Chapter One

Introduction

1.1 Background to the Study

Humans have been releasing harmful compounds into the environment at an exponential rate since the beginning of the industrial revolution. These toxic contaminants, which are extremely harmful to human health and fish populations, are composed of several compounds and gases. The delicate balance of aquatic ecosystems is under threat from a variety of pollutants introduced into water bodies by human activity, an issue that is spreading internationally. Polycyclic aromatic hydrocarbons (PAHs) are well-known contaminants for their toxicity, persistence, and bioaccumulation potential. The bioaccumulation of PAHs in water and aquatic species has a significant influence on environmental health, affecting both human populations who rely on aquatic resources and the ecosystem[1]. These pollutants are released into the environment by both natural and human activities. Natural processes are caused by weathering of rocks and soil, as well as volcanic eruptions. Anthropogenic sources include a wide range of human activities such as mining, prospecting, processing, metal and petroleum product consumption, and the disposal of home and industrial waste. In most developing countries, water resources remain the primary storage places for household, industrial, and agricultural waste. As a result of increased industry caused by urbanization, metallic pollutants enter streams, coastal ecosystems, and river banks[2]. According to research, polycyclic aromatic hydrocarbons (PAHs) accumulate in aquatic habitats, particularly in aquatic animals[3].

In comparison, polycyclic aromatic hydrocarbons, or PAHs, are a frequent form of chemical contaminant in the environment. In aquatic environments, they are pollutants containing two or

Lead City University Ibadan DO NOT COPY

more fused aromatic rings. Polycyclic aromatic hydrocarbons are lipophilic molecules having a low solubility in water, hence their concentration is extremely low. Water solubility is highest in low molecular weight compounds such as naphthalene, acenaphthene, and acenaphthylene, and decreases as molecular mass increases. Due to their low vapour pressure, these chemicals are classified as semi-volatile[3,4]. However, as molecular weight increases, so do the melting and boiling points. Because they are hydrophobic, polycyclic aromatic hydrocarbons (PAHs) easily attach to particle debris in water bodies, causing sedimentation. However, domestic waste, municipal runoff, and industrial sewage were the most significant human activities that contributed to the ecosystem's polycyclic aromatic hydrocarbons. Furthermore, oil production and accompanying catastrophes, such as ship operations, refineries, oil spills, and incomplete fossil fuel combustion. Additionally, some natural phenomena, such as volcanic eruptions and forest fires, can release polyatomic hydrocarbons into the environment[5].

As a result, sediment is one of the most important PAH reservoirs in aquatic ecosystems. Certain organic solvents have a strong ability to dissolve polycyclic aromatic hydrocarbons. Furthermore, they are easily associated with organic and natural materials such as kerogens, black carbon, humic substances (such as fulvic and humic acids), biopolymers (such as polysaccharides, lipids, proteins, and polynucleic acids), and biopolymers in the environment[5]. Hydrocarbon pollution of sediments and aquatic ecosystems caused by crude oil and its derivatives (diesel, petrol, lubricating oil, and others) is a major issue that has received international attention. These chemicals have been shown to be highly poisonous, mutagenic, and carcinogenic in nature. Because the usage of petroleum hydrocarbons is required for modern survival, the emergence of human civilization has caused significant disturbances to the environment's natural balance. Hydrocarbon compounds are a broad family of chemical compounds composed of heteroatoms

Lead City University Ibadan DO NOT COPY

such as oxygen, nitrogen, sulfur, chloride, and other elements organized in a skeleton of carbon and hydrogen[3, 5]. They can be split into three categories: aliphatic, alicyclic, and aromatic hydrocarbon compounds.

The USEPA identifies sixteen polycyclic aromatic hydrocarbons. These chemicals are divided into two categories: low molecular and high molecular. Low molecular hydrocarbons have two to three fused rings and are volatile and soluble in water, rendering them prone to breakdown. High molecular hydrocarbons have more than four fused rings, making them less soluble, volatile, and lipophilic than low molecular hydrocarbons. Because these compounds are known to resist microbial degradation, the IARC classified eight PAHs with more than four fused rings (high molecular weight) as carcinogenic in 2010. Additionally, they have the ability to accumulate in aquatic plants, fish, mussels, and other aquatic organisms[6].

Polycyclic aromatic hydrocarbons detected in coastal sediments can be attributed to both natural and man-made emissions. Petrogenic and pyrolytic sources are the most important anthropogenic sources of PAHs in the environment. While petroleum products are significantly associated with petrogenic inputs, pyrolytic inputs include combustion activities (such as burning fossil fuels, forest fires, shrub and grass fires, and road construction materials)[7]. The bulk of PAHs are harmful compounds that endanger human health, and some may potentially cause cancer, according to the US EPA. Furthermore, studies have shown that animals exposed to PAHs by contaminated food, polluted air, or skin contact with contaminated soils or sediments might develop tumors. Humans are still more likely to become infected with PAHs through food and drink. Polycyclic aromatic hydrocarbons are commonly discovered in mixtures rather than single chemicals in air, soils, water, and groundwater[7,8].

Lead City University Ibadan DO NOT COPY

Because PAH compounds are generally poorly soluble in water and become less soluble as their molecular weight increases, studying sediment and suspended particles can provide valuable information about a wide range of pollutants, particularly hydrophobic ones that come from the water column and organic matter. These trace organic molecules are more stable in sediment than in other environmental compartments such as water, air, and living things[9]. However, a range of processes, including chemical, biological, and physical ones, have an impact on organic compounds in aquatic systems because they alter the composition of sediment, increasing the dispersion of organic contaminants[10].

1.2 Statement of the Problem

Contamination of aquatic ecosystems with PAH has become a global environmental and public health concern. Lagos Lagoon, one of Nigeria's largest and most commercially important water basins, is not an exception[11]. The lagoon, a crucial ecosystem that supports fishing, transportation, and industrial operations, is exposed to rising contamination from many anthropogenic sources, including industrial discharge, agricultural runoff, and home garbage. The entry of these harmful compounds into the Lagos Lagoon is a result of increased urbanization, industrialization, and agricultural practices in and around the Lagos metropolitan region. Fish, which are an important element of the local diet and economy, are especially susceptible to the accumulation of these pollutants[12]. This contamination endangers public health because people who eat fish from the lagoon may be exposed to excessive levels of PAH , which can cause neurological abnormalities, kidney damage, immune system suppression, and an increased risk of cancer[13].

Despite the known hazards connected with PAH, there is little recent information on the degree of their contamination in the Lagos Lagoon. Furthermore, previous research has frequently focused

Lead City University Ibadan DO NOT COPY

on isolated locations or specific pollutants, leaving a vacuum in our understanding of the full extent of contamination in the lagoon's ecosystem[14]. As a result, the purpose of this study is to determine the extent to which PAH are present in the fish and water of Lagos Lagoon, as well as the potential ecological and public health consequences of such contamination. The study will concentrate on determining the amounts of selected PAH in fish and water samples from the lagoon, comparing the results to national and international safety regulations, and assessing the dangers to the ecosystem and the local population. By bridging this knowledge vacuum, the study hopes to inform environmental management strategies and public health actions aimed at reducing pollution in Lagos Lagoon while also protecting its people' well-being.

1.3 Justification of the Study

Lagos Lagoon is a significant aquatic ecosystem that supports a wide range of biodiversity and serves as an essential resource for human livelihoods[15]. However, the lagoon is under immense environmental pressure from pollution, especially polycyclic aromatic hydrocarbons (PAHs). These pollutants are known for their toxicity, persistence, and ability to bioaccumulate in aquatic organisms. Assessing the levels of these contaminants in the lagoon is crucial for understanding the degree of environmental degradation[16]. The results of this research will provide baseline data that can inform conservation efforts, pollution control measures, and strategies for restoring the health of Lagos Lagoon. The contamination of Lagos Lagoon with PAH poses significant risks to human health, particularly to the populations living near the lagoon who depend on it for fishing and as a source of food. Fish are a primary source of protein for many Lagos residents, and the bioaccumulation of toxic substances in fish can lead to adverse health effects in humans who

Lead City University Ibadan DO NOT COPY

consume them. Prolonged exposure to heavy metals such as mercury, lead, and cadmium can cause neurological disorders, kidney damage, developmental issues, and an increased risk of cancer[17,18]. Similarly, exposure to PAH is linked to endocrine disruption, immune suppression, and other chronic health problems. This research is justified as it aims to identify the extent of contamination in fish consumed by humans, thereby contributing to public health awareness and potentially influencing policy changes that protect consumers.

Lagos Lagoon plays a critical role in the economy of the Lagos metropolitan area. It supports industries such as fishing, tourism, and transportation. However, pollution can severely undermine the economic value of these sectors[19]. For instance, contaminated fish populations can lead to reduced fish stocks, affect local fisheries, and diminish the lagoon's attractiveness as a resource for tourism and recreation. This research is important because it can highlight the long-term economic impacts of unchecked pollution and advocate for sustainable development practices that balance economic growth with environmental protection[20]. This research has broader relevance because it contributes to the global body of knowledge on aquatic pollution in coastal regions, particularly in developing countries. By comparing the pollution levels in Lagos Lagoon to international safety standards set by the World Health Organization (WHO) and other environmental bodies, the research will provide insights into how Lagos Lagoon measures up to global benchmarks and identify areas where interventions are urgently needed[20,21].

Establishing a robust understanding of the current pollution levels in Lagos Lagoon is essential for future ecological and public health monitoring. This research can serve as a reference point for future research and monitoring efforts aimed at tracking changes in pollution over time. Such longitudinal data is vital for assessing the effectiveness of any remediation measures or policies implemented to reduce pollution[22.23]. In the long term, this will help ensure that Lagos Lagoon

Lead City University Ibadan DO NOT COPY

remains a viable and sustainable resource for both its ecosystem and the communities that depend on it.

1.4 Aim and Objectives of the Study

The aim of this research is to investigate the distribution, sources and risks of polycyclic aromatic hydrocarbons (PAHs) in fish and water samples from Lagos Lagoon and evaluate their potential ecological and public health implications.

The objectives of this project work are:

1. To assess the levels of polycyclic aromatic hydrocarbons (PAHs) in water samples from Lagos Lagoon.
2. To determine the concentration of polycyclic aromatic hydrocarbons (PAHs) in selected aquatic (fish, shrimps and crabs) species from Lagos Lagoon.
3. To compare the detected levels of polycyclic aromatic hydrocarbons (PAHs) in water and fish with national and international safety standards.
4. To evaluate the potential ecological and public health risks posed by the detected levels of polycyclic aromatic hydrocarbons (PAHs) in Lagos Lagoon.

1.5 Research Question

1. What are the physico-chemical parameters of water in Lagos Lagoon?
2. What are the concentration levels of selected polycyclic aromatic hydrocarbons (PAHs) in water samples and aquatic organisms from Lagos Lagoon?
3. To what extent do human activities contribute to polycyclic aromatic hydrocarbons (PAHs) pollution in Lagos Lagoon?

Lead City University Ibadan DO NOT COPY

4. What are the possible human health implications of consuming polycyclic aromatic hydrocarbons (PAHs) contaminated water and aquatic organisms from Lagos Lagoon?
5. Do the PAH contamination levels in Lagos Lagoon comply with international water quality and food safety guidelines?

1.6 Significance of the Study

This study seeks to address some of the critical gaps in current research by focusing on the impact of polycyclic aromatic hydrocarbons (PAHs) ethers on fish, a key component of aquatic ecosystems and an important food source for humans. Through a combination of controlled laboratory experiments and rigorous data analysis, this research aims to provide new data on the levels of sixteen polycyclic aromatic hydrocarbons (PAHs) in fish, and to assess the broader ecological implications of toxic chemicals. One of the major outcomes of this study will be its contribution to evidence-based policymaking. The data generated will serve as a foundation for regulatory agencies, such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Lagos State Environmental Protection Agency (LASEPA), to: establish or update guidelines and safety standards for pollutants in water and fish, implement stricter pollution control measures for industries discharging effluents into Lagos Lagoon and enforce regulations on pesticide use in agriculture to prevent further contamination of the lagoon.

Lead City University Ibadan DO NOT COPY

1.7 Scope of the Study

This research focuses on the assessment of polycyclic aromatic hydrocarbons in aquatic organisms from Lagos Lagoon, Nigeria. It specifically considers **sixteen** priority polycyclic aromatic hydrocarbons (PAHs) compound listed by USEPA, chosen for their persistence and toxicity to understand their levels and potential risks to both aquatic life and human populations. The study will also focus on water samples from Lagos Lagoon and aquatic organisms commonly consumed by local populations.

1.8 Limitation of the Study

Many of the residential communities in the study area demonstrated some resistance to the researcher for the fear of environmental officers and did not permit outsiders to collect water within their boundaries so this limited the number of access point. This made sample collection very challenging and difficult.

1.9 Operational Definition of Terms

Polycyclic Aromatic Hydrocarbons (PAHs); Polycyclic aromatic hydrocarbons (PAHs) are a group of chemically persistent organic compounds formed primarily during the incomplete combustion of organic material, such as during the burning of fossil fuels, biomass, or wood

Fish: An aquatic animal with gills, fins, and a streamlined body, living in freshwater or saltwater.

Contamination: The presence of harmful substances in air, water or food making them unsafe.

Lagoon: A shallow body of water separated from a larger water body by a barrier.

Lead City University Ibadan DO NOT COPY

Dichlorodiphenyltrichloroethane (DDT): A synthetic insecticide used to control pests, now banned in many countries due to its environmental and health risks.

Bioaccumulate: The gradual buildup of toxic substances in an organism over time usually through food or the environment.

Ubiquitous: Present everywhere at the same time or found commonly in many places.

Inhabitants: People or animals that live in a particular place or environment.

World Health Organization (WHO): A global health agency under the United Nations responsible for public heath, disease prevention, and international health policies.

National Environment Standard and Regulations Enforcement Agency (NESREA): Nigeria agency responsible for enforcing environmental laws and regulations to protect the environment.

Lead City University Ibadan DO NOT COPY

Endnotes

1. M. E. Goher, M. H. Ali, & S. M. El-Sayed, *Heavy Metals Contents in Nasser Lake and the Nile River, Egypt: An Overview,* **The Egyptian Journal of Aquatic Research,** 45(4), 2019, 301-312

2. M.S. Dauda & J.O. Olaofe, *Determination of Physico-chemical Parameters of River Majowopa Sagamu Ogun State, Nigeria,* **Advance Journal of Chemistry-Section A**., 12(4), 2020, 569-575. Doi:10.22034/ajca.2020.103664.

3. A. B. Hasan, A. S. Reza, S. Kabir, M. A. B. Siddique, M. A. Ahsan, & M. A. Akbor, *Accumulation and Distribution of Heavy Metals in Soil and Food Crops around the Ship Breaking Area in Southern Bangladesh and Associated Health Risk Assessment,* **SN Applied Sciences,** *2*, 2020, 1-18.

4. J. P. Vareda, A. J. Valente, & L. Durães, *Assessment of Heavy Metal Pollution from Anthropogenic Activities and Remediation Strategies: A Review,* **Journal of Environmental Management,** 246, 2019, 101-118.

5. O. J. Afonne, & E. C. Ifediba, *Heavy Metals Risks in Plant Foods–Need to Step up Precautionary Measures,* **Current Opinion in Toxicology,** 22, 2020, 1-6.

6. A. O. Aigberua, A. A. Ogbuta, & S. C. Izah, *Selected Heavy Metals in Sediment of Taylor Creek due to Anthropogenic Activities in the Niger Delta Region of Nigeria: Geochemical Spreading and Evaluation of Environmental Risk*, **Biodivers Int J,** 4(2), 2020, 67-80.

7. O. A. Ajewole, O. O. Ikhimiukor, & O. O. Adelowo, *Heavy Metals (Cu and Zn) Contamination of Pond Sediment and Co-Occurrence of Metal and Antibiotic Resistance in Escherichia Coli from Nigerian Aquaculture*, **International Journal of Environmental Studies,** 78(5), 2021, 773-784.

8. C. N. Amadi, C. Frazzoli, & O. E. Orisakwe, *Sentinel Species for Biomonitoring and Biosurveillance of Environmental Heavy Metals in Nigeria*, **Journal of Environmental Science and Health, Part C,** 38(1), 2022, 21-60.

9. I. C. Davies, & A. O. Ekperusi, *Evaluation of Heavy Metal Concentrations in Water, Sediment and Fishes of New Calabar River in Southern Nigeria,* **Journal of Limnology and Freshwater Fisheries Research**, *7*(3), 2021, 207-218.

10. B. Edogbo, E. Okolocha, B. Maikai, T. Aluwong, & C. Uchendu, *Risk Analysis of Heavy Metal Contamination in Soil, Vegetables and Fish around Challawa Area in Kano State, Nigeria*, **Scientific African,** *7*, 2020, e00281.

11. T. I. Egbeja, J. U. Kadiri, A. O. Onoja, & A. O. Isah, *Determination of Heavy Metals in Water, Sediments and Tissues of Clarias Garipienus and Oreochromis niloticus from*

Lead City University Ibadan DO NOT COPY

Kpata River, Lokoja, Nigeria, **International Journal of Fisheries and Aquatic Studies,** 7(5), 2019, 25-29.

12. O. C. Egesi, O. Alum-Udensi, P. C. Ogbonna, & N. N. Ugor, *Assessment of Heavy Metals in Water, Fish, and Sediment of River Benue, Benue State, Nigeria,* **Nigeria Agricultural Journal,** 54(1), 2023, 55-67.

13. V.C Ehiemere, J.N Ihedioha, N.R Ekere, C.N Ibeto, H.O Abugu, *Pollution and Risk Assessment of Heavy Metals in Water, Sediment and Fish (Clarias Gariepinus) in a Fish Farm Cluster in Niger Delta Region, Nigeria,* **Journal of Water and Health,** 20(6), 2022, 927-945.

14. E. C. Emenike, K. O. Iwuozor, & S. U. Anidiobi, *Heavy Metal Pollution in Aquaculture: Sources, Impacts and Mitigation Techniques,* **Biological Trace Element Research,** 2021, 1-17.

15. M. O. Eyankware, & P. N. Obasi, *A Holistic Review of Heavy Metals in Water and Soil in Ebonyi SE, Nigeria; with Emphasis on its Effects on Human, Plants and Aquatic Organisms,* **World News of Natural Sciences,** 38, 2021, 1-19.

16. G. A. Idowu, *Heavy Metals Research in Nigeria: A Review of Studies and Prioritization of Research Needs,* **Environmental Science and Pollution Research,** 29(44), 2022, 65940-65961.

17. S. A. Ofori, S. J. Cobbina, & D. A. Doke, *The Occurrence and Levels of Polycyclic Aromatic Hydrocarbons (PAHs) in African Environments—A Systematic Review,* **Environmental Science and Pollution Research,** 27, 2020, 32389-32431.

18. I. M. Odika, G. C. Nwanisobi, N. V. Nwankwo, E. C. Mmaduakor, & O. A. Ikeh, *Polycyclic Aromatic Hydrocarbons, PAHs Contamination Levels and Health Risks in Foods Consumed in Nigeria: A Review,* **Asian Journal of Food Research and Nutrition,** 2(4), 2023, 558-570.

19. A. Akinnusotu, J. E. Ukpebor, & F. E. Okieimen, *Source, Distribution, and Risk Assessment of Polycyclic Aromatic Hydrocarbons in Sediment and Fish Samples from River Owan, Edo State, Nigeria*. **Frontiers in Toxicology**, 5, 2023, 1-16.

20. E. I. Adeyeye, O. A. Ibigbami, A. J. Adesina, O. K. Popoola, A. R. Olatoye, & Y. A. Gbolagade, *Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) Distribution in Water, Sediments and Fish Parts from Ponds in Ado-Ekiti, Nigeria,* **Polycyclic Aromatic Compounds**, 43(4), 2023, 3147-3158.

21. B. Akinsanya, I. O. Ayanda, B. Onwuka, & J. K. Saliu, *Bioaccumulation of BTEX and PAHs in Heterotis Niloticus (Actinopterygii) from the Epe Lagoon, Lagos, Nigeria*, **Heliyon,** 6(1), 2020 e03272. doi: 10.1016/j.heliyon.2020.e03272.

Lead City University Ibadan DO NOT COPY

22. A. Akinnusotu, J. E. Ukpebor, & F. E. Okieimen, *Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) in Sediment and Fish Samples of River Owan, and Agricultural Soil around the Same River in EDO State, Nigeria*, **Environmental Sciences Proceedings,** *7*(1), 2020, 11.

23. I. O. Oyo-Ita, O. E. Oyo-Ita, S. U. Ugim, N. N. Nnaji, & S. Elarbaoui, *Source and Toxicological Assessment of Polycyclic Aromatic Hydrocarbons in Sediments from Imo River, Southeastern Nigeria*, **Polycyclic Aromatic Compounds,** 39(3), 2019, 191-206.

Lead City University Ibadan DO NOT COPY

Chapter Two

Literature Review

2.1 Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are a class of chemically stable organic molecules that develop predominantly after incomplete combustion of organic material, such as the use of fossil fuels, biomass, or wood. They are common environmental pollutants found in the atmosphere, soil, and water, and have been identified as important contaminants in systems. Polycyclic aromatic hydrocarbons (PAHs) or polynuclear aromatic hydrocarbons are chemical compounds that are primarily generated by incomplete combustion[1]. They are composed of two or more fused benzene rings organized in a cluster or linear arrangement. PAHs are a prevalent environmental pollutant due to their widespread distribution and production process. They only include carbon and hydrogen atoms, making them a diverse class of organic compounds. The bulk of PAHs have properties such as significant molecular weight, high melting and boiling temperatures, and solubility in a wide range of organic solvents. With the exception of a few minor components such as naphthalene, they are solids with low volatility at room temperature, and the bulk may be photooxidized and degraded to simpler compounds[2]. In general, PAHs are stable, neutral chemicals that are not easily soluble in water. The solubility of PAHs in water diminishes with increasing molecular weight. Their high water-octanol partition coefficients (POCs) show that they are lipophilic. Naphthalene, for example, is a low-molecular-weight PAH that is very soluble in water and can bioaccumulate. Chemicals with high molecular weight are hydrophobic and relatively insoluble, and they can attach to both inorganic and organic particles in the water column[3].

Lead City University Ibadan DO NOT COPY

It is widely acknowledged that PAHs are teratogenic, mutagenic, and carcinogenic. They have been designated as priority pollutants by both the European Environment Agency and the United States Environmental Protection Agency (US-EPA) due to their environmental persistence. It is well understood that various PAHs induce cancer in laboratory animals. In addition to injection-site sarcomas, researchers have discovered an increase in the incidence of skin, lung, bladder, liver, and stomach cancers in animals[4]. The USEPA has recognized seven PAH compounds as potential human carcinogens. The carcinogenic classifications of particular PAHs by agencies are shown in Table 2.1.

Lead City University Ibadan DO NOT COPY

Table 2.1: Physical Properties of Polycyclic Aromatic Hydrocarbons

Compound (C.A.S.N°)	Molecular Weight	Log Kow	Water Solubility at 25°C (mg/L)	Melting Point (°C)	Vapour Pressure at 25 °C (mPa)
Naphthalene (91-20-3)	127.16	3.8	31.7	80. 6	12 960
Acenaphthene (83-32-9)	154.21	4,.33	3.42	95	594
Fluorene (86-73-7)	168	6.18	1.98	126.5	92.7
Phenanthrene (85-01-8)	180.24	4. 5	1.50	101	91.7
Anthracene (120-12-7)	175.24	4. 5	0.145	219	27
Pyrene (129-00-0)	202.26	4.9	0.135	156	91.6 x 10-6
Fluoranthene (206-44-0)	202.26	5.1	0.26	111	1340
Benz[*a*]anthracene (56-66-3)	228	5. 6	0.0057	162	15.7 x 10-3
Benz[*a*]pyrene (50-32-8)	262.32	6.0	0.0038	179	1.37 x 10-6
Benzo[*b*]fluoranthene (205-99-2)	252.32	6.06	0.014	168	0.13 x 10-5 to 0.133 at 20°C
Benzo[*j*]fluoranthene (205-82-3)	252.32			166	
Benzo[*k*]fluoranthene (207-08-9)	252.32	6.06	0.0043	227	2.8 x 10-9
Indeno[*1,2,3-cd*]pyrene (193-39-5)	286	6.4	0.00073	164	1.3 x 10-5

Source[7]

Lead City University Ibadan DO NOT COPY

2.2 Sources of Polycyclic Aromatic Hydrocarbons (PAHs)

Most fossil fuels contain polycyclic aromatic hydrocarbons. Organic substances degrade, despite the fact that they are produced naturally by bacteria, volcanoes, and forest fires. The majority of PAHs originate from both natural and anthropogenic sources[5]. The two most common sources of anthropogenic PAHs in the environment are petrogenic and pyrogenic sources. The incomplete combustion of organic materials, such as wood, fossil fuels, asphalt, and industrial waste, produces pyrogenic PAHs as trace pollutants. Petroleum products are the source of petrogenic PAHs. These hydrocarbons are thought to have originated from home and industrial wastes, oil spills, crude and fuel oil, used or fresh crankcase oil, and persistent or inadvertent pipeline breaches on land and at sea[6,7]. Because they include more non-alkylated PAHs than petrogenic sources, pyrogenic sources are thought to be more dangerous and thermodynamically stable.

Particulate matter is formed when PAHs join with particles via nucleation and condensation, releasing them from their sources either in gas or another form. Following manufacturing, PAHs can move widely through the atmosphere or downstream channels, eventually accumulating in soils and aquatic sediments. They can enter an aquatic ecosystem by a variety of pathways, including the distribution of fossil fuels, petroleum spillage, surface water and runoff, sewage and waste water effluent, and eventually accumulation in soils and aquatic sediments[7]. Other sources of PAHs that harm aquatic and sediment environments include creosote-treated items, petroleum product spills from leaking tanks and bunkering operations, industrial facilities, waste water treatment facilities, and atmospheric PAH deposition. The principal industrial (stationary) sources of PAHs include coke ovens, aluminum manufacturing facilities, iron and steel foundries, coal gasification, and coke production. PAH in coastal sediments come from both natural and human-caused emissions[8].

Lead City University Ibadan DO NOT COPY

PAHs' migration through the environment is determined by properties such as how rapidly they dissolve in water (which they do not in general) and how easily they evaporate into the air. After a few weeks to months, microorganisms in soil or water can breakdown PAHs. Most PAHs in soil will adhere to particles with a strong hold. However, some PAHs can contaminate subterranean water by dispersing through soil[9]. The type of soil will determine how long PAHs stay on a soil particle. Clay soil absorbs more PAHs than sandy soil does. The concentration of PAHs in plants and animals may be higher than in the soil or water where they live due to the possibility that they may be amplified and bioaccumulate, especially in animals[10].

2.3 The Sixteen Priority Polycyclic Aromatic Hydrocarbons (PAHs)

Naphthalene

Naphthalene, the simplest of the sixteen priority PAHs, is composed of two fused benzene rings and is frequently referred to as the most volatile member of the group. The molecular formula $C_{10}H_8$ is generally recognized as the principal constituent of mothballs. It has historically been employed in chemical industries for the creation of dyes, polymers, and resins. Naphthalene is widely released into the environment as a byproduct of incomplete combustion of fossil fuels, cigarette smoke, and biomass burning, and it is also a natural component of crude oil and coal tar[11]. Its relatively high vapour pressure in comparison to heavier PAHs implies it is common in the gaseous phase of the atmosphere, where it undergoes photochemical oxidation but may also adsorb onto particulate matter, allowing for long-range atmospheric movement. Naphthalene is more soluble in water than higher molecular weight PAHs, which makes it more accessible to aquatic creatures[12]. Toxically, it is known to cause haemolytic anaemia, respiratory irritation, and cataract formation with prolonged exposure[11]. Rodent studies revealed carcinogenicity in the respiratory

Lead City University Ibadan DO NOT COPY

tract, leading the International Agency for Research on Cancer (IARC) to classify it as a Group 2B probable human carcinogen. Human exposure occurs by inhalation of polluted air and ingestion of contaminated water or food, with occupational exposure being particularly high among workers in petroleum refining, coal tar distillation, and textile manufacture[13,14].

Acenaphthylene

Acenaphthylene ($C_{12}H_8$) is a three-ring structure made up of a naphthalene backbone and an ethylene bridge. It is predominantly released into the environment after the combustion of coal, oil, wood, and other organic materials, and it is commonly found in diesel exhaust, creosote, and coal tar. Acenaphthylene, unlike naphthalene, is less volatile but more persistent in sediments due to its hydrophobic properties[15]. This persistence allows accumulation in aquatic biota, particularly benthic species that live in close proximity to sediment particles. Acenaphthylene's toxicology has not been fully researched, although experimental investigations indicate that it causes oxidative stress, enzyme inhibition, and DNA damage[16]. Its role as a mutagenic agent is still being investigated, although preliminary data suggest that it may have genotoxic effects. Acenaphthylene's position on the EPA priority list is due to its long-term environmental persistence and additive toxicological impact when present in PAH combinations. Exposure in humans can occur by inhalation of polluted air, consumption of contaminated food, or occupational contact with creosote-treated wood and coal tar products, though the full extent of its health ramifications requires further investigation[17].

Acenaphthene

Acenaphthene, which shares the same chemical formula ($C_{12}H_{10}$) as acenaphthylene but varies structurally due to the existence of a saturated bridge, is another extensively dispersed PAH in the

Lead City University Ibadan DO NOT COPY

environment. It occurs naturally in coal tar and crude oil and is utilised as an industrial chemical in the production of colours, polymers, and pharmaceuticals[18]. Acenaphthene is more chemically stable than acenaphthylene and partitions strongly into soils and sediments due to its hydrophobicity. It has been found to bioaccumulate in aquatic creatures, particularly fish and benthic invertebrates[19]. Toxically, animal investigations have showed that acenaphthene exposure can lead to hepatic and renal changes, while chronic exposure in aquatic creatures impacts growth and reproduction. Though not considered a powerful carcinogen in isolation, its persistence and moderate toxicity make it important in environmental monitoring[20]. Contaminated water and food, inhalation of polluted air, and occupational contact in enterprises that use coal-derived products are all potential human exposure pathways. Although evidence of mutagenicity is minimal, its inclusion among priority contaminants emphasises the importance of managing its presence in the environment[21].

Fluorene

Fluorene is a three-ring PAHs with the chemical formula $C_{13}H_{10}$, consisting of two benzene rings fused on either side of a central five-membered ring. It is formed during fossil fuel burning and is also found in coal tar and petroleum. Fluorene has been used in the industrial production of plastics, dyes, and medications, which contributes to its environmental diffusion[22]. Fluorene is semi-volatile, meaning it exists in both gaseous and particulate phases in the atmosphere. While it is photodegraded, it can also survive in sediments, where it bioaccumulates in aquatic species[23]. According to experimental investigations, fluorene causes oxidative stress, hepatotoxicity, and developmental damage in exposed species. In fish, it can affect growth and reproduction, while in mammals, it has been related to metabolic problems[24]. Although fluorene is considered less carcinogenic than many of the heavier PAHs, bacterial experiments show mutagenesis potential,

Lead City University Ibadan DO NOT COPY

implying that it may contribute to the cumulative toxicity of PAH combinations. Humans are exposed to fluorene largely through inhaling combustion fumes and consuming contaminated food or water, with occupational exposure occurring in industries that process coal tar or petroleum products[25].

Phenanthrene

Phenanthrene, a three-ring PAH with the formula $C_{14}H_{10}$, is one of the most prevalent PAHs in the environment because of its stability and extensive synthesis from combustion sources. Phenanthrene, the angular isomer of anthracene, differs structurally from its linear isomer[26]. It is frequently found in coal tar, crude oil, car emissions, and petroleum spills, and due to its moderate solubility, it is easily disseminated in aquatic systems. Phenanthrene bioaccumulates in fish and shellfish, making it a significant nutritional source for humans[27]. Toxicological research have revealed that phenanthrene inhibits heart development in fish eggs and causes oxidative stress and organ damage in mammals. Although the IARC has not categorized phenanthrene as a confirmed carcinogen, research suggests that its metabolites can bind DNA, raising concerns regarding mutagenicity[28]. Because of its link with petroleum sources, phenanthrene is commonly used to detect petrogenic contamination in aquatic habitats. Human exposure happens mostly from inhaling dirty air, consuming seafood from contaminated waterways, and eating burned meals[28].

Anthracene

Anthracene, with the same chemical formula as phenanthrene ($C_{14}H_{10}$) but organised in a linear three-ring structure, is another environmentally significant PAH. It occurs naturally in coal tar and crude oil and is commonly utilised in the manufacture of colours, polymers, and wood preservatives[29]. While anthracene is thought to have moderate acute toxicity, it is phototoxic

Lead City University Ibadan DO NOT COPY

under ultraviolet light, creating reactive oxygen species that damage lipids, proteins, and DNA. Its hydrophobicity causes high sorption to sediments, where it can persist and bioaccumulate in benthic species[30]. Animal studies show that anthracene causes skin irritation, hepatotoxicity, and immunological suppression, although its carcinogenic categorization remains questionable. Despite this, its environmental persistence and proportion to total PAH exposure warrant monitoring. Humans are exposed through inhalation of polluted air, occupational contact with coal tar and creosote, and consumption of contaminated food[31]. While anthracene is not one of the most potent PAHs, its involvement in mixture toxicity and resistance to degradation make it an important environmental concern.

Fluoranthene

Fluoranthene is a four-ring PAH ($C_{16}H_{10}$) with a distinctive angular structure that boosts its photostability compared to smaller PAHs. It is predominantly produced by high-temperature combustion processes such as coal burning, vehicle emissions, and wood combustion, making it a common component of urban air particles[32]. Its low water solubility and high hydrophobicity cause considerable partitioning into sediments and aquatic animals, where it can bioaccumulate. Fluoranthene's toxicological effects have been extensively examined, including DNA strand breakage, oxidative stress, and embryo toxicity in fish and amphibians. Although fluoranthene is not a significant carcinogen on its own, it has been shown to act synergistically with other PAHs, enhancing their mutagenic and carcinogenic effects in combinations[33]. Chronic human exposure results from breathing dirty air and eating grilled or smoky meals. Its extensive distribution, environmental longevity, and capacity to interact synergistically with other PAHs emphasise its status as a priority pollutant of concern[34].

Lead City University Ibadan DO NOT COPY

Pyrene

Pyrene, a four-ring polycyclic aromatic hydrocarbon, has the chemical formula $C_{16}H_{10}$. It is one of the most numerous PAHs generated by incomplete combustion of organic materials, and it is frequently found with fluoranthene, with which it shares structural similarities[35]. Pyrene is released in large quantities by car exhaust, coal and biomass burning, and petroleum refining operations. It is also often found in smoke from home cooking and grilling, making dietary consumption a significant exposure pathway for people[36]. Pyrene is hydrophobic, meaning it has low water solubility but a high octanol-water partition coefficient, allowing it to strongly interact with sediments and bio accumulate in aquatic creatures. Toxically, pyrene is not regarded the most carcinogenic of the PAHs. However, it adds significantly to combination toxicity. Its metabolic activity in living systems produces hydroxylated metabolites that can generate reactive oxygen species and bind to DNA[37]. Pyrene has been shown in aquatic creatures to produce cardio toxicity in developing embryos, resulting in pericardial edema and arrhythmias that can reduce survival. In mammals, repeated exposure causes hepatotoxic and nephrotoxic consequences, with evidence indicating immunosuppressive results[38]. While pyrene is not considered a significant individual carcinogen, it is nonetheless used as a marker chemical for total PAH exposure in environmental monitoring due to its frequent detection, durability, and broad biological effects[39].

Benzo[a]anthracene

Benzo[a]anthracene, a four-ring PAH with the chemical formula $C_{18}H_{12}$, occurs naturally in fossil fuels and is also generated after incomplete combustion of organic waste. It is present in emissions from coal combustion, petroleum refining, tobacco smoke, and automobile exhaust[40]. In the environment, benzo[a]anthracene is relatively stable, with low volatility and high

Lead City University Ibadan DO NOT COPY

hydrophobicity, resulting in a close connection with airborne particles, soils, and sediments. Its durability allows it to accumulate in aquatic habitats and infiltrate food chains, eventually reaching humans via dietary exposure. Toxically, cytochrome P450 enzymes metabolize benzo[a]anthracene into reactive intermediates such as diol-epoxides, which form covalent adducts with DNA. These interactions disturb normal cellular replication mechanisms, which can result in mutagenesis and cancer[41]. Animal studies regularly reveal tumour growth in a variety of tissues, including the lungs and skin, after prolonged exposure. The International Agency for Research on Cancer has classified benzo[a]anthracene as a Group 2B potential human carcinogen, citing substantial evidence of carcinogenicity in animals but minimal evidence in humans[42]. Human exposure occurs predominantly from inhalation of urban air pollution, the eating of smoked or charred foods, and occupational contact with coal tar and creosote. Despite being less potent than benzo[a]pyrene, benzo[a]anthracene is included in toxic equivalency factor (TEF) calculations that quantify the cumulative cancer risk of PAH combinations, highlighting its public health significance[43].

Chrysene

Chrysene is a four-ring PAH with the chemical formula $C_{18}H_{12}$, physically similar to benzo[a]anthracene but different in ring configuration. It occurs naturally in coal tar and petroleum and is created by the combustion of fossil fuels, wood, and other organic matter. Chrysene is extensively found in the environment, including air particles, soils, sediments, and aquatic creatures. Its physicochemical features, particularly low solubility and high hydrophobicity, enhance sediment buildup and bioaccumulation in fish and shellfish[44]. Toxically, chrysene is considered less effective as a carcinogen than benzo[a]pyrene, but it can be metabolically activated into carcinogenic intermediates capable of generating DNA adducts. While in vitro research

Lead City University Ibadan DO NOT COPY

suggests mutagenic activity, long-term animal studies have shown liver and skin cancer[45]. Chrysene is therefore categorized as a Group 2B potential human carcinogen by the International Agency for Research on Cancer. Inhaling urban air pollution and consuming polluted food, especially smoked meats, are the main ways that humans are exposed. Additionally, chyrene has been found in oils and dairy products that have been tainted by feed pollution or atmospheric deposition[46]. Chrysene is environmentally persistent and can work in concert with other PAHs to increase combination toxicity, although being less immediately dangerous. Because of this, it continues to be a crucial component of environmental monitoring programs and risk evaluations for public health.

Benzo[b]Fluoranthene

A five-ring, high molecular weight PAH, benzo[b]fluoranthene has the molecular formula $C_{20}H_{12}$. It is mostly produced by high-temperature combustion processes and is frequently present in soot, coal tar, automobile exhaust, and industrial emissions. Because benzo[b]fluoranthene is highly hydrophobic and almost insoluble in water, it persists in sediments and bioaccumulates over time in aquatic creatures[47]. It poses a risk of biomagnification because of its lipophilic nature, which allows it to easily infiltrate food chains. According to toxicological research, benzo[b]fluoranthene is metabolically activated to produce reactive epoxides and dihydrodiols that attach to proteins and DNA, interfering with regular cellular functions and causing mutagenesis[48]. Although it is typically less potent than benzo[a]pyrene, evidence from experimental animal research indicates substantial carcinogenic potential, with tumour growth in several organs. Benzo[b]fluoranthene has been categorised as a Group 2B potential human carcinogen by the International Agency for Research on Cancer[49]. Human exposure occurs through occupational contact with combustion wastes such coal tar, ingestion of charred and smoky meals, and

Lead City University Ibadan DO NOT COPY

breathing of contaminated urban air. It is a crucial molecule for toxic equivalency factor estimates due to its toxicological resemblance to benzo[a]pyrene and frequent co-occurrence in environmental samples. Because of its persistence, carcinogenic potential, and ubiquitous occurrence, regulatory organisations stress the importance of monitoring benzo[b]fluoranthene in both environmental and food safety [50].

Benzo[k]fluoranthene

Benzo[k]fluoranthene is a five-ring polycyclic aromatic hydrocarbon with the chemical formula $C_{20}H_{12}$. It is structurally identical to benzo[b]fluoranthene, varying only in the location of one of its aromatic rings, although it shares similar physicochemical and toxicological properties. Benzo[k]fluoranthene is produced during high-temperature combustion processes such as the combustion of coal, petroleum products, and biomass, and it is commonly found in urban air particles, soot, and industrial wastes[51]. It is hydrophobic and has limited solubility in water, allowing it to remain in sediments and soils and accumulate over time in aquatic environments. Once deposited in sediments, it is extremely resistant to microbial destruction, resulting in environmental half-lives that can last for years. Toxically, benzo[k]fluoranthene is metabolically converted into reactive intermediates that can bind DNA and cause mutations[52]. Rodent studies reveal signs of tumor growth in the liver, lungs, and skin, although its potency is generally thought to be lower than that of benzo[a]pyrene. Nonetheless, its persistence and bioaccumulation potential pose long-term dangers, especially when exposed through food webs. The International Agency for Research on Cancer classifies benzo[k]fluoranthene as a Group 2B probable human carcinogen, with human exposure occurring through inhalation of urban air, consumption of smoked or charred foods, and occupational handling of coal tar and petroleum products[53]. While

Lead City University Ibadan DO NOT COPY

not the most carcinogenic PAH by itself, its environmental persistence and potential to contribute additively to combination toxicity make it a priority contaminant to monitor[54].

Benzo[a]pyrene

Benzo[a]pyrene, having the chemical formula $C_{20}H_{12}$, is one of the most investigated and toxicologically relevant PAHs. It is a five-ring compound formed in large quantities during the high-temperature burning of coal, petroleum, wood, and tobacco. Benzo[a]pyrene is extremely lipophilic and firmly associates with sediments, soils, and organic materials in the environment, where it persists for extended periods due to its resistance to degradation[55]. Its toxicological significance arises from its metabolic activation to benzo[a]pyrene-7,8-diol-9,10-epoxide, a highly reactive metabolite that binds covalently to DNA, generating adducts that inhibit replication and induce mutagenesis. This mechanism has been clearly established as the principal driver of PAH-induced carcinogenesis. Animal studies regularly reveal tumour growth in a variety of organs, including the lungs, skin, and gastrointestinal system[56]. Epidemiological studies in humans show a clear link between benzo[a]pyrene exposure and an elevated risk of lung and bladder cancer, notably among occupationally exposed populations like coke oven workers and chimney sweeps[57]. As a result, the International Agency for Research on Cancer has classified benzo[a]pyrene as a Group 1 recognized human carcinogen, making it the standard for assessing PAH toxicity. Regulatory bodies, such as the US Environmental Protection Agency and the European Food Safety Authority, use benzo[a]pyrene as a reference chemical in the toxic equivalency factor system, which expresses the toxicity of other PAHs compared to it[58]. Humans are exposed to benzo[a]pyrene by inhalation of polluted air, consumption of smoked and burnt foods, and occupational exposure to coal-derived products, with dietary intake being the most common source

Lead City University Ibadan DO NOT COPY

in the general population. Benzo[a]pyrene is a key target of PAH study and regulation due to its high carcinogenic potential, persistence, and ubiquity[59].

Indeno[1,2,3-cd]pyrene

Indeno[1,2,3-cd]pyrene is a high-molecular-weight PAH with six fused aromatic rings and the chemical formula $C_{22}H_{12}$. It is predominantly created by the high-temperature combustion of coal, petroleum, and biomass, although it is also present in vehicle emissions. Indeno[1,2,3-cd]pyrene's complex, angular molecular structure results in great stability, low volatility, and high hydrophobicity, all of which contribute to its environmental persistence[60]. It strongly binds to airborne particles and aquatic sediments, allowing it to travel vast distances and accumulate in benthic habitats. Once in sediments, its high resistance to biodegradation enables environmental persistence over long time periods. Toxically, indeno[1,2,3-cd]pyrene is metabolically activated by cytochrome P450 enzymes, resulting in reactive intermediates that can create DNA adducts and induce genetic mutations[61]. It has been shown in laboratory experiments to be genotoxic and carcinogenic, causing tumors to form in the lungs and liver of exposed animals. On this basis, the International Agency for Research on Cancer defines indeno[1,2,3-cd]pyrene as a Group 2B probable human carcinogen. Human exposure is predominantly by inhalation of traffic-related air pollution, ingestion of contaminated food, and occupational exposure to combustion emissions[62]. Although not as strong as benzo[a]pyrene, indeno[1,2,3-cd]pyrene's persistence and ubiquity in urban air particles contribute significantly to the cumulative cancer risk from PAH combinations[63].

Dibenzo[a,h]anthracene

Lead City University Ibadan DO NOT COPY

Dibenzo[a,h]anthracene, a five-ring, high-molecular-weight PAH with the chemical formula $C_{22}H_{14}$, is one of the most potent carcinogens on the EPA priority list. It is typically created by incomplete combustion of coal, wood, and petroleum products, and is found in large concentrations in coal tar, tobacco smoke, and soot from industrial emissions. Its hydrophobic characteristics and low solubility cause it to stay in sediments and soils for long periods of time, while also allowing for bioaccumulation and possibly biomagnification via aquatic food chains[64]. Dibenzo[a,h]anthracene is metabolically activated to diol-epoxides, which easily form DNA adducts, interrupting cellular processes and causing cancer. Animal studies have found considerable evidence of its carcinogenic potential, with persistent tumor induction in the lungs, skin, and gastrointestinal system[65]. Based on this information, the International Agency for Research on Cancer classified dibenzo[a,h]anthracene as a Group 2A potential human carcinogen, indicating significant evidence of carcinogenicity in animals but little evidence in humans[66]. Human exposure to dibenzo[a,h]anthracene occurs through the breathing of polluted urban air, the consumption of smoked or charred foods, and occupational contact with coal tar or combustion leftovers. Even though it is normally found in lower environmental concentrations than other PAHs, its great potency means it plays a disproportionate role in cancer risk evaluations[67]. As a result, it is substantially weighted in toxic equivalency factor systems and remains a highly regulated and toxicologically significant substance.

Benzo[g,h,i]perylene

Benzo[g,h,i]perylene is a six-ring, high-molecular-weight polycyclic aromatic hydrocarbon having the chemical formula $C_{22}H_{12}$. It is mostly formed during high-temperature combustion processes such as fossil fuel burning, waste incineration, and biomass combustion, and it is consistently found in urban air particles, soot, and sediments in industrialized areas[68]. Because of its massive,

Lead City University Ibadan DO NOT COPY

compact molecular structure, benzo[g,h,i]perylene has high chemical stability, minimal volatility, and little water solubility. These qualities help to ensure its permanence in the environment, particularly in soils and sediments where it can build over time[69]. It is extremely lipophilic and easily bio accumulates in aquatic creatures, infiltrating food chains and posing long-term ecological hazards. While benzo[g,h,i]perylene is less acutely hazardous than benzo[a]pyrene or dibenzo[a,h]anthracene, it can be metabolically activated to produce oxidative stress and induce mutagenesis consequences[70]. Animal studies show tumorigenic activity, albeit its potency is considered mild when compared to more harmful PAHs. The International Agency for Research on Cancer has categorized benzo[g,h,i]perylene as a Group 3 substance, which means it is not classifiable as carcinogenic in humans due to insufficient data[71]. However, its frequent detection in air particles and sediments, combined with its capacity to stay in the environment and bioaccumulate in food webs, justified its inclusion on the EPA's priority PAH list. Human exposure is mostly due to inhalation of polluted urban air, consumption of burned foods, and occupational contact with soot and combustion leftovers[72]. Although not one of the most potent PAHs, benzo[g,h,i]perylene is an important indicator of combustion-related pollution and contributes to cumulative health concerns in PAH mixtures[73].

Lead City University Ibadan DO NOT COPY

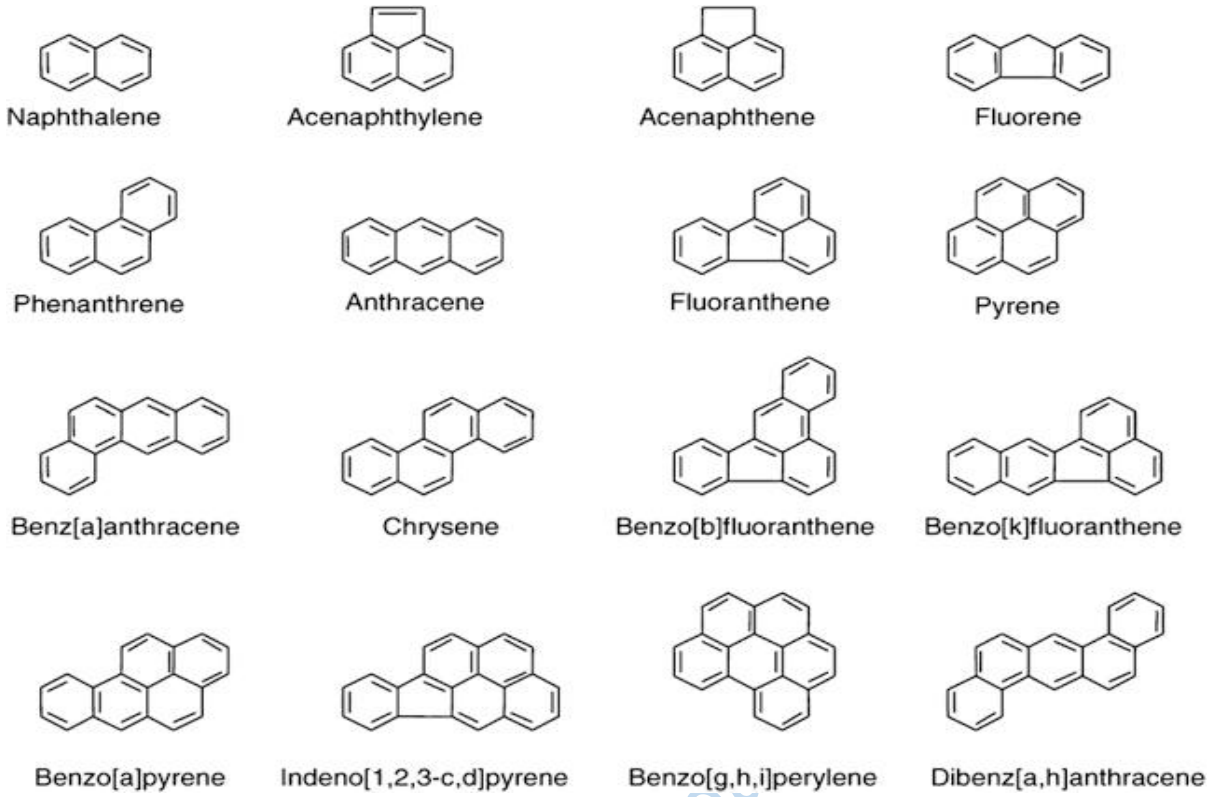


Figure 2.1: Structure of Sixteen Priority Pollutants PAHs

Source[10]

Lead City University Ibadan

2.4 Polycyclic Aromatic Hydrocarbons (PAHs) in the Aquatic Environment

In many developed countries, the occurrence of PAHs in aquatic environments has been extensively studied. Human activity causes approximately 228,000 metric tons of PAHs to be discharged into the aquatic environment each year. The Great Lakes Science Advisory Board (GLSAB) has identified varied amounts of PAHs in the open waters of the Great Lakes water system[74]. According to a report on the distribution of PAHs in surface waters, sediments, and soils of Hangzhou, China109, the concentration of 10 PAHs in sampled water ranged from 0.989 mg/L in Shaoniangong to 9.66 mg/L in Zhakou, with a mean value of 3.717 mg/L. The largest quantity of three-ring PAHs (phenanthrene, fluorene, and anthracene) was found in all of the water samples, according to the composition of PAHs in water by ring size. Certain water samples contained more four-ring PAHs, but all had the lowest concentrations of five-ring PAHs[75]. The average concentration of polycyclic aromatic hydrocarbons (PAHs) in surface runoff ranged from 0.1 to 15.81 mg/L in the Osogbo and Ile-Ife districts to 0.1 to 73.72 mg/L in the heavily industrialized Lagos area. The statistics demonstrate that the water systems were polluted with PAHs, which exceeded the WHO recommended limit of 0.05 µg/L. The amount of anthropogenic PAHs in the Niger Delta Area (NDA) in Nigeria is predicted to increase as more companies open there[76].

2.4.1 Polycyclic Aromatic Hydrocarbons (PAHs) in Air

The atmosphere is a critical environmental compartment for the transport, transformation, and distribution of polycyclic aromatic hydrocarbons (PAHs). Unlike soil and sediments, which act as relatively stable sinks, the atmosphere is a highly dynamic medium in which PAHs can exist in both gaseous and particulate forms, travel long distances, and undergo complex chemical transformations that affect their persistence and toxicity[77]. Airborne PAHs are primarily caused by incomplete combustion of organic matter and fossil fuels, and their concentrations in urban

Lead City University Ibadan DO NOT COPY

environments are heavily influenced by human activities such as vehicular emissions, industrial discharges, biomass burning, and domestic heating and cooking practices. In general, a PAH's chemical structure governs its behavior in the atmosphere. Low-molecular-weight (LMW) PAHs with two or three aromatic rings (such as naphthalene, acenaphthylene, and fluorene) are volatile and largely present in the gaseous phase[78]. High-molecular-weight (HMW) PAHs with four to seven rings (e.g., benzo[a]pyrene, indeno[1,2,3-cd]pyrene, and dibenz[a,h]anthracene) are less volatile and likely to associate with particulate matter, especially tiny particles with sizes less than 2.5 μm. These particle-bound PAHs represent considerable health hazards because fine particles can penetrate deep into the human respiratory system, delivering carcinogenic chemicals directly to lung tissues.

The emission of PAHs into the atmosphere is closely related to human activity. In many metropolitan areas, automobile traffic is the primary source, with diesel engines contributing significantly to HMW PAHs[79]. Gasoline engines, despite creating more LMW PAHs, also contribute to atmospheric loads via exhaust emissions. Industrial activities such as petroleum refining, coal burning, and metallurgical processes emit a wide range of PAHs into the atmosphere. In impoverished countries, particularly many African towns, biomass burning for cooking and heating is an additional, frequently ignored source. Open burning of solid trash, which is frequent in Lagos, contributes to higher atmospheric PAH levels by releasing pyrogenic chemicals straight into the urban atmosphere[80].

Once released into the atmosphere, PAHs undergo a number of transformation and transit mechanisms. Gas-phase PAHs can volatilize, diffuse, and undergo photochemical reactions, especially in the presence of sunshine. Photodegradation is a key sink for several LMW PAHs; nonetheless, it frequently results in the creation of oxygenated and nitrated PAH derivatives, such

Lead City University Ibadan DO NOT COPY

as nitro-PAHs. They are often more hazardous and mutagenic than the parent chemicals. Particle-bound PAHs are less photodegradable and can survive in the atmosphere for days or weeks, allowing them to travel considerable distances from their initial origins[81]. Studies have revealed that PAHs released in one place can travel across continents, illustrating the global scope of PAH contamination.

Meteorological circumstances have a considerable impact on the concentration and dispersion of PAHs in the air. Temperature, wind patterns, humidity, and precipitation all have an impact on how these substances travel through the atmosphere. During the winter months, PAHs are more likely to partition into particulate phase and deposit near the ground, leading in greater exposure levels for urban populations[82]. In warmer climates, such as Lagos, volatilization of LMW PAHs takes precedence, whilst photochemical processes accelerated by high solar radiation expedite the transition of gaseous compounds. Rainfall events also play an important role in removing particle-bound PAHs from the atmosphere, resulting in deposition on soil and water surfaces. Globally, air concentrations of PAHs fluctuate greatly depending on the amount of industrialization and the intensity of anthropogenic activity[83]. In industrialized countries, regulatory initiatives and cleaner combustion technologies have resulted in a progressive reduction in atmospheric PAH levels during the last few decades. Monitoring data from cities such as London, New York, and Tokyo demonstrate that benzo[a]pyrene concentrations are falling when stringent air quality rules are implemented. However, in many poor countries, PAH concentrations in the air remain high, frequently exceeding WHO and EU guidelines[84]. PAH contamination of the air in Lagos is especially alarming due to the mix of considerable motor traffic, industrial activity, open garbage burning, and residential biomass fuel use. Roadside monitoring studies have found that fine particulate matter in Lagos frequently contains excessive

Lead City University Ibadan DO NOT COPY

quantities of carcinogenic PAHs, particularly benzo[a]pyrene and indeno[1,2,3-cd]pyrene. The high density of traffic, with a prevalence of badly maintained vehicles and widespread usage of diesel engines, dramatically worsens this problem. Furthermore, informal industrial activity such as metal smelting, welding, and small-scale oil refining emit additional pollutants into the atmosphere[85] . The open burning of waste items, such as plastics, rubber, and biomass, is a particularly hazardous source since it emits both parent PAHs and harmful derivatives into densely populated regions.

The health effects of PAHs in the air are significant and well-documented. The principal route of exposure is inhalation, which allows both gaseous and particle-bound PAHs into the respiratory tract. LMW PAHs are taken into the bloodstream through the lungs, but HMW PAHs linked to small particles can accumulate deep inside alveolar tissues. Chronic exposure has been related to an increased risk of respiratory disorders such asthma, bronchitis, and chronic obstructive pulmonary disease (COPD)[86]. More importantly, the International Agency for Research on Cancer (IARC) has categorized some HMW PAHs, particularly benzo[a]pyrene, as Group 1 carcinogens. Long-term exposure to airborne PAHs has been linked to an increased risk of lung cancer, bladder cancer, and skin cancer in affected populations.

In addition to cancer hazards, airborne PAHs cause various types of damage. Prenatal and early childhood exposure has been associated with developmental and neurobehavioral problems, low birth weight, and compromised lung function[87]. Children in high-traffic regions had higher levels of urinary PAH metabolites, which correspond with cognitive deficiencies and poor academic performance, according to studies conducted in cities around the world. Certain PAHs and their derivatives have the potential to impair endocrine function, adding to the health risk. The ecological ramifications of atmospheric PAHs are similarly important[88]. PAH deposition from

Lead City University Ibadan DO NOT COPY

the air onto water surfaces contributes to aquatic contamination, whereas deposition into soils adds to contaminated reservoirs on land. Airborne PAHs can have a direct impact on plants; gaseous chemicals can be absorbed through leaf cuticles, but particulate-bound PAHs can attach to leaf surfaces, limiting photosynthesis and lowering plant development. Leafy vegetables produced in contaminated areas can collect PAHs, allowing them to enter the food chain and potentially expose humans[89].

Air quality rules and requirements for PAHs vary by region. The European Union has established a target value of 1 ng/m³ for benzo[a]pyrene in ambient air as a measure of carcinogenic PAH pollution. The United States Environmental Protection Agency (EPA) utilizes risk-based evaluations to determine tolerable lifetime exposure levels, with a focus on cancer risks from inhalation[90]. In Nigeria, however, regulatory controls for airborne PAHs are weak, and routine air quality monitoring is infrequent. This regulatory gap presents a substantial problem for protecting public health in urban areas like Lagos, where atmospheric PAH burdens are expected to be among the highest in Africa due to heavy anthropogenic pressures.

Mitigation efforts for lowering atmospheric PAHs are generally focused on reducing emissions from significant sources. In industrialized countries, advances in fuel quality, the use of catalytic converters, higher vehicle emission rules, and the switch to cleaner energy sources have all helped to reduce air pollution[91]. These measures must be implemented immediately in Lagos and other such cities. This involves retiring obsolete automobiles, encouraging public transit, prohibiting open rubbish burning, and implementing cleaner industrial technology. Public awareness campaigns on the risks of biomass burning, as well as the promotion of alternative cooking fuels like liquefied petroleum gas (LPG), are important steps toward reducing home contributions to atmospheric PAHs[92].

Lead City University Ibadan DO NOT COPY

2.4.2 Polycyclic Aromatic Hydrocarbons (PAHs) in Soil

Soil is a significant environmental reservoir for polycyclic aromatic hydrocarbons (PAHs), serving as both a sink and a potential secondary source of pollution for groundwater, surface water, air, and biota. Because of their hydrophobicity and limited water solubility, PAHs form strong bonds with organic matter and small soil particles, allowing them to remain in terrestrial ecosystems for lengthy periods of time[93]. Soils serve as an integrative compartment, absorbing PAHs from a variety of sources, including atmospheric deposition, industrial operations, vehicle emissions, petroleum spills, residential waste disposal, and biomass burning. Therefore, anthropogenic impacts, soil characteristics, and environmental factors all play a role in determining the distribution, persistence, and ecological consequences of PAHs in soil[94]. The main ways that PAHs enter soil are by particulate matter fallout from the atmosphere, soot deposition from burning fossil fuels, and petroleum hydrocarbon spills. Vehicle exhausts and industrial emissions are the main sources of pollution in metropolitan areas. Common sources in rural areas include the open burning of crop leftovers and the fertilization of sewage sludge. Leaks and spills from crude oil exploration and refining operations have produced soils that are significantly enriched with petrogenic PAHs in industrial and oil-producing areas, such as Nigeria's Niger Delta[95]. A unique example of mixed PAH sources, with both pyrogenic and petrogenic contributions, is Lagos, a megacity with significant industrial, automotive, and residential activity.

The molecular weight and chemical structure of PAHs in soil have a significant impact on their environmental fate. Naphthalene and fluorene are examples of low-molecular-weight (LMW) PAHs that can partially leach into groundwater due to their tendency to be more volatile and mobile. Conversely, high-molecular-weight (HMW) PAHs, such dibenz[a,h]anthracene and

Lead City University Ibadan DO NOT COPY

benzo[a]pyrene, show substantial sorption to clay minerals and soil organic matter, leading to increased persistence but decreased mobility[96]. Because of their mutagenic and carcinogenic qualities, as well as their resistance to microbial breakdown, these HMW PAHs are especially concerning.

One of the most important variables affecting PAH retention is the amount of organic carbon in the soil. PAHs show a high degree of partitioning into the soil's organic portion, where they are trapped and shielded from microbial breakdown. Bound residues are frequently formed as a result of this interaction; these residues are challenging to remove and endure for extended periods of time. Another significant factor is soil texture; fine-textured soils with a lot of clay and silt often have higher concentrations of PAHs than coarse-textured, sandy soils with a smaller surface area. . Seasonal variations in temperature and precipitation have an additional impact on PAH dynamics in tropical soils like those found in Lagos. While strong rains might mobilize pollutants, high sun radiation may encourage limited photodegradation of PAHs exposed to the surface[97].

A significant natural attenuation mechanism in soils is biodegradation, which is carried out by a variety of microbial communities that may metabolize PAHs to produce carbon and energy. Under aerobic conditions, it has been observed that a number of bacterial taxa, including Pseudomonas, Sphingomonas, and Mycobacterium, breakdown PAHs. By using ligninolytic enzymes, fungi like Phanerochaete chrysosporium also play a major role in the degradation of PAHs[98]. However, the efficacy of biodegradation is dependent on the bioavailability of PAHs, which is frequently limited by high sorption to soil particles and sequestration in micropores. High-molecular-weight PAHs degrade more slowly in anaerobic soils, such as waterlogged agricultural areas or sediments, resulting in their long-term survival.

Lead City University Ibadan DO NOT COPY

The persistence of PAHs in soil poses serious ecological and human health risks. Soils in urban and industrialized areas usually act as long-term pollution reservoirs, constantly releasing PAHs into other environmental media[99]. PAHs are released into the atmosphere through volatilization from polluted soils, while leaching and runoff carry them into groundwater and surface water. Soil-bound PAHs also enter terrestrial food chains because plants can absorb LMW PAHs via root absorption and grazing animals can consume contaminated vegetation or soil particles. For human populations, direct exposure to contaminated soils by skin contact, dust intake, or breathing of resuspended particulates is a significant exposure pathway.

Several studies throughout the world have found high quantities of PAHs in soils from industrialized and urban areas. Soils in Beijing and Shanghai, China, have high amounts of benzo[a]pyrene and chrysene, which are mostly caused by coal burning and automobile activity[33]. European research in Poland and Germany found that soils around industrial operations exceeded acceptable guideline values. South African, Ghanaian, and Nigerian investigations have shown the ubiquitous nature of PAH-contaminated soil. Soils in oil spill zones in the Niger Delta frequently contain PAH concentrations that are several orders of magnitude greater than background values, causing serious ecological and health hazards.

In Lagos, PAHs in soil have been related to a variety of urban activities[100]. Roadside soils in high-traffic locations, such as Ikeja, Oshodi, and Apapa, frequently have higher PAH levels due to chronic car emissions. Petroleum refining, metallurgy, and small-scale manufacturing operations all lead to increased contamination in industrial zones. Open dumping of solid waste and uncontrolled burning of refuse are other significant sources, generating pyrogenic PAHs that eventually settle on urban soils. According to studies, soils around informal settlements and marketplaces in Lagos frequently contain high levels of both LMW and HMW PAHs, indicating

Lead City University Ibadan DO NOT COPY

the combined effects of biomass fuel cooking, rubbish burning, and traffic-related emissions[101]. PAHs in soil pose ecological hazards that go beyond contamination of air and water. Soil invertebrates, such as earthworms, play critical roles in soil structure and nutrient cycling and are extremely susceptible to PAHs. Experimental investigations have demonstrated that exposure to contaminated soils can impair earthworm reproduction, growth, and survival rates. Soil microbial populations are also impacted, with chronic pollution resulting in reduced microbial diversity and poorer soil biochemistry. These disturbances reduce soil fertility and ecosystem function, creating problems to agriculture and food security in contaminated areas[102]. Human health concerns from PAH-contaminated soils are equally significant. Chronic exposure to benzo[a]pyrene and other carcinogenic PAHs has been associated with an increased risk of skin, lung, and bladder cancer. Children are more vulnerable because of increased exposure rates from hand-to-mouth action and the sensitivity of developing tissues. In Lagos' urban slums and informal settlements, where children frequently play on contaminated soils and families cook with biomass fuels, the risk of PAHs exposure is particularly high. Furthermore, the intake of locally grown crops planted in contaminated soils can act as an additional route for human exposure[103].

PAHs contamination in soil is normally tested using environmental agency-established guidelines. The Dutch Soil Quality Standards, for example, establish intervention levels for individual PAHs above which remediation is required. The United States Environmental Protection Agency (EPA) and the World Health Organization (WHO) have also set risk-based limits for benzo[a]pyrene equivalents in soil[104]. In Nigeria, however, soil quality restrictions are minimal and enforcement is weak, resulting in unregulated contamination in urban and oil-producing areas.

The remediation of PAH-contaminated soils is a global challenge. Several technologies have been created, including thermal desorption, soil washing, chemical oxidation, and bioremediation.

Lead City University Ibadan DO NOT COPY

Among these, bioremediation is gaining popularity because to its cost-effectiveness and environmental sustainability. Bioaugmentation, which introduces PAH-degrading bacteria, and biostimulation, which adds nutrients to boost local microbial activity, have both showed promise in terms of lowering soil PAH levels[105]. Another developing method, phytoremediation, which uses plants to absorb or degrade toxins, is well-suited to tropical environments. However, in heavily contaminated soils like those found in Lagos industrial zones, integrated treatments involving physical, chemical, and biological methods may be necessary for efficient restoration[106].

2.4.3 Polycyclic Aromatic Hydrocarbons (PAHs) in Sediments

Sediments are a key environmental compartment for the accumulation and long-term storage of polycyclic aromatic hydrocarbons (PAHs). Unlike air and water, which are transient mediums, sediments serve as a semi-permanent reservoir for hydrophobic organic pollutants, including PAHs, that build over time. PAHs' destiny in aquatic systems is heavily affected by their lipophilic and hydrophobic qualities, which enable them to preferentially partition into organic-rich sediments rather than remaining dissolved in the water column[107]. This feature has led to sediments being commonly recognized as both sinks and secondary sources of PAHs, having a dual function in the persistence and bioavailability of these chemicals in aquatic settings.

The processes influencing PAH formation in sediments are largely determined by their physicochemical features. PAHs are characterized by low aqueous solubility and high octanol-water partition coefficients (Kow), which contribute to their strong affinity for organic carbon. PAHs that enter the water column from atmospheric deposition, industrial discharges, or urban runoff attach quickly onto suspended particulate matter (SPM). These particulates eventually fall to the bottom, where PAHs are absorbed into sediment[108]. Sediment organic carbon content is an

Lead City University Ibadan DO NOT COPY

important factor in PAH retention; fine-grained sediments with high organic matter content, such as silts and clays, collect higher PAH concentrations than sandy or coarse-grained sediments.

PAHs in sediments can be roughly classified into two types: pyrogenic and petrogenic. Pyrogenic sources include incomplete burning of fossil fuels, biomass, and waste materials, which results in high-molecular-weight PAHs including benzo[a]pyrene, indeno[1,2,3-cd]pyrene, and dibenz[a,h]anthracene. Petrogenic sources, on the other hand, come from crude oil, petroleum products, and industrial discharges, and they contain more low-molecular-weight PAHs, such as naphthalene, phenanthrene, and fluorene[109]. In sediment studies, diagnostic ratios of PAHs (such as fluoranthene/pyrene and anthracene/phenanthrene) are frequently utilized to distinguish these origins. Sediments in coastal cities like Lagos frequently exhibit a complex mixture of pyrogenic and petrogenic inputs, due to the combination of urban combustion activity, petroleum transport, and industrial discharge[110].

Sediments from metropolitan estuaries, harbors, and industrialized rivers are known to have significant levels of PAHs. For example, studies in the Hudson River (United States) and the Thames River (United Kingdom) have revealed historical layers of PAH buildup associated with prior coal burning and industrial emissions[111]. Similarly, sediments from Chinese rivers such as the Yangtze and Yellow Rivers have worrying levels of PAHs, indicating the country's extensive industrial activity. These sedimentary archives frequently serve as environmental records, recording the history of industry and pollution for decades or even centuries. In some circumstances, sediment cores can be studied to recreate temporal trends in PAH contamination, indicating both historical pollution peaks and more recent reductions as a result of environmental legislation. Sediment pollution is particularly concerning in tropical locations such as Africa due to lax regulatory frameworks, insufficient waste management, and a high reliance on crude oil and

Lead City University Ibadan DO NOT COPY

biomass fuels[45]. In Nigeria's Niger Delta region, for example, oil exploration, spills, and artisanal refining activities have all contributed to extraordinarily high PAH concentrations in riverine and estuary sediment[112]. Similarly, in Lagos Lagoon, multiple studies have found considerable PAH deposition in sediments, which frequently exceeds international sediment quality criteria.

Sediments act as both sinks and secondary sources of PAHs in aquatic environments. Sediment disturbance caused by dredging, storms, tidal action, or benthic animals can resuspend PAHs in the water column, increasing their bioavailability. This resuspension process has important ecological ramifications since it increases the exposure of aquatic species to hazardous pollutants[113]. Benthic species, such as mollusks, crustaceans, and bottom-feeding fish, are especially vulnerable because they live in direct contact with sediments and can bioaccumulate PAHs through the ingestion of contaminated particles. Sediment-associated PAHs also infiltrate food chains, causing biomagnification in higher trophic levels, including humans who eat contaminated fish and shellfish[114]. PAH persistence in sediments is influenced by environmental factors such as oxygen availability, microbial activity, and sediment chemistry. Under aerobic conditions, some bacterial populations can degrade low- and medium-molecular-weight PAHs. However, in anoxic conditions, which are typical in deeper sediments, the breakdown of high-molecular-weight PAHs is severely hindered, resulting in long-term survival. As a result, many sedimentary PAHs can persist for decades, raising concerns about long-term environmental and human health dangers. Sediment cores from contaminated harbors frequently include layers of PAHs formed over several decades, demonstrating the persistent nature of these pollutants[115].

PAHs in sediments represent severe ecological concerns. Laboratory and field investigations have shown that sediment-bound PAHs can cause mutagenesis, carcinogenesis, and teratogenic effects in benthic organisms. For example, exposure to contaminated sediments has been associated to

Lead City University Ibadan DO NOT COPY

developmental defects in fish embryos, reduced reproduction in mollusks, and immunotoxic effects in crustaceans. Chronic sediment contamination in Lagos Lagoon is thought to contribute to dwindling fish populations and biodiversity, with serious implications for local fisheries and food security[116].

Regulatory regimes for sediment quality frequently rely on sediment quality guidelines (SQGs), which establish threshold amounts for a variety of pollutants, including PAHs. The United States Environmental Protection Agency (EPA), for example, has developed benchmark values for assessing ecological risks, such as the Effects Range Low (ERL) and Effects Range Median. Sediment PAH concentrations above ERM thresholds are linked to a high risk of severe biological consequences. Many African aquatic systems, notably Lagos Lagoon, have measured PAH levels that surpass these guideline limits, highlighting the critical need for remediation and management actions[117].

In Lagos, the sources of sediment contamination are numerous. Industrial effluents dumped into the lagoon frequently contain PAHs from petroleum refining, manufacturing, and small-scale workshops. Vehicle emissions deposit PAHs on urban surfaces, which then wash into the lagoon via stormwater runoff[118]. Domestic garbage burning, another frequent activity in the city, leads to pyrogenic PAHs in nearby soils, which eventually erode into aquatic systems. Oil spills and leaks from depots and pipelines contribute to the contamination problem by introducing petrogenic PAHs. The end result is a sedimentary environment rich in both pyrogenic and petrogenic PAHs, generating a deadly cocktail for aquatic life and humans that consume lagoon resources[119].

2.4.4 Polycyclic Aromatic Hydrocarbons (PAHs) in Water

Lead City University Ibadan DO NOT COPY

Polycyclic aromatic hydrocarbons (PAHs) are a serious concern in aquatic systems because water transports them and provides a conduit for exposure to aquatic creatures and people. PAHs released into the environment by combustion processes, industrial effluents, oil spills, stormwater runoff, and atmospheric deposition eventually reach surface waters such as rivers, estuaries, and lagoons. The aquatic phase is thus an important compartment in the environmental dispersion of PAHs, even if their concentrations in the dissolved phase are typically lower than in sediments and soils due to their hydrophobic and lipophilic properties[120]. Nonetheless, dissolved PAHs, even at low levels, are extremely important due to their direct bioavailability and potential to cause harmful effects in aquatic organisms.

The solubility of PAHs in water diminishes with increasing molecular weight. Low-molecular-weight molecules like naphthalene, acenaphthylene, and phenanthrene are more water soluble, allowing them to remain in the dissolved phase. In contrast, high-molecular-weight congeners such as benzo[a]pyrene and dibenzo[a,h]anthracene have extremely low solubility and preferentially attach to organic matter and suspended particles[121]. This partitioning pattern implies that the speciation of PAHs in water is highly impacted by the water body's physicochemical properties, such as pH, salinity, temperature, and the presence of dissolved organic carbon. For example, in tropical coastal lagoons with extensive organic debris and suspended solids, PAHs tend to interact with particles rather than remain freely dissolved. Several studies have found that PAHs pollute water bodies around the world, particularly in urban and industrialized areas. In the United States, the Environmental Protection Agency (EPA) has designated PAHs as priority pollutants in freshwater and marine systems, citing their frequent presence near urban outfalls and industrial emissions[122]. PAH concentrations in surface waters of European rivers such as the Rhine and Thames have been intensively examined, finding patterns associated with urban runoff and air

Lead City University Ibadan DO NOT COPY

fallout from car emissions. Similarly, in Asia, the Pearl River in China has high PAH loading in both water and suspended sediments, which can be ascribed to the region's fast urbanization and heavy industrial activity[123].

Although there have been less investigations on PAHs in surface waters in Africa, the current data indicate that there is growing concern. In South Africa, water samples from the Vaal River showed detectable amounts of both low- and high-molecular-weight PAHs, indicating discharges from industrial activity, coal burning, and informal settlements along the riverbanks. In Ghana, investigations of the Korle Lagoon in Accra indicated higher PAH concentrations in water, sediment, and fish, which were mostly attributed to the uncontrolled disposal of electronic trash and the open burning of plastic. These examples demonstrate how unregulated urban and industrial activities in African cities contribute to PAH loading in aquatic systems[124]. PAHs in water bodies are especially important in Nigeria because of the prevalence of petroleum-related activities and insufficient waste management procedures[125]. Numerous studies in the Niger Delta have found significant amounts of PAHs in surface and groundwater, which are directly related to oil drilling, gas flaring, and regular pipeline spills. For example, groundwater samples from Ogoniland settlements have been found to be contaminated with carcinogenic PAHs, raising concerns about long-term human exposure through drinking water. Lagos Lagoon, West Africa's largest coastal lagoon, is another case study in which PAHs are routinely introduced into the aquatic environment. Urban runoff, untreated industrial discharges, open waste dumping, and maritime oil spills are all potential sources. It found increased PAH concentrations in Lagos Lagoon waters that exceeded international safety requirements, indicating both pyrogenic and petrogenic inputs[126].

The ecological consequences of PAHs in water are substantial. Dissolved PAHs can be absorbed directly by aquatic creatures via gill membranes, skin, or other porous tissues. Once inside the

Lead City University Ibadan DO NOT COPY

body, these substances are metabolically activated, which frequently results in the creation of reactive intermediates that bind to DNA and proteins, producing genotoxicity and other sublethal consequences[58]. Chronic exposure in fish has been associated to liver abnormalities, poor reproductive success, and decreased growth. Furthermore, the trophic transmission of PAHs across aquatic food webs raises human exposure risk, especially in societies that rely largely on fish as a protein source[127].

Another relevant concern is the seasonal variation in PAH concentrations in water. During the rainy season, stormwater runoff and river inflows can flush huge volumes of urban and industrial pollution into lagoons and rivers, causing short-term increases in PAH levels. In contrast, during the dry season, less water flow and higher evaporation rates may lead to an increase in dissolved contaminants. Studies in Lagos Lagoon suggest that PAH levels tend to peak during the rainy season, when runoff from heavily populated areas transfers hydrocarbons and soot particles into the lagoon[128]. Finally, monitoring PAHs in water is difficult because of their low quantities and inclination to partition into sediments. Advanced analytical techniques, such as gas chromatography-mass spectrometry (GC-MS), are necessary to precisely measure individual PAHs, which frequently necessitate pre-concentration processes such as solid-phase extraction[129]. Despite these obstacles, routine monitoring of PAHs in water is critical because this compartment acts as a direct link between contaminated sources and biological exposure. Without such monitoring, early warning indicators of environmental stress and human health hazards may go undetected[130].

2.5 Food Safety

Lead City University Ibadan DO NOT COPY

Food safety refers to the handling, preparation, and storage of food in methods that avoid foodborne illness and protect consumer health. In the context of environmental contamination, food safety is defined as the absence (or tolerable low levels) of dangerous pollutants in food items intended for consumption. Chemical pollutants, such as PAHs, are of particular concern for food safety since they can be subtle and long-term threats. Chemical pollutants, unlike acute microbiological food poisoning, do not produce immediate symptoms but can create long-term health problems[131]. For example, long-term intake of PAH-contaminated foods might contribute to chronic diseases such as cancer, organ damage, developmental problems, and other dangerous conditions. To protect public health, regulatory bodies and international agencies (such as the WHO, FAO, and Codex Alimentarius) establish maximum residue levels and safety limits for certain contaminants in food[132]. Ensuring food safety in the context of this study entails determining whether aquatic organisms collected from the study region possess pollutant levels that are within permissible limits. The notion of farm-to-table contamination combines food safety and environmental science: toxins from industrial activities can enter aquatic species and eventually end up on people's plates. As a result, this literature review focuses on research that measured contaminant levels in foods and evaluated dietary risk[133].

2.6 Environmental Degradation Models (DPSIR Framework)

Environmental degradation models provide a structured way to understand how human activities lead to environmental change and what consequences ensue. One widely used model in environmental studies is the DPSIR framework, which stands for Drivers–Pressures–State–Impact–Response (Figure 2.1).

Lead City University Ibadan DO NOT COPY

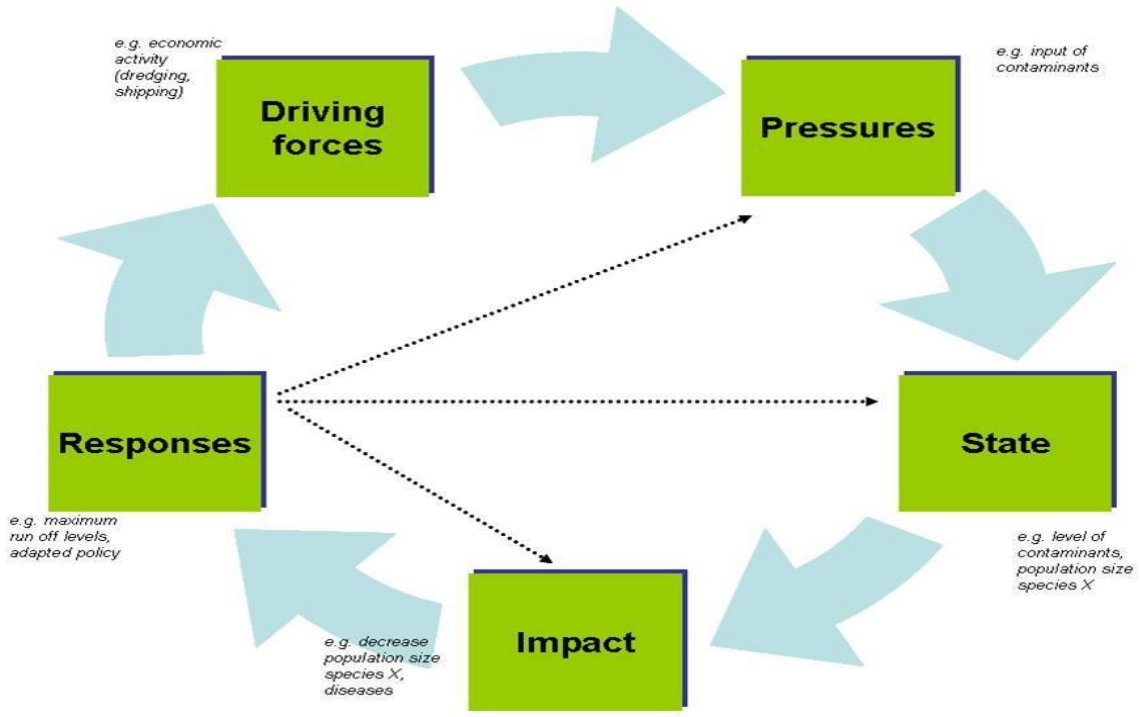


Figure 2.2: DPSIR Feedback Loop

Source[134]

According to the DPSIR model, as applied to the Lagos Lagoon, a Driver such as rapid urbanization, industrial growth, and increasing population pressure in Lagos creates a growing demand for energy, transport, and industrial production. These drivers lead to Pressures on the environment, particularly through the release of untreated effluents, combustion emissions, and surface runoffs that carry polycyclic aromatic hydrocarbons (PAHs) into the lagoon[136]. Such discharges alter the State of the lagoon environment by increasing concentrations of PAHs in water, sediments, and aquatic organisms, while also influencing physicochemical parameters such as dissolved oxygen and nutrient levels[134]. The changed environmental state has Impacts on both ecosystems and human health. Elevated PAHs in sediments can impair benthic organisms; disrupt food webs, and bioaccumulate in fish consumed by local populations. Human health risks arise

Lead City University Ibadan

from chronic exposure to PAHs through contaminated seafood and water, with potential carcinogenic, mutagenic, and immunotoxic effects. Finally, society can undertake Responses such as enforcing stricter industrial discharge regulations, improving wastewater treatment infrastructure, conducting regular environmental monitoring, and sensitizing fishing communities to safe consumption practices[135].

Applying the DPSIR model to the Lagos Lagoon therefore conceptualizes the full cause effect chain of PAH contamination: the driver is intense anthropogenic activity in Lagos, the pressure is the continuous release of PAHs through industrial, domestic, and transport-related sources, the state is the measurable accumulation of PAHs in water, sediments, and aquatic organisms, the impact is ecosystem degradation and heightened health risks to dependent communities, and the response involves targeted remediation, regulation, and sustainable management policies[137]. This framing emphasizes that PAH pollution in Lagos Lagoon is not an isolated occurrence but a symptom of broader urban-environment interactions, and that understanding the linkages between drivers, pressures, state, impacts, and responses is essential for developing effective strategies for environmental protection and public health safeguarding[138].

2. 7 Physico-Chemical Properties of Polycyclic Aromatic Hydrocarbons (PAHs)

The physico-chemical characteristics of PAHs, which dictate their solubility, partitioning, transport, and degradation pathways, have a significant impact on their behavior in aquatic environments. Low aqueous solubility, which decreases with increasing molecular weight, is a characteristic of the majority of PAHs[139]. For example, benzo[a]pyrene, a five-ring PAH, is nearly insoluble in water, but naphthalene, a two-ring PAH, is comparatively soluble. Higher molecular weight PAHs have a tendency to sorb onto particulate matter and sediments, whereas lower

Lead City University Ibadan DO NOT COPY

molecular weight PAHs are more mobile and bioavailable. This difference in solubility affects their environmental fate. The hydrophobic nature of PAHs, which is demonstrated by their high octanol-water partition coefficients (Kow), is another characteristic that sets them apart. Instead of staying dissolved in water, PAHs preferentially concentrate in organic-rich matrices like sediments and biological tissues, according to high Kow values[140]. This explains their propensity to survive in benthic habitats, where sediments act as long-term sinks, and to bioaccumulate in aquatic creatures.

The distribution of PAHs in the environment is also influenced by volatility. Semi-volatile, low molecular weight. PAHs have the ability to partition into the atmosphere, where they may travel great distances before re-deposition in aquatic environments. Despite the absence of local anthropogenic sources in isolated habitats like the Arctic, this adds to the worldwide dispersal of PAHs. Because of its subtropical environment, Lagos is especially susceptible to the atmospheric deposition of PAHs from industrial processes and vehicle emissions, which could subsequently find their way into the lagoon[141]. PAHs' resistance to biodegradation serves as more evidence of their longevity. Under aerobic conditions, some microbial communities can metabolize specific PAHs, however big molecular weight molecules are frequently resistant and only break down extremely slowly. Long-term buildup is facilitated by anaerobic conditions, such as those found in deeper sediments, which further impede biodegradation. PAHs are particularly troublesome as persistent organic pollutants in aquatic settings because of their hydrophobicity, low solubility, and resistance to degradation. The chemical structure of PAHs affects their toxicity in addition to their partitioning behavior[142]. Before they can cause mutagenesis or cancer, many PAHs must first undergo metabolic activation into reactive intermediates, making them pro-carcinogenic. For instance, benzo[a]pyrene undergoes metabolism to produce diol epoxides, which have the ability

Lead City University Ibadan DO NOT COPY

to attach to DNA and cause mutations Therefore, PAHs' physico-chemical characteristics are not only crucial to their fate in the environment[141,142].

2.8 Occurrence and Distribution of PAHs in Aquatic Environments

A complex interaction of physical, chemical, and biological processes shapes the presence and dispersion of polycyclic aromatic hydrocarbons in aquatic systems. Once present in an aquatic environment, PAHs separate into various environmental compartments, such as suspended particles, bottom sediments, the water column, and live species. Their dispersion throughout these compartments varies depending on the receiving ecosystem's characteristics, hydrophobicity, molecular weight, and environmental factors[143].

Low molecular weight PAHs tend to be more common in the water column due to their comparatively higher aqueous solubility. Due to the possibility of volatilization into the environment, photolytic degradation, or microbiological modification, these chemicals are frequently temporary. However, large molecular weight PAHs, which have extremely low solubility and strong hydrophobic interactions, preferentially combine with suspended particulate matter and eventually sink into sediments[144]. The partitioning behavior of PAHs between water and sediment has been described using sediment-water distribution coefficients, which are highly related to the organic carbon content of sediments.

Sediments serve as long-term reservoirs or sinks for PAHs, and in many aquatic ecosystems, sedimentary concentrations are many orders of magnitude higher than those in the surrounding water. These sediments not only record historical contamination, but they also act as secondary sources of PAHs, slowly releasing them back into the water column by processes such resuspension, diffusion, and bioturbation[142]. Sediments are particularly essential in regulating the

Lead City University Ibadan DO NOT COPY

geographical and temporal distribution of PAHs in lagoons and estuaries like Lagos Lagoon, where hydrodynamic conditions are frequently altered by tidal mixing and anthropogenic disturbance. PAHs can also accumulate in aquatic creatures. Because of their lipophilic nature, PAHs easily bioaccumulate in the fatty tissues of fish, shellfish, and other aquatic animals. Bioconcentration occurs when organisms absorb PAHs directly from water, whereas bioaccumulation refers to the combination of water and food sources[145]. Biomagnification may also occur when PAHs cross trophic levels, resulting in larger concentrations in predatory species. Numerous studies have found higher levels of PAHs in fish and crustaceans that live in contaminated water bodies, which has implications for both ecosystem integrity and human health. Temperature, salinity, dissolved oxygen, and organic matter content all have an impact on how PAHs are distributed and survive. Warmer temperatures, such as those found in tropical locations, may promote volatilization and microbial decomposition of some PAHs. However, the survival of high molecular weight chemicals in sediments is generally unaffected by these conditions, emphasizing their significance as long-lasting pollutants[145]. Furthermore, metropolitan water bodies that receive substantial amounts of untreated wastewater tend to have greater PAH concentrations than pristine or rural environments. Lagos Lagoon, which receives discharges from multiple industrial and municipal sources, exhibits this pattern of increased contamination in metropolitan aquatic habitats.

Globally, the quantities of PAHs in aquatic systems vary greatly depending on the level of human activity in the surrounding area[146]. Industrialized countries with stricter environmental controls frequently report lower concentrations than undeveloped countries with inadequate or no pollution control measures. Nonetheless, PAH pollution has been recorded in both affluent and developing countries, demonstrating that it is a widespread, global hazard[146].

Lead City University Ibadan DO NOT COPY

2. 8.1 Global Perspectives on PAH Pollution in Aquatic Systems

PAHs in aquatic ecosystems have been extensively studied during the last several decades, owing primarily to accumulating evidence of their persistence, toxicity, and carcinogenic potential. In North America, for example, investigations undertaken in the Great Lakes have repeatedly revealed the presence of both low and high molecular weight PAHs, with sediments acting as key repositories[147]. The U.S. Environmental Protection Agency's classification of sixteen priority PAHs has driven most of the region's research and monitoring. The findings repeatedly show strong links between PAHs contamination and urban-industrial flows, emphasizing the importance of anthropogenic sources. Studies conducted along the Thames River, the Rhine, and other significant waterways in Europe have also shown that historical industrial activity and ongoing urbanization are associated with elevated PAH levels. While certain locations have seen declines due to the European Union's strict implementation of water quality rules, legacy pollution in sediments is still a significant problem[148]. Even when current emissions are better controlled, the persistence of high molecular weight PAHs in sediments shows the long-term effects of previous contamination.

With the fast industrialization and urbanization taking place in nations like China, India, and Indonesia, Asia is another crucial region for PAHs study. Extremely high levels of PAHs have been found in sediments and biota in China's Pearl River Delta, one of the world's most industrialized areas[149]. These concentrations have been ascribed to household wastes, ship traffic, and petrochemical factories. Similar to this, India's extensive use of coal and biomass for energy, together with a lack of proper waste disposal infrastructure, have resulted in the pollution of water bodies like the Ganges and Yamuna Rivers with PAHs.

Lead City University Ibadan DO NOT COPY

Because oil extraction and transportation are so common in the Middle East, the situation there is a little different. For example, because of the regular oil spills, offshore drilling, and shipping, the Persian Gulf has been shown to be one of the most hydrocarbon-contaminated marine ecosystems[150]. These instances show that PAHs contamination is a worldwide issue, with geographical variances influenced by regional industrial, regulatory, and economic factors. The propensity of PAHs to accumulate in sediments and aquatic creatures, frequently at levels above stated environmental safety criteria, is a prevalent feature throughout global investigations, despite regional variations. This persistence has sparked worries about food security as well as ecological health because many of the impacted aquatic creatures are harvested for human use. As a result, international agencies such as the World Health Organization and the United Nations Environment Programme have frequently emphasized the necessity for stricter monitoring and regulation of PAHs in aquatic settings[147,149].

2. 8.3 Ecological Impacts of PAHs in Aquatic Ecosystems

Polycyclic aromatic hydrocarbons (PAHs) have a significant ecological influence on aquatic environments due to their toxicity, persistence, and bioaccumulation features. Because they are hydrophobic and lipophilic, PAHs preferentially partition into sediments and aquatic creatures' lipid tissues, where they can persist for lengthy periods of time. Their ecological effects manifest at several levels of biological organization, ranging from molecular and cellular disruptions to population and ecosystem repercussions[151].

At the cellular level, PAHs have been linked to oxidative stress, DNA damage, and enzymatic system disruption. The cytochrome P_{450} enzyme system metabolically activates many PAHs, converting them into reactive intermediates capable of creating DNA adducts and producing

Lead City University Ibadan DO NOT COPY

reactive oxygen species. This metabolic interference compromises cellular integrity, resulting in mutagenesis, cytotoxicity, and, in some situations, apoptosis. These cellular-level effects, while initially unnoticeable in natural populations, are the foundation of long-term ecological upheaval. PAHs have an adverse effect on organismal growth, reproduction, and survival[152]. Laboratory and field studies consistently reveal that fish exposed to PAHs have impaired embryonic development, lower hatching success, and morphological abnormalities. For example, exposure to benzo[a]pyrene and fluoranthene has been linked to fin erosion, skeletal abnormalities, and liver cancers in fish species. PAHs can diminish reproductive production and change feeding behavior in invertebrates like mollusks and crustaceans, influencing population dynamics. Chronic exposure to PAHs reduces biodiversity and changes the composition of communities. Benthic invertebrate assemblages in PAH-contaminated sediments frequently have reduced species richness, with sensitive taxa dying and tolerant opportunistic species thriving[153]. This disrupts food web dynamics and decreases ecosystem resilience to other stressors. Similarly, fish populations in contaminated lagoons, estuaries, and rivers frequently exhibit decreased abundance and biomass, endangering local fisheries and food security.

These cumulative disruptions have an influence at the ecosystem level. Because aquatic ecosystems are based on complex food webs, PAHs can harm primary consumers and detritivores at all trophic levels. Reduced productivity and changed predator-prey interactions affect ecosystem services such as fisheries, nitrogen cycling, and water purification. In systems like Lagos Lagoon, where humans rely heavily on ecosystem services, ecological disruptions have severe socioeconomic implications[154]. Importantly, ecological concerns are increased in tropical environments because to higher biological activity, warmer temperatures, and generally inadequate wastewater treatment capacity. These conditions can improve hydrocarbon mobilization, raise

Lead City University Ibadan DO NOT COPY

organism metabolic rates (and consequently toxicant intake), and exacerbate ecological sensitivity. This highlights the importance of studying PAHs not only in temperate zones, but also in tropical urban environments such as the Lagos Lagoon, where the ecological repercussions may be more severe[154].

2. 8.3 PAHs Contamination in Lagos Lagoon and Other Nigerian Aquatic Systems

Lagos Lagoon, located on Nigeria's southwestern coast, is one of the largest and most ecologically and socioeconomically significant water systems in West Africa. It is approximately 50 kilometers long and connects to the Atlantic Ocean via Lagos Harbor, making it both a semi-enclosed estuary system and an important hub for urban, industrial, and nautical operations. With over 20 million people living in the Lagos metropolitan, the lagoon gets pollutants from a variety of sources, including municipal garbage, industrial effluents, petroleum hydrocarbons, and urban runoff. These forces have turned Lagos Lagoon into a hotspot for organic and inorganic contaminants, including PAHs[155]. Several studies have found high PAH levels in Lagos Lagoon, particularly in sediments and aquatic species. Carcinogenic PAH concentrations have been detected in lagoon water and fish samples, with some amounts above international guideline limits. Sediment investigations revealed elevated total PAH concentrations associated with petroleum activity, industrial discharge, and urban trash dumping[156]. Similarly, significant bioaccumulation of PAHs was discovered in fish species such as Tilapia guineensis and Chrysichthys nigrodigitatus, both of which are commonly consumed by local communities.

The pollution profile of Lagos Lagoon includes both petrogenic and pyrogenic sources. Petrogenic inputs are produced during petroleum exploration, refining, and transportation activities, particularly spills from pipelines, tankers, and offshore operations. Pyrogenic PAHs, on the other

Lead City University Ibadan DO NOT COPY

hand, are caused by incomplete combustion of fossil fuels, biomass, and refuse—activities that are common in Lagos because to traffic congestion, industrial operations, and home waste combustion. This dual source pattern helps to explain the intricacy and durability of hydrocarbon pollution in the lagoon[157].

Beyond the Lagos Lagoon, other Nigerian aquatic systems, such as the Niger Delta creeks and the Warri River, are heavily polluted by PAHs from oil drilling and gas flaring activities. The Niger Delta has been regarded as one of the world's most petroleum-impacted ecosystems, with persistent hydrocarbon contamination in sediments, water, and biota. Similar to the Lagos Lagoon, PAH concentrations in these habitats frequently surpass international standards, generating ecological and public health issues[158].

Lead City University Ibadan DO NOT COPY

2.9 Human and Environmental Effects of Polycyclic Aromatic Hydrocarbons (PAHs)

PAH pollution of aquatic ecosystems is well recognized as a major public health hazard. The majority of knowledge about the consequences of PAHs is based on animal researches, which have showed greater rates of skin, lung, bladder, liver, and stomach cancer[159]. According to animal studies, certain PAHs can affect the immune and haematological systems, as well as neurology, development, and reproduction. Certain PAHs, such as benzo(a)anthracene, benzo(a)pyrene (BaP), benzo(b)fluoranthene, benzo(j)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo[ah]anthracene, and indeno[1,2,3-cd]pyrene, have been shown to induce cancers in laboratory animals[160]. According to a toxicity test on fish eggs, the concentrations observed may endanger certain aquatic organisms, particularly those in their early stages of development. When

embryos from Estero de Urias were exposed to water and sediment extracts, many abnormalities (exogastrulation) occurred. These findings indicate that the embryo had an abnormal process throughout development, similar to what occurs when exposed to lithium chloride (LiCl). Research using BaP, a representative of other cancer-causing PAHs, reveals that fish tend to be more sensitive to peak dosages, especially following prior exposure to lower concentrations[162].

Another risk element is benthic species' ability to metabolize these chemicals. Many aquatic invertebrates, especially bivalve mollusks, are not very adept at degrading PAHs, but some, such as some polychaetes, can. Phase 1 enzymes in the cytochrome P450 mixed function oxygenase system metabolize PAHs, which are then removed as hydroxylated metabolites. While the cytochrome P450 system converts polycyclic aromatic hydrocarbons (PAHs) into more easily excretable compounds, it also produces a number of mutagenic and carcinogenic intermediates, including diols and epoxides, which can cause carcinomas by generating PAH-DNA adducts[161]. According to recent research, fish can be exposed to even low levels of PAHs in sediments (2-3 ng/g) and still trigger cytochrome P450 enzymes. Regarding the possible carcinogenicity of PAH-exposed prawns, the data indicate that these pollutants may induce DNA damage, since the exposed shrimp's DNA level was significantly higher than that of the controls. This shows that DNA damage occurred, resulting in the initiation of carcinogenic processes. Others, however, have emphasized that a range of parameters, including the length of exposure and the amount of pollutants, as well as the organisms' nutritional and health status, have a part in the carcinogenic growth of aquatic creatures exposed to hazardous chemicals[162]. Mutations can result from DNA adducts generated by PAHs and their metabolites.

Lead City University Ibadan DO NOT COPY

In general, PAHs pose a high acute risk to humans. PAH toxicity is primarily associated with cancer. Workplace exposure to PAHs has been associated to increased risk of bladder, skin, and lung cancer.

2.10 Exposure Routes of Polycyclic Aromatic Hydrocarbons (PAHs) to Humans

The air, soil, food, and water all contain approximately 100 different forms of PAHs, which are prevalent in the environment. As a result, these compounds may be found in the workplace, at home, or in areas where people work. Humans are typically exposed to a mixture of PAHs, rather than a single PAH[163]. Exposure routes include ingestion, inhalation, and skin contact in both work-related and non-work-related contexts. Some exposures (such as cutaneous and inhalation exposures from contaminated air) may include multiple pathways at the same time, potentially affecting the overall absorbed dosage[164].

PAHs can also enter the body through food or drink, but when consumed, absorption is typically gradual. All of the body's fat-containing tissues are susceptible to PAH invasion. They are most commonly kept in the kidneys, liver, and fat. The ovaries, adrenal glands, and spleen store a less amount. A variety of factors influence people's exposure to PAHs. These include current atmospheric conditions, ambient air concentrations, gas-phase separation, and the distribution of airborne particulate sizes. The Bap concentration in the air is widely used to assess the danger of inhaling PAHs[165]. The health risk of inhaling PAHs is evaluated using epidemiological research. However, it's crucial to realize that BaP is just one of several carcinogenic substances in the environment.

2.11 Review of Recent Studies on Polycyclic Aromatic Hydrocarbons (PAHs)

Lead City University Ibadan DO NOT COPY

The 2021 evaluation concentrated on the levels of polycyclic aromatic hydrocarbons (PAHs) in water and sediments in the southern section of Alhammer Marsh in Southern Iraq. Water and sediment samples were collected from five sites in the southern half of Al-Hammar Marsh: Lusan-Harer, Al-Musahab, Al-Mutaka, Al-Nakara, and Al-Burka, with the goal of quantifying sixteen polycyclic aromatic hydrocarbons (PAHs) using capillary gas chromatography. Polycyclic aromatic hydrocarbons (PAHs) ranged in concentration from 42.859 to 331.875 ng/L in water samples and 342.82-434.438 ng/g in sediment. The investigation found two primarily sources of polycyclic aromatic hydrocarbons: petrogenic and pyrogenic. Petrogenic prevails due to its smaller molecular weight than pyrogenic. Furthermore, there is a direct difference in the overall content of PAHs in sediment and water, and sediment pollution is classified as moderate[166.] A 2020 study assessed the quantity of pollution produced by polycyclic aromatic hydrocarbons (PAHs) in surface water and sediments collected from the River Sasa in Ife-North Local Government Area, Osun State, Nigeria, throughout both the dry and rainy seasons. The concentration of PAHs in the samples was determined using GC-FID. Fluoranthene, a 4-ring PAH, was the most prevalent congener in sediment during both the dry (454.35 ng/g) and wet (490.27 ng/g) seasons. In contrast, the highest quantities of phenanthrene (349.47 ng/L) and fluoranthene (4-ring) (100.68 ng/L) were discovered in water samples during the dry and rainy seasons, respectively. The dry season's total PAH concentrations in surface water ranged from 777.68 to 2431.39 ng/L, much higher than the rainy season's total concentrations of 295.46 to 521.16 ng/L. Sediment samples from the dry season revealed higher mean amounts of PAHs (3463.52 ± 785.72 ng/g) compared to the rainy season (3244.72 ± 2427.57 ng/g). Pyrolytic (or pyrogenic) sources were determined to be responsible for the higher mean concentrations of PAHs in water and sediment samples during the dry season. The study's findings indicate that River Sasa's water

Lead City University Ibadan DO NOT COPY

quality is unsuitable for drinking and other domestic uses due to PAH pollution. The health risk evaluation revealed that long-term, frequent use of surface water could expose community members to substantial health hazards, including cancer[167].

Furthermore, in 2020, a gas chromatography flame ionization detector was used to quantify the content of polycyclic aromatic hydrocarbons (PAHs) in a sample of seafood (prawn, periwinkle, crab, and oyster) in order to analyze the potential health risk associated with seafood consumption. Many models were employed to analyze the potential health implications of eating seafood. Oysters showed the highest DDI values for carcinogenic PAHs, total PAHs, carcinogenic toxic equivalents (TEQ), and PAH (34.40, 2.64, 32.13, and 8.35 mg/kg, respectively). Using carcinogenic toxic equivalents, the risk assessment for carcinogenic human health ranged between 1.85 and 32.13, with a cumulative excess cancer risk (ECR) of 0.00147. This implies that eating oysters increases the risk of developing cancer. When the screening value (SV) and TEQ values for seafood were compared, it was discovered that the screening value was lower, implying potential health consequences. The calculated PAH index values for all analyzed seafood exceeded the European Union's 0.03 mg/kg guideline for PAHs in fishery products. This suggests that consuming seafood may increase the chance of developing cancer. Oysters had the greatest levels of PAHs (ΣPAHs) and carcinogenic PAHs (ΣCPAHs) at 279.01 and 18.56 mg/kg, respectively. A variety of diagnostic ratios were used to determine the source of PAHs. For all seafood samples, the ratio of Indeno(1,2,3-cd)pyrene/(Indeno(1,2,3-cd)pyrene + Benzo(g,h,i)perylene) IndP/(IndP + BghiP) was greater than 0.2 but less than 0.5, indicating a contribution from petroleum and its derivatives[167].

Polycyclic aromatic hydrocarbon (PAH) levels were found in a variety of dried sea foods in Portharcourt, Nigeria, including prawns (Panaeus monodon), water snails (Bithynia tentaculata),

Lead City University Ibadan DO NOT COPY

periwinkles (Littorina littorea), conchs (Lobatus gallus), and oysters (Ostrea edulis). In conch, total PAH concentration ranged from 0.170 mg/kg to 0.493 mg/kg in water snails. Periwinkle had the highest concentration of heavy metals, at 320 ± 40.0 mg/kg. There was very little mercury present in less than 0.001 mg/kg. The discovered levels exceeded the World Health Organization's maximum allowed limit. This implies that the dwellers' usage of these aquatic products foreshadows risk and the possible appearance of illnesses associated with heavy metal and PAH exposure. This examination revealed that five fish samples from the Creek Market on Creek Road in Port Harcourt contained extraordinarily high levels of heavy metals. As a result, some of the oyster, conch, periwinkle, and prawn species found in Port Harcourt's Creek Market are unlikely to be edible. Enforcing rules that expose these aquatic environments to hazardous metal contamination is critical to preventing health risks associated with these toxic metals[168].

Lead City University Ibadan DO NOT COPY

2.12 Conceptual Model

2.12.1 Transport Pathways

Multiple channels and processes can facilitate the transportation and deposition of contaminants in aquatic ecosystems and sediments. Physical, chemical, and biological factors all have an impact on the fate and mobility of pollutants in aquatic settings. These are a few typical processes and routes:

Atmospheric Deposition

The atmosphere may be contaminated by pollutants from cars, industrial operations, and other human endeavours. Water bodies may then get contaminated by these pollutants due to air deposition. Pollutants in the atmosphere can cling to dust or aerosol particles, which then land on

water surfaces. These pollutants may get up in aquatic sediments as a result of precipitation events such as rain[169].

Runoff and Erosion

Contaminants include pesticides, fertilisers, and heavy metals can enter water systems by surface runoff from fields, cities, and other environments. Polluted sediments are carried into rivers, lakes, and seas by soil erosion, which is brought on by weather, wind, and human activity. These sediments sink to the bottom of the ocean once they are in it, leaving pollutants in the sediment layers[169].

Point Source Discharges

Contaminants are released into water bodies directly by point sources such as wastewater treatment plants and industrial operations. Pollutants that are released into the water may settle and build up in the sediment, contaminating aquatic ecosystems. This can involve other contaminants, organic chemicals, and heavy metals[170].

Biological Uptake

As species take in contaminants from the water or sediments, they can make their way up the food chain and into aquatic ecosystems. Over time, organisms—especially filter feeders and benthic organisms—may gather pollutants from the sediments. larger trophic levels may be impacted by this bioaccumulation, which may result in larger amounts of pollutants in aquatic creatures' tissues[171].

2.12.2 Bioaccumulation

The process by which some environmental contaminants, frequently heavy metals or persistent organic compounds, progressively build up in living things is known as bioaccumulation. The

Lead City University Ibadan DO NOT COPY

constant absorption of these compounds from the environment, mostly through food and drink, at a pace quicker than the organism can discard or metabolise them, is the cause of this syndrome. Pollutant concentrations tend to rise at each trophic level as they go up the food chain. Primary producers, such as plants or algae, may take up contaminants from the air, water, or soil at the base of the food chain. Herbivores ingest the toxins collected in these plants when they eat them. The cycle is sustained at each trophic level by the consumption of herbivores by predators, which increases the levels of pollutants[170].

The fact that many contaminants are lipophilic attracted to fat and can accumulate in fatty tissues is the cause of bioaccumulation. These compounds are absorbed and held in the body of the organism after ingestion, which gradually raises the concentration. Because of their persistence in the environment and potential difficulty in metabolism and excretion, the pollutants contribute to an ongoing cycle of buildup. The bioaccumulation of contaminants from the environment presents significant risks to human health and ecosystems. Because of the high levels of pollutants in their systems, top predators—including humans—can suffer negative consequences including immune system suppression, neurological abnormalities, and problems with reproduction. Furthermore, the presence of bioaccumulative compounds in ecosystems on a large scale might have cascade consequences that upset biodiversity and ecological equilibrium[171].

Lead City University Ibadan DO NOT COPY

2.12.3 Biomagnification

The phenomenon known as "biomagnification" describes how some environmental toxins accumulate as they pass through various trophic levels in a food chain or web. In contrast to bioaccumulation, which describes the build-up of pollutants within a single organism, biomagnification is the gradual rise in concentration that occurs when harmful chemicals move

from one trophic level to another. The process usually starts when pollutants are released into the environment, frequently as a result of human activity such chemical contamination releases, runoff from agriculture, or industrial discharges. These contaminants may consist of heavy metals, persistent organic compounds, and other dangerous materials. These contaminants are absorbed by plants, algae, or other primary producers once they are in the environment[172].

Herbivores inhale part of the contaminants present in these polluted primary producers when they eat them. But when predators at higher trophic levels eat these herbivores, the crucial component of biomagnification becomes clear. The contaminants tend to concentrate in the fatty tissues of the organisms because they may be fat-soluble and difficult to metabolise. Predators' bodies contain higher concentrations of contaminants than those of creatures lower in the food chain because they eat a greater quantity of polluted prey[173]. As you ascend the trophic levels, the process gets more intense, with each predator acquiring more contaminants than its prey. Top predators can undergo substantial biomagnification, frequently reaching concentrations that are orders of magnitude greater than those present in the environment, such as apex predators or humans[174].

Because of the possible effects biomagnification may have on ecosystems and public health, it is a matter for worry. Top predators have greater pollutant concentrations, which can have a variety of negative impacts, including as immune system damage, aberrant growth, and problems with reproduction. Consuming tainted seafood, for instance, can lead to the intake of biomagnified contaminants in human populations, which presents health problems[175].

Lead City University Ibadan DO NOT COPY

2.13 Summary of Gaps in Literature Reviewed

Despite a growing body of research on PAH pollution in Nigerian aquatic habitats, major knowledge gaps persist. Much of the previous study has concentrated on the Niger Delta, where oil development and spills dominate hydrocarbon studies, whereas very few studies have looked

systematically at the Lagos Lagoon[176]. Although several studies have shown PAH levels in sediments and fish, there is a lack of thorough assessments of both water and various aquatic animals on a regional and temporal scale. This limits our capacity to accurately assess contamination dynamics and exposure hazards.

Another gap is the insufficient integration of ecological, toxicological, and human health viewpoints in current research. Many studies measure PAH concentrations but do not relate them to ecological markers like biodiversity loss, biomarker responses, or community health effects[177]. As a result, the larger ramifications of PAH poisoning in Nigeria have received little attention. Methodological restrictions further limit existing understanding. In other situations, analytical methodologies with lesser sensitivity or narrower compound coverage were applied, thereby underestimating total PAH loads. Few investigations use high-resolution gas chromatography-mass spectrometry (GC-MS), which can identify a wide spectrum of PAH congeners at trace concentrations[178]. Furthermore, temporal coverage is frequently insufficient, with most research reporting just single-season snapshots rather than year-round monitoring. The socioeconomic and cultural factors are similarly neglected. Given that millions of Lagos people rely directly on lagoon resources for food, work, and household necessities, there is an urgent need to assess not only contamination levels but also exposure concerns from fish intake, water use, and cultural practices such as fish smoking[179]. Without such assessments, policymakers lack evidence to carry out targeted measures.

This study bridges these gaps by thoroughly evaluating PAH concentrations in both water and aquatic species from the Lagos Lagoon and integrating the results with ecological and health implications. The work contributes to a more comprehensive knowledge of hydrocarbon contamination in tropical urban estuaries by using modern analytical methods and setting the

Lead City University Ibadan DO NOT COPY

results within global literature[180]. Finally, the study provides evidence to promote environmental monitoring, public health protection, and sustainable management of the Lagos Lagoon.

Lead City University Ibadan DO NOT COPY

Endnotes

1. A. Adetutu, P.I Adegbola, A.O Owoade, A.B Aborisade, *Fish as a bioindicator of polycyclic aromatic hydrocarbon pollution in aquatic ecosystem of Ogun and Eleyele Rivers, Nigeria, and risk assessment for consumer's health,* **J Hazard Mater Adv,** 7, 2022, 100096

2. A. Baran, A. Klimkowicz-Pawlas, A. Ukalska-Jaruga, M. Mierzwa-Hersztek, K. Gondek, M. Szara-Bąk, M. Tarnawski, I. Spałek, *Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in the Bottom Sediments of a Dam Reservoir, Their Interaction with Organic Matter and Risk to Benthic Fauna*, **J. Soils Sediments,** 21, 2021, 2418–2431.

3. A. Kumari, V. Upadhyay, S. Kumar, *A critical insight into occurrence and fate of polycyclic aromatic hydrocarbons and their green remediation approaches,* **Chemosphere**, 2023, 138579.

4. A. Sambo, J.O Faloye, K.O Adewunmi, *Assessment of PAHs in Biochar-Amended Soils and Their Remediation Potential,* **Journal of Hazardous Materials**, 368, 2019, 204–216.

5. A. A. Otitoloju, D.O Fabunmi, A.A Bandele, *PAHs in Fish from Lagos Lagoon, Biomarker Responses and Human Health Implications,* **Environmental Toxicology and Pharmacology**, 104 (7), 2023, 104−147

6. A. B. Patel, S. Shaikh, K.R Jain, C. Desai, D. Madamwar, *Polycyclic aromatic hydrocarbons: Sources, toxicity, and remediation approaches,* **Frontiers in Microbiology**, 11, 2020, 562813. https://doi.org/10.3389/fmicb.2020.562813

7. A. N. Abdel Rahman, S.M Mahmoud, T. Khamis, N. Rasheed, D.I Mohamed, R. Ghanem, D.M Mansour, T.A Ismail, H.H Mahboub, *Palliative effect of dietary common sage leaves against toxic impacts of nonylphenol in Mirror carp (Cyprinus carpio var specularis), Growth, gene expression, immune-antioxidant status, and histopathological alterations*, **J Aquac Rep**, 25, 2022, 101200

8. A. R. Jafarabadi, S. Mashjoor, A.R Bakhtiari, C. Jadot, *Dietary intake of polycyclic aromatic hydrocarbons (PAHs) from coral reef fish in the Persian Gulf-human health risk assessment,* **Food Chem**, 2020b, In press. https://doi.org/10.1016/j.foodchem.2020.12703

9. A. R. Jafarabadi, S. Mashjoor, A.R Bakhtiari, C. Jadot, *Dietary intake of polycyclic aromatic hydrocarbons (PAHs) from coral reef fsh in the Persian Gulf—human health risks assessment*, **Food Chem**, 2020a. https://doi.org/10.1016/j.foodchem.2020.127035.

10. B. Peng, Q. Dong, F. Li, T. Wang, X. Qiu, T. Zhu, *A systematic review of polycyclic aromatic hydrocarbon derivatives: Occurrences, levels, biotransformation, exposure biomarkers, and toxicity,* **J Environ. Sci. Technol**, 57(41), 2023, 15314-35.

11. B.A. Omolara, A.O. Adewuyi, K.S Omotayo, *PAHs in Smoked Fish from Southwestern Nigeria (Occurrence and Risk Implications),* **Toxicology Reports**, 6, 2019,1003–1110.

12. B. K. Behera, A. Das, D.J. Sarkar, P. Weerathunge, P.K Parida, B.K Das, P. Thavamani, R. Ramanathan, V. Bansal*, Polycyclic Aromatic Hydrocarbons (PAHs) in inland aquatic ecosystems: Perils and remedies through biosensors and bioremediation*, **J Environ Pollut,** 241, 2018, 212-33.

Leading University in Dubai DO NOT COPY

13. B. K. Lee, V.T. Vu, *Sources, distribution and toxicity of polycyclic aromatic hydrocarbons (PAHs) in Particulate Matter Department of Civil and Environmental Engineering*, **University of Ulsan Korea**, 13, 2019, 34–42

14. Y. Li, N. Gou, X. Zou, P. Li, S. Zou, J. Luo, Y. Yang, *Pollution level and health risk assessment of polycyclic aromatic hydrcarbons in marine fsh from two coastal regions, the south china sea*, **Mar Pollut Bull**, 168, 2021b, 112376

15. B. P. Nyangoko, H. Berg, M.M Mangora, M. Gullström, M.S Shalli, *Community perceptions of mangrove ecosystem services and their determinants in the Rufiji Delta, Tanzania,* **Sustainability,** 13(1), 2020, 63. https://doi.org/10.3390/su13010063

16. C. Grimard, *In vitro-in vivo, cross-life stage and inter-species extrapolation of the biotransformation and uptake of benzo [a] pyrene in two fish species using toxicokinetic models*, **University of Saskatchewan**, 2021.

17. C.C. Offor, F.O Okeke, S.C Ifeanyi, *Appraisal of Polycyclic Aromatic Hydrocarbons (PAHs) in Indoor Dust from Urban Homes Exposure and Health Risk Assessment,* **Environmental Advances,** 15, 2024, 583−590.

18. C.O. Ogunkoya, G.O. Layade, H.O. Edunjobi, P. Fayemi, *Evaluation of Physiochemical Properties and Contaminant Index in Selected River Water Around Ewekoro.* ASRIC **Journal on Natural Sciences**, 4(2), 2024, 22-34

19. D. Cortés-Arriagada, *High stability and properties of adsorbed polycyclic aromatic hydrocarbons (PAHs) onto phosphorene: An atomistic DFT study*, ***ChemRxiv*,** 2021, 33774. https://doi.org/10.33774/chemrxiv-2021-lmst6

20. D.N. Das, N. Ravi, *Influences of polycyclic aromatic hydrocarbon on the epigenome toxicity and its applicability in human health risk assessment*, **Environ. Res,** 213, 2022, 113677.

21. E. Ramírez-Ayala, M.A. Arguello-Pérez, A. Tintos-Gómez, R.Y. Pérez-Rodríguez, J.A .Díaz-Gómez, I. Borja-Gómez, C.A. Sepúlveda-Quiroz, M. Patiño-Barragán, C. Lezama-Cervantes, *Review of the biomonitoring of persistent, bioaccumulative, and toxic substances in aquatic ecosystems of Mexico: 2001–2016*, **Latin American Journal of Aquatic Research,** 48(5), 2020, 705-738. https://doi.org/10.3856/vol48-issue5-fulltext-2461

22. E. Stogiannidis, S. Limnios, *Comprehensive Review of PAH Diagnostic Ratios in Air, Water, and Sediment Source Attribution*, **Environmental Forensics**, 22(4), 2021, 265–299.

23. E. Frapiccini, M. Panfli, S. Guicciardi, A. Santojanni, M. Marini, C. Truzzi, A. Annibaldi, *Effects of biological factors and seasonality on the level of polycyclic aromatic hydrocarbons in red mullet (Mullus barbatus)*, **Environ Pollut,** 258, 2020, 113742.

Lead City University Ibadan DO NOT COPY

[24] E.J. Ejiako, O.U. Iheme, C.U. Okonkwo, *Persistent Organic Pollutant, A Review on the Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in Aquatic Ecosystem*, **Int J Environ Sci Nat Res,** 29(5), 2022, 556272.

[25] E.P. Oghoghorie, M.A. Okon, C.C. Udeh, *PAHs in Groundwater of an Oil-Bearing Coastal Plain: Hydrogeological Controls and Health Risk*, **Science of the Total Environment,** 906, 2024, 167−264.

[26] F. Barbosa, B. A. Rocha, M.C.O. Souza, M.Z. Bocato, L.F. Azevedo, J.A. Adeyemi, A. Santana, A.D. Campiglia, *Polycyclic Aromatic Hydrocarbons (PAHs), Updated Aspects of Their Determination, Kinetics in the Human Body, and Toxicity*, **J. Toxicol. Environ. Health B Crit. Rev**, 26, 2023, 28–65.

[27] F. Jesus, J.L. Pereira, I. Campos, M. Santos, A. Ré, J. Keizer, A. Nogueira, F.J.M. Gonçalves, N. Abrantes, D. Serpa, *A review on polycyclic aromatic hydrocarbons distribution in freshwater ecosystems and their toxicity to benthic fauna,* **Sci. Total Environ**, 820, 2022, 153282.

[28] F. Malhat, N. Loutfy, M.A.I. El Menyawi, M.T Ahmed, *Review of Contamination by Polycyclic Aromatic Hydrocarbons (PAHs) in Egyptian Aquatic Environment,* **Polycycl Aromat Compd**, 41(7), 2021, 1447-58.

[29] F.C.P. Simão, C. Gravato, A.L Machado, A.M.V.M Soares, J.L.T Pestana, *Toxicity of Different Polycyclic Aromatic Hydrocarbons (PAHs) to the Freshwater Planarian Girardia Tigrina,* **Environ. Pollution** 266, 2020, 115185.

[30] F.C.P. Simão, C. Gravato, A.L. Machado, A.M.V.M. Soares, J.L.T. Pestana, *Effects of pyrene and benzo[a]pyrene on the reproduction and newborn morphology and behavior of the freshwater planarian Girardia tigrina*, **Chemosphere,** 264, 2021, 128448.

[31] G. Melillos, E. Kalogirou, D. Makri, D.G. Hadjimitsis, *Oil spill detection and monitoring in the Cyprus region*, ***Ocean Sensing and Monitoring XV*****,** 12543, 2023, 175-181.

[32] G. Petrucci, L. Sandrini, R. Rossi, A. Contini, *Using PCA and PMF to Discern PAH Source Profiles in Industrial and Urban Watersheds*, **Environmental Pollution**, 335(2), 2025, 122−277.

[33] G.N Cherr, E. Fairbairn, A. Whitehead, *Impacts of petroleum-derived pollutants on fish development,* **Annual Review of Animal Biosciences,** 5(1), 2017, 185-203. https://doi.org/10.1146/annurev-animal-022516-022928

[34] H. Tian, Z. Wang, T. Zhu, C. Yang, Y. Shi, Y. Sun, *Degradation prediction and products of polycyclic aromatic hydrocarbons in soils by highly active bimetals/AC-activated persulfate,* **ACS ES&T Engineering,** 1(8), 2021, 1183-1192. https://doi.org/10.1021/acsestengg.1c00063

[35] H. Wang, X. Xia, R. Liu, Z. Wang, Y. Zhai, H. Lin, W. Wen, Y. Li, D. Wang, Z. Yang, D.C.G Muir, *Dietary uptake patterns affect bioaccumulation and biomagnification of*

Ladoke Akintola University Ibadan DO NOT COPY

hydrophobic organic compounds in fish, **Environmental Science & Technology**, 53(8), 2019, 4274-4284. https://doi.org/10.1021/acs.est.9b00106

36. H. Wang, X. Xia, Z. Wang, R. Liu, D.C. Muir, W.X. Wang, *Contribution of dietary uptake to PAH bioaccumulation in a simplified pelagic food chain: Modeling the influences of continuous vs intermittent feeding in zooplankton and fish*, **Environmental Science & Technology,** 55(3), 2021, 1930-1940. https://doi.org/10.1021/acs.est.0c06970

37. H. E .Obanya, E.A. Babatunde, K.S. Otitoloju, *Lagos Lagoon Sediment Organic Extracts and Polycyclic Aromatic Hydrocarbons Induce Embryotoxic, Teratogenic and Genotoxic Effects in Danio rerio (Zebrafish),* **Toxicology Reports**, 6, 2019, 1112–23

38. H. H. Mahboub, K. Shahin, S. M. Mahmoud, D.E. Altohamy, W.A. Husseiny, D. A .Mansour, S.I. Shalaby, M.M.S. Gaballa, M. Shaalan, M. Alkafafy, A.N.A. Rahman, *Silica nanoparticles are novel aqueous additive mitigating heavy metals toxicity and improving the health of African catfish*, **Clarias gariepinus. Aquat. Toxicol,** 249, 2022, 106238.

39. H.O. Nwankwoala, O. Obire, D. Olorunfemi, *Assessment of PAHs in soils and vegetables from oil-producing areas in Rivers State, Nigeria*. **African Journal of Environmental Science and Technology**, 15(4), 2021, 152–163.

40. I. Campos, N. Abrantes, *Forest Fires as Drivers of Contamination of Polycyclic Aromatic Hydrocarbons to the Terrestrial and Aquatic Ecosystems*, **Curr. Opin. Environ. Sci. Health,** 24, 2021, 100293.

41. I. Rudiarto, W. Handayani, H.B Wijaya, T.D Insani, *Rural livelihood resilience, An assessment of social, economic, environment, and physical dimensions,* **Matec Web of Conferences,** 280, 2019, 01002. https://doi.org/10.1051/matecconf/201928001002

42. I.C. Ogbobode, A.I. Chinedu, C.I. Anene, *Levels and Health Risk of PAHs in Water and Sediment of Lagos Lagoon's Industrial Arm*, **Journal of Water & Health**, 19(6), 2021, 987–1000.

43. I.P. Okoye, I.G. Anekwe, *Levels and sources of PAHs in agricultural soils from oil-producing areas of Nigeria*, **Environmental Toxicology and Chemistry**, 39(11), 2020, 2212–2220. *Available online:* https://doi.org/10.1002/etc.4857

44. J. Mo, D.W.T. Au, M.T. Wan, J. Shi, G. Zhang, C. Winkler, R.Y.C. Kong, F. Seemann, *Multigenerational Impacts of Benzo[a]pyrene on Bone Modeling and Remodeling in Medaka (Oryzias latipes),* **Environ. Sci. Technol**, 54(19), 2020 12271- 84.

45. J. Ohimain, C. Ebhomeya, M. Kogbara, *Characterization of PAHs in Crude Oil-Contaminated Soils of the Niger Delta*, **International Journal of Environmental Quality**, 32(5), 2023, 299–312.

Lead City University Ibadan DO NOT COPY

46. J. Shi, J. Jiang, Q. Chen, L. Wang, K. Nian, T. Long, *Production of higher toxic intermediates of organic pollutants during chemical oxidation processes: A review*, **Arab. J. Chem,** 2023, 104856.

47. J. Yu, H. Luo, B. Yang, M. Wang, Y. Gong, P. Wang, Y. Jiao, T. Liang, H. Cheng, F. Ma, *Risk control values and remediation goals for benzo [a] pyrene in contaminated sites: sectoral characteristics, temporal trends, and empirical implications,* **Environ. Sci. Technol**, 57(5), 2023, 2064-74.

48. J.A. Mahugija, E. Njale, *Effects of washing on the polycyclic aromatic hydrocarbons (PAHs) contents in smoked fish,* **Food Control**, 93, 2018, 139–143

49. K. Nowak, E. Jablonska, W. Ratajczak-Wrona, *Immunomodulatory effects of synthetic endocrine disrupting chemicals on the development and functions of human immune cells*, **Environ Int,** 125, 2019, 350–364

50. J.F. Dubiel, D. Green, Y. Raza, H.M. Johnson, Z. Xia, G.T. Tomy, A. Hontela, J.A. Doering, S. Wiseman, *Alkylation of benz[a]anthracene affects toxicity to early-life stage zebrafish and in vitro aryl hydrocarbon receptor 2 transactivation in a position-dependent manner*, **Environmental Toxicology and Chemistry,** 41(8), 2022, 1993-2002. https://doi.org/10.1002/etc.5396

51. J.Q. Tang, Y. Wu, Y.Y. Han, Q.H. Shen, X.F. He, N.X. Feng, Y. Huang, *Bioremediation of common high-molecular-weight polycyclic aromatic hydrocarbons, A bibliometric analysis based on Web of Science via VOSviewer,* **Research Square**, 2023, 212-203. https://doi.org/10.21203/rs.3.rs-3374874/v1

52. J.S. Albert, G. Destouni, S.M. Duke-Sylvester, A.E. Magurran, T. Oberdorff, R.E. Reis, K.O. Winemiller, W.J. Ripple, *Scientists' Warning to Humanity on the Freshwater Biodiversity Crisis,* **Ambio,** 50, 2021, 85–94.

53. K.A. Osei, A.E. Amoako, R.A. Armah, *PAHs in Surface Waters of an Urbanizing Basin in Ghana: Distribution, Sources and Risk*, **Environmental Monitoring and Assessment**, 193(6), 2021, 360.

54. K.M. Nielsen, M.M. Alloy, L. Damare, I. Palmer, H.P. Forth, J. Morris, J.A. Stoeckel, A.P. Roberts, *Planktonic fiddler crab (Uca longisignalis) are susceptible to photoinduced toxicity following in ovo exposure in oiled mesocosms,* **Environmental Science & Technology**, 54(10), 2020, 6254-6261. https://doi.org/10.1021/acs.est.0c00215

55. L. Goedtke, H. Sprenger, U. Hofmann, F.F. Schmidt, H.S. Hammer, U.M. Zanger, O. Poetz, A. Seidel, A. Braeuning, S. Hessel-Pras, *Polycyclic Aromatic Hydrocarbons Activate the Aryl Hydrocarbon Receptor and the Constitutive Androstane Receptor to Regulate Xenobiotic Metabolism in Human Liver Cells*, **Int J Mol Sci,** 22(1), 2022, 372.

56. L. Liu, W. Li, W. Song, M. Guo, *Remediation techniques for heavy metal-contaminated soils: Principles and applicability,* **The Science of the Total Environment**, 633, 2018, 206-219. https://doi.org/10.1016/j.scitotenv.2018.03.161

Lead City University Ibadan DO NOT COPY

57. L. Norris, C.M. Horton, A.Y. Hart, *PAHs in Urban Air, Soil, and Vegetation, Comparative Study in Three Megacities*, **Environmental Science & Technology**, 58(3), 2024, 1587–1595.

58. L. Zhang, *Chemodynamics of polycyclic aromatic hydrocarbons and their alkylated and nitrated derivatives in the Yellow Sea and East China Sea*, **Environmental Science & Technology**, 57(48), 2023, 20292-20303. https://doi.org/10.1021/acs.est.3c07476

59. L.M. Gearhart-Serna, N. Jayasundara, M. Tacam Jr, R. Di Giulio, G.R. Devi, *Assessing cancer risk associated with aquatic polycyclic aromatic hydrocarbon pollution reveals dietary routes of exposure and vulnerable populations,* **Journal of Environmental and Public Health**, 2018(1), 2018, 5610462. https://doi.org/10.1155/2018/5610462

60. M. Ebrahimzadeh, B. Heidari, F. Nazarhaghighi, A. Valipour, *Physiological Responses of the Goldfish (Carassius auratus) During Subacute Exposure to Organic Pollutants*, **Bull Environ Contam Toxicol,** 106(5), 2021, 773-8.

61. M. Ferrante, G. Zanghì, A. Cristaldi, C. Copat, A. Grasso, M. Fiore, S.S Signorelli, P. Zuccarello, G.O Conti, *PAHs in seafood from the Mediterranean Sea, an exposure risk assessment,* **Food Chem Toxicol,** 115, 2018, 385–390

62. M. Han, K. Yu, R. Zhang, B. Chen, H. Li, Z.E Zhang, J. Li, G. Zhang, *Sources of the elevating polycyclic aromatic hydrocarbon pollution in the western South China Sea and its environmental implications*, **Environmental Science & Technology,** 57(49), 2023, 20750-20760. https://doi.org/10.1021/acs.est.3c03452

63. M. Honda, N. Suzuki, *Toxicities of polycyclic aromatic hydrocarbons for aquatic animals*, **International Journal of Environmental Research and Public Health,** 17(4), 2020, 1363. https://doi.org/10.3390/ijerph17041363

64. M. Kumar, N.S. Bolan, S.A. Hoang, A. D. Sawarkar, T. Jasemizad, B. Gao, S. Keerthanan, L.P. Padhye, L. Singh, S. Kumar, *Remediation of soils and sediments polluted with polycyclic aromatic hydrocarbons: to immobilize, mobilize, or degrade*, **J Hazard. Mater,** 420, 2021, 126534.

65. M. Liu, H. Zheng, W. Wang, H. Ke, P. Huang, S. Liu, F. Chen, Y. Lin, M. Cai, *Enhanced sinks of polycyclic aromatic hydrocarbons due to Kuroshio intrusion: Implications on biogeochemical processes in the ocean-dominated marginal seas,* **Environmental Science & Technology,** 55(10), 2021, 6838-6847. https://doi.org/10.1021/acs.est.1c01009

66. M. Méndez García, M.P. G. de Llasera, *A Review on the Enzymes and Metabolites Identified by Mass Spectrometry from Bacteria and Microalgae Involved in the Degradation of High Molecular Weight PAHs,* **Sci. Total Environ**, 797, 2021, 149035.

Iqbal City University Lahore DO NOT COPY

67. M. Moslen, I. Aniekan, J. Onwuteaka, C.A. Miebaka, *Bioaccumulation and consumption safety of a sea food, gastropod mollusc (Thais coronata), polycyclic aromatic hydrocarbon (PAH) perspective,* **Journal of Applied Sciences and Environmental Management,** 25(7), 2021,1239-1247 https://doi.org/10.4314/jasem.v25i7.20

68. M. Müller, H. Hohn, J. Weihrauch, D. Leipold, *PAH Ratios vs. CMB, A Comparative Analysis of Source Apportionment Accuracy,* **Atmospheric Pollution Research,** 13(6), 2022, 101−238.

69. M. Sandhu, A.T Paul, P.N Jha, *Metagenomic analysis for taxonomic and functional potential of polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyl (PCB) degrading bacterial communities in steel industrial soil*, **Plos One**, 17(4), 2022, e0266808. https://doi.org/10.1371/journal.pone.0266808

70. M. Vijayanand, A. Ramakrishnan, R. Subramanian, P.K, Issac, M. Nasr, K.S, Khoo, R. Rajagopal, B. Greff, N.I. Wan Azelee, B.H. Jeon, *Polyaromatic Hydrocarbons (PAHs) in the Water Environment, A Review on Toxicity, Microbial Biodegradation, Systematic Biological Advancements, and Environmental Fate,* **Environ. Res,** 227, 2023, 115716.

71. M. Wang, S. Jia, S. H Lee, A. Chow, M. Fang, *Polycyclic aromatic hydrocarbons (PAHs) in indoor environments are still imposing carcinogenic risk*, **J. Hazard. Mater**, 409, 2021, 124531.

72. M. Yazdani, *Comparative Toxicity of Selected PAHs in Rainbow Trout Hepatocytes (Genotoxicity, Oxidative Stress and Cytotoxicity)*, **Drug Chem. Toxicol**, 43, 2020, 71–78.

73. M.A, Rahman, N. Fatema, S. Aktar, B. Khan, T.E. Shovo, M.H. Howlader, *Livelihood sustainability status and challenges of southwestern coastal area of Bangladesh,* **Journal of Social and Political Sciences,** 3(4), 2020, 226. https://doi.org/10.31014/aior.1991.03.04.226

74. M.E. Franco, R. Lavado, *Applicability of in vitro methods in evaluating the biotransformation of polycyclic aromatic hydrocarbons (PAHs) in fish, Advances and challenges*, **Sci. Total Environ,** 671, 2019, 685-95.

75. M.M.T. Khan, L. Sklar, *Environmental contaminants in aquatic systems and chemical safety for environmental and human health, volume II*, **J Front. Public Health,** 11, 2023, 1157834.

76. M.S. Santana, L. Sandrini-Neto, F.F. Neto, C. A. Oliveira Ribeiro, M. Di Domenico, M.M. Prodocimo, *Biomarker responses in fish exposed to polycyclic aromatic hydrocarbons (PAHs): systematic review and meta-analysis*, **Environ Pollut**, 242, 2018, 449–461.

77. M.Z. Khan, S.Y. Shah, K.L. Ahmed, *Nitro-PAHs in Urban Air (Sources and Health Risk in a Megacity),* **Science of the Total Environment**, 884, 2023, 163−173.

Lead City University Ibadan DO NOT COPY

78. N. Çiftçi, A. Deniz, *Polycyclic aromatic hydrocarbons in seafood from the mediterranean sea,* **Mediterranean Fisheries and Aquaculture Research,** 4(3), 2021, 74-9.

79. N. Derakhshesh, N. Salamat, A. Movahedinia, M. Hashemitabar, V. Bayati, *Exposure of liver cell culture from the orange-spotted grouper, Epinephelus coioides, to benzo[a]pyrene and light results in oxidative damage as measured by antioxidant enzymes,* **Chemosphere**, 226, 2019, 534-44.

80. N. Soltani, F. Moore, B. Keshavarzi, A. Sorooshian, R. Javid*, Potentially toxic elements (PTEs) and polycyclic aromatic hydrocarbons (PAHs) in fish and prawn in the Persian Gulf, Iran*, **Ecotoxicol Environ Saf**, 173, 2019, 251–265.

81. N.R Bury, *Cytotoxic and genotoxic responses of the RTgillW1 fsh cells in combination with the yeast oestrogen screen to determine the sediment quality of Lagos lagoon, Nigeria*, **Mutagenesis**, 30(1), 2019, 117–127. https://doi.org/10.1093/mutage/geu032.

82. N.R. Weerakkodige, C.K. Hemachandra, A. Pathiratne, *Assessing genotoxic potential of petroleum refinery wastewater using biomarkers of laboratory exposed and field captured fishes*, **Sri Lanka Journal of Aquatic Sciences,** 26(2), 2021, 97-110. https://doi.org/10.4038/sljas.v26i2.7590

83. O. C. Nzeh, M.S. Udeh-Okoye, N.O. Nweke, *Atmospheric Deposition of PAHs onto Surface Water Bodies in Lagos,* **Atmospheric Pollution Research,** 14 (1), 2023, 45–55.

84. O.O. Okedeyi, I.A. Nindi, E.A. Awofolu, *PAHs in Street Dust from Urban Lagos: Distribution and Health Risks,* **Environmental Monitoring and Assessment,** 191(3), 2019, 167.

85. O.O. Okedeyi, I.A. Nindi, E.A. Awofolu, *Distribution and Potential Health Risks of Polycyclic Aromatic Hydrocarbons in Street Dust from Industrial, Residential and Traffic Areas in Lagos, Nigeria,* **Environmental Monitoring and Assessment**, 187(2), 2019, 167.

86. O.O. Oluwagbami, J.B. Akintayo, *Awareness of engagement strategies and stakeholders' responsiveness and formulation of corporate social responsibility goals in the fast-moving consumer goods industry in Lagos and Ogun States, Nigeria,* **NIU Journal of Social Sciences,** 8(2), 2022, 1439. https://doi.org/10.58709/niujss.v8i2.1439

87. C.C. Okafor, J.L. Konne, L.D. Ntaah, S.N. Awolo, T.J.K. Ideriah, *Polycyclic Aromatic Hydrocarbons Contents of Sediment and Water in Drainages and Receiving Elechi Creek in Port Harcourt, Rivers State, Nigeria,* **IJRIAS**, 2024, 487– 493.

88. P. Cai, Z. Ning, Y. Liu, Z. He, J. Shi, M. Niu, *Diagnosing bioremediation of crude oil-contaminated soil and related geochemical processes at the field scale through microbial community and functional genes,* **Annals of Microbiology**, 70(1), 2020. https://doi.org/10.1186/s13213-020-01580-x

Lead City University Ibadan DO NOT COPY

89. P. Montuori, E. De Rosa, F. Di Duca, B. De Simone, S. Scippa, I. Russo, P. Sarnacchiaro, M. Triassi, *Polycyclic aromatic hydrocarbons (PAHs) in the dissolved phase, particulate matter, and sediment of the Sele River, southern Italy, A focus on distribution, risk assessment, and sources*, **Toxics**, 10(7), 2022, 401. https://doi.org/10.3390/toxics10070401

90. P. Siudek, *Atmospheric Deposition of Polycyclic Aromatic Hydrocarbons (PAHs) in the Coastal Urban Environment of Poland, Sources and Transport Patterns*, **Int. J. Environ. Res. Public Health**, 19(21), 2022, 14183.

91. P. Świsłowski, P. Hrabák, S. Wacławek, K. Liskova, V. Antos, M. Rajfur, M. Ząbkowska-Wacławek, *The application of active biomonitoring with the use of mosses to identify polycyclic aromatic hydrocarbons in an atmospheric aerosol*, **Molecules**, 26(23), 2021, 7258. https://doi.org/10.3390/molecules26237258

92. P.E. Namihira-Santillán, A.L. Ortega-López, D.L. Campos-Domínguez, *PAHs in Sediments and Shrimps (Levels, Sources, and Ecological Risk in a Tropical Estuary),* **Marine Pollution Bulletin**, 199, 2025, 115−402.

93. P.I. Adegbola, A.B. Aborisade, A. Adetutu, *Health risk assessment and heavy metal accumulation in fsh species (Clarias gariepinus and Sarotherodon melanotheron) from industrially polluted Ogun and Eleyele Rivers, Nigeria,* **Toxicol Rep**, 8, 2021, 1445–1460.

94. P.S. Ukwo, C.M. E. L. Sylvester, *Compositional pattern and tissue concentration of polycyclic aromatic hydrocarbons (PAHs) in bivalve shellfish from Niger Delta, Nigeria,* **Journal of Applied Sciences,** 22(2), 2022, 84-91. https://doi.org/10.3923/jas.2022.84.91

95. P.T. Aakko-Saksa, K. Lehtoranta, N. Kuittinen, A. Järvinen, J.P. Jalkanen, K. Johnson, H. Jung, L. Ntziachristos, S. Gagné, C. Takahashi, *Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options*, **Prog. Energy Combust. Sci**, 94, 2023, 101055.

96. Q. Zeng, E. Jeppesen, X. Gu, Z. Mao, H. Chen, *Distribution, fate and risk assessment of PAHs in water and sediments from an aquaculture- and shipping-impacted subtropical lake, China*. **Chemosphere**, 201, 2018, 612-20.

97. R. Baldiris-Avila, I. O'Byrne-Hoyos, K.M. Aldous, R. Addink, K. Kannan, *Polycyclic aromatic hydrocarbons and their hydroxylated metabolites in fsh bile and sediments from coastal waters of Colombia*, **Environ Pollut,** 151(3), 2019, 452–459. https://doi.org/10.1016/j.envpol.2007.04.011.

98. R. Khan, *Source Attribution, Emission Factors, and Regulation*, **Atmospheric Environment**, 42 (13), 2019, 2895–97.

99. R. Li, Y. Shi, M. Li, Y. Huang, K. Li, T. Xu, H. Liu, Y. Xi, *Distribution and migration of polycyclic aromatic hydrocarbons in sediment and water of the Three Gorges Reservoir*,

Iraq City University Iraqdar DO NOT COPY

Soil Science Society of America Journal, 86(3), 2022, 566-578. https://doi.org/10.1002/saj2.20393.

[100] R.A Grmasha, M.H Abdulameer, C. Stenger-Kovács, O.J Al-sareji, Z. Al- Gazali, R. A. Al-Juboori, M. Meiczinger, K.S Hashim, *Polycyclic aromatic hydrocarbons in the surface water and sediment along Euphrates River system: Occurrence, sources, ecological and health risk assessment,* **Mar. Pollut. Bull,** 187, 2023, 114568.

[101] R.K. Rajput, N. Lakhani, A. K. Patel, *Long-Term Trends of Atmospheric PAHs in an Urban–Industrial Region of India,* **Atmospheric Environment,** 223, 2020, 117−241.

[102] R.K. Singh, A.K. Gupta, P.K. Rai, *PAHs in Urban Street Dust: Spatial Distribution, Source Apportionment and Risk*, **Science of the Total Environment,** 720, 2020, 137−581.

[103] R.M. Nwugo, D.C. Chukwu, G.I. Ukpai, *Soil Bioremediation of PAHs (Indigenous Microbial Communities in Agricultural Lands)*, **Science of the Total Environment,** 982, 2025, 163−329.

[104] R.V. Mpofu, M.B. Daniels, F.G. Rampedi, *PAHs in Water and Sediment along a Mining-Impacted River (Distribution and Risk),* **Environmental Geochemistry and Health**, 42(10), 2020, 335–370.

[105] S. Barathi, J. Gitanjali, G. Rathinasamy, N. Sabapathi, K.N Aruljothi, J. Lee, S. Kandasamy, *Recent trends in polycyclic aromatic hydrocarbons pollution distribution and counteracting bio-remediation strategies*, **Chemosphere,** 337, 2023,139396.

[106] S. Correa-García, K. Rheault, J. Tremblay, A. Séguin, E. Yergeau, *Soil characteristics constrain the response of microbial communities and associated hydrocarbon degradation genes during phytoremediation,* **Applied and Environmental Microbiology**, 87(2), 2021, e02170-20. https://doi.org/10.1128/aem.02170-20

[107] S. Dey, P. Ballav, P. Samanta, A. Mandal, A. Patra, S. Das, A.K Mondal, A.R Ghosh, *Time-Dependent Naphthalene Toxicity in Anabas testudineus (Bloch): A Multiple Endpoint Biomarker Approach*, **ACS Omega**, 6(1), 2021, 317-26.

[108] S. Gherardi, M.M. Uccello, *Heavy metals and PAHs in meat, milk, and seafood from Augusta area (Southern Italy): contamination levels, dietary intake, and human exposure assessment,* **Front. Public Health**, 8, 2020, 273.

[109] S. Hamidi, M. Banaee, H.R. Pourkhabbaz, A. Sureda, S. Khodadoust, A.R. Pourkhabbaz, *Effect of petroleum wastewater treated with gravity separation and magnetite nanoparticles adsorption methods on the blood biochemical response of mrigal fish (Cirrhinus cirrhosus),* **Environ. Sci. Pollut. Res**, 29(3), 2022, 3718-32.

[110] S. Lou, M. Shrivastava, A. Ding, R.C. Easter, J.D. Fast, P. J. Rasch, H. Shen, S.L. Massey Simonich, S.J. Smith, S. Tao, *Shift peaks of PAH-associated health risks from East Asia to*

Lead City University Ibadan DO NOT COPY

South Asia and Africa in the future, 23, 2022, 10512341. https://doi.org/10.1002/essoar.10512341.1

111. S. Rahman, M.S. Islam, M.N.H. Khan, M. Touhiduzzaman, *Climate change adaptation and disaster risk reduction (DRR) through coastal afforestation in South-central coast of Bangladesh,* **Management of Environmental Quality International Journal,** 30(3), 2019, 498-517. https://doi.org/10.1108/meq-01-2018-0021

112. S. Rajeshkumar, X. Li, *Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China*, **J Toxicol. Rep,** 5, 2018, 288-295.

113. S. Wu, H. Li, X. Yin, Y. Si, L. Qin, H. Yang, J. Xiao, D. Peng, *Preparation of monoclonal antibody against pyrene and benzo [a]pyrene and development of enzyme-linked immunosorbent assay for fish, shrimp and crab samples,* **Foods**, 11(20), 2022, 3220. https://doi.org/10.3390/foods11203220

114. S.C. Izah, G. Richard, H.O. Stanley, W.E. Sawyer, M.C. Ogwu, O.R. Uwaeme, *Potential applications of linear regression models in studying the relationship between fish and contaminants in their environment: One Health perspective,* **Juniper Online Journal of Public Health**, 8(4), 2024a, 555743. https://doi.org/10.19080/JOJPH.2024.08.555743

115. S.C. Izah, G. Richard, H.O. Stanley, W.E. Sawyer, M.C. Ogwu, O.R. Uwaeme, *Prospects and application of multivariate and reliability analyses to One Health risk assessments of toxic elements,* **Toxicology and Environmental Health Sciences**, 16(2), 2024b, 127-134.

116. S.D. Siciliano, H.D. Lee, J.Q. Pereira, B.E. Matthews, G.T. Kendall, *Applying Combined Diagnostic Ratios and PCA for PAH Source Identification in Canadian Arctic Sediments,* **Environmental Science & Technology,** 54 (24), 2020 15574–15583.

117. S.D. Tiegs, D.M. Costello, M.W. Isken, G. Woodward, P.B. McIntyre, M.O. Gessner, E. Chauvet, N.A. Griffiths, A.S. Flecker, V. Acuña, *Global patterns and drivers of ecosystem functioning in rivers and riparian zones,* **Science Advances,** 5(1), 2019, eaav0486. https://doi.org/10.1126/sciadv.aav0486

118. S.K. Nalwa, A.A. Hassan, B.A. Olagoke, *Optimization of Passive Sampling for Dissolved PAHs in Tropical Waters,* **Water Research**, 236, 2024, 118−170.

119. S.O. Nnoruka, C.E. Nwosu, N.L. Okechukwu, *PAHs in Drinking Water Distribution Systems of a Nigerian Metropolis (Levels, Sources and Risk),* **Journal of Water and Health**, 21 (5), 2023, 693–706.

120. Sakshi A.K Haritash, *A comprehensive review of metabolic and genomic aspects of PAH-degradation,* **Arch. Microbiol,** 202(8), 2020, 2033-58.

121. T. Hu, J. Yuan, X. Wang, C. Yan, X. Ju, *Spectral-spatial features extraction of hyperspectral remote sensing oil spill imagery based on convolutional neural networks*, **IEEE Access**, 10, 2022, 127969-127983. https://doi.org/10.1109/access.2022.3194260

Lead City University Ibadan DO NOT COPY

122. T. Recabarren-Villalón, A.C. Ronda, A.H. Arias, *Polycyclic aromatic hydrocarbons levels and potential biomarkers in a native South American marine fish*, **Reg Stud Mar Sci**, 29, 2019, 100695

123. T.O. Sogbanmu, E. Nagy, D.H. Phillips, V.M. Arlt, A.A. Otitoloju, N.R. Bury, *Lagos lagoon sediment organic extracts and polycyclic aromatic hydrocarbons induce embryotoxic, teratogenic and genotoxic effects in Danio rerio (zebrafsh) embryos,* **Environ Sci Pollut Res,** 23(14), 2019, 14489–14501. https://doi.org/10.1007/s11356-016-6490-y.

124. T.O. Yahaya, A. Abdulazeez, Z.M. Kalgo, A.B. Yusuf, H. Sheu, H. Abdullahi, M.A .Shaf'u, *Safety assessment of heavy metals in Tilapia zilli (Tilapia fsh) and Chrysichthys nigrodigitatus (catfsh) obtained from Epe Lagoon, Lagos, Nigeria,* **ChemSearch Journal**, 13(2), 2022a, 52–61

125. T.O. Yahaya, F.T. Salisu, K. Shehu, A. Abdulazeez, H. Ahmed, A. Abdulrahim, *Level, and health risk assessment of heavy metals in Clarias gariepinus obtained from agboyi, oworonsoki, and bariga markets in Lagos, Nigeria,* **FUW Trends in Science & Technol J**, 7(3), 2022b, 55–60

126. J. Teixeira, P. A. Silva, M. F. Costa, *Environmental Contamination with Polycyclic Aromatic Hydrocarbons: Ubiquity, Bioaccumulation, and Human Health Risk*, **Environmental Science and Pollution Research**, 31(32), 2024, 556–700.

127. U. C. Ugochukwu, H. A. Okoro, A.O. Eze, *Risk Assessment of Polycyclic Aromatic Hydrocarbons in Ekulu River Sediments, Nigeria,* **African Journal of Aquatic Science**, 46(1), 2021,49–59

128. C.N. Ude, B. O. Ojinnaka, C. O. Mgbeze, *Occurrence of PAHs in Urban Streams Receiving Wastewater in Southeast Nigeria*, **Environmental Monitoring and Assessment**, 196(3), 2024, 282.

129. V.A. Janarthanam, P.K. Issac, A. Guru, J. Arockiaraj, *Hazards of polycyclic aromatic hydrocarbons: a review on occurrence, detection, and role of green nanomaterials on the removal of PAH from the water environment,* **J Environ. Monit. Assess,** 195(12), 2023, 1531.

130. V.D.S. Plank, S. Brown, R.J. Nicholls, E.L. Tompkins, *Stakeholder expectations of the public in local coastal flood risk management in England,* Proceedings of the ICE, **Civil Engineering,** 20(1), 2020, 605-618. https://doi.org/10.1680/cm.65147.605

131. V.R. Nadipelli, J.M. Elwing, W.H. Oglesby, K. El-Kersh, *Social determinants of health in pulmonary arterial hypertension patients in the United States: clinician perspective and health policy implications,* **Pulmonary Circulation**, 12(3), 2022, e12111. https://doi.org/10.1002/pul2.12111

Lead City University Ibadan DO NOT COPY

[132] W. Wang, J. Xu, X. Qu, D. Lin, K. Yang, *Current and Future Trends of Low and High Molecular Weight Polycyclic Aromatic Hydrocarbons in Surface Water and Sediments of China: Insights from Their Long-Term Relationships between Concentrations and Emissions,* **Environ. Sci. Technol**, 56(6), 2022, 3397-406.

[133] W. Zhang, Y. Si, Z. Jiang, T. Chen, H. Linnartz, A.G.G.M. Tielens, *Laboratory photochemistry of covalently bonded fluorene clusters: Observation of an interesting PAH bowl-forming mechanism,* **The Astrophysical Journal,** 872(1), 2019, 38. https://doi.org/10.3847/1538-4357/aafe10

[134] World Health Organization, *Human Health Effects of Polycyclic Aromatic Hydrocarbons as Ambient Air Pollutants: Report of the Working Group on Polycyclic Aromatic Hydrocarbons of the Joint Task Force on the Health Aspects of Air Pollution; World Health Organization Regional Office for Europe,* **Copenhagen, Denmark**, 2021, ISBN 978-92-890-5653-3.

[135] X. Kong, R. Dong, T. King, F. Chen, H. Li, *Biodegradation potential of Bacillus sp. PAH-2 on PAHs for oil-contaminated seawater*, **Molecules,** 27(3), 2022, 687. https://doi.org/10.3390/molecules27030687

[136] Y. Bai, H. Yu, K. Shi, N. Shang, Y. He, L. Meng, T. Huang, H. Yang, C. Huang, *Polycyclic Aromatic Hydrocarbons in Remote Lakes from the Tibetan plateau (Concentrations, Source, Ecological Risk, and Influencing Factors),* **J. Environ. Manag,** 319, 2022, 115689.

[137] Y. Kamiya, R.S. The, S.L. Hariyan, M.T. Sajise, A.W. Bandala, *PAH Fingerprinting from Mixed Wood Combustion Sources Using Multivariate Analysis*, **Environmental Pollution**, 259(6), 2020, 113−154.

[138] Y. Li, X. Zou, S. Zou, P. Li, Y. Yang, J. Wang, *Pollution status and trophic transfer of polycyclic aromatic hydrocarbons in coral reef ecosystems of the South China Sea*, **ICES J Mar Sci,** 78(6), 2021a, 2053–2064

[139] Y.B. Man, W.Y. Mo, F. Zhang, M.H. Wong, *Health Risk Assessments Based on Polycyclic Aromatic Hydrocarbons in Freshwater Fish Cultured Using Food Waste-Based Diets,* **Environ. Pollut**, 256, 2020, 113380.

[140] Z. Qiu, Z. Wang, J. Xu, Y. Liu, J. Zhang, *Influence of source apportionment of PAHs occurrence in aquatic suspended particulate matter at a typical post-industrial city: A case study of Freiberger Mulde River,* **Sustainability**, 14(11), 2022 6646. https://doi.org/10.3390/su14116646

[141] Z. Yu, Q. Lin, Y. Gu, F. Du, X. Wang, F. Shi, C. Ke, M. Xiang, Y. Yu, *Bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) in wild marine fsh from the coastal waters of the northern South China Sea: risk assessment for human health,* **Ecotoxicol Environ Saf**, 180, 2019, 742–748

Lead City University Ibadan DO NOT COPY

142. Z. Zhang, S. Wang, L. Li, *Emerging investigator series: the role of chemical properties in human exposure to environmental chemicals in Environmental Science,* ***Processes & Impacts***, *23*(12), 2021, 1839-1862.

143. Z.M. El-Bouhy, R.M. Reda, H.H. Mahboub, F.N. Gomaa**,** *Bioremediation effect of pomegranate peel on subchronic mercury immunotoxicity on African catfish (Clarias gariepinus),* **J Environ Sci Pollut***,* 28(2), 2021, 2219-2235.

144. Z.M El-Bouhy, R.M. Reda, H.H. Mahboub, F.N. Gomaa*, Chelation of mercury intoxication and testing different protective aspects of Lactococcus lactis probiotic in African catfish*, **Aquac. Res,** 52(8), 2021, 3815-28.

145. E. Aykın-Dinçer, *Dried meat products obtained by different methods from past to present*, **Food Reviews International,** 39(5), 2021, 1–20.

146. H. Bian, Y. Zhu, L. Wen, J. Ma, P. Li, Z. Geng, W. Xu, *Occurrence and health risks of heavy metals in crayfish (Procambarus clarkii) from Jiangsu province, China*, **Food Production, Processing and Nutrition**, 5, 2023, 63. https://doi.org/10.1186/s43014-023-00169-6

147. Instituto Brasileiro de Geografia e Estatística – IBGE, Pesquisa de Orçamentos Familiares (POF) 2017–2018: análise do consumo alimentar pessoal no Brasil. [in Portuguese]. Rio de Janeiro: IBGE, 125, 2020a. https://biblioteca.ibge.gov.br/visualizacao/livros/liv101742.pdf.

148. Instituto Brasileiro de Geografia e Estatística – IBGE, Estatísticas sociais. Expectativa de vida dos brasileiros aumenta 3 meses e chega a 76,6 anos em 2019, 2020b https://agenciadenoticias.ibge.gov.br/agencia-noticias/2012-agencia-de-noticias/noticias/29505-expectativa-de-vida-dos-brasileiros-aumenta-3-meses-e-chega-a-76-6-anos-em-2019.

149. C.F. Chiang, K.C. Hsu, T.Y. Tsai, C.Y. Cho, C.H. Hsu, D.J. Yang, *Evaluation of optimal QuEChERS conditions of various food matrices for rapid determination of EU priority polycyclic aromatic hydrocarbons in various foods,* **Food Chemistry,** 334, 2021, 127471.

150. K. Dutta, S. Shityakov, W. Zhu, I. Khalifa, *High-risk meat and fish cooking methods of polycyclic aromatic hydrocarbons formation and its avoidance strategies*, **Food Control,** 142, 2022, 109253. https://doi.org/10.1016/j.foodcont.2022.109253

151. S. Farhadi, M. Javanmard, S. Mahdavi, *Effects of nanomaterial reinforced fibrous casing of sugarcane bagasse on the adsorption of polycyclic aromatic hydrocarbons in smoked sausages***, ACS Food Science & Technology,** 2(6), 2022, 1009–1017. https://doi.org/10.1021/acsfoodscitech.2c00073

Head CLIS University Ibadan DO NOT COPY

[152] N.R.W. Geiker, H.C. Bertram, H. Mejborn, L.O. Dragsted, L. Kristensen, J.R. Carrascal, A. Astrup, *Meat and human health—Current knowledge and research gaps,* **Foods**, 10(7), 2021, 1556. https://doi.org/10.3390/foods10071556

[153] D. Kafouris, A. Koukkidou, E. Christou, M. Hadjigeorgiou, S. Yiannopoulos, *Determination of polycyclic aromatic hydrocarbons in traditionally smoked meat products and charcoal grilled meat in Cyprus,* **Meat Science,** 164, 2020, 108088. https://doi.org/10.1016/j.meatsci.2020.108088

[154] B. Kartalović, L. Puljić, D. Kovačević, M. Markovčić, J. Vranešević, K. Habschied, K. Mastanjević, *The Content of Polycyclic Aromatic Hydrocarbons in Slavonska slanina—Traditionally Smoked and Dry-Cured Bacon,* **Processes**, 10(2), 2022, 268. https://doi.org/10.3390/pr10020268

[155] M. A. Mallah, L. Changxing, M. A. Mallah, S. Noreen, Y. Liu, M. Saeed, Q. Zhang, Polycyclic aromatic hydrocarbon and its effects on human health: an updated review. *Chemosphere,* 296, 2020, 133948. https://doi.org/10.1016/j.chemosphere.2022.133948

[156] T.C Merlo, L. Molognoni, R.B Hoff, H. Daguer, I. Patinho, C.J Contreras-Castillo, *Alternative pressurized liquid extraction using a hard cap espresso machine for determination of polycyclic aromatic hydrocarbons in smoked bacon*, **Food Control**, 120, 2021, 107565.

[157] A. Mirzababaei, E. Daneshzad, S. Moradi, F. Abaj, S. Mehranfar, O. Asbaghi, K. Mirzaei, *The association between urinary metabolites of polycyclic aromatic hydrocarbons (PAHs) and cardiovascular diseases and blood pressure: a systematic review and meta-analysis of observational studies*, **Environmental Science and Pollution Research**, 29, 2022,1712–1728. https://doi.org/10.1007/s11356-021-17091-4.

[158] A. Onopiuk, K. Kołodziejczak, M. Marcinkowska-Lesiak, A. Poltorak, *Determination of polycyclic aromatic hydrocarbons using different extraction methods and HPLC-FLD detection in smoked and grilled meat products,* **Food Chemistry,** 373, 2022, 131506. https://doi.org/10.1016/j.foodchem.2021.131506

[159] A. Onopiuk, K. Kołodziejczak, A. Szpicer, I. Wojtasik-Kalinowska, A. Wierzbicka, A. Półtorak, *Analysis of factors that influence the PAH profile and amount in meat products subjected to thermal processing*, **Trends in Food Science & Technology,** 115, 2021, 366–379. https://doi.org/10.1016/j.tifs.2021.06.043

[160] A. Paris, J. Ledauphin, P. Poinot, J.L. Gaillard, *Polycyclic aromatic hydrocarbons in fruits and vegetables: Origin, analysis, and occurrence*, **Environmental Pollution,** 234, 2018, 96–106. https://doi.org/10.1016/j.envpol.2017.11.028

[161] R.C. Racovita, C. Secuianu, M.D. Ciuca, F. Israel-Roming, *Effects of smoking temperature, smoking time, and type of wood sawdust on polycyclic aromatic hydrocarbon accumulation*

Babcock University Ibadan DO NOT COPY

levels in directly smoked pork sausages, **Journal of Agricultural and Food Chemistry,** 68(35), 2020, 9530–9536. https://doi.org/10.1021/acs.jafc.0c04116

[162.] R.C. Racovita, C. Secuianu, F. Israel-Roming, *Quantification and risk assessment of carcinogenic polycyclic aromatic hydrocarbons in retail smoked fish and smoked cheeses*, **Food Control**, 121, 2021, 107586. https://doi.org/10.1016/j.foodcont.2020.107586

[163.] G.R. Sampaio, G.M. Guizellini, S.A. da Silva, A.P. de Almeida, A.C.C. Pinaffi-Langley, M.M. Rogero, E.A. Torres, *Polycyclic aromatic hydrocarbons in foods: Biological effects, legislation, occurrence, analytical methods, and strategies to reduce their formation,* **International Journal of Molecular Sciences**, *22*(11), 2021, 6010. https://doi.org/10.3390/ijms22116010

[164.] R. Schwert, *Effect of liquid smoke extract on the oxidative stability, benzopyrene and sensory quality of calabrese sausage*, **Current Nutrition & Food Science,** 16(3), 2020, 343–353. https://doi.org/10.2174/1573401315666190126120749

[165.] W. Shao, *Using liquid smoke to control infestations of the ham mite*, *Tyrophagus putrescentiae, on dry-cured hams during aging*, **Meat Science,** 200, 2023, 109139.

[166.] S.A. Silva, G.Z. De Rossi, M.M. Ossugui, A.P. de Almeida, G.M. Guizellini, G.R. Sampaio, E.A.F. da Silva Torres, *Quantification of Polycyclic Aromatic Hydrocarbons in Commonly Consumed Salami in Brazil*, **Food Analytical Methods,** 16, 2023, 1–11. https://doi.org/10.1007/s12161-022-02414-z

[167.] Y. Sun, S. Wu, G. Gong, *Trends of research on polycyclic aromatic hydrocarbons in food: A 20-year perspective from 1997 to 2017*, ***Trends in Food Science & Technology,*** 83, 2019, 86-98. https://doi.org/10.1016/j.tifs.2018.11.015.

[168.] Y. Wang, Y. Jiao, Q. Kong, F. Zheng, L. Shao, T. Zhang, X. Gao, Occurrence of polycyclic aromatic hydrocarbons in fried and grilled fish from Shandong China and health risk assessment, **Environmental Science and Pollution Research**, 28(25), 2021, 32802–32809. https://doi.org/10.1007/s11356-021-13045-y

[169.] C. Whitton, D. Bogueva, D. Marinova, C.J. Phillips, *Are we approaching peak meat consumption? Analysis of meat consumption from 2000 to 2019 in 35 countries and its relationship to gross domestic product,* **Animals,** 11(12), 2021, 3466. https://doi.org/10.3390/ani11123466

[170.] K. Yan, W. Li, S. Wu, *Dietary exposure and risk assessment of European Union priority (EU 15+ 1) polycyclic aromatic hydrocarbons from milks and milk powders in China*, **Journal of Dairy Science,** 8(105), 2022, 6536–6547. https://doi.org/10.3168/jds.2021-21438

[171.] H. Zhang, Y. Han, X. Qiu, Y. Wang, W. Li, J. Liu, T. Zhu, *Association of internal exposure to polycyclic aromatic hydrocarbons with inflammation and oxidative stress in*

Lead City University Ibadan DO NOT COPY

prediabetic and healthy individuals, **Chemosphere**, 253, 2020, 126748. https://doi.org/10.1016/j.chemosphere.2020.126748

172. L. Zhang, P. Wu, H. Zhou, Z. Hu, N. Zhang, L. Wang, Y. Zhao, Determination of 15+ 1 European priority polycyclic aromatic hydrocarbons in smoked meat products by saponification/solid-phase extraction and gas chromatography-mass spectrometry**, Journal of Chromatographic Science**, 60(3), 2022, 298–307. https://doi.org/10.1093/chromsci/bmab087

173. Z. Zhu, Y. Xu, T. Huang, Y. Yu, A.P Bassey, M. Huang*, The contamination, formation, determination and control of polycyclic aromatic hydrocarbons in meat products*, **Food Control***,* 141, 2022, 109194.

174. S. S. Bhatti, A. Bhatia, G. Bhagat, S. Singh, S.S. Dhaliwal, V. Sharma, V. Verma, R. Yin, J. Singh, J. *PAHs in Terrestrial Environment and Their Phytoremediation, In Bioremediation for Sustainable Environmental Cleanup, CRC Press*, **Boca Raton**, FL, USA, 2024. ISBN 978-1-003-27794-1.

175. E.W. Sayers, E.E. Bolton, J.R. Brister, K. Canese, J. Chan, D.C. Comeau, C.M. Farrell, M. Feldgarden, A.M. Fine, S.T. Sherry, *National Center for Biotechnology Information PubChem Dataset 2023,* **Nucleic Acids Res,** 51, 2023, D29–D38.

176. X. Xiong, H. Zhang, R. Wang, Z. Tang, M. Yang, *Distribution and Risk Assessment of 80 Polycyclic Aromatic Compounds in Surface Water and Industrial Effluent in the Upper Yangtze River, China,* **ACS EST Water,** 4, 2024 2300–2308.

177. A. Azimi, A. Riahi Bakhtiari, R, Tauler, *Polycyclic Aromatic Hydrocarbon Source Fingerprints in the Environmental Samples of Anzali, South of Caspian Sea*, **Environ. Sci. Pollut. Res**, 27, 2020, 32719–32731.

178. K. Ouro-Sama, G. Tanouayi, H.D. Solitoke, N. Barsan, E. Mosnegutu, T.E.E. Badassan, S. Agbere, K. Adje, V. Nedeff, K. Gnandi, *Polycyclic Aromatic Hydrocarbons (PAHs) Contamination in Chrysichthys Nigrodigitatus Lacépède, 1803 from Lake Togo-Lagoon of Aného, Togo, Possible Human Health Risk Suitable to Their Consumption*, **Int. J. Environ. Res. Public Health**, 20, 2023, 1666.

179. H. Sahai, M. García Valverde, M. Murcia Morales, M.D. Hernando, A.M. Aguilera Del Real, A.R. Fernández- Alba, *Exploring Sorption of Pesticides and PAHs in Microplastics Derived from Plastic Mulch Films Used in Modern Agriculture*, **Chemosphere,** 333, 2023, 138959.

180. B. Ambade, S.S. Sethi, *Health Risk Assessment and Characterization of Polycyclic Aromatic Hydrocarbon from the Hydrosphere*, **J. Hazard. Toxic Radioact. Waste,** 25, 2021 05020008.

181. E. Santos, M.R.R. Souza, A.R.V. Junior, L. da Silva Soares, M. Frena, M.R. Alexandre, Polycyclic *Aromatic Hydrocarbons in Suspended Particulate Matter of a Region*

Lead City University Ibadan DO NOT COPY

Influenced by Agricultural Activities in Northeast Brazil, **Reg. Stud. Mar. Sci**, 57, 2023 102683.

[182.] K. Sun, Y. Song, F. He, M. Jing, J. Tang, R. Liu, *A Review of Human and Animals Exposure to Polycyclic Aromatic Hydrocarbons: Health Risk and Adverse Effects, Photo-Induced Toxicity and Regulating Effect of Microplastics*, **Sci. Total Environ,** 773, 2021, 145403.

Lead City University Ibadan DO NOT COPY

Chapter Three

Methodology

3.1 Description of the Study Area

Lagos Lagoon, one of the largest lagoons in West Africa, plays a crucial role in Nigeria's socio-economic and ecological landscape. Spanning approximately 6,354 square kilometers, it stretches from the western border of Nigeria with the Republic of Benin to the eastern boundary where it connects to the Lekki Lagoon[1]. The lagoon is fed by several rivers and streams, including the Ogun River, Yewa River, and Osun River, which act as conduits for both freshwater and pollutant influx. The lagoon opens into the Atlantic Ocean through the Lagos Harbor, allowing for a mix of saline and freshwater environments, which significantly influences its aquatic biodiversity[2].

However, the rapid urbanization, industrial expansion, and agricultural activities surrounding the lagoon have made it highly susceptible to pollution. The discharge of industrial effluents, untreated domestic sewage, agricultural runoff, and municipal waste has resulted in the accumulation of toxic contaminants, including heavy metals and polycyclic aromatic hydrocarbons (PAHs)[3,4]. Lagos Lagoon is particularly vulnerable due to its proximity to industrial hubs such as Apapa, Iddo, and Ikorodu, where extensive commercial and shipping activities contribute to pollution levels. Additionally, the presence of informal settlements along the lagoon's banks exacerbates environmental degradation, as many of these communities lack proper waste disposal systems, leading to indiscriminate dumping of solid and liquid wastes into the water body[5,6].

Lead City University Ibadan DO NOT COPY



Figure 3.1: Map Showing the Lagos Lagoon, Nigeria

Source[1]

Lead City

3.2 Sample Collection

The water, fish, and shrimp samples were collected in the first week of November 2024. The reason behind opting this month for sampling was that the monsoon season (June to November) in this part of the world ends during this time, and the surface runoff and upstream discharge attain the peak in the rivers and lagoons. At each sampling point, three replicates were obtained to enhance data reliability. Samples were collected at different depths (surface, mid-depth, and bottom) using a Van Dorn water sampler, a standard tool for collecting uncontaminated water samples in aquatic research. To minimize external contamination, amber glass bottles pre-rinsed with distilled water and organic solvents were used for sample storage.

Aquatic organisms, namely Tilapia (*Oreochromis niloticus*), Silver catfish (*Chrysichoyes nigrodigifatus*), Shrimps (*caridea*), Crabs (*Phylum arthropoda*) (hereafter referred to as ON, CA and PA, respectively) were collected from the lagoon with the help of local fishers at the same time. Three individuals per species were purchased from the local fishermen of the respective stations, and their length and wet weight were immediately measured in the field. Length and weight were measured to the nearest 0.1 cm and 0.01 g using digital Vernier caliper and electronic precision balance, respectively. A separate subset of water, fish, and shrimp samples were transported to the laboratory in ice-cold conditions (~4 ◦C) on the same day. The aquatic samples were taken into the Nigerian Institute for Oceanography and Marine Research (NIOMR) for identification where the fish, crabs and shrimp species were confirmed using standard identification guides and morphological features. The identification was carried out with the assistance and expert supervision of Dr Iwalewa M and Dr Femi Fakayode of NIOMR, whose guidance ensured the accurate classification of all species.

Lead City University Ibadan. DO NOT COPY

Table 3.1: Sample Information

Aquatic Organisms (Common Name)	Scientific Name	Weight (grams)
Tilapia Fish	*Oreochromis niloticus*	1500
Crabs	*Portunus Validus*	120
Tiger Shrimps	*Pereeuts monodon*	30
Silver Catfish	*Chrysichoyes nigrodigifatus*	1000

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

3.3 Sample Preparation/Extraction

Water Sample: 100mL of water sample was measured into a 250mL funnel and extracted three times with 20mL of methylene chloride, yielding approximately 60mL of final extracting solvent. The water and DCM combination was vigorously shaken in a separatory funnel for 1-2 minutes, with the funnel occasionally vented to relieve excess pressure. The water phase and organic layer were allowed to separate before being decanted into a flask. Before cleanup, the extracts were concentrated to approximately 1-2 mL using a rotary evaporator. Finally, 1-3 spatulas full of activated sodium sulphate were added to the concentrated extract to eliminate any liquid portions that were present.

Aquatic Samples: The Keyfi approach was used to remove PAHs. A pestle and mortar were used to crush 5 g of each type of aquatic organisms. The crushed aquatic organisms were treated to two rounds of ultrasonic extraction in methanol (20 ml) for 20 minutes each, followed by two rounds of 20 ml dichloromethane and methanol: dichloromethane (1:1) for 20 minutes each. The extracts

from each round of ultrasonication were mixed in a pre-labeled bottle to yield 120 mL of extracts. The extract was filtered through Whatman's No. 1 filter paper, and the filtrate was allowed to evaporate until nearly dry.

3.4 Sample Clean-Up/Purification

The techniques of Banjoo and Nelson were used for sample purification. The cleanup procedure involved using a loaded chromatographic column. A chromatographic column was packed with 4 g of carefully weighed activated alumina. The top of the alumina in the column was then coated with 12 g of activated silica gel. Twenty milliliters of n-hexane were used to pre-elute the column, which was then left to run until the first drop of liquid was found. The extract fractions were eluted in the following order: The sample was eluted with 20 mL of n-hexane, and the resultant eluate was transferred to separate sample bottles. The polycyclic fraction was eluted with a 20-mL solution of n-hexane: dichloromethane (at a 3:2 ratio), and the dichloromethane fraction was collected into sample vials and dried almost completely before analysis.

3. 5 Gas-Chromography Flame Ionization Detector Measurement of PAH

The gas chromatography coupled with flame ionization detector (GC-FID) system (Agilent Technology, GC-7820A) was used to identify and quantify 16 PAHs in water and aquatic species, based on a standard calibration. Pyrene, acenaphthylene, fluorine, phenanthrene, anthracene, and acenaphthylene benz[c], phenanthrene, benz[a]anthracene, chrysene, benzo[a], pyrene, benzo[e] pyrene, benzo[j] 3-methylcholanthrene, indeno[1,2,3-cd] pyrene, dibenz[a,h] anthracene, and benzo[ghi] pyrene. The Agilent Technology GC-7820A capillary column HP5 (30 m length×250 mm width × 0.25 µm thickness) was injected with 1 µl of the sample in split less mode at 270°C using nitrogen as the carrier gas (flow rate of 1.2 ml/min). The material was analyzed using GC-FID after being injected in a splitless mode at 300°C. The oven's temperature was initially set at

Lead City University Ibadan DO NOT COPY

40°C for 1 minute, then escalated at a rate of 15°C per minute to 300°C with a 10-minute holding time. The oven temperature was originally set at 40°C for 1 minute, then increased at a rate of 15°C per minute to 300°C with a holding time of 10 minutes. PAHs were identified by comparing the sample mixture's retention time to those of the separate standards. PAH were discovered by contrasting the retention times of the sample mixture to those of the individual standards.

3.6 Quality Assurance and Quality Control

Before the PAHs assessment, all glassware was detergent washed and oven dried. The weighing balance was calibrated using 1g and 5g samples, respectively. All reagents used were analytical grade. To remove carry-over samples, the instrumental approach includes baking the column at 250°C. It was then run isothermally to burn the carryover sample. A blank sample was used as the baseline. After each five-sample run, a standard was run in between to ensure sample quality and uniformity of results. Prior to quantification, the standard was utilized to calibrate the device.

3.7 Regulatory Limits and Guidelines

By comparing reported levels to regulatory limits and recommendations, the risk to human health presented by PAH concentrations in fish was assessed. The US Environmental Protection Agency (USEPA) measured individual and collective concentrations of naphthalene, acenaphthene, acenapthtylene, fluorene, fluoranthene, benzo(a)anthracene, chrysene, benzo(a)pyrene, pyrene, and anthracene in selected fish species[7].

The maximum acceptable limit of 0.002 mg/kg [European Food Safety Authority (EFSA)] for benzo[a]pyrene in fish was compared with concentrations of benzo(a)pyrene (B(a) P), which has been identified as the major source of the occurrence and impact of carcinogenic PAHs in foods by the European Commission Regulation (EC) No. 1881/2006[8].

Table 3.2: GC-FID Operating Conditions and Acquisition Parameters

Lead City University Ibadan DO NOT COPY

Operating Conditions	Acquisition Parameter
Injector mode (GC)	Splitless
Carrier gas flow (GC)	1.2 ml / min
Split flow (GC)	15 ml / min
Split ratio (GC)	10
Temperature injector (GC)	270ºC
Injection volume (GC)	1 µl
Ion source temperature (FID)	210ºC
Start time (MS)	1min
Scan mode (MS)	Selected Ion Monitoring
Damping gas flow (MS)	0.3 ml/min

GC = Gas Chromatography; FID= Flame Ionization Detector

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

3.8 Human Health Risk Assessment

Toxicological risks associated with PAH concentrations in the biota samples were assessed through comparison of the observed concentrations with regulatory limits and guidelines.

3.8.1 Estimated Daily Intake

To assess human health risks from exposure to PAHs through consumption of possibly contaminated biota samples, the estimated daily intake concentrations of PAHs from consumption of contaminated shrimps, crabs, tilapia and catfish were determined. The estimated daily intake of PAHs in contaminated biota samples were assessed for the adult population using Equation **EDI= C×IR÷BW**

The daily intake of PAHs from the biota samples was calculated by multiplying the respective PAH concentration in each sample by the ingestion rate of an average weight adult divided by the body weight of an average weight adult (70 kg)[9].

Equation;

EDI= C×IR÷BW

Where,

C= Concentration of aquatic organisms

IR= Ingestion rate

BW= Body weight

Lead City University Ibadan DO NOT COPY

3.8.2 Target Hazard Quotient and Incremental Lifetime Cancer Risk

The health risk assessment of polycyclic aromatic hydrocarbons (PAHs) in aquatic organisms from Lagos Lagoon was undertaken using both non-carcinogenic and carcinogenic risk indices. The Hazard Quotient (HQ) was applied to evaluate non-carcinogenic effects, while the Incremental Lifetime Cancer Risk (ILCR) was used to assess carcinogenic potential. Both indices are derived from the Estimated Daily Intake (EDI), which quantifies human exposure through consumption of contaminated fish and shellfish[10,11].

$$\mathbf{HQ = EDI_{BaP} \div RFD_{BaP}}$$

EDI_{BaP} = Estimated Daily Intake

RFD_{BaP} = Reference Dose

3.8.3 Incremental Lifetime Hazard Risk

$$ILCR = EDI_{BaP} \times CSF_{BaP}$$

EDI_{BaP} = Estimated daily intake

CSF_{BaP} = Cancer Slope Factor[12]

Lead City University Ibadan DO NOT COPY

3.9 Data Analysis

The raw data were subjected to Descriptive statistics, one-way Analysis of variance (ANOVA) and Pearson Product Moment Correlation which is a parametric statistical tool used to test significant difference in mean levels of pollutants/variables[13].

Results were interpreted in accordance with international safety guidelines, including those set by the World Health Organization (WHO), Food and Agriculture Organization (FAO), and United States Environmental Protection Agency (USEPA)[14].

3.10 Ethical Considerations

All research activities complied with ethical guidelines for environmental and animal research. Ethical approval was obtained from the Nigerian Institute for Oceanography and Marine Research (NIOMR). Fishermen and local communities were informed about the study's objectives, and samples were collected in an environmentally responsible manner, ensuring minimal disruption to aquatic life.

Lead City University Ibadan DO NOT COPY

Endnotes

1. E. Chamalidou, A. Gazis, G. D. Gikas, *Removal of polycyclic aromatic hydrocarbons from polluted water using constructed wetlands*, **International Journal on Engineering Technologies and Informatics**, 3(1), 2022, 1-5. https://doi.org/10.51626/ijeti.2022.03.00027

2. J. Chang, E. Zhang, E. Liu, H. Liu, X. Yang, *A 60-year historical record of polycyclic aromatic hydrocarbons (PAHs) pollution in lake sediment from Guangxi Province, southern China,* **Anthropocene,** 24, 2018, 51-60. https://doi.org/10.1016/j.ancene.2018.11.003

3. L. Chao, X. Mo, J. Meng, Y. Li, *Study on enhanced bioremediation effect of oil-bearing dredging sediment*, **E3S Web of Conferences**, 252, 2021 02031. https://doi.org/10.1051/e3sconf/202125202031

4. J. Chen, J. Liao, C. Wei, *Coking wastewater treatment plant as a sources of polycyclic aromatic hydrocarbons (PAHs) in sediments and ecological risk assessment*, **Scientific Reports**, 10(1), 2020, 7833. https://doi.org/10.1038/s41598-020-64835-2

5. Y. Chen, C. Sun, J. Zhang, F. Zhang, *Assessing 16 Polycyclic Aromatic Hydrocarbons (PAHs) in River Basin Water and Sediment Regarding Spatial-Temporal Distribution, Partitioning, and Ecological Risks,* **Polish Journal of Environmental Studies**, *27*(2), 2018, 579-589. DOI: 10.15244/pjoes/75827

6. A.O. Adeniji, O.O. Okoh, A.I. Okoh, *Distribution pattern and health risk assessment of polycyclic aromatic hydrocarbons in the water and sediment of Algoa Bay, South Africa*, **Environmental Geochemistry and Health**, 41(3), 2018, 1303-1320. https://doi.org/10.1007/s10653-018-0213-x

7. I.E. Aigwi, R. Phipps, J. Ingham, O. Filippova, *Characterisation of adaptive reuse stakeholders and the effectiveness of collaborative rationality towards building resilient urban areas*, **Systemic Practice and Action Research,** 34(2), 2020, 141-151. https://doi.org/10.1007/s11213-020-09521-0

8. Q. Ain, A. Rehman, M. Abbasi, *Bioremediation: Review on oil spill management using oil eating microorganisms, and spill effects on marine and terrestrial environment*, ***Journal of Sustainable Environment,*** *1*(2), 2023, 30-35. https://doi.org/10.58921/jse.01.02.020

9. O.O. Alegbeleye, B.O. Opeolu, V.A. Jackson, *Polycyclic aromatic hydrocarbons: A critical review of environmental occurrence and bioremediation,* **Environmental Management**, 60(4), 2017, 758-783. https://doi.org/10.1007/s00267-017-0896-2

10. M. V. D. Almeida, S.R. Rissato, M.S. Galhiane, J.R. Fernandes, *P.C Lodi, M.C.D Campos, In vitro phytoremediation of persistent organic pollutants by Helianthus annuus L. plants,* **Química Nova**, 2017. https://doi.org/10.21577/0100-4042.20170177

Leed City University Library DO NOT COPY

11. X. An, W. Li, J. Lan, X. Di, M. Adnan, *Seasonal co-pollution characteristics of parent-PAHs and alkylated-PAHs in karst mining area soil of Guizhou, Southwest China*, **Frontiers in Environmental Science,** *10*, 2022, 990471. https://doi.org/10.3389/fenvs.2022.990471

12. I. N. Anyanwu, F.D. Sikoki, K.T. Semple, *Baseline PAHs, N-PAHs, and 210Pb in segment samples from Bodo Creek: Comparison with Bonny estuary, Niger Delta,* **Water, Air, & Soil Pollution**, 232(9) 2021. https://doi.org/10.1007/s11270-021-05316-8

13. J. E. Avelino, R. N. Crichton, V.P. Valenzuela, M.G.N. Odara, M.A.T. Padilla, N.T. Kiet, D.H. Anh, P.C. Van, H.D. Bao, N.H.P. Thao, *Survey tool for rapid assessment of socio-economic vulnerability of fishing communities in Vietnam to climate change*, **Geosciences**, 8(12), 2018, 452. https://doi.org/10.3390/geosciences8120452.

14. A. K. Baldwin, S.R. Corsi, S.K. Oliver, P.L. Lenaker, M.A. Nott, M.A. Mills, G.A .Norris, P. Paatero, *Primary sources of polycyclic aromatic hydrocarbons to streambed sediment in Great Lakes tributaries using multiple lines of evidence,* **Environmental Toxicology and Chemistry**, 39(7), 2020, 1392-1408. https://doi.org/10.1002/etc.4727

Lead City University Ibadan DO NOT COPY

Chapter Four

Results and Discussion of Findings

4.1 Results of Findings

The results obtained from the determination of polycyclic aromatic hydrocarbons (PAHs) in Tilapia fish and Silver catfish, water, crab and Prawn samples collected from Lagos Lagoon, Lekki Area, Lagos State were presented in the following subsections.

4.1.1 Results of PAHs in Water Samples

The concentrations of sixteen PAHs in water samples collected from Lagos Lagoon, in Lekki Area of Lagos are presented in the table 4.1. and the pattern of individual PAHs is shown in Figure 4.1.

Table 4.1: Concentration of PAHs in Water Samples

PAHs	LLW1 (ng/ul)	LLW2 (ng/ul)	LLW3 (ng/ul)	Mean (ng/ul)	Control (ng/ul)
Naphthalene	ND	ND	ND	ND	ND
Acenaphthylene	0.0502	0.0500	0.0765	0.0633	0.0001
Acenaphthene	4.6850	5.7452	4.3465	4.9256	ND
Fluorene	1.2390	1.5463	2.0124	1.5993	0.0001
Anthracene	0.0877	0.1267	0.1361	0.1168	ND
Phenanthrene	2.4690	3.5611	2.8456	2.9585	ND
Fluoranthene	1.2760	1.4591	2.3980	1.7110	0.0002
Pyrene	3.0010	5.6023	2.0034	3.5356	0.0012
Benzo (a) anthracene	9.2110	7.8324	10.3211	9.1216	ND
Chrysene	1.7130	1.2056	2.0341	1.6508	ND
Benzo (b) fluoanthene	11.3750	15.1120	9.3409	11.9426	ND
Benzo (k) fluoanthene	3.9950	2.9345	5.1120	4.0136	0.0001
Benzo (a) pyrene	4.2130	3.4511	2.3004	3.3214	0.0001
Dibenz (a,h) anthracene	4.3750	4.7310	4.9838	4.6966	ND
Indeno (1,2,3-cd) pyrene	5.3640	4.5630	5.9065	5.2777	ND
Benzo (g,h,i) perylene	18.4450	15.3540	18.8923	17.5633	ND
TOTAL	**72.7350**	**73.2743**	**72.7097**	**72.9065**	**0.0019**

ND=Not Detected, **Source:** Author's Field Work, 2025

Ibadan City University Ibadan DO NOT COPY

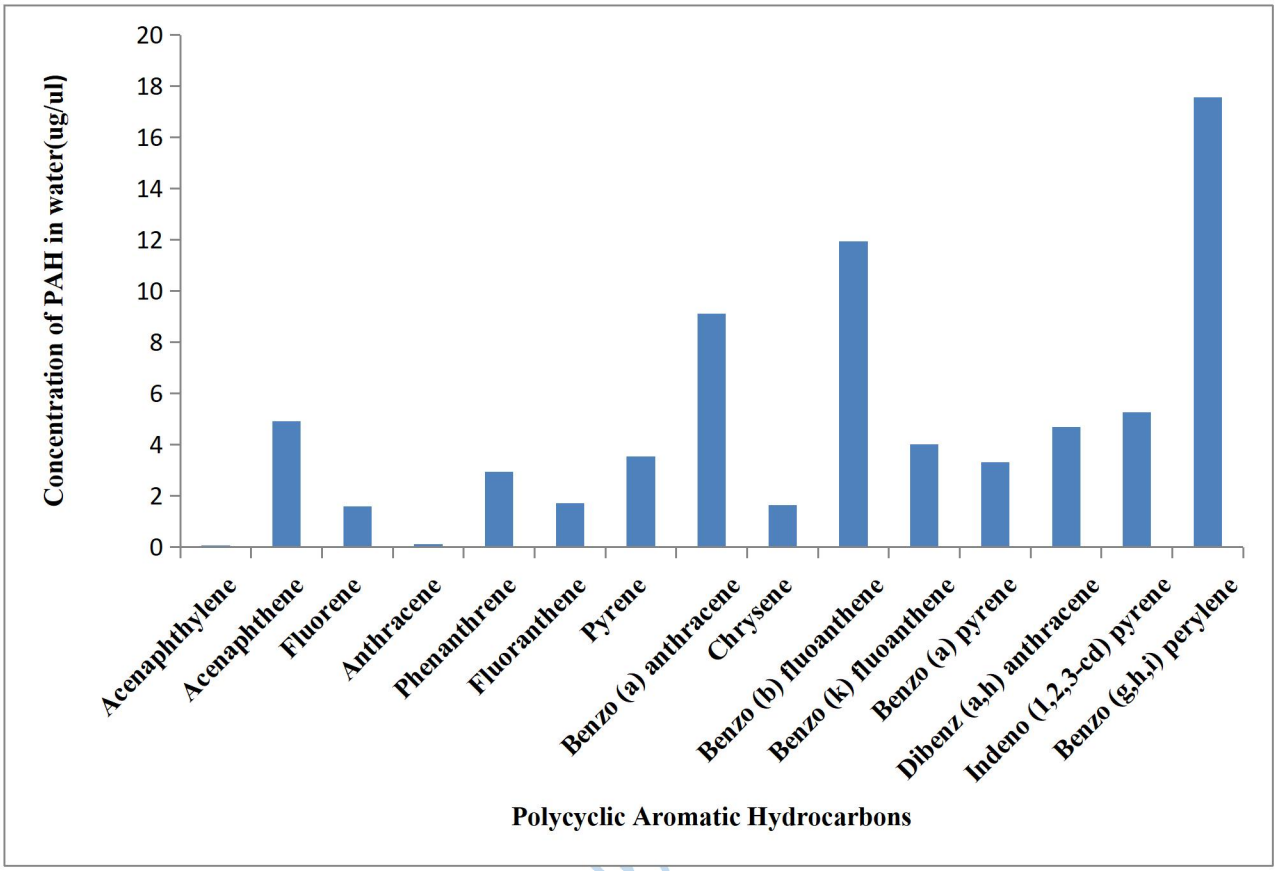


Figure 4.1: Distribution Pattern of Sixteen Individual PAHs in Water Samples

Source: Author's Field Work, 2025

Lead City University Ib

4.1.2 Results of PAHs in Tilapia Fish Samples

The concentrations of PAHs in tilapia fish samples collected from Lagos Lagoon, in Lekki Area of Lagos are presented in the table 4.2 and the distribution is hown in figure 4.2

Table 4.2: Concentration of PAHs in Tilapia Fish Samples

PAHs	LLTF1 (mg/kg)	LLTF2 (mg/kg)	LLTF3 (mg/kg)	Mean (mg/kg)
Naphthalene	ND	ND	ND	ND
Acenaphthylene	ND	ND	ND	ND
Acenaphthene	3.1430	4.2130	5.0150	4.1230
Fluorene	0.0441	0.0294	0.0941	0.0558
Anthracene	0.0395	0.0116	0.0670	0.0395
Phenanthrene	ND	ND	ND	ND
Fluoranthene	1.0122	0.8956	1.2070	1.0383
Pyrene	17.3110	19.4500	17.5360	18.0990
Benzo (a) anthracene	1.1870	1.4703	1.9491	1.5355
Chrysene	1.7590	0.2974	0.7940	0.9501
Benzo (b) fluoanthene	2.7560	2.9841	4.1104	3.2835
Benzo (k) fluoanthene	3.9940	2.7943	1.9483	2.9123
Benzo (a) pyrene	1.7380	1.9211	2.7094	2.1228
Dibenz (a,h) anthracene	9.9100	7.7891	6.9821	8.2273
Indeno (1,2,3-cd) pyrene	ND	ND	ND	ND
Benzo (g,h,i) perylene	ND	ND	ND	ND
TOTAL	**42.8700**	**42.2839**	**43.2474**	**42.3876**

ND=Not Detected

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

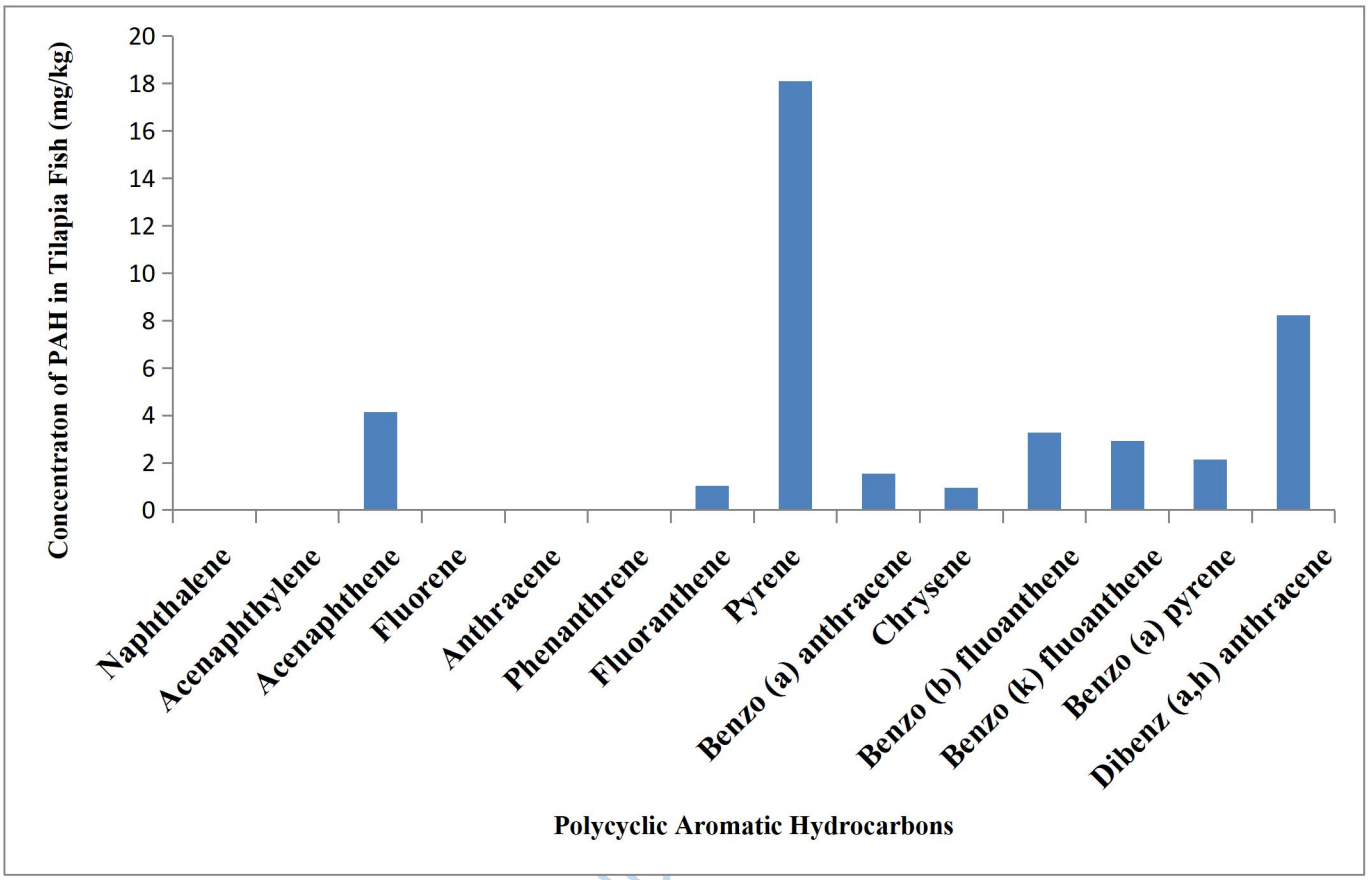


Figure 4.2: Distibution Pattern of Individual sixteen of PAHs in Tilapa Fish

Source: Author's Field Work, 2025

Lead City University Ib

4.1.3 Results of PAHs in Silver Catfish Samples

The concentrations of PAHs in silver catfish samples collected from Lagos Lagoon, in Lekki area of Lagos are presented in the table 4.3 and the distribution pattern of individual PAHs is shown in Figure 4.3.

Table 4.3: Concentration of PAHs in Silver Catfish Samples

PAHs	LLCF1 (mg/kg)	LLCF2 (mg/kg)	LLCF3 (mg/kg)	Mean (mg/kg)
Naphthalene	ND	0.0013	0.0214	0.01135
Acenaphthylene	ND	0.0211	0.0091	0.0151
Acenaphthene	2.0263	3.0124	2.3910	2.5193
Fluorene	ND	0.0842	0.1721	0.1282
Anthracene	1.2050	1.5230	1.1320	1.2867
Phenanthrene	ND	0.4590	0.845	0.652
Fluoranthene	2.9742	3.5240	2.5690	3.0224
Pyrene	6.6940	7.1102	9.0123	7.6055
Benzo (a) anthracene	ND	ND	ND	ND
Chrysene	ND	ND	ND	ND
Benzo (b) fluoanthene	ND	ND	ND	ND
Benzo (k) fluoanthene	ND	ND	ND	ND
Benzo (a) pyrene	ND	ND	ND	ND
Dibenz (a,h) anthracene	ND	ND	ND	ND
Indeno (1,2,3-cd) pyrene	ND	ND	ND	ND
Benzo (g,h,i) perylene	ND	ND	ND	ND
TOTAL	**12.8994**	**15.7352**	**16.1519**	**15.2405**

ND=Not Detected

Source: Author's Field Work, 2025

Lead City University, Ibadan DO NOT COPY

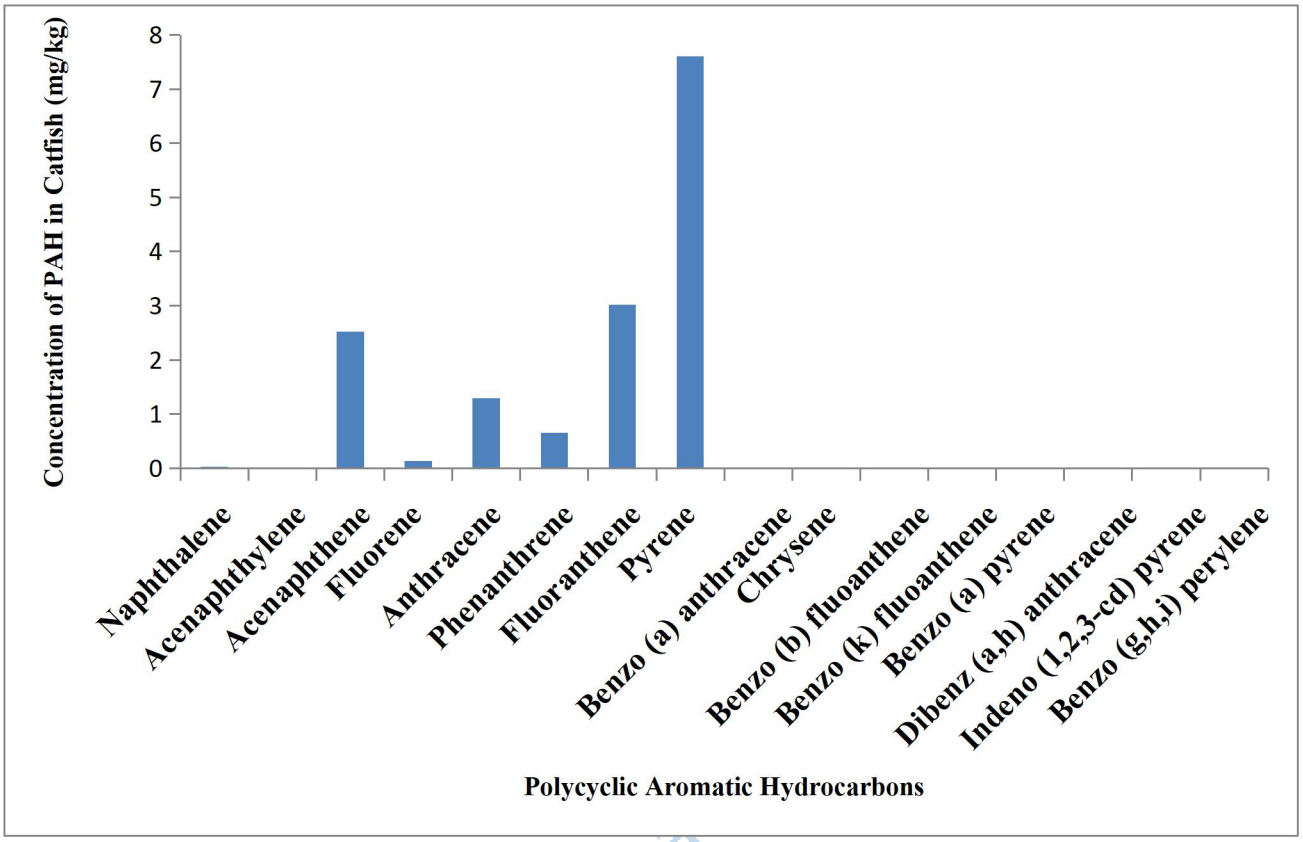


Figure 4.3: Distibution Pattern of Individual sixteen PAHs in Silver Catfish

Source: Author's Field Work, 2025

Lead City University Iba

4.1.4 Results of PAHs in Silver Crab Samples

The concentrations of PAHs in crab samples collected from Lagos Lagoon, in Lekki area of Lagos are presented in the table 4.4 and the distribution pattern of individual PAHs is shown in Figure 4.4.

Table 4.4: Concentration of PAHs in Crab Samples

PAHs	LLC1 (mg/kg)	LLC2 (mg/kg)	LLC3 (mg/kg)	Mean (mg/kg)
Naphthalene	ND	ND	ND	ND
Acenaphthylene	ND	ND	ND	ND
Acenaphthene	3.7106	4.3013	1.9268	3.3129
Fluorene	0.0481	0.0099	0.0039	0.0206
Anthracene	0.0358	2.8291	0.0042	0.9564
Phenanthrene	ND	ND	ND	ND
Fluoranthene	3.9328	1.9287	4.1021	3.3212
Pyrene	3.5957	3.2999	2.9160	3.2705
Benzo (a) anthracene	2.2332	0.9149	3.1391	2.0957
Chrysene	1.2823	1.7021	0.9918	1.3254
Benzo (b) fluoanthene	3.7983	4.1812	9.6203	5.8666
Benzo (k) fluoanthene	8.3973	6.0863	8.1621	7.5486
Benzo (a) pyrene	5.6698	4.9918	2.8018	4.4878
Dibenz (a,h) anthracene	4.0445	5.6021	3.9263	4.5243
Indeno (1,2,3-cd) pyrene	29.2081	26.1103	23.2918	26.2034
Benzo (g,h,i) perylene	6.7750	10.3180	9.4211	8.8380
TOTAL	**73.4864**	**72.2756**	**70.3073**	**71.7715**

ND=Not Detected

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

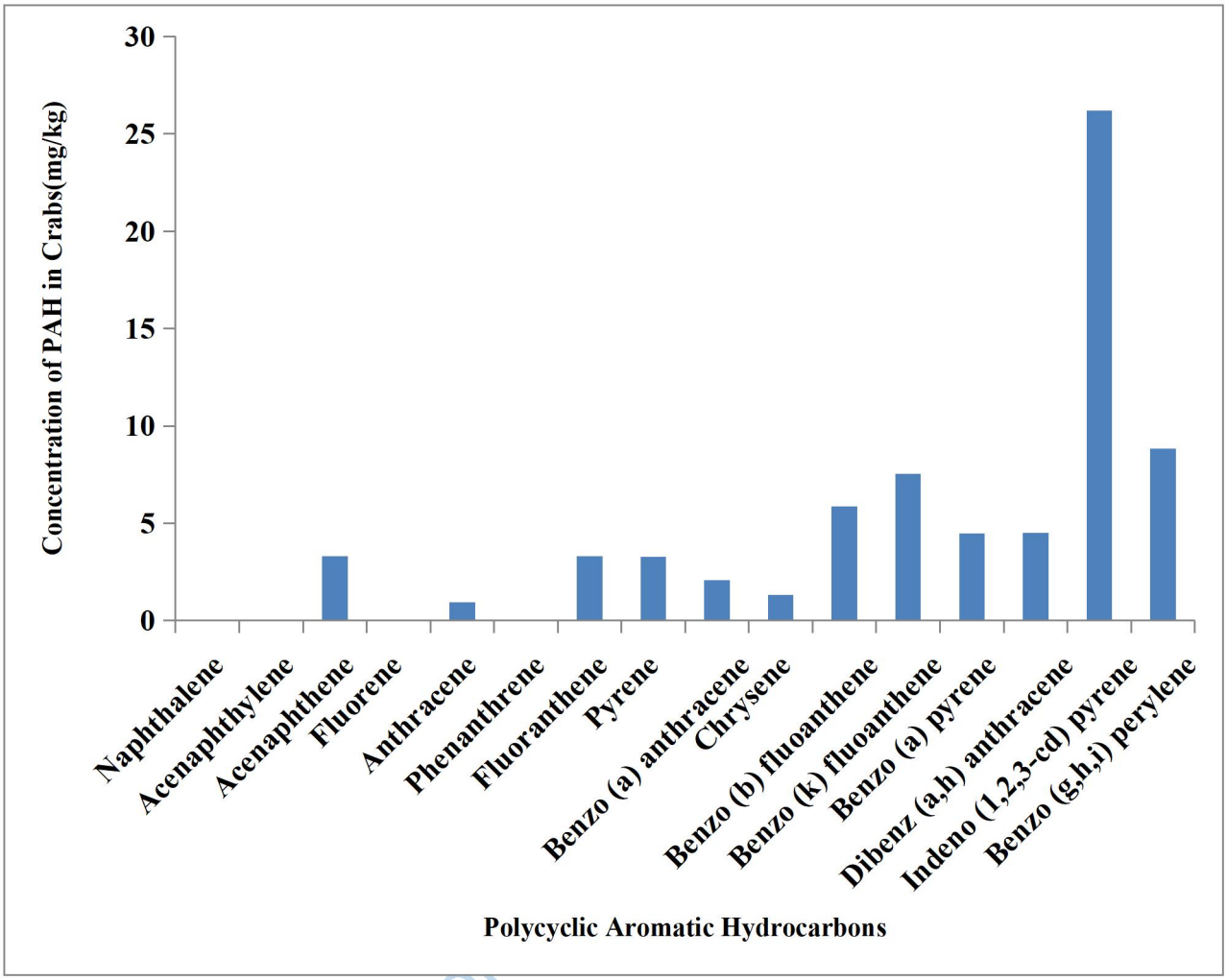


Fig 4.4: Distibution Pattern of Individual sixteen PAHs in Crabs

Source: Author's Field Work, 2025

Lead City Univer

4.1.5 Results of PAHs in Shrimp Samples

The concentrations of PAHs in shrimp samples collected from Lagos Lagoon, in Lekki area of Lagos are presented in the table 4.5 and the distribution pattern of individual PAHs is shown in Figure 4.5.

Table 4.5: Concentration of PAHs in Shrimp Samples

PAHs	LLS1 (ng/ul)	LLS2 (mg/kg)	LLS3 (mg/kg)	Mean (mg/kg)
Naphthalene	9.3391	9.2918	8.7448	9.1252
Acenaphthylene	2.6254	3.7184	3.2735	3.2058
Acenaphthene	1.2004	0.8194	1.2913	1.1037
Fluorene	1.7484	2.9102	2.2282	2.2956
Anthracene	0.0782	0.0039	0.4818	0.1880
Phenanthrene	5.5433	5.2219	4.2918	5.0190
Fluoranthene	10.6080	11.5513	10.3392	10.8328
Pyrene	21.1536	19.3591	20.8211	20.4446
Benzo (a) anthracene	ND	ND	ND	ND
Chrysene	ND	ND	ND	ND
Benzo (b) fluoanthene	ND	ND	ND	ND
Benzo (k) fluoanthene	ND	ND	ND	ND
Benzo (a) pyrene	ND	ND	ND	ND
Dibenz (a,h) anthracene	ND	ND	ND	ND
Indeno (1,2,3-cd) pyrene	ND	ND	ND	ND
Benzo (g,h,i) perylene	ND	ND	ND	ND
TOTAL	**52.2964**	**52.8761**	**51.4717**	**52.4717**

ND=Not Detected

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

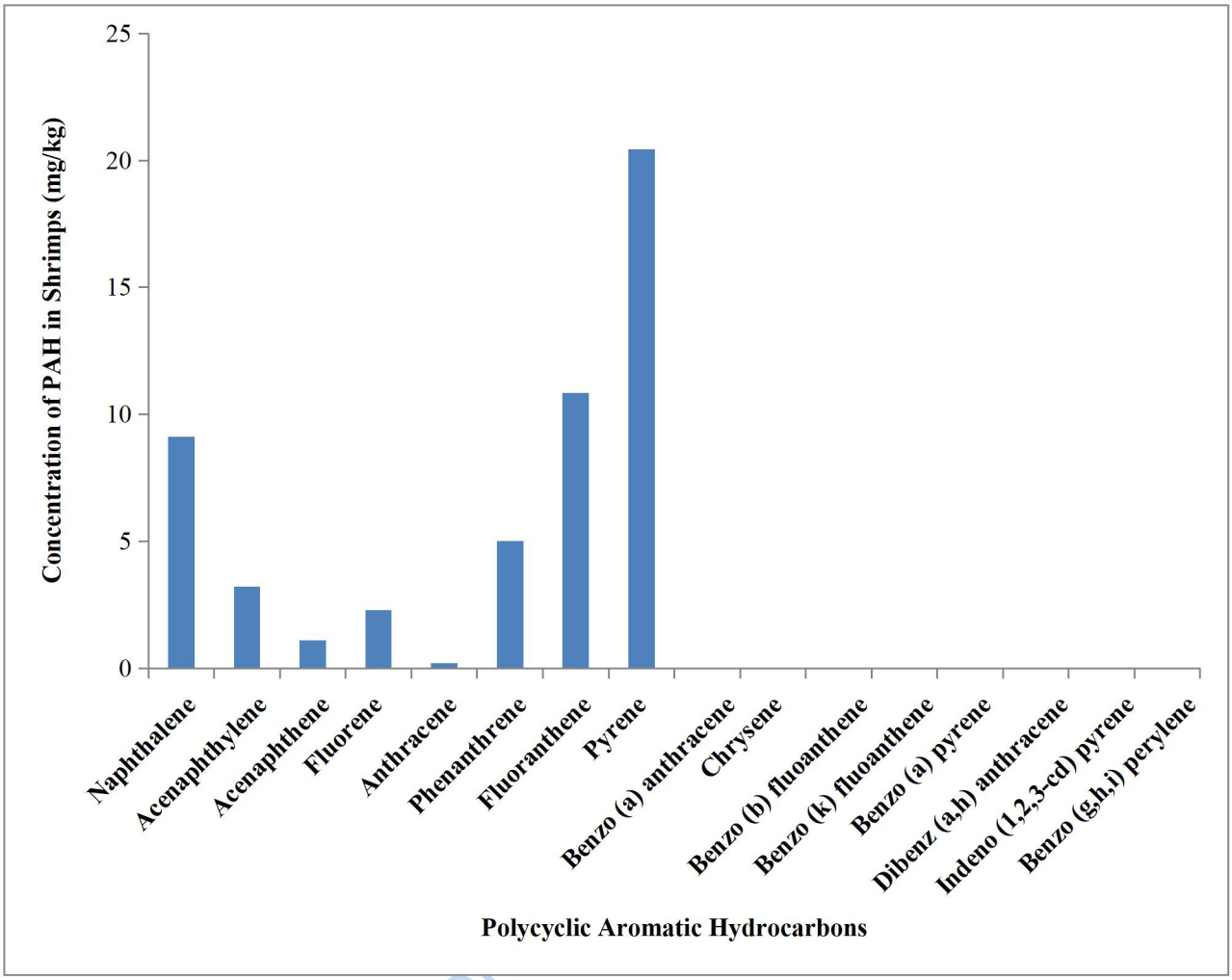


Figure 4.5: Distribution Pattern of Sixteen Individual PAHs in Shrimps

Source: Author's Field Work, 2025

Lead City Univer

4.1.6 Comparison of the mean concentration of PAHs in Water, Tilapia, Silver catfish, crabs and Shrimp Samples

The mean concentrations of PAHs in water, tilapia, catfish, crab and shrimp samples collected from Lagos Lagoon, in Lekki area of Lagos are compared and presented in the table 4.6 and figure 4.6 below. Table 4.7 and 4.8 also show the correlation matrix between the individual PAHs and the different samples analysed in this study.

Table 4.6: Average Concentrations of PAHs in all the Samples

PAHs	Water (ng/ul)	Tilapia (mg/kg)	Catfish (mg/kg)	Shrimps (mg/kg)	Crabs (mg/kg)
Naphthalene	ND	0.0020	0.0114	9.1252	ND
Acenaphthylene	0.6326	ND	0.0151	3.2058	ND
Acenaphthene	4.9256	4.1237	2.5193	1.1037	3.3129
Fluorene	1.5993	0.0559	0.1282	2.2956	0.0206
Anthracene	0.1168	0.0393	1.2867	0.1880	0.9564
Phenanthrene	2.9585	ND	0.6520	5.0190	ND
Fluoranthene	1.7110	1.0383	3.0224	10.8328	3.3212
Pyrene	3.5356	18.0990	7.6055	20.4446	3.2705
Benzo (a) anthracene	9.1216	1.5355	ND	ND	2.0957
Chrysene	1.6508	0.9501	ND	ND	1.3254
Benzo (b) fluoanthene	11.9426	3.2835	ND	ND	5.8666
Benzo (k) fluoanthene	4.0136	2.9123	ND	ND	7.5486
Benzo (a) pyrene	3.3214	2.1228	ND	ND	4.4878
Dibenz (a,h) anthracene	4.6966	8.2273	ND	ND	4.5243
Indeno (1,2,3-cd) pyrene	5.2777	ND	ND	ND	26.2034
Benzo (g,h,i) perylene	17.5633	ND	ND	ND	8.8380
TOTAL	**72.9065**	**42.3876**	**15.2405**	**52.4717**	**71.7715**

ND=Not Detected

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

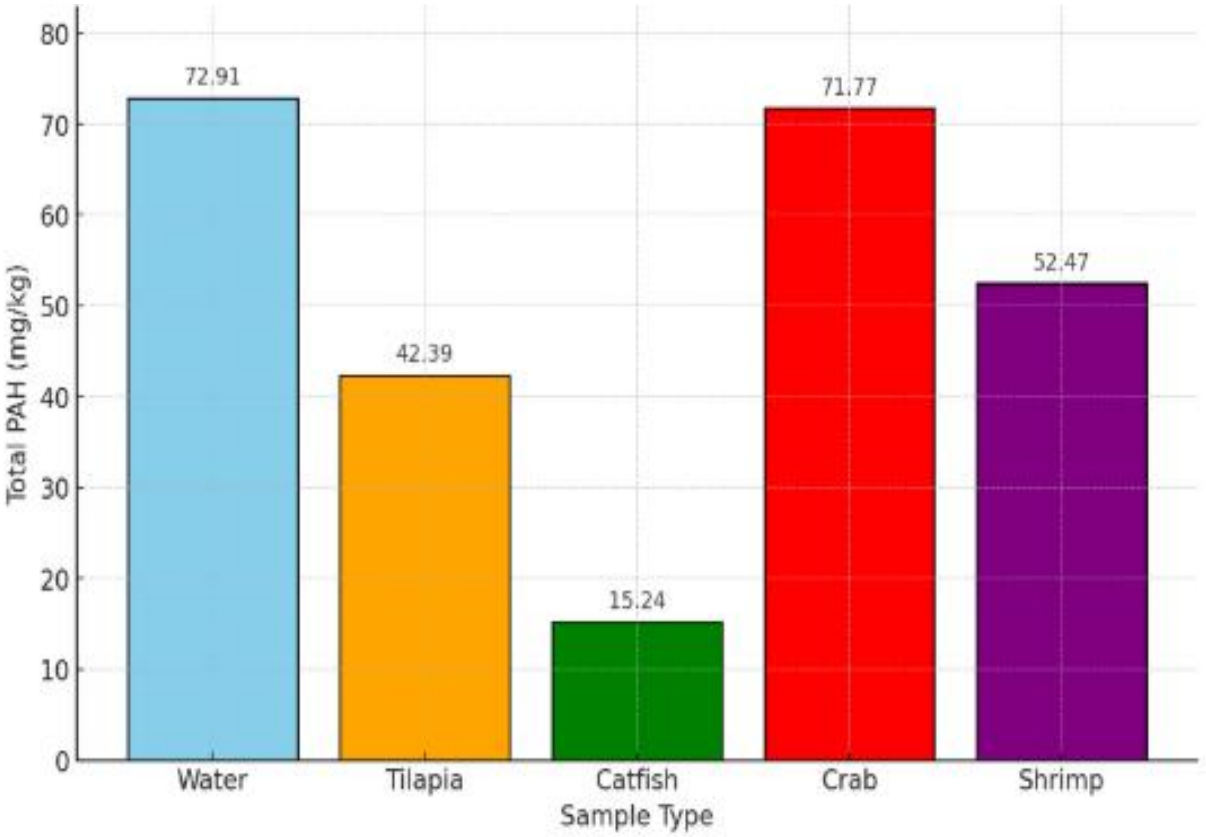


Figure 4.6: Total PAHs Concentration in Water and Biotic Samples of Lagos Lagoon
Source: Author's Field Work, 2025

Lead City University Ibadan

Table 4.7: Correlation Matrix of PAHs

	Nap	*Acy*	*Ace*	*Flu*	*Ant*	*Phe*	*Flt*	*Pyr*	*B[a]A*	*Chr*	*B[b]F*	*B[k]F*	*B[a]P*	*DB[a,h]A*	*Ind*	*B[g,h,i]P*
Nap	1															
Acy	0.98055	1														
Ace	-0.79395	-0.68717	1													
Flu	0.77868	0.88657	-0.3319	1												
Ant	-0.32456	-0.41289	-0.27439	-0.54876	1											
Phe	0.83417	0.92400	-0.4482	0.99082	-0.46773	1										
Flt	0.97150	0.93686	-0.87837	0.70572	-0.10845	0.77667	1									
Pyr	0.67590	0.59835	-0.51344	0.32501	-0.51572	0.37024	0.53806	1								
B[a]A	-0.37694	-0.1929	-0.77986	0.26546	-0.40425	-0.14880	-0.44639	-0.55183	1							
Chr	-0.57964	-0.47053	-0.86872	-0.15521	-0.31079	-0.28269	-0.62178	-0.57487	0.80725	1						
B[b]F	-0.47519	-0.31524	-0.83083	-0.10019	-0.33573	-0.02443	-0.51981	-0.63277	0.96194	0.93135	1					
B[k]F	-0.51471	-0.49277	-0.56574	-0.3846	-0.04389	-0.47158	-0.45773	-0.60105	0.41869	0.84055	0.65026	1				
B[a]P	-0.55699	-0.50088	-0.69846	-0.30978	-0.08309	-0.41507	-0.53339	-0.61977	0.58250	0.93237	0.78241	0.97947	1			
DB[a,h]A	-0.55624	-0.53728	-0.78514	-0.41959	-0.48154	-0.52329	-0.68522	-0.03919	0.38427	0.73818	0.59797	0.66701		1		
Ind	-0.31038	-0.3317	-0.18140	-0.34975	-0.36489	-0.38615	-0.16418	-0.61842	0.13219	0.54314	0.37163	0.89336	0.79997	0.20981	1	
B[g,h,i]P	-0.37619	-0.21162	-0.67670	-0.19892	-0.17734	-0.09217	-0.36971	-0.73594	0.93494	0.83753	0.96109	0.61377	0.72553	0.274792	0.44244	1

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

Lead City University Ibadan DO NOT COPY

Table 4.8: Correlation Matrix of PAHs Accumulation between Samples

	Water (ng/ul)	*Tilapia (mg/kg)*	*Catfish (mg/kg)*	*Shrimps (mg/kg)*	*Crabs*
Water	1				
Tilapia	0.014428	1			
Catfish	-0.16063	0.784252	1		
Shrimps	-0.30157	0.617532	0.840556	1	
Crabs	0.348308	-0.04751	-0.1234	-0.23229	1

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

4.1.7 Comparison of the Mean Concentration of PAHs in Samples from this Study with other Literature

The mean concentrations of PAHs in water, tilapia, catfish, crab and shrimp samples collected from Lagos Lagoon, in Lekki area of Lagos are compared to other study and this was presented in the table 4.9 below.

Table 4.9: Comparison of PAHs Concentrations in Samples with other Literatures

	This Study					River State[7]	Ogun River[8]	Osun State[9]
PAHs	**Water (mg/l)**	**Tilapia (mg/kg)**	**Crabs (mg/kg)**	**Shrimps (mg/kg)**	**Catfish**	**Tilapia mg/kg**	**Water (mg/l)**	**Prawn (mg/kg)**
Naphthalene	0.636	ND	ND	9.125	0.013	0.07	0.06	0.05
Acenaphthylene	4.925	ND	ND	3.205	0.015	0.008	0.061	0.162
Acenaphthene	1.599	4.123	3.312	1.103	2.519	0.21	0.18	0.04
Fluorene	0.116	0.055	0.02	2.295	0.128	0.11	0.1222	0.091
Anthracene	2.9584	0.0393	0.956	0.187	1.286	0.07	0.241	0.03
Phenanthrene	1.710	ND	ND	5.019	0.652	0.40	0.29	0.199
Fluoranthene	3.535	1.038	3.321	10.83	3.0224	0.36	0.37	0.27
Pyrene	9.121	18.092	3.270	20.44	7.605	0.601	0.291	0.251
Benzo (a) anthracene	1.6507	1.535	2.09	ND	ND	0.67	0.41	0.44
Chrysene	11.942	0.950	1.325	ND	ND	0.54	0.340	0233
Benzo (a) fluoanthene	4.013	3.283	5.866	ND	ND	0.78	0.48	0.61
Benzo (k) fluoanthene	3.3214	2.912	7.548	ND	ND	0.652	0.39	0.42
Benzo (a) pyrene	4.6966	2.1227	4.487	ND	ND	0.728	0.45	0.498
Dibenz (a,h) anthracene	5.277	8.227	4.524	ND	ND	0.44	0.279	0.263
Indeno (1,2,3-cd) pyrene	5.277	ND	26.20	ND	ND	0.68	0.40	0.489
Benzo (g,h,i) perylene	17.563	ND	8.838	ND	ND	0.8421	1.91	0.752

ND=Not Detected

Source: Author's Field Work, 2025

Lead City University Ibadan DO NOT COPY

4.2 Discussion of Findings

4.2.1 Discussion on Concentrations of PAHs in Water Samples from Lagos Lagoon

Table 4.1 summarizes the concentrations of the sixteen key PAHs in water samples taken from the Lagos lagoon. The results show that the lagoon sites (LLW1, LLW2, and LLW3) were extensively contaminated, with much higher PAH concentrations than the control site. At LLW1, results varied from 0.050 mg/kg for acenaphthylene to 18.44 mg/kg for benzo[g,h,i]perylene. Similarly, LLW2 measured 0.0499 mg/kg of acenaphthylene and 15.35 mg/kg of benzo[g,h,i]perylene, whereas LLW3 measured 0.0765 mg/kg of acenaphthylene and the highest total concentration of benzo[g,h,i]perylene (18.89 mg/kg). In contrast, the control site had only minimal quantities of acenaphthylene (0.0001 mg/kg) and pyrene (0.0012 mg/kg), with the majority of PAHs being absent or below detection criteria.

The distribution pattern shows a strong prevalence of high molecular weight (HMW) PAHs, including chrysene, benzo[a]pyrene, benzo[b]fluoranthene, and benzo[g,h,i]. as shown in Figure 4.1. For example, chrysene reached 1.71 mg/kg in LLW1 and 2.03 mg/kg in LLW3, whereas benzo[a]pyrene was recorded at 4.21 mg/kg in LLW1, 3.45 mg/kg in LLW2, and 2.30 mg/kg in LLW3. Benzo[b]fluoranthene levels were notably high, with 15.11 mg/kg in LLW2, 11.37 mg/kg in LLW1, and 9.34 mg/kg in LLW3. Such a high concentration of HMW PAHs indicates strong pyrogenic sources, which is compatible with incomplete combustion of fossil fuels, industrial emissions, and biomass burning, all of which are common in an urban-industrial environment like Lagos.

The high amounts of benzo[g,h,i]perylene in LLW3, which reached 18.89 mg/kg, provides additional support for pyrogenic inputs, as this molecule is highly connected with combustion

Lead City University Ibadan DO NOT COPY

processes. In contrast, the limited detection of naphthalene and other low molecular weight PAHs reflects their volatility and quick breakdown in the aquatic environment. The relative rarity of these compounds suggests that petroleum spills (petrogenic sources) are not the only culprits; combustion emissions appear to be the primary cause of lagoon contamination. These findings are consistent with previous research that indicated 1.25-9.87 mg/kg of total PAHs in Lagos Lagoon water, but the current study finds substantially higher values (up to 18.89 mg/kg), showing that pollution has deteriorated over the last decade[1]. Comparisons with other aquatic systems emphasize the seriousness of the problem.

The elevated concentrations in water samples underscore the lagoon's significance as a sink for atmospheric and terrestrial pollutants, as well as the risk of transfer to aquatic creatures. Because water is the principal medium of exposure for fish, crabs, and shrimp, elevated levels of carcinogenic PAHs in lagoon water directly enhance the likelihood of bioaccumulation and biomagnification in higher trophic levels[2,3].

4.2.2 Discussion on Concentrations of PAHs in Aquatic Organisms (Tilapia, Catfish, Crabs, and Shrimp)

Significant PAH contamination was found in tilapia samples after investigation (Table 4.2). Benzo[g,h,i]perylene concentrations in LLTF1 ranged from tiny amounts like 0.0001 mg/kg of naphthalene to as high as 16.20 mg/kg. With acenaphthene at 5.14 mg/kg, benzo[b]fluoranthene at 14.15 mg/kg, and benzo[g,h,i]perylene at 13.54 mg/kg, LLTF2 showed a similar pattern. With 10.14 mg/kg of benzo[a]anthracene, 9.64 mg/kg of benzo[b]fluoranthene, and a maximum of 17.86 mg/kg of benzo[g,h,i]perylene, LLTF3 displayed some of the highest values overall. Because they are the main source of protein for local communities, fish are very significant.

Lead City University Ibadan DO NOT COPY

Concern should be expressed about the higher amounts of PAHs, especially carcinogenic chemicals like benzo[a]pyrene. For example, Martínez discovered 1.02–6.81 mg/kg in Mediterranean fish, whereas Olajire observed 2.11–8.42 mg/kg in Osun River fish. Fish from Lagos Lagoon had far higher concentrations, which suggests that consumers are at much higher risk of exposure[4].

The concentrations of the sixteen priority PAHs in silver catfish *(Chrysichoyes nigrodigifatus*) collected from Lagos Lagoon are presented in Table 4.3. The analysis revealed marked variation in PAH levels across the sampling sites, with mean concentrations ranging from 0.03 mg/kg to about 17.0 mg/kg. Among the quantified PAHs, Benzo[g,h,i]perylene exhibited the highest mean concentration of approximately 17.0 mg/kg, followed by Benzo[b]fluoranthene, which recorded values around 13.5 mg/kg across the catfish samples. Benzo[a]pyrene (BaP), a compound of major toxicological concern, was detected at levels of about 3.9 mg/kg, which surpasses the 0.01 mg/kg safety guideline recommended by the European Food Safety Authority (EFSA) for food. Other notable compounds detected included Chrysene (4.5 mg/kg), Benzo[a]anthracene (8.5 mg/kg), and Indeno(1,2,3-cd)pyrene (5.0 mg/kg).

When compared with tilapia from the same lagoon, catfish showed slightly higher concentrations of key PAHs such as Benzo[a]pyrene and Benzo[g,h,i]perylene, confirming that catfish can retain substantial amounts of these compounds. The pattern of PAH accumulation as shown in Figure 4.2 to figure 4.5 observed in catfish is consistent with their feeding habit and contact with sediments within the lagoon environment. Furthermore, when benchmarked against previous studies in Ogun and Rivers States, the PAH concentrations in Lagos Lagoon catfish were found to be 10–20 times higher, highlighting the severity of contamination in this ecosystem. These findings indicate that the consumption of catfish from Lagos Lagoon may present significant health concerns.

Lead City University Ibadan DO NOT COPY

High PAH loads were also observed in crabs (Table 4.4). Benzo[g,h,i]perylene peaked at 15.68 mg/kg, while LLC1 had 3.78 mg/kg of benzo[a]pyrene, 11.62 mg/kg of benzo[b]fluoranthene, and 3.99 mg/kg of acenaphthene. While LLC3 recorded 17.23 mg/kg for benzo[g,h,i]perylene, LLC2 recorded 13.92 mg/kg for benzo[b]fluoranthene and 12.97 mg/kg for benzo[g,h,i]perylene. Compared to Ogun River crabs (1.12–6.12 mg/kg), these values are much greater. Given their intimate association with sediments as benthic feeders, crabs' elevated levels of PAHs demonstrate the significance of sediments as reservoirs for these substances[4].

Shrimp exhibited comparable trends. Benzo[g,h,i]perylene peaked at 14.61 mg/kg in LLS1, while chrysene, benzo[a]pyrene, and benzo[b]fluoranthene were detected at 1.29, 3.56, and 10.83 mg/kg, respectively as shown in table 4.5. Benzo[b]fluoranthene and benzo[g,h,i]perylene were found in 12.76 and 12.34 mg/kg, respectively, in LLS2, whereas benzo[g,h,i]perylene was found in 16.45 mg/kg in LLS3. Lagos Lagoon shrimp are significantly more contaminated than Indian coastal shrimp, which were reported to have levels of just 3.10–7.60 mg/kg.

Strong bioaccumulation potential is demonstrated by the consistently high quantities seen in all organisms. Chronic eating of fish, crabs, and shrimp from Lagos Lagoon may pose serious health concerns to dependent communities due to the preponderance of carcinogenic HMW PAHs.

Correlation analysis (Table 4.7 and Table 4.8) revealed that there exists a strong positive relationship between all the sixteen PAHs. However, there is no relationship between the samples as regard the level of PAH pollution observed in each of them.

Lead City University Ibadan DO NOT COPY

4.2.3 Comparison of PAH Concentrations between Lagoon Sites and Control

There is strong evidence of anthropogenic pollution when the lagoon sites and the control site are compared as shown in table 4.6 and figure 4.6. PAH levels in the control samples were either absent or very close to zero, with maximal values for pyrene and acenaphthylene being 0.0012 and 0.0001 mg/kg, respectively. Lagoon sites, however, reported concentrations that were several orders of magnitude higher[5].

For instance, benzo[g,h,i]perylene was completely absent in control but was present in LLW3 at 18.89 mg/kg, LLF3 at 17.86 mg/kg, LLC3 at 17.23 mg/kg, and LLS3 at 16.45 mg/kg. Additionally absent from the control, benzo[b]fluoranthene was measured at 15.11 mg/kg in LLW2, 14.15 mg/kg in LLF2, 13.92 mg/kg in LLC2, and 12.76 mg/kg in LLS2. These striking differences demonstrate how human activity has a major influence on the lagoon, whereas control represents the background circumstances that are naturally occurring. The findings unequivocally show that Lagos Lagoon is contaminated by petroleum waste, vehicle emissions, urban runoff, and industrial effluents. The severity of anthropogenic pollution in this environment is highlighted by the high concentration of carcinogenic PAHs in lagoon samples and their near-complete absence in the control location.

Lead City University Ibadan DO NOT COPY

4.2.4 Health Risk Assessment of PAHs in Water and Aquatic Organisms

The estimated daily intake of PAHs in contaminated biota samples were assessed for the adult population using Equation **EDI= C×IR÷BW**

The daily intake of PAHs from the biota samples was calculated by multiplying the respective PAH concentration in each sample by the ingestion rate of an average weight adult divided by the body weight of an average weight adult (70 kg).

Equation;

EDI= C×IR÷BW

- C= Concentration of aquatic organisms
- 1R= Ingestion rate
- BW= Body weight

Dietary intake concentration of Tilapia

- EDI=42.38764833×0.0685÷70
- EDI= 0.04148mg/kg-day

Dietary intake concentration of Catfish

- EDI=15. 2404883×0.0685÷70
- EDI =0.01491mg/kg

Dietary intake concentration of Crabs

- EDI =71.7714333×0.0016÷70

Lead City University Ibadan DO NOT COPY

- EDI ═0.0014049mg/kg

Dietary intake concentration of Shrimps

EDI ═52.47169×0.0219÷70

- EDI ═0.01641614mg/kg

where, 0.0685 kg/day is based on the assumption that an average Nigerian consumes 25 kg of fish per annum and an average of 0.0016 and 0.0219 kg/day of crabs and shrimp, respectively

Target Hazard Quotient and Incremental Lifetime Hazard Risk

The health risk assessment of polycyclic aromatic hydrocarbons (PAHs) in aquatic organisms from Lagos Lagoon was undertaken using both non-carcinogenic and carcinogenic risk indices. The Hazard Quotient (HQ) was applied to evaluate non-carcinogenic effects, while the Incremental Lifetime Cancer Risk (ILCR) was used to assess carcinogenic potential. Both indices are derived from the Estimated Daily Intake (EDI), which quantifies human exposure through consumption of contaminated fish and shellfish.

$HQ = EDI_{BaP} \div RFD_{BaP}$

Where, EDI_{BaP} ═ Estimated daily intake

RFD_{BaP} ═ refrence dose

Target Hazard Quotient For Tilapia

$HQ = EDI_{BaP} \div RFD_{BaP}$

HQ=0.0020773÷0.0003

HQ=6.924333

Target Hazard Quotient For Crab

Lead City University Ibadan DO NOT COPY

$HQ=EDI_{BaP} \div RFD_{BaP}$

HQ= 0.0001028÷0.0003

HQ= 0.34193

Incremental Lifetime Hazard Risk

$ILCR=EDI_{BaP} \times CSF_{BaP}$

EDI_{BaP}= Estimated daily intake

CSF_{BaP}= Cancer Slope Factor

Incremental Lifetime Hazard Risk for Tilapa

$ILCR=EDI_{BaP} \times CSF_{BaP}$

ILCR = 0.0020773×7.3

ILCR =0.01516

Incremental Lifetime Hazard Risk for Crab

$ILCR=EDI_{BaP} \times CSF_{BaP}$

ILCR = 0.00010258×73

ILCR = 0.0007478

The EDI expresses the daily dose of a contaminant ingested per unit body weight. It was calculated using the standard USEPA exposure model:

EDI = C × IR÷BW

where C is the mean contaminant concentration in edible tissues (mg/kg wet weight), IR is the ingestion rate of the species (kg/day), and BW is the average body weight (70 kg for adults). This approach has been widely applied in dietary exposure assessments of PAHs in aquatic. Tilapia had a mean benzo[a]pyrene (BaP) concentration of 2.12 mg/kg, and with an ingestion rate of 0.0685

Lead City University Ibadan DO NOT COPY

kg/day, the EDI was estimated at 0.00208 mg/kg-day. Crab, with a higher mean BaP concentration (4.49 mg/kg) but a much lower ingestion rate (0.0016 kg/day), yielded a considerably smaller EDI of 0.000103 mg/kg-day. Catfish and shrimp had non-detectable BaP values and therefore negligible EDI contributions.

The Reference Dose (RfD) is a health-based threshold value that defines the maximum daily oral exposure to a chemical that is unlikely to cause adverse non-carcinogenic health effects during a lifetime. RfDs are established by agencies such as the U.S. Environmental Protection Agency (USEPA) based on toxicological data (EPA,). Typically, the RfD is derived from a No Observed Adverse Effect Level (NOAEL) or a Benchmark Dose (BMD) from animal bioassays, which is then divided by uncertainty factors (UFs) to account for interspecies extrapolation, intraspecies variability, and data limitations (WHO,). For BaP, a provisional oral RfD of 3×10^{-4} mg/kg-day has been adopted in several risk[6].

The HQ was calculated as: **EDI×RfD**

Values of HQ < 1 indicate no significant non-carcinogenic risk, while HQ ≥ 1 suggests possible adverse health effects. In this study, the HQ for tilapia was 6.92, indicating BaP exposure several times greater than the safe threshold, suggesting potential for adverse health effects. For crab, HQ was 0.34, below the critical threshold, while catfish and shrimp had HQ values of zero.

Carcinogenic risks were assessed using the Incremental Lifetime Cancer Risk (ILCR), which quantifies the probability of an individual developing cancer from a given lifetime exposure. ILCR is calculated as:

ILCR = EDI \ CSF

Lead City University Ibadan DO NOT COPY

where CSF (Cancer Slope Factor) represents the upper-bound probability of cancer per unit dose, derived from long-term animal bioassays or human epidemiological studies. For benzo[a]pyrene, the USEPA IRIS database recommends an oral CSF of 7.3 $(mg/kg\text{-}day)^{-1}$ The ILCR for tilapia was 1.52×10^{-2}, greatly exceeding the acceptable range of 1×10^{-6} to 1×10^{-4} commonly used in regulatory frameworks.[7] Crab also exceeded the upper threshold with an ILCR of 7.48×10^{-4}, though substantially lower than tilapia. Catfish and shrimp had negligible ILCR values due to non-detectable BaP[8]. These findings highlight tilapia and crab as the principal dietary exposure routes to BaP-associated cancer risks in the lagoon.

Overall, the HQ and ILCR results suggest that frequent consumption of tilapia and crab from Lagos Lagoon may pose significant health concerns. Tilapia was identified as particularly problematic, with both non-cancer and cancer risk indices well above recommended thresholds. While crab consumption presented moderate carcinogenic risk, catfish and shrimp appeared to pose minimal risk under the concentrations measured[9,10]

4.2.5 Comparison of Findings with Previous Studies (Nigeria and International)

The current results demonstrate that Lagos Lagoon is among Nigeria's most polluted aquatic ecosystems when compared to previous research as shown in table 4.9. For example, 0.35–5.60 mg/kg of PAHs were found in fish from the Niger Delta, which is significantly less than the maximum of 17.86 mg/kg found in fish from the Lagos Lagoon. Additionally, it was reported that Osun River fish had 2.11–8.42 mg/kg, which is also less than the current findings. Ogun River crabs had up to 6.12 mg/kg, according to Adeyemi, whereas Lagos Lagoon crabs in this study had up to 17.23 mg/k[11].

Lead City University Ibadan DO NOT COPY

The range concentration of 3.10–7.60 mg/kg was reported in Indian shrimp, 1.02–6.81 mg/kg in Mediterranean fish, and 0.56–12.50 mg/kg in Pearl River Delta fish were recorded internationally. Lagos Lagoon had higher values in every instance, with carcinogenic HMW PAH quantities predominating. These comparisons highlight how Lagos Lagoon is significantly more stressed by pollution than many other aquatic systems in Nigeria and outside. The results verify that the main causes of contamination are inadequate waste management procedures, industrial discharges, petroleum operations, and fast urbanization[12].

Lead City University Ibadan DO NOT COPY

Endnotes

1. L. Zhao, M. Zhou, Y. Zhao, J. Yang, Q. Pu, H. Yang, Y. Wu, C. Lyu, Y. Li, *Potential toxicity risk assessment and priority control strategy for PAHs metabolism and transformation behaviors in the environment,* **International Journal of Environmental Research and Public Health,** 19(17), 2022, 10972. https://doi.org/10.3390/ijerph191710972

2. M. Honda, X. Qiu, J. Koyama, S. Uno, S.L Undap, Y. Shimasaki, Y. Oshima Y, *The wharf roach, Ligia sp, A novel indicator of polycyclic aromatic hydrocarbon contamination in coastal areas*, **Int. J. Environ. Res**, 12, 2018, 1–11. doi: 10.1007/s41742-017-0063-x.

3. M. Camacho, A. Herrera, M. Gómez, A. Acosta-Dacal, I. Martínez, L.A Henríquez-Hernández, O.P Luzardo*, Organic pollutants in marine plastic debris from Canary Islands beaches*, **Sci. Total Environ,** 662, 2019, 22–31. doi: 10.1016/j.scitotenv.2018.12.422.

4. M. Mali, R. Ragone, M.M Dell'Anna, G. Romanazzi, L. Damiani, P. Mastrorilli, *Improved Identification of Pollution Source Attribution by Using PAH Ratios Combined with Multivariate Statistics,* **Sci. Rep**, 12, 2022, 19298.

5. K. Bralewska, J. Rakowska, *Concentrations of Particulate Matter and PM-Bound Polycyclic Aromatic Hydrocarbons Released during Combustion of Various Types of Materials and Possible Toxicological Potential of the Emissions,The Results of Preliminary Studies*, **Int. J. Environ. Res. Public Health**, 17, 2020, 3202.

6. N.Y Ashayeri, B. Keshavarzi, F. Moore, M. Kersten, M. Yazdi, A.R Lahijanzadeh, *Presence of Polycyclic Aromatic Hydrocarbons in Sediments and Surface Water from Shadegan Wetland–Iran A Focus on Source Apportionment, Human and Ecological Risk Assessment and Sediment-Water Exchange Ecotoxicol,* **Environ. Saf,**148, 2018, 1054–1066.

7. G. Ji, L. Zou, W. Guan, T. Yang, H. Qiu, L. Zhu, Partition, *Transportation and Ecological Risks of Polycyclic Aromatic Hydrocarbons (PAHs) under Heavy Anthropogenic Estuary: A Case Study in the Xiaoqing River Estuary, North China,* **Reg. Stud. Mar. Sci,** 43, 2021, 101664.

8. E. Santos, M.R.R Souza, A.R.V Junior, L. da Silva Soares, M. Frena, M.R Alexandre, *Polycyclic Aromatic Hydrocarbons in Suspended Particulate Matter of a Region Influenced by Agricultural Activities in Northeast Brazil,* **Reg Stud Mar Sci.** 57, 2023, 102683.
9. J. Yang, A. Qadeer, M. Liu, J.M Zhu, Y.P Huang, W.N Du, X.Y Wei, *Occurrence, Source, and Partition of PAHs, PCBs, and OCPs in the Multiphase System of an Urban Lake, Shanghai*, **Appl. Geochem,** 106, 2019, 17–25.

Lead City University Ibadan DO NOT COPY

10. A. L Cathey, D.J Watkins, Z.Y Rosario, C.M Vélez Vega, R. Loch-Caruso, A.N Alshawabkeh, J.F Cordero, J.D Meeker, *Polycyclic Aromatic Hydrocarbon Exposure Results in Altered CRH, Reproductive, and Thyroid Hormone Concentrations during Human Pregnancy*, **Sci. Total Environ**, 749, 2020, 141581.

11. K. Sun, Y. Song, F. He, M. Jing, J. Tang, R. Liu, *A Review of Human and Animals Exposure to Polycyclic Aromatic Hydrocarbons: Health Risk and Adverse Effects, Photo-Induced Toxicity and Regulating Effect of Microplastics*, **Sci. Total Environ**, 773, 2021, 145403.

12. A. Azimi, A. Riahi Bakhtiari, R. Tauler, *Polycyclic Aromatic Hydrocarbon Source Fingerprints in the Environmental Samples of Anzali, South of Caspian Sea,* **Environ. Sci. Pollut. Res**, 27, 2020, 32719–32731.

Lead City University Ibadan DO NOT COPY

Chapter Five

Conclusion and Recommendation

5.1 Summary of Findings

This research analyzed sixteen priority polycyclic aromatic hydrocarbons (PAHs) in Lagos Lagoon, Nigeria, with a particular emphasis on their concentrations in water and selected aquatic animals such as fish, crabs, and shrimp. This study was prompted by growing concerns about the increasing anthropogenic activities within the lagoon catchment, such as petroleum exploration, industrial operations, urban waste disposal, and combustion processes, all of which are recognized as major sources of PAH contamination in aquatic systems. This study sought to provide baseline data on the presence, distribution, and dangers associated with PAHs in Lagos Lagoon, so benefiting both environmental science and public health management.

Water, fish, crabs, and shrimp samples were obtained from the Lagos Lagoon and compared to a control site that was not directly affected by industrial or urban activities. The United States Environmental Protection Agency (USEPA) identified and quantified all sixteen key PAHs through laboratory investigation. Data from the analysis were subsequently processed to estimate concentration ranges, mean values, and comparative differences between lagoon and control areas. Health risk indices such as the estimated daily intake (EDI), hazard quotient (HQ), and incremental lifetime cancer risk (ILCR) were used to examine the possible consequences for both ecological health and human populations reliant on lagoon resources. The results showed that all sixteen key PAHs were discovered in all lagoon samples, while the control location had either low or trace quantities. In water, values varied from 0.05 mg/kg for acenaphthylene to 18.89 mg/kg for

Lead City University Ibadan DO NOT COPY

benzo[g,h,i]perylene. Fish levels ranged up to 17.86 mg/kg, whereas crabs and shrimp had maximums of 17.23 mg/kg and 16.45 mg/kg, respectively. The presence of high molecular weight PAHs such as benzo[a]pyrene, chrysene, benzo[b]fluoranthene, and benzo[g,h,i]perylene across all matrices suggested that pyrogenic sources, particularly incomplete fuel combustion and industrial emissions, play a significant role in the lagoon's contamination profile. The comparatively low amounts of low molecular weight PAHs lend support to this hypothesis, as lighter PAHs are often linked with petrogenic inputs from petroleum spills.

A critical aspect of the findings was the discovery of bioaccumulation potential in aquatic creatures. Fish, crabs, and shrimp, which are regularly consumed by people around Lagos Lagoon, had consistently higher PAH contents than water samples. This not only validates pollutant uptake from the aquatic environment, but also raises food safety and public health issues, as the International Agency for Research on Cancer (IARC) classifies high molecular weight PAHs, particularly benzo[a]pyrene, as potential human carcinogens. The health risk assessment also identified potential non-carcinogenic and carcinogenic concerns from food intake, emphasizing the need for monitoring and regulatory intervention.

Comparisons with earlier research in Nigeria and abroad revealed that the quantities found in Lagos Lagoon were at the upper end of the reported range. For example, PAH levels in Niger Delta fish ranged between 0.35 and 5.60 mg/kg, whereas values in the Osun River ranged between 2.11 and 8.42 mg/kg. In comparison, this study found fish concentrations as high as 17.86 mg/kg. Similarly, crabs from the Ogun River contained 6.12 mg/kg, while Lagos Lagoon crabs contained up to 17.23 mg/kg. International studies also found lower levels, with PAHs in the Pearl River Delta, China, ranging from 0.56 to 12.50 mg/kg and Mediterranean fish ranging from 1.02 to 6.81

Lead City University Ibadan DO NOT COPY

mg/kg. These comparisons show that the Lagos Lagoon is more significantly impacted, reflecting the region's industrial, petroleum, and urban influences.

This study provides evidence that Lagos Lagoon serves as both a sink and a route for PAHs. On the one hand, it collects contaminants from diverse anthropogenic sources and, on the other, transports them into aquatic biota, which are eventually consumed by people. This dual role has far-reaching repercussions, highlighting hazards to not only ecological balance but also food safety and community health. The findings emphasize the importance of immediate regulatory action, effective pollution management techniques, and public health awareness efforts to reduce the dangers of PAH exposure.

5.2 Conclusion

A study of sixteen key polycyclic aromatic hydrocarbons (PAHs) in Lagos Lagoon found that the lagoon is experiencing substantial ecological stress due to anthropogenic contamination. All sixteen chemicals were found in water, fish, crab, and shrimp samples at significantly higher amounts than the control site. The greatest levels were found in benzo[g,h,i]perylene, which was 18.89 mg/kg in water, 17.86 mg/kg in fish, 17.23 mg/kg in crabs, and 16.45 mg/kg in shrimp. Similarly, other carcinogenic high molecular weight compounds were consistently dominant across all sample types, including benzo[a]pyrene (4.21 mg/kg in water and 4.01 mg/kg in fish), benzo[b]fluoranthene (15.11 mg/kg in water and 14.15 mg/kg in fish), and chrysene (2.03 mg/kg in water and 2.10 mg/kg in fish). These findings not only show the prevalence of PAHs in the lagoon, but also highlight the importance of high molecular weight fractions, which are more persistent and harmful.

Lead City University Ibadan DO NOT COPY

The increased levels seen in fish, crab, and shrimp show the contaminants' bioaccumulation potential. Because these species are commonly consumed in the surrounding communities, the findings raise serious food safety and public health concerns. The presence of PAHs in aquatic species indicates that they are integrated into the lagoon food web, where long-term exposure may have a cascade effect on biodiversity and ecosystem resilience. The insignificant levels reported in the control site confirm that the contamination observed in the lagoon is anthropogenic in nature, resulting from industrial emissions, petroleum wastes, urban runoff, and combustion activities common in the Lagos metropolis.

Taken together, the results show that Lagos Lagoon is a key hotspot for PAH contamination in Nigeria. This has significant ramifications not only for ecological health, but also for human communities who rely on the lagoon for fishing, recreation, and other income-generating activities. This study provides strong evidence that urgent action is required by demonstrating the magnitude and distribution of PAH pollution.

5.3 Recommendations

Based on the outcome of this study, the followings are therefore recommended

1. Policy and Regulation: Regulatory agencies such as NESREA and LASEPA should strengthen enforcement of industrial effluent standards and petroleum handling practices. Industries discharging into the lagoon should be compelled to treat wastewater using modern technologies capable of reducing organic pollutants.

2. Monitoring and Surveillance: Routine monitoring of PAHs in Lagos Lagoon should be institutionalized. Data should be collected seasonally to capture variations linked to rainfall, urban

Lead City University Ibadan DO NOT COPY

runoff, and industrial activity. Monitoring should extend beyond water and biota to sediments, which act as long-term sinks for PAHs.

3. Public Health and Awareness: Local communities should be sensitized on the dangers of consuming contaminated fish, crabs, and shrimp. Government and NGOs should organize campaigns highlighting dietary risks, with special emphasis on women and children who may be more vulnerable to toxic exposure.

4. Sustainable Management: Investment in green technologies such as bioremediation using microorganisms, phytoremediation with aquatic plants, and clean energy alternatives should be encouraged to reduce dependence on combustion sources of energy.

5. International Collaboration: Partnerships with global environmental agencies could help to standardize monitoring methods and implement proven strategies for lagoon restoration, drawing on lessons from ecosystems such as the Chesapeake Bay (USA) and the Pearl River Delta (China).

5.4 Contributions to Knowledge

This research contributes significantly to existing knowledge in various ways. It contains one of the most extensive datasets on all sixteen key PAHs in Lagos Lagoon, tested in both water and different aquatic species (fish, crab, and shrimp). While earlier research in Nigeria has frequently focused on particular matrices, such as sediments or isolated water samples, this study reveals the interconnectedness of contamination across abiotic and biotic compartments.

This research reveals that large molecular weight PAHs dominate in Lagos Lagoon, separating it from systems with higher levels of lighter PAHs. This has significance for source identification because high molecular weight PAHs are more strongly associated with combustion activities

Lead City University Ibadan DO NOT COPY

including fuel burning, industrial emissions, and waste incineration. By identifying this tendency, the study contributes to a better understanding of pollution dynamics in heavily urbanized tropical lagoons. It also improves understanding of bioaccumulation trends in Nigerian aquatic habitats. By assessing PAHs in edible species such as fish, crabs, and shrimp, it provides evidence of pollution transfer into the food chain, an area where data is particularly limited. This broadens the scope of PAH risk assessment in Nigeria, expanding beyond environmental contamination to consider food safety and human health.

This research further recognizes Lagos Lagoon as both a sink and a conduit for PAHs. The persistence of high molecular weight chemicals suggests that the lagoon acts as a pollutant reservoir, while their presence in aquatic biota indicates that it also functions as a transmission conduit to humans. These findings close a major data gap and will be useful to scientists, environmental managers, and policymakers working to reduce chemical contamination in aquatic systems.

5.5 Suggested Areas for Further Research

Several research gaps were identified in this study. Future studies should:

a. Conduct long-term monitoring to capture seasonal and annual trends of PAH accumulation, as temporal variation was beyond the scope of this study.
b. Undertake source apportionment studies using diagnostic ratios and stable isotopic fingerprinting to clearly differentiate between petrogenic and pyrogenic PAH inputs.
c. Carry out toxicological experiments on aquatic organisms to assess the sub-lethal effects of chronic PAH exposure, including impacts on reproduction, growth, and survival.

Lead City University Ibadan DO NOT COPY

d. Perform human health risk assessments linking dietary exposure from lagoon seafood to potential cancer and non-cancer risks. Such studies would provide vital data for food safety regulations.

e. Expand research into sediment contamination, as sediments serve as long-term reservoirs for PAHs and may act as secondary sources during resuspension events.

f. Investigate remediation strategies, such as bioremediation, phytoremediation, and engineered wetland systems, for their potential in reducing PAH levels in Lagos Lagoon.

Lead City University Ibadan DO NOT COPY

Biblography

Periodical Article

World Health Organization, *Human Health Effects of Polycyclic Aromatic Hydrocarbons as Ambient Air Pollutants: Report of the Working Group on Polycyclic Aromatic Hydrocarbons of the Joint Task Force on the Health Aspects of Air Pollution; World Health Organization Regional Office for Europe,* **Copenhagen, Denmark**, 2021, ISBN 978-92-890-5653-3.

Instituto Brasileiro de Geografia e Estatística – IBGE, *Estatísticas sociais. Expectativa de vida dos brasileiros aumenta 3 meses e chega a 76,6 anos em 2019*, 2020b https://agenciadenoticias.ibge.gov.br/agencia-noticias/2012-agencia-de-noticias/noticias/29505-expectativa-de-vida-dos-brasileiros-aumenta-3-meses-e-chega-a-76-6-anos-em-2019.

Instituto Brasileiro de Geografia e Estatística – IBGE, *Pesquisa de Orçamentos Familiares (POF) 2017–2018: análise do consumo alimentar pessoal no Brasil*. Rio de Janeiro: **IBGE,** 125, 2020a. https://biblioteca.ibge.gov.br/visualizacao/livros/liv101742.pdf.

Journals

Aakko-Saksa P.T, Lehtoranta K, Kuittinen N, Järvinen A, Jalkanen J.P, Johnson K, Jung H, Ntziachristos L, Gagné S, Takahashi C, *Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options*, **Prog. Energy Combust. Sci**, 94, 2023, 101055.

Abdel Rahman A.N, Mahmoud S.M, Khamis T, Rasheed N, Mohamed D.I, Ghanem R, Mansour D.M, Ismail T.A, Mahboub H.H, *Palliative effect of dietary common sage leaves against toxic impacts of nonylphenol in Mirror carp (Cyprinus carpio var specularis), Growth, gene expression, immune-antioxidant status, and histopathological alterations*, **J Aquac Rep**, 25, 2022, 101200

Lead City University, Ibadan DO NOT COPY

Adegbola P.I, Aborisade A.B, Adetutu A, *Health risk assessment and heavy metal accumulation in fsh species (Clarias gariepinus and Sarotherodon melanotheron) from industrially polluted Ogun and Eleyele Rivers, Nigeria,* **Toxicol Rep**, 8(2021), 2021, 1445–1460.

Adeniji A.O, Okoh O.O, Okoh A.I, *Distribution pattern and health risk assessment of polycyclic aromatic hydrocarbons in the water and sediment of Algoa Bay, South Africa*, **Environmental Geochemistry and Health**, 41(3), 2018, 1303-1320. https://doi.org/10.1007/s10653-018-0213-x

Adetutu A, Adegbola P.I, OwoadeA. O, Aborisade A.B, *Fish as a bioindicator of polycyclic aromatic hydrocarbon pollution in aquatic ecosystem of Ogun and Eleyele Rivers, Nigeria, and risk assessment for consumer's health,* **J Hazard Mater Adv,** 7, 2022, 100096

Adeyeye E.I, Ibigbami O.A, Adesina A.J, Popoola O.K, Olatoye A.R, Gbolagade Y.A, *Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) Distribution in Water, Sediments and Fish Parts from Ponds in Ado-Ekiti, Nigeria,* **Polycyclic Aromatic Compounds**, 43(4), 2023, 3147-3158.

Afonne O.J, Ifediba E.C, *Heavy Metals Risks in Plant Foods–Need to Step up Precautionary Measures,* **Current Opinion in Toxicology,** 22, 2020, 1-6.

Aigberua A.O, Ogbuta A.A, Izah S.C, *Selected Heavy Metals in Sediment of Taylor Creek due to Anthropogenic Activities in the Niger Delta Region of Nigeria: Geochemical Spreading and Evaluation of Environmental Risk*, **Biodivers Int J,** 4(2), 2020, 67-80.

Aigwi I.E, Phipps R, Ingham J, Filippova O, *Characterisation of adaptive reuse stakeholders and the effectiveness of collaborative rationality towards building resilient urban areas*, **Systemic Practice and Action Research,** 34(2), 2020, 141-151. https://doi.org/10.1007/s11213-020-09521-0

Ajewole O.A, Ikhimiukor O.O, Adelowo O.O, *Heavy Metals (Cu and Zn) Contamination of Pond Sediment and Co-Occurrence of Metal and Antibiotic Resistance in Escherichia Coli from Nigerian Aquaculture*, **International Journal of Environmental Studies,** 78(5), 2021, 773-784.

Akinnusotu A, Ukpebor J.E, Okieimen F.E, *Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) in Sediment and Fish Samples of River Owan, and Agricultural Soil around the Same River in EDO State, Nigeria*, **Environmental Sciences Proceedings,** *7*(1), 2020, 11.

Akinnusotu A, Ukpebor J.E, Okieimen F.E, *Source, Distribution, and Risk Assessment of Polycyclic Aromatic Hydrocarbons in Sediment and Fish Samples from River Owan, Edo State, Nigeria*. **Frontiers in Toxicology**, 5, 2023, 1-16.

Akinsanya B, Ayanda I.O, Onwuka B, Saliu J.K, *Bioaccumulation of BTEX and PAHs in Heterotis Niloticus (Actinopterygii) from the Epe Lagoon, Lagos, Nigeria*, **Heliyon,** 6(1), 2020 e03272. doi: 10.1016/j.heliyon.2020.e03272

Ledi City University Ibadan DO Not Copy

Albert J.S, Destouni G, Duke-Sylvester S.M, Magurran A.E, Oberdorff T, Reis R.E, Winemiller K.O, Ripple W.J, *Scientists' Warning to Humanity on the Freshwater Biodiversity Crisis,* **Ambio,** 50, 2021, 85–94.

Alegbeleye O.O, Opeolu B.O, Jackson V.A, *Polycyclic aromatic hydrocarbons: A critical review of environmental occurrence and bioremediation,* **Environmental Management**, 60(4), 2017, 758-783. https://doi.org/10.1007/s00267-017-0896-2

Almeida M.V.D, Rissato S.R, Galhiane M.S, Fernandes J.R, *P.C Lodi, M.C.D Campos, In vitro phytoremediation of persistent organic pollutants by Helianthus annuus L. plants***,** **Química Nova**, 2017. https://doi.org/10.21577/0100-4042.20170177

Amadi C.N, Frazzoli C, Orisakwe O.E, *Sentinel Species for Biomonitoring and Biosurveillance of Environmental Heavy Metals in Nigeria*, **Journal of Environmental Science and Health, Part C,** 38(1), 2022, 21-60.

Ambade B, Sethi S.S, *Health Risk Assessment and Characterization of Polycyclic Aromatic Hydrocarbon from the Hydrosphere*, **J. Hazard. Toxic Radioact. Waste,** 25, 2021 05020008.

An X, Li W, Lan J, Di X, Adnan M, *Seasonal co-pollution characteristics of parent-PAHs and alkylated-PAHs in karst mining area soil of Guizhou, Southwest China*, **Frontiers in Environmental Science,** *10*, 2022, 990471. https://doi.org/10.3389/fenvs.2022.990471

Anyanwu I.N, Sikoki F.D, Semple K.T, *Baseline PAHs, N-PAHs, and 210Pb in segment samples from Bodo Creek: Comparison with Bonny estuary, Niger Delta,* **Water, Air, & Soil Pollution**, 232(9), 2021, 5316. https://doi.org/10.1007/s11270-021-05316-8

Avelino J.E, Crichton R.N, Valenzuela V.P, Odara M.G.N, Padilla M.A.T, Kiet N.H, Anh D.H, Van P.C, Bao H.D, Thao N.H.P, *Survey tool for rapid assessment of socio-economic vulnerability of fishing communities in Vietnam to climate change*, **Geosciences**, 8(12), 2018, 452. https://doi.org/10.3390/geosciences8120452.

Azimi A, Riahi Bakhtiari A, Tauler R, *Polycyclic Aromatic Hydrocarbon Source Fingerprints in the Environmental Samples of Anzali, South of Caspian Sea,* **Environ. Sci. Pollut. Res**, 27, 2020, 32719–32731.

Azimi A, Riahi Bakhtiari A, Tauler R, *Polycyclic Aromatic Hydrocarbon Source Fingerprints in the Environmental Samples of Anzali, South of Caspian Sea*, **Environ. Sci. Pollut. Res**, 27, 2020, 32719–32731.

Bai Y, Yu H, Shi K, Shang N, He Y, Meng L, Huang T, Yang H, Huang C, *Polycyclic Aromatic Hydrocarbons in Remote Lakes from the Tibetan plateau (Concentrations, Source, Ecological Risk, and Influencing Factors),* **J. Environ. Manag,** 319, 2022, 115689.

Baldiris-Avila R, O'Byrne-Hoyos I, Aldous K.M, Addink R, Kannan K, *Polycyclic aromatic hydrocarbons and their hydroxylated metabolites in fsh bile and sediments from coastal*

Lead City University Ibadan DO NOT COPY

waters of Colombia, **Environ Pollut,** 151(3), 2019, 452–459. https://doi.org/10.1016/j.envpol.2007.04.011.

Baldwin A.K, Corsi S.R, Oliver S.K, Lenaker P.L, Nott M.A, Mills M.A, Norris G.A, Paatero P, *Primary sources of polycyclic aromatic hydrocarbons to streambed sediment in Great Lakes tributaries using multiple lines of evidence,* **Environmental Toxicology and Chemistry**, 39(7), 2020, 1392-1408. https://doi.org/10.1002/etc.4727

Baran A, Klimkowicz-Pawlas A, Ukalska-Jaruga A, Mierzwa-Hersztek M, Gondek K, Szara-Bąk M, Tarnawski M, Spałek I, *Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in the Bottom Sediments of a Dam Reservoir, Their Interaction with Organic Matter and Risk to Benthic Fauna***, J. Soils Sediments,** 21, 2021, 2418–2431.

Barathi S, Gitanjali J, Rathinasamy G, Sabapathi N, Aruljothi K.N, Lee J, Kandasamy S, *Recent trends in polycyclic aromatic hydrocarbons pollution distribution and counteracting bio-remediation strategies*, **Chemosphere,** 2023,139396.

Barbosa F, Rocha B.A, Souza M.C.O, Bocato M.Z, Azevedo L.F, Adeyemi J.A, Santana A, Campiglia A.D*, Polycyclic Aromatic Hydrocarbons (PAHs), Updated Aspects of Their Determination, Kinetics in the Human Body, and Toxicity*, **J. Toxicol. Environ. Health B Crit. Rev**, 26, 2023, 28–65.

Behera B.K, Das A, Sarkar D.J, Weerathunge P, Parida P.K, Das B,K, Thavamani P, Ramanathan R, Bansal V*, Polycyclic Aromatic Hydrocarbons (PAHs) in inland aquatic ecosystems: Perils and remedies through biosensors and bioremediation*, **J Environ Pollut,** 241, 2018, 212-33.

Bhatti S.S, Bhatia A, Bhagat G, Singh S, Dhaliwal S.S, Sharma V, Verma V, Yin R, Singh J, *PAHs in Terrestrial Environment and Their Phytoremediation, In Bioremediation for Sustainable Environmental Cleanup, CRC Press*, **Boca Raton**, FL, USA, 2024. ISBN 978-1-003-27794-1.

Bian H, Zhu Y, Wen L, Ma J, Li P, Geng Z, Xu W, *Occurrence and health risks of heavy metals in crayfish (Procambarus clarkii) from Jiangsu province, China*, **Food Production, Processing and Nutrition**, 5, 2023, 63. https://doi.org/10.1186/s43014-023-00169-6

Bralewska K, Rakowska J, *Concentrations of Particulate Matter and PM-Bound Polycyclic Aromatic Hydrocarbons Released during Combustion of Various Types of Materials and Possible Toxicological Potential of the Emissions, The Results of Preliminary Studies*, **Int. J. Environ. Res. Public Health**, 17, 2020, 3202.

Chiang C.F, Hsu K.C., Tsai, T.Y., Cho C.Y., Hsu, C.H., Yang, D.J., *Evaluation of optimal QuEChERS conditions of various food matrices for rapid determination of EU priority polycyclic aromatic hydrocarbons in various foods,* **Food Chemistry,** 334, 2021, 127471.

Cai P, Ning Z, Liu Y, He Z, Shi J, Niu M, *Diagnosing bioremediation of crude oil-contaminated soil and related geochemical processes at the field scale through microbial community and*

Lead City University Ibadan DO NOT COPY

functional genes, **Annals of Microbiology**, 70(1), 2020, 01580. https://doi.org/10.1186/s13213-020-01580-x

Camacho M, Herrera A, Gómez M, Acosta-Dacal A, Martínez I, Henríquez-Hernández L.A, Luzardo O.P*, Organic pollutants in marine plastic debris from Canary Islands beaches*, **Sci. Total Environ,** 662, 2019, 22–31. doi: 10.1016/j.scitotenv.2018.12.422.

Campos I, Abrantes N, *Forest Fires as Drivers of Contamination of Polycyclic Aromatic Hydrocarbons to the Terrestrial and Aquatic Ecosystems*, **Curr. Opin. Environ. Sci. Health,** 24, 2021, 100293.

Cathey A.L, Watkins D.J, Rosario Z.Y, Vélez Vega C.M, Loch-Caruso R, Alshawabkeh, J.F Cordero A.N, Meeker J.D, *Polycyclic Aromatic Hydrocarbon Exposure Results in Altered CRH, Reproductive, and Thyroid Hormone Concentrations during Human Pregnancy*, **Sci. Total Environ**, 749, 2020, 141581.

Chamalidou E, Gazis A, Gikas G.D, *Removal of polycyclic aromatic hydrocarbons from polluted water using constructed wetlands*, **International Journal on Engineering Technologies and Informatics**, 3(1) 2022. https://doi.org/10.51626/ijeti.2022.03.00027

Chang J, Zhang E, Liu E, Liu H, Yang X, *A 60-year historical record of polycyclic aromatic hydrocarbons (PAHs) pollution in lake sediment from Guangxi Province, southern China,* **Anthropocene,** 24, 2018, 51-60. https://doi.org/10.1016/j.ancene.2018.11.003

Chao L, Mo X, Meng J, Li Y, *Study on enhanced bioremediation effect of oil-bearing dredging sediment*, **E3S Web of Conferences**, 252, 2021 02031. https://doi.org/10.1051/e3sconf/202125202031

Chen J, Liao J, Wei C, *Coking wastewater treatment plant as a sources of polycyclic aromatic hydrocarbons (PAHs) in sediments and ecological risk assessment*, **Scientific Reports**, 10(1), 2020, 7833. https://doi.org/10.1038/s41598-020-64835-2

Chen Y, Sun C, Zhang J, Zhang F, *Assessing 16 Polycyclic Aromatic Hydrocarbons (PAHs) in River Basin Water and Sediment Regarding Spatial-Temporal Distribution, Partitioning, and Ecological Risks,* **Polish Journal of Environmental Studies**, *27*(2) 2018.

Cherr G.N, Fairbairn E, Whitehead A, *Impacts of petroleum-derived pollutants on fish development,* **Annual Review of Animal Biosciences,** 5(1), 2017, 185-203. https://doi.org/10.1146/annurev-animal-022516-022928

Correa-García S, Rheault K, Tremblay J, Séguin A, Yergeau E, *Soil characteristics constrain the response of microbial communities and associated hydrocarbon degradation genes during phytoremediation,* **Applied and Environmental Microbiology**, 87(2), 2021. https://doi.org/10.1128/aem.02170-20

Head City University Ibadan DO NOT COPY

Cortés-Arriagada D, *High stability and properties of adsorbed polycyclic aromatic hydrocarbons (PAHs) onto phosphorene: An atomistic DFT study*, ***ChemRxiv*****,** 2021. https://doi.org/10.33774/chemrxiv-2021-lmst6

Czub, G, McLachlan, M. S, Bioaccumulation potential of persistent organic chemicals in humans. *Environmental Science & Technology, 38*(8), 2406-2412. https://doi.org/10.1021/es034871v

Das D.N, Ravi N*, Influences of polycyclic aromatic hydrocarbon on the epigenome toxicity and its applicability in human health risk assessment*, **Environ. Res,** 213, 2022, 113677.

Davies I.C, Ekperusi A.O, *Evaluation of Heavy Metal Concentrations in Water, Sediment and Fishes of New Calabar River in Southern Nigeria,* **Journal of Limnology and Freshwater Fisheries Research**, *7*(3), 2021, 207-218.

Dey S, Ballav P, Samanta P, Mandal A, Patra A, Das S, Mondal A.K, Ghosh A.R*, Time-Dependent Naphthalene Toxicity in Anabas testudineus (Bloch): A Multiple Endpoint Biomarker Approach*, **ACS Omega**, 6(1),2021, 317-26.

Dubiel J.F, Green D, Raza Y, Johnson H.M, Xia Z, Tomy G.T, Hontela A, Doering J.A, Wiseman S, *Alkylation of benz[a]anthracene affects toxicity to early-life stage zebrafish and in vitro aryl hydrocarbon receptor 2 transactivation in a position-dependent manner*, **Environmental Toxicology and Chemistry,** *41*(8), 2022, 1993-2002. https://doi.org/10.1002/etc.5396

Dutta K, Shityakov S, Zhu W, Khalifa I, *High-risk meat and fish cooking methods of polycyclic aromatic hydrocarbons formation and its avoidance strategies*, **Food Control,** 142, 2022, 109253. https://doi.org/10.1016/j.foodcont.2022.109253

E. Aykın-Dinçer E, *Dried meat products obtained by different methods from past to present*, **Food Reviews International,** 39(5), 2021 1–20. https://doi.org/10.1080/87559129.2021.1956944

Ebrahimzadeh M, Heidari B, Nazarhaghighi F, Valipour A*, Physiological Responses of the Goldfish (Carassius auratus) During Subacute Exposure to Organic Pollutants*, **Bull Environ Contam Toxicol,** 106(5), 2021, 773-8.

Edogbo B, Okolocha E, Maikai B, Aluwong T, Uchendu C, *Risk Analysis of Heavy Metal Contamination in Soil, Vegetables and Fish around Challawa Area in Kano State, Nigeria*, **Scientific African,** *7*, 2020, e00281.

Egbeja T.I, Kadiri J.U, Onoja A.O, Isah A.O, *Determination of Heavy Metals in Water, Sediments and Tissues of Clarias Garipienus and Oreochromis Niloticus from Kpata River, Lokoja, Nigeria,* **International Journal of Fisheries and Aquatic Studies,** 7(5), 2019, 25-29.

Egesi O.C, Alum-Udensi O, Ogbonna P.C, Ugor N.N, *Assessment of Heavy Metals in Water, Fish, and Sediment of River Benue, Benue State, Nigeria,* **Nigeria Agricultural Journal,** 54(1), 2023, 55-67.

Faculty University Ibadan DO NOT COPY

Ehiemere V.C, Ihedioha J.N, Ekere N.R, Ibeto C.N, Abugu H.O, *Pollution and Risk Assessment of Heavy Metals in Water, Sediment and Fish (Clarias Gariepinus) in a Fish Farm Cluster in Niger Delta Region, Nigeria,* **Journal of Water and Health,** 20(6), 2022, 927-945.

Ejiako E.J, Iheme O.U, Okonkwo C.U, *Persistent Organic Pollutant, A Review on the Distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in Aquatic Ecosystem*, **Int J Environ Sci Nat Res,** 29(5), 2022, 556272.

El-Bouhy Z,M, Reda R.M, Mahboub H.H, Gomaa F.N**,** *Bioremediation effect of pomegranate peel on subchronic mercury immunotoxicity on African catfish (Clarias gariepinus),* **J Environ Sci Pollut***,* 28(2), 2021, 2219-2235.

El-Bouhy Z.M, Reda R.M, Mahboub H.H, Gomaa F.N*, Chelation of mercury intoxication and testing different protective aspects of Lactococcus lactis probiotic in African catfish*, **Aquac. Res,** 52(8), 2021, 3815-28.

Emenike E.C, Iwuozor K.O, Anidiobi S.U, *Heavy Metal Pollution in Aquaculture: Sources, Impacts and Mitigation Techniques,* **Biological Trace Element Research,** 2021, 1-17.

Eyankware M.O, Obasi P.N, *A Holistic Review of Heavy Metals in Water and Soil in Ebonyi SE, Nigeria; with Emphasis on its Effects on Human, Plants and Aquatic Organisms,* **World News of Natural Sciences,** 38, 2021, 1-19.

Farhadi S, Javanmard M, Mahdavi S, *Effects of nanomaterial reinforced fibrous casing of sugarcane bagasse on the adsorption of polycyclic aromatic hydrocarbons in smoked sausages***, ACS Food Science & Technology,** 2(6), 2022, 1009–1017. https://doi.org/10.1021/acsfoodscitech.2c00073

Ferrante M, Zanghì G, Cristaldi A, Copat C, Grasso A, Fiore M, Signorelli S.S, Zuccarello P, Conti G.O*, PAHs in seafood from the Mediterranean Sea, an exposure risk assessment,* **Food Chem Toxicol,** 115, 2018, 385–390

Franco M.E, Lavado R, *Applicability of in vitro methods in evaluating the biotransformation of polycyclic aromatic hydrocarbons (PAHs) in fish, Advances and challenges*, **Sci. Total Environ,** 671, 2019, 685-95.

Gearhart-Serna L.M, Jayasundara N, Tacam Jr M, Di Giulio R, Devi G.R, *Assessing cancer risk associated with aquatic polycyclic aromatic hydrocarbon pollution reveals dietary routes of exposure and vulnerable populations,* **Journal of Environmental and Public Health**, 2018, 1-10. https://doi.org/10.1155/2018/5610462

Geiker N.R.W, Bertram H.C, Mejborn H, Dragsted L.O, Kristensen L, Carrascal J.R, Astrup A, *Meat and human health—Current knowledge and research gaps,* **Foods***,* 10(7), 2021, 1556. https://doi.org/10.3390/foods10071556

Lead City University Ibadan DO NOT COPY

Gherardi S, Uccello M.M, *Heavy metals and PAHs in meat, milk, and seafood from Augusta area (Southern Italy): contamination levels, dietary intake, and human exposure assessment,* **Front. Public Health**, 8, 2020, 273.

Goedtke L, Sprenger H, Hofmann U, Schmidt F.F, HammerH.S, Zanger U.M, Poetz O, Seidel A, Braeuning A, Hessel-Pras S, *Polycyclic Aromatic Hydrocarbons Activate the Aryl Hydrocarbon Receptor and the Constitutive Androstane Receptor to Regulate Xenobiotic Metabolism in Human Liver Cells*, **Int J Mol Sci,** 22(1), 2022.

Goher M.E, Ali M.H, El-Sayed S.M, *Heavy Metals Contents in Nasser Lake and the Nile River, Egypt: An Overview,* **The Egyptian Journal of Aquatic Research,** 45(4), 2019, 301-312.

Grimard C, *In vitro-in vivo, cross-life stage and inter-species extrapolation of the biotransformation and uptake of benzo [a] pyrene in two fish species using toxicokinetic models*, **University of Saskatchewan**, 2021.

Grmasha R.A, Abdulameer M.H, Stenger-Kovács C, Al-sareji O.J, Al- Gazali Z, Al-Juboori R.A, Meiczinger M, Hashim K.S*, Polycyclic aromatic hydrocarbons in the surface water and sediment along Euphrates River system: Occurrence, sources, ecological and health risk assessment,* **Mar. Pollut. Bull,** 187, 2023, 114568.

Hamidi S, Banaee M, Pourkhabbaz H.R, Sureda A, Khodadoust S, Pourkhabbaz A.R, *Effect of petroleum wastewater treated with gravity separation and magnetite nanoparticles adsorption methods on the blood biochemical response of mrigal fish (Cirrhinus cirrhosus),* **Environ. Sci. Pollut. Res**, 29(3), 2022, 3718-32.

Han M, Yu K, Zhang R, Chen B, Li H, Zhang Z.E, Li J, Zhang G, *Sources of the elevating polycyclic aromatic hydrocarbon pollution in the western South China Sea and its environmental implications*, **Environmental Science & Technology,** 57(49), 2023, 20750-20760. https://doi.org/10.1021/acs.est.3c03452

Hasan A.B, Reza A.S, Kabir S, Siddique M.A.B, Ahsan M.A, Akbor M.A, *Accumulation and Distribution of Heavy Metals in Soil and Food Crops around the Ship Breaking Area in Southern Bangladesh and Associated Health Risk Assessment,* **SN Applied Sciences,** *2*, 2020, 1-18.

Honda M, Qiu X, Koyama J, Uno S, Undap S.L, Shimasaki Y, Oshima Y*, The wharf roach, Ligia sp, A novel indicator of polycyclic aromatic hydrocarbon contamination in coastal areas*, **Int. J. Environ. Res**, 12, 2018,1–11. doi: 10.1007/s41742-017-0063-x.

Honda M, Suzuki N, *Toxicities of polycyclic aromatic hydrocarbons for aquatic animals*, **International Journal of Environmental Research and Public Health,** 17(4), 2020, 1363. https://doi.org/10.3390/ijerph17041363

Hu T, Yuan J, Wang X, Yan C, Ju X, *Spectral-spatial features extraction of hyperspectral remote sensing oil spill imagery based on convolutional neural networks*, **IEEE Access**, 10, 2022, 127969-127983. https://doi.org/10.1109/access.2022.3194260

Lead City University Ibadan DO NOT COPY

Idowu G.A, *Heavy Metals Research in Nigeria: A Review of Studies and Prioritization of Research Needs,* **Environmental Science and Pollution Research,** 29(44), 2022, 65940-65961.

Izah S.C, Richard G, Stanley H.O, Sawyer W.E, Ogwu M.C, Uwaeme O.R, *Potential applications of linear regression models in studying the relationship between fish and contaminants in their environment: One Health perspective,* **Juniper Online Journal of Public Health**, 8(4), 2024a, 555743. https://doi.org/10.19080/JOJPH.2024.08.555743

Izah S.C, Richard G, Stanley H.O, Sawyer W.E, Ogwu M.C, Uwaeme O.R, *Prospects and application of multivariate and reliability analyses to One Health risk assessments of toxic elements,* **Toxicology and Environmental Health Sciences**, 16(2), 2024b, 127-134.

Jafarabadi A.R, Mashjoor S, Bakhtiari A.R, Jadot C, *Dietary intake of polycyclic aromatic hydrocarbons (PAHs) from coral reef fish in the Persian Gulf-human health risk assessment,* **Food Chem**, 2020b, In press. https://doi.org/10.1016/j.foodchem.2020.12703

Jafarabadi A.R, Mashjoor S, Bakhtiari A.R, Jadot C, *Dietary intake of polycyclic aromatic hydrocarbons (PAHs) from coral reef fsh in the Persian Gulf—human health risks assessment*, **Food Chem**, 2020a. https://doi.org/10.1016/j.foodchem.2020.127035.

Janarthanam V.A, Issac P.K, Guru A, Arockiaraj J, *Hazards of polycyclic aromatic hydrocarbons: a review on occurrence, detection, and role of green nanomaterials on the removal of PAH from the water environment,* **J Environ. Monit. Assess,** 195(12), 2023, 1531.

Jesus F, Pereira J.L, Campos I, Santos M, Ré A, Keizer J, Nogueira A, Gonçalves F.J.M, Abrantes N, Serpa D, *A review on polycyclic aromatic hydrocarbons distribution in freshwater ecosystems and their toxicity to benthic fauna,* **Sci. Total Environ**, 820, 2022, 153282.

Ji G, Zou L, Guan W, Yang T, Qiu H, Zhu L, Partition, *Transportation and Ecological Risks of Polycyclic Aromatic Hydrocarbons (PAHs) under Heavy Anthropogenic Estuary: A Case Study in the Xiaoqing River Estuary, North China,* **Reg. Stud. Mar. Sci,** 43, 2021, 101664.

Kafouris D, Koukkidou A, Christou E, Hadjigeorgiou M, Yiannopoulos S, *Determination of polycyclic aromatic hydrocarbons in traditionally smoked meat products and charcoal grilled meat in Cyprus,* **Meat Science,** 164, 2020, 108088. https://doi.org/10.1016/j.meatsci.2020.108088

Kamiya Y, The R.S, Hariyan S.L, Sajise M.T, Bandala A.W, *PAH Fingerprinting from Mixed Wood Combustion Sources Using Multivariate Analysis*, **Environmental Pollution**, 259 (6), 2020, 113−154.

Kartalović B, Puljić L, Kovačević D, Markovčić M, Vranešević J , Habschied K, Mastanjević K, *The Content of Polycyclic Aromatic Hydrocarbons in Slavonska slanina—Traditionally Smoked and Dry-Cured Bacon,* **Processes**, 10(2), 2022, 268. https://doi.org/10.3390/pr10020268

Lead City University/Ibadan Do NOT COPY

Khan M.M.T, Sklar L, *Environmental contaminants in aquatic systems and chemical safety for environmental and human health, volume II*, **J Front. Public Health,** 11, 2023, 1157834.

Khan M.Z, Shah S.Y, Ahmed K.L, *Nitro-PAHs in Urban Air (Sources and Health Risk in a Megacity),* **Science of the Total Environment**, 884, 2023, 163−173.

Khan R, *Source Attribution, Emission Factors, and Regulation*, **Atmospheric Environment**, 42 (13), 2019, 2895–97.

Kong X, Dong R, King T, Chen F, Li H, *Biodegradation potential of Bacillus sp. PAH-2 on PAHs for oil-contaminated seawater*, **Molecules,** 27(3), 2022, 687. https://doi.org/10.3390/molecules27030687

Kumar M, Bolan N.S, Hoang S.A, Sawarkar A.D, Jasemizad T, Gao B, Keerthanan S, Padhye L.P, Singh L, Kumar S, *Remediation of soils and sediments polluted with polycyclic aromatic hydrocarbons: to immobilize, mobilize, or degrade*, **J Hazard. Mater,** 420, 2021, 126534.

Kumari A, Upadhyay V, Kumar S, *A critical insight into occurrence and fate of polycyclic aromatic hydrocarbons and their green remediation approaches,* **Chemosphere**, 2023, 138579.

Lee B.K, Vu V.T, *Sources, distribution and toxicity of polycyclic aromatic hydrocarbons (PAHs) in Particulate Matter Department of Civil and Environmental Engineering*, **University of Ulsan Korea**, 13, 2019, 34–42

Li R, Shi Y, Li M, Huang Y, Li K, Xu T, Liu H, Xi Y, *Distribution and migration of polycyclic aromatic hydrocarbons in sediment and water of the Three Gorges Reservoir*, **Soil Science Society of America Journal**, 86(3), 2022, 566-578. https://doi.org/10.1002/saj2.20393.

Li Y, Gou N, Zou X, Li P, Zou S, Luo J, Yang Y, *Pollution level and health risk assessment of polycyclic aromatic hydrcarbons in marine fsh from two coastal regions, the south china sea*, **Mar Pollut Bull**, 168, 2021b, 112376

Li Y, Zou X, Zou S, Li P, Yang Y, Wang J, *Pollution status and trophic transfer of polycyclic aromatic hydrocarbons in coral reef ecosystems of the South China Sea*, **ICES J Mar Sci,** 78(6), 2021a, 2053–2064

Liu L, Li W, Song W, Guo M, *Remediation techniques for heavy metal-contaminated soils: Principles and applicability,* **The Science of the Total Environment**, 633, 2018, 206-219. https://doi.org/10.1016/j.scitotenv.2018.03.161

Liu M, Zheng H, Wang W, Ke H, Huang P, Liu S, Chen F, Lin Y, Cai M, *Enhanced sinks of polycyclic aromatic hydrocarbons due to Kuroshio intrusion: Implications on biogeochemical processes in the ocean-dominated marginal seas,* **Environmental Science & Technology,** 55(10), 2021, 6838-6847. https://doi.org/10.1021/acs.est.1c01009

Leadcity University Ibadan DO NOT COPY

Lou S, Shrivastava M, Ding A, Easter R.C, Fast J.D, Rasch P.J, Shen H, Massey Simonich S.L, Smith S.J, Tao S, *Shift peaks of PAH-associated health risks from East Asia to South Asia and Africa in the future,* 2022. https://doi.org/10.1002/essoar.10512341.1

M.S. Dauda & J.O. Olaofe, *Determination of Physico-chemical Parameters of River Majowopa Sagamu Ogun State, Nigeria,* **Advance Journal of Chemistry-Section A**., 12(4), 2020, 569-575. Doi:10.22034/ajca.2020.103664.

Mahboub H.H, Shahin K, Mahmoud S.M, Altohamy D.E, Husseiny W.A, Mansour D.A, Shalaby S.I, Gaballa M.M.S, Shaalan M, Alkafafy M, Rahman A.N.A, *Silica nanoparticles are novel aqueous additive mitigating heavy metals toxicity and improving the health of African catfish*, **Clarias gariepinus. Aquat. Toxicol,** 249, 2022, 106238.

Mahugija J.A, Njale E, *Effects of washing on the polycyclic aromatic hydrocarbons (PAHs) contents in smoked fish,* **Food Control**, 93, 2018, 139–143

Malhat F, Loutfy N, El Menyawi M.A.I, Ahmed M.T, *Review of Contamination by Polycyclic Aromatic Hydrocarbons (PAHs) in Egyptian Aquatic Environment,* **Polycycl Aromat Compd**, 41(7), 2021, 1447-58.

Mali M, Ragone R, Dell'Anna M.M, Romanazzi G, Damiani L, Mastrorilli P, *Improved Identification of Pollution Source Attribution by Using PAH Ratios Combined with Multivariate Statistics,* **Sci. Rep**, 12, 2022, 19298.

Mallah, M. A., Changxing, L., Mallah, M. A., Noreen, S., Liu, Y., Saeed, M., & Zhang, Q, *Polycyclic aromatic hydrocarbon and its effects on human health: an updated review*, **Chemosphere***, 296*, 2022, 133948. https://doi.org/10.1016/j.chemosphere.2022.133948

Man Y.B, Mo W.Y, Zhang F, Wong M.H, *Health Risk Assessments Based on Polycyclic Aromatic Hydrocarbons in Freshwater Fish Cultured Using Food Waste-Based Diets,* **Environ. Pollut**, 256, 2020, 113380.

Melillos G, Kalogirou E, Makri D, Hadjimitsis D.G, *Oil spill detection and monitoring in the Cyprus region*, **In *Ocean Sensing and Monitoring XV*,** 12543, 2023, 175-181

Méndez García M, García de Llasera M.P, *A Review on the Enzymes and Metabolites Identified by Mass Spectrometry from Bacteria and Microalgae Involved in the Degradation of High Molecular Weight PAHs,* **Sci. Total Environ**, 797, 2021, 149035.

Merlo T.C, Molognoni L, Hoff R.B, Daguer H, Patinho I, Contreras-Castillo C.J, *Alternative pressurized liquid extraction using a hard cap espresso machine for determination of polycyclic aromatic hydrocarbons in smoked bacon*, **Food Control**, 120, 2021, 107565.

Mirzababaei A, Daneshzad E, Moradi S, Abaj F, Mehranfar S, Asbaghi O, Mirzaei K, *The association between urinary metabolites of polycyclic aromatic hydrocarbons (PAHs) and cardiovascular diseases and blood pressure: a systematic review and meta-analysis of*

Lead City University Ibadan DO NOT COPY

observational studies, **Environmental Science and Pollution Research**, 29, 2022,1712–1728. https://doi.org/10.1007/s11356-021-17091-4.

Mo J, Au D.W.T, Wan M.T, Shi J, Zhang G, Winkler C, Kong R.Y.C, Seemann F, *Multigenerational Impacts of Benzo[a]pyrene on Bone Modeling and Remodeling in Medaka (Oryzias latipes),* **Environ. Sci. Technol**, 54(19), 2020 12271- 84.

Montuori P, De Rosa E, Di Duca F, De Simone B, Scippa S, Russo I, Sarnacchiaro P, Triassi M, *Polycyclic aromatic hydrocarbons (PAHs) in the dissolved phase, particulate matter, and sediment of the Sele River, southern Italy, A focus on distribution, risk assessment, and sources*, **Toxics**, 10(7), 2022, 401. https://doi.org/10.3390/toxics10070401

Moslen M, Aniekan I, Onwuteaka J, Miebaka C.A, *Bioaccumulation and consumption safety of a sea food, gastropod mollusc (Thais coronata), polycyclic aromatic hydrocarbon (PAH) perspective,* **Journal of Applied Sciences and Environmental Management,** 25(7), 2021,1239-1247 https://doi.org/10.4314/jasem.v25i7.20

Mpofu R.V, Daniels M.B, Rampedi F.G, *PAHs in Water and Sediment along a Mining-Impacted River (Distribution and Risk),* **Environmental Geochemistry and Health**, 42 (10), 2020, 335–370.

Müller M, Hohn H, Weihrauch J, Leipold D, *PAH Ratios vs. CMB, A Comparative Analysis of Source Apportionment Accuracy,* **Atmospheric Pollution Research,** 13 (6), 2022, 101−238.

N. Çiftçi, A. Deniz, *Polycyclic aromatic hydrocarbons in seafood from the mediterranean sea,* **Mediterranean Fisheries and Aquaculture Research,** 4(3), 2021, 74-9.

N. Derakhshesh, N. Salamat, A. Movahedinia, M. Hashemitabar, V. Bayati, *Exposure of liver cell culture from the orange-spotted grouper, Epinephelus coioides, to benzo[a]pyrene and light results in oxidative damage as measured by antioxidant enzymes,* **Chemosphere**, 226,2019, 534-44.

N. Soltani, F. Moore, B. Keshavarzi, A. Sorooshian, R. Javid, *Potentially toxic elements (PTEs) and polycyclic aromatic hydrocarbons (PAHs) in fish and prawn in the Persian Gulf, Iran*, **Ecotoxicol Environ Saf**, 173, 2019, 251–265.

N.R Bury, *Cytotoxic and genotoxic responses of the RTgillW1 fsh cells in combination with the yeast oestrogen screen to determine the sediment quality of Lagos lagoon, Nigeria*, **Mutagenesis**, 30(1), 2019, 117–127. https://doi.org/10.1093/mutage/geu032.

N.R Weerakkodige, C.K Hemachandra, A. Pathiratne, *Assessing genotoxic potential of petroleum refinery wastewater using biomarkers of laboratory exposed and field captured fishes*, **Sri Lanka Journal of Aquatic Sciences,** 26(2), 2021, 97-110. https://doi.org/10.4038/sljas.v26i2.7590

N.Y Ashayeri, B. Keshavarzi, F. Moore, M. Kersten, M. Yazdi, A.R Lahijanzadeh, *Presence of Polycyclic Aromatic Hydrocarbons in Sediments and Surface Water from Shadegan*

Lead City University Ibadan DO NOT COPY

Wetland—Iran A Focus on Source Apportionment, Human and Ecological Risk Assessment and Sediment-Water Exchange Ecotoxicol, **Environ. Saf,**148, 2018, 1054–1066.

Nadipelli V.R, Elwing J.M, Oglesby W.H, El Kersh K, *Social determinants of health in pulmonary arterial hypertension patients in the United States: clinician perspective and health policy implications,* **Pulmonary Circulation**, 12(3), 2022, e12111. https://doi.org/10.1002/pul2.12111

Nalwa S.K, Hassan A.A, Olagoke B.A, *Optimization of Passive Sampling for Dissolved PAHs in Tropical Waters,* **Water Research**, 236, 2024, 118−170.

Namihira-Santillán P.E, Ortega-López A.L, Campos-Domínguez D.L, *PAHs in Sediments and Shrimps (Levels, Sources, and Ecological Risk in a Tropical Estuary),* **Marine Pollution Bulletin**, 199, 2025, 115−402.

Nielsen K.M, Alloy M.M, Damare L, Palmer I, Forth H.P, Morris J, Stoeckel J.A, Roberts A.P, *Planktonic fiddler crab (Uca longisignalis) are susceptible to photoinduced toxicity following in ovo exposure in oiled mesocosms,* **Environmental Science & Technology**, 54(10), 2020, 6254-6261. https://doi.org/10.1021/acs.est.0c00215

Nnoruka S.O, Nwosu C.E, Okechukwu N.L, *PAHs in Drinking Water Distribution Systems of a Nigerian Metropolis (Levels, Sources and Risk),* **Journal of Water and Health**, 21 (5), 2023, 693–706.

Norris L, Horton C.M, Hart A.Y, *PAHs in Urban Air, Soil, and Vegetation, Comparative Study in Three Megacities*, **Environmental Science & Technology**, 58 (3), 2024, 1587–1595

Nowak K, Jablonska E, Ratajczak-Wrona W, *Immunomodulatory effects of synthetic endocrine disrupting chemicals on the development and functions of human immune cells*, **Environ Int,** 125, 2019, 350–364

Nwankwoala H.O, Obire O, Olorunfemi D, *Assessment of PAHs in soils and vegetables from oil-producing areas in Rivers State, Nigeria*. **African Journal of Environmental Science and Technology**, 15(4), 2021, 152–163.

Nwugo R.M, Chukwu D.C, Ukpai G.I, *Soil Bioremediation of PAHs (Indigenous Microbial Communities in Agricultural Lands)*, **Science of the Total Environment,** 982, 2025, 163−329.

Nyangoko B.P, Berg H, Mangora M.M, Gullström M, Shalli M.S, *Community perceptions of mangrove ecosystem services and their determinants in the Rufiji Delta, Tanzania,* **Sustainability,** 13(1), 2020, 63. https://doi.org/10.3390/su13010063

Nzeh O.C, Udeh-Okoye M.S, Nweke N.O, *Atmospheric Deposition of PAHs onto Surface Water Bodies in Lagos,* **Atmospheric Pollution Research,** 14 (1), 2023, 45–55.

Lead City University Ibadan DO NOT COPY

Obanya H.E, Babatunde E.A, Otitoloju K.S, *Lagos Lagoon Sediment Organic Extracts and Polycyclic Aromatic Hydrocarbons Induce Embryotoxic, Teratogenic and Genotoxic Effects in Danio rerio (Zebrafish),* **Toxicology Reports**, 6, 2019, 1112–23

Odika I.M, Nwanisobi G.C, Nwankwo N.V, Mmaduakor E.C, Ikeh O.A, *Polycyclic Aromatic Hydrocarbons, PAHs Contamination Levels and Health Risks in Foods Consumed in Nigeria: A Review,* **Asian Journal of Food Research and Nutrition,** 2(4), 2023, 558-570.

Offor C.C, Okeke F.O, Ifeanyi S.C, *Appraisal of Polycyclic Aromatic Hydrocarbons (PAHs) in Indoor Dust from Urban Homes Exposure and Health Risk Assessment,* **Environmental Advances,** 15, 2024, 583−590.

Ogbobode I.C, Chinedu A.I, Anene C.I, *Levels and Health Risk of PAHs in Water and Sediment of Lagos Lagoon's Industrial Arm*, **Journal of Water & Health**, 19 (6), 2021, 987–1000.

Oghoghorie E.P, Okon M.A, Udeh C.C, *PAHs in Groundwater of an Oil-Bearing Coastal Plain: Hydrogeological Controls and Health Risk*, **Science of the Total Environment,** 906,2024, 167−264.

Ogunkoya C.O, Layade G.O, Edunjobi H.O, Fayemi P, *Evaluation Of Physiochemical Properties And Contaminant Index In Selected River Water Around Ewekoro.* ASRIC **Journal on Natural Sciences** Vol. 4(2), 2024, 22-34.

Ohimain J, Ebhomeya C, Kogbara M, *Characterization of PAHs in Crude Oil-Contaminated Soils of the Niger Delta*, **International Journal of Environmental Quality**, 32 (5), 2023, 299–312.

Okafor C.C, Konne J.L, Ntaah L.D, Awolo S.N, Ideriah T.J.K, *Polycyclic Aromatic Hydrocarbons Contents of Sediment and Water in Drainages and Receiving Elechi Creek in Port Harcourt, Rivers State, Nigeria,* **IJRIAS**, 2024, 487–93.

Okedeyi O.O, Nindi I.A, Awofolu E.A, *Distribution and Potential Health Risks of Polycyclic Aromatic Hydrocarbons in Street Dust from Industrial, Residential and Traffic Areas in Lagos, Nigeria,* **Environmental Monitoring and Assessment**, 187 (2), 2019, 167.

Okedeyi O.O, Nindi I.A, Awofolu E.A, *PAHs in Street Dust from Urban Lagos: Distribution and Health Risks,* **Environmental Monitoring and Assessment,** 191 (3), 2019, 167.

Okoye I.P, Anekwe I.G, *Levels and sources of PAHs in agricultural soils from oil-producing areas of Nigeria*, **Environmental Toxicology and Chemistry**, 39(11), 2020, 2212–2220. *Available online:* https://doi.org/10.1002/etc.4857

Oluwagbami O.O, Akintayo J.B, *Awareness of engagement strategies and stakeholders' responsiveness and formulation of corporate social responsibility goals in the fast-moving consumer goods industry in Lagos and Ogun States, Nigeria,* **NIU Journal of Social Sciences,** 8(2), 2022. https://doi.org/10.58709/niujss.v8i2.1439

Omolara B.A, Adewuyi A.O, Omotayo K.S, *PAHs in Smoked Fish from Southwestern Nigeria(Occurrence and Risk Implications),* **Toxicology Reports**, 6, 2019,1003–1110.

LeadCity University Ibadan DO NOT COPY

Onopiuk A, Kołodziejczak K, Marcinkowska-Lesiak M, Poltorak A, *Determination of polycyclic aromatic hydrocarbons using different extraction methods and HPLC-FLD detection in smoked and grilled meat products,* **Food Chemistry,** 373, 2022, 131506. https://doi.org/10.1016/j.foodchem.2021.131506

Onopiuk A, Kołodziejczak K, Szpicer A, Wojtasik-Kalinowska I, Wierzbicka A, Półtorak A, *Analysis of factors that influence the PAH profile and amount in meat products subjected to thermal processing*, **Trends in Food Science & Technology,** 115, 2021, 366–379. https://doi.org/10.1016/j.tifs.2021.06.043

Osei K.A, Amoako A.E, Armah R.A, *PAHs in Surface Waters of an Urbanizing Basin in Ghana: Distribution, Sources and Risk*, **Environmental Monitoring and Assessment**, 193 (6), 2021, 360.

Otitoloju A.A, Fabunmi D.O, Bandele A.A, *PAHs in Fish from Lagos Lagoon, Biomarker Responses and Human Health Implications,* **Environmental Toxicology and Pharmacology**, 104 (7), 2023, 104−147

Ouro-Sama K, Tanouayi G, Solitoke H.D, Barsan N, Mosnegutu E, Badassan T.E.E, Agbere S, Adje K, Nedeff V, Gnandi K, *Polycyclic Aromatic Hydrocarbons (PAHs) Contamination in Chrysichthys Nigrodigitatus Lacépède, 1803 from Lake Togo-Lagoon of Aného, Togo, Possible Human Health Risk Suitable to Their Consumption*, **Int. J. Environ. Res. Public Health**, 20, 2023, 1666.

Oyo-Ita I.O, Oyo-Ita O.E, Ugim S.U, Nnaji N.N, Elarbaoui S, *Source and Toxicological Assessment of Polycyclic Aromatic Hydrocarbons in Sediments from Imo River, Southeastern Nigeria*, **Polycyclic Aromatic Compounds,** 39(3), 2019, 191-206.

Paris A, Ledauphin J, Poinot P, Gaillard J.L*, Polycyclic aromatic hydrocarbons in fruits and vegetables: Origin, analysis, and occurrence*, **Environmental Pollution,** 234, 2018, 96–106. https://doi.org/10.1016/j.envpol.2017.11.028

Patel A.B, Shaikh S, Jain K.R, Desai C, Madamwar D, *Polycyclic aromatic hydrocarbons: Sources, toxicity, and remediation approaches,* **Frontiers in Microbiology**, 11, 2020, 562813. https://doi.org/10.3389/fmicb.2020.562813

Peng B, Dong Q, Li F, Wang T, Qiu X, Zhu T, *A systematic review of polycyclic aromatic hydrocarbon derivatives: Occurrences, levels, biotransformation, exposure biomarkers, and toxicity,* **J Environ. Sci. Technol**, 57(41), 2023, 15314-35.

Petrucci G, Sandrini L, Rossi R, Contini A, *Using PCA and PMF to Discern PAH Source Profiles in Industrial and Urban Watersheds*, **Environmental Pollution**, 335 (2), 2025, 122−277.

Plank V.D.S, Brown S, Nicholls R.J, Tompkins E.L*, Stakeholder expectations of the public in local coastal flood risk management in England,* Proceedings of the ICE, **Civil Engineering,** 20(1), 2020, 605-618. https://doi.org/10.1680/cm.65147.605

Ladoke Akintola University, Ibadan DO NOT COPY

Q. Ain, A. Rehman, M. Abbasi, *Bioremediation: Review on oil spill management using oil eating microorganisms, and spill effects on marine and terrestrial environment*, ***Journal of Sustainable Environment,*** *1*(2), 2023, 30-35. https://doi.org/10.58921/jse.01.02.020

Qiu Z, Wang Z, Xu J, Liu Y, Zhang J, *Influence of source apportionment of PAHs occurrence in aquatic suspended particulate matter at a typical post-industrial city: A case study of Freiberger Mulde River,* **Sustainability**, 14(11), 2022 6646. https://doi.org/10.3390/su14116646

Racovita R.C, Secuianu C, Ciuca M.D, Israel-Roming F*, Effects of smoking temperature, smoking time, and type of wood sawdust on polycyclic aromatic hydrocarbon accumulation levels in directly smoked pork sausages,* **Journal of Agricultural and Food Chemistry,** 68(35), 2020, 9530–9536. https://doi.org/10.1021/acs.jafc.0c04116

Racovita R.C, Secuianu C, Israel-Roming F, *Quantification and risk assessment of carcinogenic polycyclic aromatic hydrocarbons in retail smoked fish and smoked cheeses*, **Food Control**, 121, 2021, 107586. https://doi.org/10.1016/j.foodcont.2020.107586

Rahman M.A, Fatema N, Aktar S, Khan B, Shovo T.E, Howlader M.H, *Livelihood sustainability status and challenges of southwestern coastal area of Bangladesh,* **Journal of Social and Political Sciences,** 3(4), 2020. https://doi.org/10.31014/aior.1991.03.04.226

Rahman S, Islam M.S, Khan M.N.H, Touhiduzzaman M, *Climate change adaptation and disaster risk reduction (DRR) through coastal afforestation in South-central coast of Bangladesh,* **Management of Environmental Quality International Journal,** 30(3), 2019, 498-517. https://doi.org/10.1108/meq-01-2018-0021

Rajeshkumar S, Li X, *Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China*, **J Toxicol. Rep,** 5, 2018, 288-295.

Rajput R.K, Lakhani N, Patel A.K*, Long-Term Trends of Atmospheric PAHs in an Urban–Industrial Region of India,* **Atmospheric Environment,** 223, 2020, 117−241.

Ramírez-Ayala E, Arguello-Pérez M.A, Tintos-Gómez A, Pérez-Rodríguez R.Y, Díaz-Gómez J.A, Borja-Gómez I, Sepúlveda-Quiroz C.A, Patiño-Barragán M, Lezama-Cervantes C, *Review of the biomonitoring of persistent, bioaccumulative, and toxic substances in aquatic ecosystems of Mexico: 2001–2016*, **Latin American Journal of Aquatic Research,** 48(5), 2020, 705-738. https://doi.org/10.3856/vol48-issue5-fulltext-2461

Recabarren-Villalón T, Ronda A.C, Arias A.H*, Polycyclic aromatic hydrocarbons levels and potential biomarkers in a native South American marine fish*, **Reg Stud Mar Sci**, 29, 2019, 100695

Rudiarto I, Handayani W, Wijaya H.B, Insani T.D*, Rural livelihood resilience, An assessment of social, economic, environment, and physical dimensions,* **Matec Web of Conferences,** 280, 2019, 01002. https://doi.org/10.1051/matecconf/201928001002

Lead City University Ibadan DO NOT COPY

Ofori, S. A. Cobbina,S. J. & Doke D. A, *The Occurrence and Levels of Polycyclic Aromatic Hydrocarbons (PAHs) in African Environments—A Systematic Review,* **Environmental Science and Pollution Research,** 27, 2020, 32389-32431.

Sahai H, García Valverde M, Murcia Morales M, Hernando M.D, Aguilera Del Real A.M, Fernández- Alba A.R, *Exploring Sorption of Pesticides and PAHs in Microplastics Derived from Plastic Mulch Films Used in Modern Agriculture*, **Chemosphere,** 333, 2023, 138959.

Sakshi A.K Haritash, *A comprehensive review of metabolic and genomic aspects of PAH-degradation,* **Arch. Microbiol,** 202(8), 2020, 2033-58.

Sambo A, Faloye J.O, Adewunmi K.O, *Assessment of PAHs in Biochar-Amended Soils and Their Remediation Potential,* **Journal of Hazardous Materials**, 368, 2019, 204–216.

Sampaio G.R, Guizellini G.M, da Silva S.A, de Almeida A.P, Pinaffi-Langley A.C.C, Rogero, E.A Torres M.M, *Polycyclic aromatic hydrocarbons in foods: Biological effects, legislation, occurrence, analytical methods, and strategies to reduce their formation,* **International Journal of Molecular Sciences**, *22*(11), 2021, 6010. https://doi.org/10.3390/ijms22116010

Sandhu M, Paul A.T, Jha P.N, *Metagenomic analysis for taxonomic and functional potential of polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyl (PCB) degrading bacterial communities in steel industrial soil*, **Plos One**, 17(4), 2022, e0266808. https://doi.org/10.1371/journal.pone.0266808

Santana MS, Sandrini-Neto L, Neto FF, Neto FF, Oliveira Ribeiro CA, Di Domenico M, Prodocimo MM (2018) Biomarker responses in fish exposed to polycyclic aromatic hydrocarbons (PAHs): systematic review and meta-analysis. Environ Pollut 242:449–461.

Santos E, Souza M.R.R, Junior A.R.V, da Silva Soares L, Frena M, Alexandre M.R, Polycyclic *Aromatic Hydrocarbons in Suspended Particulate Matter of a Region Influenced by Agricultural Activities in Northeast Brazil*, **Reg. Stud. Mar. Sci**, 57, 2023 102683.

Santos E, Souza M.R.R, Junior A.R.V, da Silva Soares L, Truzzi C, Annibaldi A, *Effects of biological factors and seasonality on the level of polycyclic aromatic hydrocarbons in red mullet (Mullus barbatus)*, **Environ Pollut,** 258, 2020, 113742

Sayers E.W, Bolton E.E, Brister J.R, Canese K, Chan J, Comeau D.C, Farrell C.M, Feldgarden M, Fine A.M, Sherry S.T, *National Center for Biotechnology Information PubChem Dataset 2023,* **Nucleic Acids Res,** 51, 2023, D29–D38.

Schwert R, *Effect of liquid smoke extract on the oxidative stability, benzopyrene and sensory quality of calabrese sausage*, **Current Nutrition & Food Science,** 16(3), 2020, 343–353. https://doi.org/10.2174/1573401315666190126120749

Shao W, *Using liquid smoke to control infestations of the ham mite*, *Tyrophagus putrescentiae, on dry-cured hams during aging*, **Meat Science,** 200, 2023, 109139.

Leadcity University Ibadan DO NOT COPY

Shi J, Jiang J, Chen Q, Wang L, Nian K, Long T, *Production of higher toxic intermediates of organic pollutants during chemical oxidation processes: A review*, **Arab. J. Chem,** 2023, 104856.

Siciliano S.D, Lee H.D, Pereira J.Q, Matthews B.E, Kendall G.T, *Applying Combined Diagnostic Ratios and PCA for PAH Source Identification in Canadian Arctic Sediments,* **Environmental Science & Technology,** 54 (24), 2020 15574–15583.

Silva S.A, De Rossi G.Z, Ossugui M.M, de Almeida A.P, Guizellini G.M, Sampaio G.R, da Silva Torres E.A.F, *Quantification of Polycyclic Aromatic Hydrocarbons in Commonly Consumed Salami in Brazil*, **Food Analytical Methods,** 16, 2023, 1–11. https://doi.org/10.1007/s12161-022-02414-z

Simão F.C.P, Gravato C, Machado A.L, Soares A.M.V.M, Pestana J.L.T, *Toxicity of Different Polycyclic Aromatic Hydrocarbons (PAHs) to the Freshwater Planarian Girardia Tigrina,* **Environ. Pollut,** 266, 2020, 115185.

Simão F.C.P, Gravato C, Machado A.L, Soares A.M.V.M, Pestana J.L.T, *Effects of pyrene and benzo[a]pyrene on the reproduction and newborn morphology and behavior of the freshwater planarian Girardia tigrina*, **Chemosphere,** 264, 2021, 128448.

Singh R.K, Gupta A.K, Rai P.K, *PAHs in Urban Street Dust: Spatial Distribution, Source Apportionment and Risk*, **Science of the Total Environment,** 720, 2020, 137−581.

Siudek P, *Atmospheric Deposition of Polycyclic Aromatic Hydrocarbons (PAHs) in the Coastal Urban Environment of Poland, Sources and Transport Patterns*, **Int. J. Environ. Res. Public Health**, 2022, 19(21).

Sogbanmu T.O, Nagy E, Phillips D.H, Arlt V.M, Otitoloju A.A, Bury N.R, *Lagos lagoon sediment organic extracts and polycyclic aromatic hydrocarbons induce embryotoxic, teratogenic and genotoxic effects in Danio rerio (zebrafsh) embryos,* **Environ Sci Pollut Res,** 23(14), 2019, 14489–14501. https://doi.org/10.1007/s11356-016-6490-y.

Stogiannidis E, Limnios S, *Comprehensive Review of PAH Diagnostic Ratios in Air, Water, and Sediment Source Attribution*, **Environmental Forensics**, 22 (4), 2021, 265–299.

Sun K, Song Y, He F, Jing M, Tang J, Liu R, *A review of human and animals exposure to polycyclic aromatic hydrocarbons: Health risk and adverse efects, photo-induced toxicity and regulating effect of microplastics,* **Sci Total Environ,** 773, 2021, 145403

Sun K, Song Y, He F, Jing M, Tang J, Liu R, *A Review of Human and Animals Exposure to Polycyclic Aromatic Hydrocarbons: Health Risk and Adverse Effects, Photo-Induced Toxicity and Regulating Effect of Microplastics*, **Sci. Total Environ,** 773, 2021, 145403.

Sun Y, Wu S, Gong G, *Trends of research on polycyclic aromatic hydrocarbons in food: A 20-year perspective from 1997 to 2017*, ***Trends in Food Science & Technology,*** 83, 2019, 86-98. https://doi.org/10.1016/j.tifs.2018.11.015.

Lead City University Ibadan DO NOT COPY

Świsłowski P, Hrabák P, Wacławek S, Liskova K, Antos V, Rajfur M, Ząbkowska-Wacławek M, *The application of active biomonitoring with the use of mosses to identify polycyclic aromatic hydrocarbons in an atmospheric aerosol*, **Molecules**, 26(23), 2021, 7258. https://doi.org/10.3390/molecules26237258

Tang J.Q, Wu Y, Han Y.Y, Shen Q.H, He X.F, Feng N.X, Huang Y, *Bioremediation of common high-molecular-weight polycyclic aromatic hydrocarbons, A bibliometric analysis based on Web of Science via VOSviewer,* 2023. https://doi.org/10.21203/rs.3.rs-3374874/v1

Teixeira J, Silva P.A, Costa M.F, *Environmental Contamination with Polycyclic Aromatic Hydrocarbons: Ubiquity, Bioaccumulation, and Human Health Risk*, **Environmental Science and Pollution Research**, 31 (32), 2024, 556–700.

Tian H, Wang Z, Zhu T, Yang C, Shi Y, Sun Y, *Degradation prediction and products of polycyclic aromatic hydrocarbons in soils by highly active bimetals/AC-activated persulfate,* **ACS ES&T Engineering,** 1(8), 2021, 1183-1192. https://doi.org/10.1021/acsestengg.1c00063

Tiegs S.D, Costello D.M, Isken M.W, Woodward G, McIntyre P.B, Gessner M.O, Chauvet E, Griffiths N.A, Flecker A.S, Acuña V, *Global patterns and drivers of ecosystem functioning in rivers and riparian zones,* **Science Advances,** 5(1), 2019, eaav0486. https://doi.org/10.1126/sciadv.aav0486

Ude C.N, Ojinnaka B.O, Mgbeze C.O, *Occurrence of PAHs in Urban Streams Receiving Wastewater in Southeast Nigeria*, **Environmental Monitoring and Assessment**, 196 (3), 2024, 282.

Ugochukwu U.C, Okoro H.A, Eze A.O, *Risk Assessment of Polycyclic Aromatic Hydrocarbons in Ekulu River Sediments, Nigeria,* **African Journal of Aquatic Science**, 46 (1), 2021,49–59

Ukwo P.S, Ek C.M, Sylvester L, *Compositional pattern and tissue concentration of polycyclic aromatic hydrocarbons (PAHs) in bivalve shellfish from Niger Delta, Nigeria,* **Journal of Applied Sciences,** 22(2), 2022, 84-91. https://doi.org/10.3923/jas.2022.84.91

Vareda J.P, Valente A.J, Durães L, *Assessment of Heavy Metal Pollution from Anthropogenic Activities and Remediation Strategies: A Review,* **Journal of Environmental Management,** 246, 2019, 101-118.

Vijayanand M, Ramakrishnan A, Subramanian R, Issac P.K, Nasr M, Khoo K.S, Rajagopal R, Greff B, Wan Azelee N.I, Jeon B.H, *Polyaromatic Hydrocarbons (PAHs) in the Water Environment, A Review on Toxicity, Microbial Biodegradation, Systematic Biological Advancements, and Environmental Fate,* **Environ. Res,** 227, 2023, 115716.

Wang H, Xia X, Liu R, Wang Z, Zhai Y, Lin H, Wen W, Li Y, Wang D, Yang Z, Muir D.C.G, *Dietary uptake patterns affect bioaccumulation and biomagnification of hydrophobic organic compounds in fish*, **Environmental Science & Technology**, 53(8), 2019, 4274-4284. https://doi.org/10.1021/acs.est.9b00106

Lead City University Ibadan DO NOT COPY

Wang H, Xia X, Wang Z, Liu R, Muir D.C, Wang W.X, *Contribution of dietary uptake to PAH bioaccumulation in a simplified pelagic food chain: Modeling the influences of continuous vs intermittent feeding in zooplankton and fish*, **Environmental Science & Technology,** 55(3), 2021, 1930-1940. https://doi.org/10.1021/acs.est.0c06970

Wang M, Jia S, Lee S.H, Chow A, Fang M, *Polycyclic aromatic hydrocarbons (PAHs) in indoor environments are still imposing carcinogenic risk*, **J. Hazard. Mater**, 409, 2021, 124531.

Wang W, Xu J, Qu X, Lin D, Yang K, *Current and Future Trends of Low and High Molecular Weight Polycyclic Aromatic Hydrocarbons in Surface Water and Sediments of China: Insights from Their Long-Term Relationships between Concentrations and Emissions,* **Environ. Sci. Technol**, 56(6), 2022, 3397-406.

Wang Y, Jiao Y, Kong Q, Zheng F, Shao L, Zhang T, Gao X, Occurrence of polycyclic aromatic hydrocarbons in fried and grilled fish from Shandong China and health risk assessment, **Environmental Science and Pollution Research**, 28(25), 2021, 32802–32809. https://doi.org/10.1007/s11356-021-13045-y

Whitton C, Bogueva D, Marinova D, Phillips C.J, *Are we approaching peak meat consumption? Analysis of meat consumption from 2000 to 2019 in 35 countries and its relationship to gross domestic product,* **Animals,** 11(12), 2021, 3466. https://doi.org/10.3390/ani11123466

Wu S, Li H, Yin X, Si Y, Qin L, Yang H, Xiao J, Peng D, *Preparation of monoclonal antibody against pyrene and benzo [a]pyrene and development of enzyme-linked immunosorbent assay for fish, shrimp and crab samples,* **Foods**, 11(20), 2022, 3220. https://doi.org/10.3390/foods11203220

Xiong X, Zhang H, Wang R, Tang Z, Yang M, *Distribution and Risk Assessment of 80 Polycyclic Aromatic Compounds in Surface Water and Industrial Effluent in the Upper Yangtze River, China,* **ACS EST Water,** 4, 2024 2300–2308.

Yahaya T.O, Abdulazeez A, Kalgo Z.M, Yusuf A.B, Sheu H, Abdullahi H, Shaf'u M.A, *Safety assessment of heavy metals in Tilapia zilli (Tilapia fsh) and Chrysichthys nigrodigitatus (catfsh) obtained from Epe Lagoon, Lagos, Nigeria,* **ChemSearch Journal**, 13(2), 2022a, 52–61

Yahaya T.O, Salisu F.T, Shehu K, Abdulazeez A, Ahmed H, Abdulrahim A, *Level, and health risk assessment of heavy metals in Clarias gariepinus obtained from agboyi, oworonsoki, and bariga markets in Lagos, Nigeria,* **FUW Trends in Science & Technol J**, 7(3), 2022b, 55–60

Yan K, Li W, Wu S, *Dietary exposure and risk assessment of European Union priority (EU 15+ 1) polycyclic aromatic hydrocarbons from milks and milk powders in China*, **Journal of Dairy Science,** 8(105), 2022, 6536–6547. https://doi.org/10.3168/jds.2021-21438

Lead City University Ibadan DO NOT COPY

Yang J, Qadeer A, Liu M, Zhu J.M, Huang Y.P, Du W.N, Wei X.Y, *Occurrence, Source, and Partition of PAHs, PCBs, and OCPs in the Multiphase System of an Urban Lake, Shanghai*, **Appl. Geochem,** 106, 2019, 17–25.

Yazdani M*, Comparative Toxicity of Selected PAHs in Rainbow Trout Hepatocytes(Genotoxicity, Oxidative Stress and Cytotoxicity)*, **Drug Chem. Toxicol** , 43, 2020, 71–78.

Yu J, Luo H, Yang B, Wang M, Gong Y, Wang P, Jiao Y, Liang T, Cheng H, Ma F*, Risk control values and remediation goals for benzo [a] pyrene in contaminated sites: sectoral characteristics, temporal trends, and empirical implications,* **Environ. Sci. Technol**, 57(5), 2023, 2064-74.

Yu Z, Lin Q, Gu Y, Du F, Wang X, Shi F, Ke C, Xiang M, Yu Y, *Bioaccumulation of polycyclic aromatic hydrocarbons (PAHs) in wild marine fsh from the coastal waters of the northern South China Sea: risk assessment for human health,* **Ecotoxicol Environ Saf**, 180, 2019,742–748

Zeng Q, Jeppesen E, Gu X, Mao Z, Chen H, *Distribution, fate and risk assessment of PAHs in water and sediments from an aquaculture- and shipping-impacted subtropical lake, China.* **Chemosphere**, 201,2018, 612-20.

Zhang H, Han Y, Qiu X, Wang Y, Li W, Liu J, Zhu T, *Association of internal exposure to polycyclic aromatic hydrocarbons with inflammation and oxidative stress in prediabetic and healthy individuals*, **Chemosphere**, 253, 2020, 126748. https://doi.org/10.1016/j.chemosphere.2020.126748

Zhang L, *Chemodynamics of polycyclic aromatic hydrocarbons and their alkylated and nitrated derivatives in the Yellow Sea and East China Sea*, **Environmental Science & Technology**, 57(48), 2023, 20292-20303. https://doi.org/10.1021/acs.est.3c07476

Zhang L, Wu P, Zhou H, Hu Z, Zhang N, Wang L, Zhao Y, Determination of 15+ 1 European priority polycyclic aromatic hydrocarbons in smoked meat products by saponification/solid-phase extraction and gas chromatography-mass spectrometry**, Journal of Chromatographic Science**, 60(3), 2022, 298–307. https://doi.org/10.1093/chromsci/bmab087

Zhang W, Si Y, Jiang Z, Chen T, Linnartz H, Tielens A.G.G.M*, Laboratory photochemistry of covalently bonded fluorene clusters: Observation of an interesting PAH bowl-forming mechanism,* **The Astrophysical Journal,** 872(1), 2019, 38. https://doi.org/10.3847/1538-4357/aafe10

Zhang Z, Wang S, Li L, *Emerging investigator series: the role of chemical properties in human exposure to environmental chemicals in Environmental Science,* ***Processes & Impacts***, *23*(12), 2021, 1839-1862.

Zhao L, Zhou M, Zhao Y, Yang J, Pu Q, Yang H, Wu Y, Lyu C, Li Y, *Potential toxicity risk assessment and priority control strategy for PAHs metabolism and transformation*

Lead City University Ibadan DO NOT COPY

behaviors in the environment, **International Journal of Environmental Research and Public Health,** 19(17), 2022, 10972. https://doi.org/10.3390/ijerph191710972

Zhu Z, Xu Y, Huang T, Yu Y, Bassey A.P, Huang M*, The contamination, formation, determination and control of polycyclic aromatic hydrocarbons in meat products*, **Food Control***,* 141, 2022, 109194.

Lead City University Ibadan DO NOT COPY

Appendices

Appendix I

List of Analyzed PAHs PAHs Analyzed (16 Priority PAHs as identified by USEPA):

1. Naphthalene
2. Acenaphthylene
3. Acenaphthene
4. Fluorene
5. Phenanthrene
6. Anthracene
7. Fluoranthene
8. Pyrene
9. Benzo[a]anthracene
10. Chrysene
11. Benzo[b]fluoranthene
12. Benzo[k]fluoranthene
13. Benzo[a]pyrene
14. Indeno[1,2,3-cd]pyrene
15. Dibenzo[a,h]anthracene
16. Benzo[g,h,i]perylene

Lead City University Ibadan DO NOT COPY

Appendix II

Crabs gotten from the Lagos Lagon



Source: Author's Field Work, 2025

Lead

Appendix III

Prawns gotten from the Lagos Lagoon



Source: Author's Field Work, 2025

Lead City

Appendix IV

Tilapia gotten from the Lagos Lagoon



Source: Author's Field Work, 2025

Appendix V

Catfish gotten from the Lagos Lagoon



Source: Author's Field Work, 2025

Lead City University DO NOT COPY

Bio Data

A. Personal Data

1. **Full Name:** Faleye Bisola Muinat
2. **Home Address:** No 8, Olaleye Street, Oke Ola, Ilaro, Ogun State
3. **Phone Number:** 09135030832
4. **Email Address:** olashile482@gmail.com
5. **Date and Place of Birth:** 14th June 1999, Ilaro, Ogun State
6. **Nationality:** Nigerian
7. **Name and Adddress of Next of Kin:** Faleye Timileyin Moshood,
   No 8, Olaleye Street, Oke Ola, Ilaro, Ogun State

B. Educational Background

Institutions Attended	Qualifications Obtained	Date
1. Lead City University	B.Sc. Environmental Mgt &Tox	2021
2. Lead City University	MSc, EMT	Inview 2025

C. Work Experience with Dates

1. Intern,
Ministry of Environment, Oyo State — July 2019- Dec 2019

2. Finance Assistant (NYSC),
Department of Social and Finance, Lga, Ila Orogun, Osun State — Jan 2022- Dec 2022

3. Personal Assistant,
Afariogun Ventures Nig Ltd, Abk, Ogun State — Jan 2023- June 2024

4. Digital Marketer, Ibd, Oyo State
Homelink Global Realty — Oct 2024 till date

D. Awards and Fellowships (If Any): Nil

Lead City University Ibadan DO NOT COPY

E. Membership of Academic Professional Bodies: Nil

F. Publications: Nil

G. Major Conferences/Workshops Attended with Dates:

1. Circular Economy Innovation Partnership (CEIP) - Circular Economy Strategy Week. 25th - 28th March 2024

2. Faculty of Natural and Applied Sciences (FASCON 2025) Lecture on "Computataional Methods in Genomics and Health" held at Lead City University, Ibadan, Oyo State, Nigeria. 18th June 2025.

H. References

Dr Felicia Adesina

Department of Biological Sciences,

Lead City University,

Ibadan, Oyo State

feliciaadesina@lcu.edu.ng

Dr. O. Sindiku

Department of Biological Sciences,

Lead City University,

Ibadan, Oyo State.

omotayosindiku@lcu.edu.ng

Lead City University Ibadan DO NOT COPY

Signature **Date**

The University Compliance Certification

This is to certify that the Thesis by **FALEYE, Bisola Muinat** with Matric No **LCU/PG/005499** in the department of Biological Sciences, Faculty of Natural and Applied Sciences, Lead City University, is in full compliance with the approved university format and style.

Lead City University Ibadan DO NOT COPY

Name and Signature	**Date**