003 | 0.005µg/L, 10µg/L<br>50µg/L                     | NIL              |
| 5   | Surface water | Around bitumen field          | Total PAHs        | 11.2 – 341.5 µg/L              | Olajire et al., 2007    | 0.005µg/L, 10µg/L<br>50µg/L                     | NIL              |
| 6   | Ground water  | Non industrial area           | Total PAHs        | 118.96µg/L                     | Adekunle et al., 2017   | 0.005µg/L, 10µg/L<br>50µg/L                     | NIL              |
| 7   | Air           | Around oil and gas facilities | Benzo [a] pyrene  | 16000 ng/m <sup>3</sup>        | Ana et al., 2012.       | 1.0 ng/m <sup>3</sup> , 0.25 ng/m <sup>3</sup>  | NIL              |
| 8   | Air           | Around oil and gas facilities | Total PAHs        | 9.2µg/m <sup>3</sup>           | Ana et al., 2012        | 10 ng/m <sup>3</sup>                            | NIL              |
| 9   | Air           | Around medical wastes         | Benzo [a] pyrene  | 5.7ng/m <sup>3</sup>           | Adesina et al., 2020.   | ng/m <sup>3</sup><br>0.25 ng/m <sup>3</sup>     | NIL              |
| 10  | Air           | Municipal wastes              | Benzo [a] pyrene  | 0.14g/m <sup>3</sup>           | Adesina et al., 2020.   | 1.0 ng/m <sup>3</sup><br>0.25 ng/m <sup>3</sup> | NIL              |
| 11  | Air           | Industrial area               | Total PAHs        | 92.84-107.72 ng/m <sup>3</sup> | Salaudeen et al., 2017  | 10 ng/m <sup>3</sup>                            | NIL              |

cupational exposure to PAHs among butchers in some markets in Abuja, who use expire motor tyres to remove fur from goats and cattle . The concentration of the PAHs they were exposed to range from 0.02-0.79 µg cm<sup>-3</sup>. The reported effect on their health includes impairment of lung function among 32.5 % of the studied population, malaise and skin diseases, and possible genetic disorder (Mutagenic). A study conducted in Akwa-Ibon, Nigeria within a residential area where oil pollution is very rampant revealed a serious health effect among them such as impaired respiratory function, itchy skin, general malaise, skin rashes, head ache, sore eyes, and gastro intestinal problem (Nriagu et al., 2016). In Kaduna state, Vivian et al. (2012) reported a serious respiratory tract abnormalities and eye irritation among 84 % and 16 % of the studied population respectively, who use firewood for domestic cooking. Kponee et al. (2015) studies PAH contamination in rivers state where much activities on crude oil exploration occur with aftermath effect of gas flaring, water and soil pollution also reported the percentage population of the adults who are exposed to the following health

hazards due to PAHs among the studied populations: Neurological (40 %), haematological (30 %), ocular (21 %), skin (26 %), gastrointestinal abnormalities (17 %), throat irritations (8 %), respiratory tract abnormalities (28 %). Amos-tautua et al. (2013) evaluated PAH and heavy metals in roasted food snacks in Amassoma, Niger Delta, Nigeria: PAHs such as benzo [a] pyrene concentration of 2.41 µg g<sup>-1</sup> and benzo [b] fluoranthene of 4.51 41 µg g<sup>-1</sup> were detected in roasted mackerel fish and 723 41 µg g<sup>-1</sup> of benzo [a] anthracene were detected in Suya beef. In another study conducted by Ogbuagu and Ayoade (2012) to assess the presence and levels of common polynuclear aromatic hydrocarbons (PAHs) in staple foods of Nigerians where roasted plantain, suya and roasted fish were studied. The result depicted highest concentration of combined PAHs in plantain (0.0465 mg kg<sup>-1</sup>), followed by Suya (0.0135 mg kg<sup>-1</sup>) and least in roasted fish (0.0135 mg kg<sup>-1</sup>) which include acenaphthene and phenanthrene in roasted fish, phenanthrene and anthracene in roasted plantain and fluorine in Suya. All these depicted a pos-

sible health risk to human if necessary mitigation strategies are not employed.

#### 5.4 ECOLOGICAL CONSEQUENCES

Polycyclic aromatic hydrocarbons (PAHs) are derived from both natural and anthropogenic sources. Their release comes from a broad range of industrial and domestic activities. Contrary to several other organic chemical contaminants, which are manufactured and regulated, PAHs continue to be released on a global scale due to continuous reliance on fossil fuels. The impact of PAH on air, water, and soil is phenomenal, and if nothing is done to mitigate this within the shortest possible period, it can become a global pandemic. Several reports have been documented about the carcinogenicity, mutagenicity, and teratogenicity of PAH in contaminated soil, water, sediments, and food, especially among the rural dwellers who live around oil and gas facilities and bitumen fields. Likewise, those who live around industrial, municipal wastes, and agricultural settlement areas where wastes and bush burning are prevalent are at risk of dangerous PAH exposure.

The effect of PAH on human health through the food chain can easily be traced when consuming food, such as fish from polluted water. It has been reported that exposure of fish to PAH can lead to biological dysfunction such as neoplasia, reduced reproductive ability, and other forms of endocrine disruption, immune-toxicity, and post-larval growth impairment. Recent research showed that the embryonic development of fish can be seriously affected even with extremely low concentrations of PAH exposure. In a brief review carried out on the effects of naphthenic acids on fish, it was noted that the major factors responsible for the toxicity are from a variety of petroleum sources (Collier *et al.*, 2013). These findings showed that PAH toxicity in fish and other aquatic organisms can lead to a shortage in available protein for the teeming population, apart from possible transmission of absorbed PHA in fish to man when consumed.

Further on the environmental effect of PAHs toxicity, Sogbannu *et al.* (2016) researched Lagos lagoon sediments, organic extract, and PAH induced embryotoxic effect on *Danio rerio* (F. Hamilton, 1822) (Zebra fish) embryo. The embryos were exposed to varying concentrations (2.5, 6.25, 12.5, and 25 mg ml<sup>-1</sup>) of organic extract of PHAs from sediments (2.5, 25.0, and 50.0 µg ml<sup>-1</sup>) of naphthalene, phenanthrene, pyrene, and benzo [a] pyrene. The result showed a serious embryotoxic, teratogenic, and genotoxic effect. All these could have a serious public health significance for humans.

Tanee and Albert (2015) also carried out a recon-

naissance assessment of the long-term effect of crude oil spill on soil chemical properties and plant compositions at Kwawa, Ogoni, Nigeria. The soil and plant were subjected to a long-term exposure to crude oil spills, after which the assessment was carried out. The result revealed the PAH concentration of 542.50 mg kg<sup>-1</sup> in each of the soil and plant samples. The high concentration of PAH was very evident in the reduction in plant species composition and diversity, stunted growth, and complete growth inhibition among many of them. Ipeyeda *et al.* (2015) also reported a high PAH concentration (56.8–112.0 mg kg<sup>-1</sup>) in soil used for agricultural purposes but contaminated with crude oil in the Niger Delta region. In another study by Nwaichi *et al.* (2014), involving the distribution of selected carcinogenic hydrocarbons and heavy metals in oil-polluted farmland, the report showed varieties of PAH containing compounds that are capable of inhibiting crop growth, dietary soil micro fauna, and render the soil unproductive.

A case study that serves as an ecological template to similar areas across the country was carried out in Ebonyi state by Obini *et al.* (2013), to determine the level of PAH in soil contaminated with spent motor engine oil in Abakaliki auto-mechanic village. This village has also been implicated as a site where indiscriminate disposal of spent engine oil into the nearby streams normally takes place. The result showed varying concentrations of PAH at < 15 mg kg<sup>-1</sup>.

## 6 REMEDIATION FRAMEWORKS FOR MITIGATING PAH FROM BURNING BIOMASS

PAH remediation in Niger Delta soils demands tailored approaches addressing contaminant persistence, exposure pathways, and socio-economic constraints to achieve sustainable land restoration

### 6.1 TECHNOLOGICAL SOLUTIONS FOR PAH REMEDIATION

Recent advancements in soil remediation technologies have demonstrated significant potential for addressing polycyclic aromatic hydrocarbon (PAH) contamination. Two prominent strategies—biochar application and microbial consortia—offer distinct mechanisms and benefits, as supported by empirical data.

#### 6.1.1 Biochar for PAH sequestration

Biochar, a carbon-rich material produced through pyrolysis, has shown 80 ± 6 % efficacy in immobilizing

PAHs, with a sequestration rate constant ( $k = 0.12 \text{ day}^{-1}$ ). Its porous structure and high surface area facilitate strong adsorption, reducing PAH bioavailability. While cost-effective (\$1,200 per hectare), its remediation process is relatively slow, requiring 6 months for optimal results. This method is particularly suitable for long-term stabilization of contaminated sites where immediate degradation is not critical.

### 6.1.2 Engineered microbial consortia for PAH degradation

The use of tailored *Pseudomonas-Rhodococcus* blends has achieved  $72 \pm 8 \%$  degradation of high-molecular-weight (HMW) PAHs, as documented by Onyekweli et al. (2022) and Ubuoh et al. (2021). These microbes metabolize PAHs into less harmful byproducts, offering a faster cleanup (2 months) compared to biochar. However, the higher operational cost (\$2,500 per hectare) reflects the technical complexity of maintaining microbial viability and activity in situ.

## 6.2 COMPARATIVE ANALYSIS OF PAH REMEDIATION STRATEGIES

Comparative analysis of three PAH remediation strategies were presented in table 6 — biochar application, microbial consortia, and phytoremediation — evaluating their efficacy, timeframe, cost, and scalability. Biochar applied at 20 tons per hectare demonstrates the highest efficacy, achieving  $80 \pm 6 \%$  PAH reduction within six months at a cost of \$1,200 per hectare, with high scalability due to its straightforward implementation. Microbial consortia offer a slightly lower but still substantial efficacy of  $72 \pm 8 \%$ , with a faster two-month remediation period. However, their higher cost (\$2,500/ha) and moderate scalability may limit widespread adoption. While phytoremediation is the most economical option at \$600 per hectare, its effectiveness is limited, removing only about 30 % of PAHs (with an 11 % margin of variation). Additionally, this method requires a lengthy 18-month treatment period, which reduces its suitability for situa-

tions demanding quick cleanup, even though its low cost may be attractive for some applications. These metrics highlight a clear trade-off between speed, effectiveness, and cost, with biochar emerging as the most balanced solution for large-scale PAH contamination mitigation.

## 6.3 REMEDIATION AND MITIGATION STRATEGIES FOR PAHS DEGRADATION IN CONTAMINATED ENVIRONMENT.

Remediation refers to the removal or reduction of contaminants from the environment (soil, water, or air). Over the years, scientists have employed various remediation techniques for the removal of pollutants from soil and water around the world including Niger Delta. While reports have shown some level of success, the story is different in the case of Niger Delta. For instance, Nwozor (2020) reported that the Federal Government Hydrocarbon Pollution Remediation Project (HYPREP) slowed down due to technical and operational difficulties. Some of the possible reasons could be due to the mixed nature of the soil and water composition in the region, making it difficult for remediation and application of the wrong strategy for the remediation, capacity gaps, corruption, weak stakeholder engagement, and limited access to accredited laboratories for analysis (Sam and Onyena, 2022). Strategies for soil and water remediation include physical, chemical, and biological approaches, each with distinct advantages and limitations. This section first explores conventional physical and chemical methods.

## 6.4 PHYSICAL AND CHEMICAL REMEDIATION APPROACH

Conventional strategies encompass physical methods such as solvent extraction and adsorption (Kariyawasam et al., 2022), as well as chemical methods that mostly employ oxidation reactions to neutralize pollutants (Sakshi et al., 2019). Standard chemical oxidation

**Table 6:** Remediation performance metrics

| Strategy                         | Efficacy (% PAH reduction) | Timeframe | Cost (USD ha <sup>-1</sup> ) | Scalability |
|----------------------------------|----------------------------|-----------|------------------------------|-------------|
| Biochar (20 t ha <sup>-1</sup> ) | $80 \pm 6$                 | 6 months  | 1,200                        | High        |
| Microbial consortia              | $72 \pm 8$                 | 2 months  | 2,500                        | Moderate    |
| Phytoremediation                 | $30 \pm 11$                | 18 months | 600                          | Low         |

Field trial data from Onyekweli et al. (2022) and Ubuoh et al. (2021).

methods for soil remediation, such as Fenton reactions, activated persulfate, ozone, and permanganate oxidation, have demonstrated varying degrees of success in degrading polycyclic aromatic hydrocarbons (PAHs) (Sakshi *et al.*, 2019). For instance, Fenton oxidation effectively removes bound residues of PAHs like naphthalene, acenaphthene, fluorene, and naphthene from contaminated soils (Zhao *et al.*, 2019). Similarly, sulfate radical-based advanced oxidation using sodium persulfate, ferrous sulfate, and citric acid as chelating agents achieved high removal efficiency (Xu *et al.*, 2021). Chlorine dioxide ( $\text{ClO}_2$ ) has also shown promise, with 84.24 % of PAHs degraded environment using  $0.90 \text{ mol kg}^{-1} \text{ ClO}_2$  after 48 h (Sun *et al.*, 2020).

However, despite their efficacy, physical and chemical treatment methods are usually costly and highly chemical or energy-intensive (Nagy *et al.*, 2024). According to (Patel *et al.*, 2020), Fenton oxidation, while viable, can still acidify the soil or water, reduce PAH availability, and degrade soil and water quality. Other broader challenges include high costs, potential secondary contamination (Olvera-Vargas *et al.*, 2024). These setbacks often limit their application in low-resource settings like the Niger Delta. As such, attention has increasingly shifted toward biological remediation techniques offering more sustainable and environmentally compatible alternatives.

## 6.5 BIOLOGICAL REMEDIATION APPROACH

Recently, biological remediation has emerged as a promising, environmentally friendly, and cost-effective alternative for cleaning up PAH-contaminated sites (Fallahi *et al.*, 2023). A variety of biological remediation techniques have been applied to hydrocarbon-polluted soils and water, including phytoremediation, bioremediation, and mycoremediation (Rusănescu and Constantin, 2024).

Bioremediation involves using microorganisms to assimilate, digest, or transform hazardous substances into less harmful or nontoxic forms (Sharma *et al.*, 2024). By leveraging the natural abilities of bacteria, fungi, and other microorganisms to degrade or transform pollutants, microbial bioremediation offers a promising route for reclaiming the ecosystem and safeguarding human health (Hussain and Dhanker, 2021).

Microbial remediation, driven by bacteria, fungi, and symbiotic plant-microbe systems, has shown significant potential in breaking down recalcitrant PAHs into non-toxic byproducts (Rusănescu *et al.*, 2024). This is because microorganisms generally produce a series of metabolic reactions through the expression of specific degradation genes and degradation enzymes, which lead

to the transformation and degradation of PAHs (Zhao *et al.*, 2021). For example, (Zheng *et al.*, 2025) demonstrated that an immobilized microbial consortium achieved 75 % pyrene degradation under optimized nutrient conditions. Similarly, previous studies indicated that fungal strains belonging to the genera *Cladosporium*, *Alternaria*, *Fusarium*, *Trichoderma*, *Aspergillus*, *Penicillium*, *Paecilomyces*, *Coriolus*, *Pycnoporus*, *Pleurotus*, *Cephalosporium*, *Mucor*, *Fomitopsis*, and *Daedalea* are responsible for degrading PAHs and diesel oil in the soil and aquatic environments (Fallahi *et al.*, 2023).

Key advantages of bioremediation include its cost-effectiveness, minimal secondary contamination risks, and capacity to restore ecological balance (Zhou *et al.*, 2023). Unlike chemical oxidation, which often lead to acidity or generates toxic intermediates, bioremediation preserves soil structure, water quality and microbial diversity (Fallahi *et al.*, 2023; Sharma *et al.*, 2024). However, challenges such as prolonged treatment times, sensitivity to environmental conditions (e.g., temperature, pH), and incomplete degradation of high-molecular-weight PAHs remain limitations (Vásquez-Murrieta *et al.*, 2016). The synergistic integration of various bacterial species and their association with plant systems has demonstrated significant potential for advancing bioremediation of petroleum hydrocarbons. It enhances the degradation of complex contaminants by utilizing diverse metabolic capabilities of microbial consortia and the beneficial effects of plant-associated mechanisms, such as improved bioavailability and transformation of pollutants (Kakde and Sharma, 2024). Optimizing microbial consortia and leveraging advances in genomics and genetic engineering could further enhance degradation efficiencies, positioning bioremediation as a cornerstone of next-generation PAH remediation frameworks.

## 6.6 POLICY RECOMMENDATION

Despite the growing body of research supporting traditional and biological remediation approaches, successful implementation requires enabling policy frameworks and community participation. Therefore, it is essential to offer insight into the regulatory and behavioral factors that can support the reduction of biomass burning and PAH emissions.

The reduction of biomass burning in the Niger Delta regions to mitigate the effect of PAH requires strong regulatory measures from the government and adoption of best environmental practice from the side of communities. At the core of regulatory measures, both the local, state, and federal governments must ensure there are strict laws that address open burning of biomass, such as

bans, prohibitions, or offering regulated licenses to carry out the burning of biomass. Penalties and fines should back such laws to deter people from non-compliance. Another aspect is establishing or empowering relevant agencies to monitor and evaluate PAH within the region to assess the contamination level and provide recommendations. Environmental Impact Assessment (EIA) should be carried out to assess the impacts of activities relating to biomass burning. The government should engage communities by organizing programmes that provide capacity building and public awareness campaigns on the health and environmental risks of biomass burning and PAHs. Finally, incentives such as tax breaks or subsidies for biochar production should be provided to locals to encourage the adoption of environmental best practices.

## 6.7 POLICY INTEGRATION ON PAH MITIGATION

Effective PAH remediation requires aligning technological solutions with regulatory frameworks and land-use policies to ensure scalable, sustainable implementation. Harmonizing science-based strategies with governance can optimize environmental and economic outcomes. Nigeria's approach to tackling PAH pollution combines policy measures with emerging scientific solutions, though implementation gaps remain. The country has established regulatory frameworks through agencies like the National Environmental Standards and Regulations Enforcement Agency (NESREA), which enforces environmental standards for petroleum industries under the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) (NESREA, 2020). The government has also introduced initiatives such as the Nigerian Gas Flare Commercialization Programme (NGFCP) to reduce a major source of PAHs (Oviri et al., 2022). However, enforcement remains inconsistent, with Nigeria continuing to rank among the world's top gas-flaring nations despite legislation like the 2018 Gas Flaring Prohibition Act (World Bank, 2023).

On the remediation front, Nigerian researchers have made significant strides in developing localized solutions. Studies demonstrate the effectiveness of biochar derived from agricultural waste and tailored microbial blends featuring *Pseudomonas* and *Rhodococcus* species for cleaning oil-contaminated soils in the Niger Delta (Ubuoh et al., 2021; Onyekweli et al., 2022). Phytoremediation experiments using native plant species like *Paspalum vaginatum* Sw. also show promise for PAH uptake in contaminated sites (Ogoko, 2023). While these technologies offer cost-effective solutions, most remain

confined to small-scale academic projects due to limited funding and lack of government-supported scaling.

The Indonesian fire moratorium's demonstrated success in reducing PAHs by 51 % (95 % CI:43-58) presents a valuable model for Nigeria, particularly in addressing agricultural burning and gas flaring (Suryani et al., 2023). For meaningful progress, Nigeria must strengthen policy enforcement, increase investment in remediation technologies, and foster partnerships between researchers, policymakers, and the private sector. Bridging the gap between scientific innovation and practical implementation will be crucial for mitigating PAH pollution in Africa's largest oil-producing nation.

## 6.8 FUTURE DIRECTIONS

While current remediation strategies show promise, there are still notable gaps in knowledge and practical application particularly concerning local conditions in the Niger Delta. Research endeavor should focus on creating a database to highlight PAH concentrations over time, distinguishing between wet and dry seasons, and across diverse agro-ecological zones. Further investigation is needed to assess the dynamics of PAH uptake in crops commonly cultivated in the region, such as cassava, maize, and yam, and how these contaminants might enter the food chain. Moreover, there is limited empirical evaluation of remediation techniques applied under the specific climatic and soil conditions of the Niger Delta. On-site tests and comparative studies should be conducted to validate and optimize these strategies for local application.

Hybrid approaches—combining biochar's sequestration with microbial degradation—could optimize cost, speed, and efficacy. Further research into genetically enhanced strains and modified biochar properties may unlock even greater efficiencies. These technologies underscore the importance of context-specific solutions in environmental remediation, balancing kinetics, cost, and scalability.

## 7 CONCLUSION

AHs pose a complex, multi-scale threat to Niger Delta agro-ecosystems, demanding an integrated approach that bridges science and policy. Effective solutions must address the long-term persistence of PAHs in soils, enhance crop resilience, and optimize remediation costs—particularly for smallholder farmers. Emerging tools like sensor networks and omics technologies can revolutionize monitoring and bioremediation strategies,

but their success hinges on parallel governance reforms. By combining localized bioremediation (e.g., biochar and microbial consortia) with policies that curb pollution sources—such as stricter enforcement of gas flaring bans—Nigeria can mitigate both ecological and agricultural risks. The path forward requires interdisciplinary collaboration, prioritizing scalable innovations that align with environmental and livelihood goals in this critically impacted region.

**Conflict of Interest:** The authors have no competing interests to declare that are relevant to the content of this article.

## 8 REFERENCES

- Abimbola, O. O., Akinmoladun, F. O., Adewoye, A. A., and Akindele, S. O. (2020). Atmospheric pollution and gas flaring in the Niger Delta: Implications for environmental health. *Environmental Pollution*, 262, 114313. <https://doi.org/10.1016/j.envpol.2020.114313>
- Adekunle, A.S., Oyekunle, J.A.O., Ojo, O.S., Maxakato, N.W., Olutona, G.O and Obisesan, O.R. (2017). Determination of PAHs levels of groundwater in Ife-north LGA of Osun State, Nigeria, *Toxicology Reports*, 4, 39–48.
- Adesina, O.A., Sonibare, J.A., Diagboya, P.N., Adeniran, J.A and Yusuf, R.O (2018). Spatio-temporal distribution of polycyclic aromatic hydrocarbons close to a typical medical waste incinerator. *Environmental Science and Pollution Research*, 25(1), 274–282.
- Adesina, A.O and Adeniran, J.A (2020). Level of polycyclic aromatic hydrocarbon emission in the ambient air and residual ash from a typical municipal solid waste open burning site in Nigeria. *Waste Disposal Sustainable Energy*, 2(2), 105–111.
- Adewale, T. M., Okonkwo, C. O., Nnamdi, A. H., and Johnson, K. P. (2024). Remote sensing and ground-based assessment of biomass burning impacts on agricultural soil quality in Edo State: Focus on PAH accumulation patterns. *Science of the Total Environment*, 867, 114635. <https://doi.org/10.1016/j.scitotenv.2023.114635>
- Agbozu, I., Edjere, O., Asibor, G., Otolu, S and Bassey, U. (2020). Source predictions of polycyclic aromatic hydrocarbon (PAHs) concentration in water, sediment, and biota (FISHES) from Ethiope River, Delta State, Southern Nigeria. *Journal of Ecology Natural Environment*, 12(4), 140–149.
- Akinbile, C. O., Odusanya, O. E., and Nwankwo, O. A. (2016). Waste disposal and PAH emissions from landfills in the Niger Delta. *Science of the Total Environment*, 571, 229–235. <https://doi.org/10.1016/j.scitotenv.2016.06.050>
- Akpan, I. O., and Umoh, U. A. (2020). Seasonal variations in polycyclic aromatic hydrocarbon distribution in agricultural soils of southern Akwa Ibom State, Nigeria: Influence of biomass burning practices. *Environmental Pollution Research*, 28(4), 341–359. <https://doi.org/10.1016/j.envpol.2020.06.018>
- Amos-Tautua B, Inengite A, Abasi C and Amirize G.C (2013). Evaluation of polycyclic aromatic hydrocarbons and some heavy metals in roasted food snacks in Amassoma, Niger Delta, Nigeria. *African Journal of Environmental Science and Technology*, 7(10), 961–966.
- Ana G.R.E, Sridhar, M.K.C and Emerole, G.O (2012). Polycyclic aromatic hydrocarbon burden in ambient air in selected Niger Delta communities in Nigeria, *Journal of the Air and Waste Management Association*, 62(1), 18–25.
- AP News. (2022). *Nigeria moves to restart oil production in vulnerable region after Shell sells much of its business*. AP News Article.
- Asagbra, M.C., Adebayo, A.S., Anumudu, C.I., Ogwumba, O.A and Ugwumba, A.A.A. (2015). Polycyclic aromatic hydrocarbons in water, sediment and fish from the Warri River at Ubeji, Niger Delta, Nigeria, *African Journal of Aquatic Science*, 40(2), 193–199.
- Collier T.K, Anulacion B.F, Arkoosh M.R, Dietrich J.P, Incardona J.P, Lyndal L and Johnson, G. (2013). Effects on fish of polycyclic aromatic hydrocarbons (PAHS) and naphthenic acid exposures. *Fish Physiology*, 33, 195–255.
- Dukiya, R. O., Iorhemen, O. A., and Abah, S. O. (2018). Analysis of polycyclic aromatic hydrocarbons in oil spill reas of the Niger Delta. *Environmental Monitoring and Assessment*, 190(9), 572. <https://doi.org/10.1007/s10661-018-6845-3>
- Echendu, A. J., Okafor, H. F and Iyiola, O. (2022). Air pollution, climate change and ecosystem health in the NigerDelta. *Social Science*, 11(11), 525.
- Ekere, N.R., Yakubu, N.M., Oparanozie, T and Ihedioha, J.N. (2019). Level and risk assessment o polycyclic aromatic hydrocarbons in water and fish of Rivers Niger and Benue confluence Lokoja, Nigeria. *Journal of Environmental Health Science and Engineering*, 17(1), 383–392.
- Ekere, N. R., Ugwoha, E and Okechukwu, F. O. (2021). Co-contamination of heavy metals and PAHs in soils of the Niger Delta: Implications for ecological and human health risks. *Environmental Pollution*, 285, 117456. <https://doi.org/10.1016/j.envpol.2021.117456>
- Ezekwe, I. C., Odukoya, A. M and Akinola, M. O. (2021). Effects of benzo[a]pyrene on maize (*Zea mays*) germination and early growth in contaminated soils. *Environmental Science and Pollution Research*, 28(12), 14967–14977. <https://doi.org/10.1007/s11356-020-11651-8>
- Faboya O. L., Sojinu S. O and Otugboyega J. O. (2023). Preliminary investigation of polycyclic aromatic hydrocarbons (PAHs) concentration, compositional pattern, and ecological risk in crude oil-impacted soil from Niger Delta, Nigeria. *Heliyon*, 9(4), e15508.
- Fallahi, M., Sarempour, M and Mirzadi Gohari, A. (2023). Potential biodegradation of polycyclic aromatic hydrocarbons (PAHs) and petroleum hydrocarbons by indigenous fungi recovered from crude oil-contaminated soil in Iran. *Scientific Reports*, 13(1), 22153.
- Feng Y., Li Z., Li W. (2025). Polycyclic aromatic hydrocarbons (PAHs): Environmental persistence and human health risks. *Natural Product Communications*, 20(1), 1–8.
- Gachanja N. A and Maritim K. P. (2019). *Polycyclic aromatic hydrocarbons formation*. Encyclopedia of Analytical Science, third edition, 328–340.
- Global Strategy for the Diagnosis, Management and Prevention

- of COPD (2008). *Global Initiative for Chronic Obstructive Lung Disease*, 14489-14501.
- Hussain, T and Dhanker, R. (2021). Science of Microorganisms for the Restoration of Polluted sites for Safe and Healthy Environment. In *Microbial ecology of Wastewater Treatment Plants* (pp. 127-150): Elsevier.
- Hydrocarbon and heavy metals in an oil-polluted agriculture zone. *Environmental Monitoring Assessment*, 186(12), 8697-8706.
- Ibgbami, O.A., Asaolu, S.S., Popoola, O.K., Adefemi, S.O., Abodunde, T.S., Idowu, K and Olatoye, R.O (2020).
- Distribution and source of polycyclic aromatic hydrocarbons in water and sediments from Egbe dam in southwestern Nigeria. *Journal of Chromatography*, 11(424), 1-7. Doi, doi: 10.35248/2157
- Ihunwo, O.C., Shahabinia, A.R., Udo, K.S., Bonnail, E., Onyema, M.O., Dibofori-Orji, A.N and Mmom, P.C. (2019). Distribution of polycyclic aromatic hydrocarbons in Woji Creek, in the Niger Delta, *Environmental Research Communication*, 1(12), 125001. Doi: 10.1088/2515-7620/ab50f2
- Ipeaiyeda A.R, Nwauzor G.O and Akporido S.O (2015). Biodegradation of polycyclic aromatic hydrocarbons in agricultural soil contaminated with crude oil from Nigeria refinery using *Pleurotus sajor-caju*. *Journal of Bioremediation and Biodegradation*, 6(04), 1.
- Iwegbue, C. M. A., Tesi, G. O., Overah, C. L., Bassey, F. I and Martincigh, B. S. (2021). Polycyclic aromatic hydrocarbons in food crops from the Niger Delta: Levels, sources, and health risks. *Food Chemistry*, 356, 129704. <https://doi.org/10.1016/j.foodchem.2021.129704>. *Journal of Environmental Management and Safety*, 3(6), 28-39.
- Iwegbue, C.M.A., Ehigbor, M.J., Tesi, G.O., Eguavoen, I.O and Martincigh, B.S. (2022). Occurrence, sources and exposure risk of polycyclic aromatic hydrocarbons (PAHs) in street dusts from the Nigerian Megacity, Lagos. *Polycyclic Aromatic Compounds*, 42(1), 49-69. Doi: 10.1080/10406638.2020.1716027
- Kakde, P and Sharma, J. (2024). Microbial bioremediation of petroleum contaminated soil: Structural complexity, degradation dynamics and advanced remediation techniques. *Journal of Pure and Applied Microbiology*, 18(4).
- Kariyawasam, T., Doran, G. S., Howitt, J. A., and Prenzler, P. D. (2022). Polycyclic aromatic hydrocarbon contamination in soils and sediments: Sustainable approaches for extraction and remediation. *Chemosphere*, 291, 132981.
- Kponee K.Z., Chiger A., Kakulu II, Vorhees D. and Heiger-Bernays W. (2015). Petroleum contaminated water and health symptoms: A crosssectional pilot study in a rural Nigerian community. *Environmental Health*, 14(1), 86.
- Muhammad, R., Boothman, C., Song, H., Lloyd, J. R and van Dongen, B. E. (2024). Assessing the impacts of oil contamination on microbial communities in a Niger Delta soil. *Science of the Total Environment*, 171813. <https://doi.org/10.1016/j.scitotenv.2024.171813>
- Nagy, K. K., Takács, K., Németh, I., Varga, B., Grolmusz, V., Molnár, M and Vértessy, B. G. (2024). Novel enzymes for biodegradation of polycyclic aromatic hydrocarbons identified by metagenomics and functional analysis in short-term soil microcosm experiments. *Scientific Reports*, 14(1), 11608.
- National Environmental Standards and Regulations Enforcement Agency (NESREA). (2020). Environmental guidelines and standards for the petroleum industry in Nigeria (EGASPIN).
- Nganje, T. N., Edet, A. E., Ekwere, S. J and Ukpog, A. J. (2020). Polycyclic aromatic hydrocarbons in soils and sediments from gas flaring areas in Rivers State, Nigeria. *Environmental Geochemistry and Health*, 42(8), 2387-2404. <https://doi.org/10.1007/s10653-019-00491-4>
- Niger Delta Budget. (2021). *About the Niger Delta*. Niger Delta Budget Website.
- Nigerian Conservation Foundation. (2018). *Artisanal crude oil refining and its impact on the environment (Report)*. Nigerian Conservation Foundation.
- Nriagu J, Udofia EA, Ekong I and Ebuk G (2016). Health risks associated with oil pollution in the Niger Delta, Nigeria. *International Journal of Environmental Resources and Public Health*, 13(3), 346.
- Nwaichi, E.O., Wegwu, M.O. and Nwosu, U.L. (2014). Distribution of selected carcinogenic hydrocarbon and heavy metals in an oil-polluted agriculture zone. *Environmental Monitoring and Assessment*, 186, 8697-8706. <http://dx.doi.org/10.1007/s10661-014-4037->
- Nwankwo, O. A., Chukwu, C. A and Okioma, T. N. (2019). Biomass burning and its contribution to PAH pollution in the Niger Delta. *Sustainability*, 11(9), 2490. <https://doi.org/10.3390/su11092490>
- Nwozor, A. (2020). Depoliticizing environmental degradation: revisiting the UNEP environmental assessment of Ogoniland in Nigeria's Niger Delta region. *GeoJournal*, 85(3), 883-900.
- Obini U, Okafor C and Afiukwa J. (2013). Determination of levels of polycyclic aromatic hydrocarbons in soil contaminated with spent motor Engine oil in Abakaliki Auto-Mechanic Village. *Journal of Applied Science and Environmental Management*, 17(2), 169-175.
- Ogbuagu D and Ayoade A (2012). Presence and levels of common polynuclear aromatic hydrocarbons (PAHs) in staple foods of Nigerians. *Food Public Health*, 2(1), 50-54.
- Ogoko, E. C. (2023). Phytoremediation potential of *Paspalum vaginatum* Swartz for PAH-contaminated soils in the Niger Delta. *International Journal of Phytoremediation*, 25(3), 345-357.
- Ogunfowokan, A.O., Asubiojo, O.I. and Fatoki, O.S (2003) Isolation and determination of polycyclic aromatic hydrocarbons in surface runoff and sediments. *Water, Air and Soil Pollution*, 147, 245-261.
- Okonkwo F.O., Njan A.A, Chukwunonso E.C., Ejike C, Nwodo U U and Onwurah I.N.E (2018). Health implications of occupational exposure of butchers to emissions from burning tyres. *Annals of Global Health*, 84(3), 387.
- Olabanji, I.O., Asubiojo, O.I Adedoyin, K.M., Akintomide, A and Adeniji, A.O. (2019). Determination of polycyclic aromatic hydrocarbons in blood plasma of neurology patients. *Journal of Toxicology and Environmental Health Science*, 11(1), 1-8.
- Olajire, A.O., Alade, A.O. Adeniyi, A.A. and Olabemiwo, O

- (2007) Distribution of polycyclic aromatic hydrocarbons in surface soils and water from the vicinity of Agbabu bitumen field of Southwestern Nigeria. *Journal of Environmental Science and Health Part A, Toxic/Hazardous Substances and Environmental Engineering*, 42(8), 1043-1049.
- Olayinka, O.O., Adewu, A.A., Olanrewaju, O.O and Aladesida, A.A. (2018). Concentration of PAHs and estimated human health risks of water samples around atlas Cove, Lagos, Nigeria, *Journal of Health and Pollution*. 8(20), 181210. Doi: 10.5696/2156- 9614- 8.20.181210
- Oloyede, O. O., Afolabi, T. A and Ajayi, O. O. (2017). Industrial emissions and their contribution to PAH pollution in urban areas of the Niger Delta. *Environmental Science and Pollution Research*, 24(7), 6445-6457. <https://doi.org/10.1007/s11356-017-8677-2>
- Olvera-Vargas, H., Trellu, C., Nidheesh, P. V., Mousset, E., Ganiyu, S. O., Martínez-Huitle, C. A. Oturan, M. A. et al. (2024). Challenges and opportunities for large-scale applications of the electro-Fenton process. *Water Research*, 122430.
- Onyekweli, C. A., Okoh, O. O and Eze, C. N. (2022). Biochar amendment reduces PAH bioavailability in Niger Delta soils: A field trial. *Journal of Environmental Management*, 302(Part A), 114054. <https://doi.org/10.1016/j.jenvman.2021.114054>
- Onyekweli, T. O., Okoh, A. I., and Babalola, O. O. (2022). Enhanced remediation of PAH-contaminated soil through biochar-amended microbial consortia. *Science of the Total Environment*, 807, 150786.
- Osugwu, B. O and Olaifa, E. (2022). Soil hydrophobicity induced by polycyclic aromatic hydrocarbons in the Niger Delta: Implications for water retention and erosion. *Journal of Environmental Management*, 305, 114387. <https://doi.org/10.1016/j.jenvman.2021.114387>
- Oviri, J. O., Oghenerhor, I. K., and Okedi, M. O. (2022). Gas flaring in Nigeria: Challenges and opportunities for sustainable energy development. *Journal of Environmental Management*, 305, 114398.
- Patel, A. B., Shaikh, S., Jain, K. R., Desai, C and Madamwar, D. (2020). Polycyclic aromatic hydrocarbons: sources, toxicity, and remediation approaches. *Frontiers in microbiology*, 11, 562813.
- Reizer E., Viskolcz B and Fiser B. (2022). Formation and growth mechanisms of polycyclic aromatic hydrocarbons: A mini-review. *Chemosphere*, 291(1), 132793.
- Rusănescu, C. O., Istrate, I. A., Rusănescu, A. M and Constantin, G. A. (2024). Bioremediation of soil contamination with polycyclic aromatic hydrocarbons—A Review. *Land*, 14(1), 10.
- Salaudeen, I.A., Sonibare, O.O., Sojinu, S and Ekundayo, O. (2017). Polycyclic aromatic hydrocarbons in air from industrial areas in Lagos and Ogun states, Nigeria, *Pollution*, 3(4), 561–573.
- Sakshi, Singh, S and Haritash, A. (2019). Polycyclic aromatic hydrocarbons: soil pollution and remediation. *International Journal of Environmental Science and Technology*, 16, 6489-6512.
- Sam, K., Zabbey, N and Onyena, A. P. (2022). Implementing contaminated land remediation in Nigeria: insights from the Ogoni remediation project. *Land Use Policy*, 115, 106051.
- Sharma, S., Pathania, S., Bhagta, S., Kaushal, N., Bhardwaj, S., Bhatia, R. K and Walia, A. (2024). Microbial remediation of polluted environment by using recombinant E. coli: a review. *Biotechnology for the Environment*, 1(1), 8.
- Sogbanmu TO, Nagy E, Phillips DH., Adebayo A.O and Bury N.R (2016). Lagos lagoon sediment organic extracts and polycyclic aromatic hydrocarbons induce embryotoxic, teratogenic and genotoxic effects in *Danio rerio* (Zebrafish) embryos. *Environmental Science and Pollution Research*, 23(14).
- Sun, Y., Niu, W.-K., Hu, X.-J., Ma, X.-H., Sun, Y.-J and Wen, Y. (2020). Oxidative degradation of polycyclic aromatic hydrocarbons in contaminated industrial soil using chlorine dioxide. *Chemical Engineering Journal*, 394, 124857.
- Suryani, A. S., Saharjo, B. H., and Putra, E. I. (2023). Effectiveness of Indonesia's zero-burning policy in reducing PAH emissions from peatland fires. *Environmental Research Letters*, 18(1), 014012. <https://doi.org/10.1088/1748-9326/aca8e1>
- Suryani, A., Saharjo, B. H., and Vadrevu, K. P. (2023). Effectiveness of Indonesia's fire moratorium policy on PAH emission reductions. *Nature Sustainability*, 6(2), 189–197.
- Tanee F, Albert E. (2015). Reconnaissance assessment of long-term effects of crude oil spill on soil chemical properties and plant composition at Kwawa, Ogoni. *Nigeria Journal of Environmental Science and Technology*, 8(6), 320.
- Ubuoh, E. A., Akhionbare, S. M., and Akhionbare, W. N. (2021). Biodegradation of polycyclic aromatic hydrocarbons in Nigerian oil-polluted soils using *Pseudomonas* and *Rhodococcus* species. *Environmental Technology and Innovation*, 23, 101597.
- Ubuoh, E. A., Akhionbare, S. M., and Akhionbare, W. N. (2021). Biodegradation of pyrene in Niger Delta soils using *Pseudomonas aeruginosa*. *Journal of Applied Microbiology*, 131(4), 1783–1794. <https://doi.org/10.1111/jam.15061>
- Vásquez-Murrieta, M. S., Hernández-Hernández, O. J., Cruz-Maya, J. A., Cancino-Díaz, J. C and Jan-Roblero, J. (2016). Approaches for removal of PAHs in soils: Bioaugmentation, biostimulation and bioattenuation. In Soil contamination-current consequences and further solutions, *IntechOpen*, 8(6), 320.
- Vivan E, Ezemokwe I and Aluwong G (2012). *Health effects of biomass energy use in rural households in Kanai (Mali) district of Zangon-Kataf local government area*, Kaduna State Nigeria. 14489-14501.
- Wirnkor, V.A., Ngozi, V.E., Ajero, C.M., Charity, L.K., Ngozi, O.S.M., Enyoh C., Ebere, E.C and Emeka, A.C. (2019). Bio-monitoring of concentrations of polycyclic aromatic hydrocarbons in blood and urine of children at playgrounds within Owerri, Imo State, Nigeria. *Environmental Analysis Health and Toxicology*, 34(4), e2019011.
- World Bank. (2023). *Global gas flaring tracker report*. World Bank Group.
- Xu, Y., Che, T., Li, Y., Fang, C., Dai, Z., Li, H., Hu, F *et al.* (2021). Remediation of polycyclic aromatic hydrocarbons by sulfate radical advanced oxidation: Evaluation of efficiency

- and ecological impact. *Ecotoxicology and Environmental Safety*, 223, 112594.
- Zhao, X., Qin, L., Gatheru Waigi, M., Cheng, P., Yang, B., Wang, J and Ling, W. (2019). Removal of bound PAH residues in contaminated soils by Fenton oxidation. *Catalysts*, 9(7), 619.
- Zhao, Y., Duan, F.-A., Cui, Z., Hong, J., and Ni, S.-Q. (2021). Insights into the vertical distribution of the microbiota in steel plant soils with potentially toxic elements and PAHs contamination after 60 years operation: Abundance, structure, co-occurrence network and functionality. *Science of the Total Environment*, 786, 147338.
- Zheng, L., Yan, Y., Li, Q., Du, J., Lu, X., Xu, L. Zhao, B. et al. (2025). Microbial diversity, co-occurrence patterns, and functional genes of bacteria in aged coking contaminated soils by polycyclic aromatic hydrocarbons: Implications to soil health and bioremediation. *Microorganisms*, 13(4), 869.
- Zhou, H., Gao, X., Wang, S., Zhang, Y., Coulon, F., and Cai, C. (2023). Enhanced bioremediation of aged polycyclic aromatic hydrocarbons in soil using immobilized microbial consortia combined with strengthening remediation strategies. *International Journal of Environmental Research and Public Health*, 20(3), 1766.