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Source Apportionment And Biodegradation Of Polycyclic Aromatic Hydrocarbons: A Review

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Abstract Persistent environmental contaminants known as polycyclic aromatic hydrocarbons are produced when organic compounds burn incompletely. Natural sources, such as industrial activities and forest fires, can release them into the environment. For pollution prevention and mitigation to be effective, source apportionment is essential. Pollution can be reduced by PAH biodegradation. Advanced analytical methods like GC- MS and emulsion-specific stable isotope analysis can identify PAHs in environmental samples. PAHs are a major environmental concern, forming from both natural and human activities. Assaying water, soil, and deposition samples helps identify implicit sources, such as petrogenic, pyrogenic, or biogenic sources. These sources are resistant to riding, pyrolysis, and bioavailability independently. PAHs are polyhydroxy composites with physical, chemical, and environmental properties. They can suffer chemical responses, adsorb to organic matter, and be degraded by microorganisms. Strategies to alleviate dangerous PAHs and soot formation in combustion systems are pivotal. PAHs are carcinogens that can cause cancer, reproductive issues, and neurological diseases. Regulatory compliance, civic runoff, stormwater operation, and environmental conditions can alleviate their impact. Biodegradation rates are determined by microbial community composition and co-contaminant relations. Pseudomonas turukhanskesis is a microorganism able to degrade polycyclic sweet hydrocarbons like phenanthrene, anthracene, pyrene, fluoranthene, and benzo(b) pyrene, using them as energy and reducing dangerous composites for organism growth. The USEPA, EU Directive, OSHA, and WHO have established guidelines for polycyclic aromatic hydrocarbons (PAHs) to protect human health and the environment. However, research gaps exist due to high pollution levels in African species, water, and sediment quality. The U.S. government and other organizations set standards for controlling polycyclic aromatic hydrocarbons (PAHs) concentration in the workplace and environment. The World Health Organization sets a lifetime lung cancer risk of 87×10-6 ng m-3, while the European Commission sets a PM10 concentration of 1 ng m-3. Strategies for PAH contamination include strengthening regulatory frameworks, monitoring, public awareness, and research.

Keywords: *polycyclic aromatic hydrocarbons, Source apportionment, biodegradation*

1.0 INTRODUCTION

According to the Agency for Toxic Substances and Disease Registry (ATSDR), Polycyclic Aromatic Hydrocarbons are a group of over 100 different chemicals that are formed during the incomplete burning of coal, oil, and gas, garbage, or other organic substances (Kumar *et al.,* 2022). As defined by the International Agency for Research on Cancer (IARC), PAHs are a class of organic compounds consisting of two or more fused aromatic rings (IARC, 2021). They are ubiquitous environmental pollutants formed through the incomplete combustion of organic matter.

According to the United States Environmental Protection Agency (US EPA), PAHs are defined as a class of chemicals that occur naturally in the environment and are also produced as a result of the incomplete combustion of organic matter, such as coal, oil, gas, and biomass (Dandajeh *et al.,* 2021). PAHs can be sourced from natural sources such as forest fires, volcanic eruptions, and diagenesis of organic matter, as well as anthropogenic sources like incomplete combustion of fossil fuels, industrial processes, vehicle emissions, and waste incineration (Abdel-Shafy & Mansour, 2016).

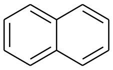
Polycyclic Aromatic Hydrocarbons are widespread environmental pollutants, causing toxicity and bioaccumulation. They are generated from various sources, including wildfires, volcanic activity, and industrial activities (Ortega-Calvo & Gschwend, 2010). The global impact of PAHs is significant, as they can be absorbed into air, water, soils, and sediments, causing long-term contamination in aquatic environments (Tang & Wang, 2024). Human health concerns include long-term exposure to PAHs, which can lead to cancer, developmental issues, immune system suppression, and reproductive harm (Guan *et al.,* 2023). Environmental impacts include toxic effects on aquatic life, particularly benthic organisms, which can bioaccumulate in the food web, affecting fish, amphibians, birds, and mammals (Abbasi *et al.,* 2024). In Africa, PAHs are increasingly recognized as a growing environmental concern due to rapid industrialization, urbanization, and oil and gas exploration (Dietrich *et al.,* 2022). In Uganda, the Albertine Graben region faces significant challenges related to PAH contamination due to oil exploration, urbanization, and traditional biomass burning. Collaboration with international organizations and environmental agencies could help enhance Uganda's capacity to monitor and mitigate PAH pollution (S. Li, 2024).

The environmental fate and transport of PAHs are crucial for effective mitigation and can inform pollution prevention and remediation strategies. Their low water solubility leads to partitioning into sediments and biota, which can persist in the environment (Mitchell *et al*., 2023). Many PAHs are carcinogenic, mutagenic, and teratogenic to humans and wildlife, and can bioaccumulate in the food chain, causing adverse effects on aquatic organisms. Source apportionment is important for effective mitigation and can inform pollution prevention and remediation strategies (Guo *et al.,* 2023). Biodegradation of PAHs can be an important natural attenuation process for PAH-contaminated environments. Some PAHs can be degraded by microorganisms under aerobic and anaerobic conditions, making it an important natural attenuation process for PAH-contaminated environments (Kurwadkar *et al*., 2023). In the Albertine Graben region, like in any other region, PAHs are transported and accumulated due to their hydrophobic nature. Aquatic currents, sediment resuspension, and riverine transport facilitate the long-range distribution of PAHs within the region (Shen *et al*., 2021). Bioaccumulation of PAHs in aquatic organisms can lead to their transfer through the food chain, potentially impacting ecosystem health and human exposure.

Biodegradation of PAHs can be influenced by factors such as oxygen availability, temperature, nutrient levels, and the presence of specific PAH-degrading microorganisms (Wang *et al.,* 2023). Understanding the biodegradation potential of indigenous microbes could also inform the development of bioremediation strategies for PAH-contaminated water and sediments. Advanced analytical methods, such as gas chromatography-mass spectrometry (GC-MS) and compound-specific stable isotope analysis, can be employed to identify the sources of PAHs in environmental samples (Dahlberg *et al*., 2020). Multivariate statistical techniques, such as principal component analysis and positive matrix factorization, can also be used to apportion the relative contributions of different PAH sources (Xu *et al.,* 2021).

Examples of the most common priority polycyclic aromatic hydrocarbons and their chemical structures

PAHs have a cyclic, planar structure with a conjugated system of π-electrons, allowing for electron delocalization and compound stability (Kingputtapong *et al.,*2022). The number of fused rings can vary, resulting in different structures like naphthalene or coronene. The fused aromatic rings create a planar molecular structure, stabilized by π-electrons (Kadri *et al.,*2017). PAHs' rigidity is due to strong carbon-carbon bonds and the absence of rotatable bonds (Berger *et al.,*2015). They are hydrophobic, meaning they are non-polar, due to the presence of carbon-hydrogen bonds and the absence of polar functional groups. This hydrophobic nature contributes to their solubility in non-polar solvents and their tendency to accumulate in lipid-rich environments (Ghosh & Mukherji, 2023).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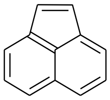
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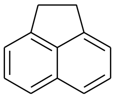
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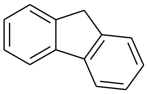
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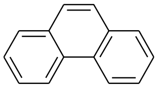
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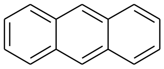
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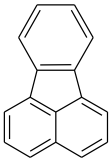
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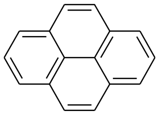
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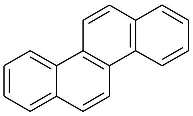
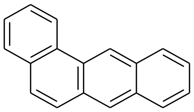

Chrysene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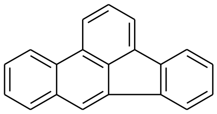
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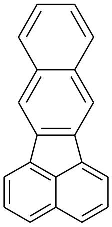
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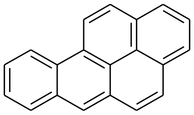
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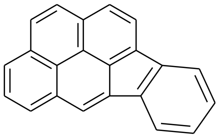
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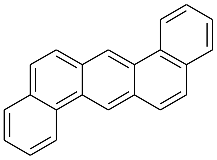
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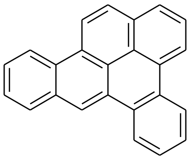
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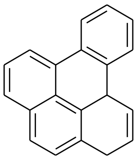
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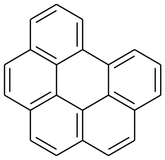
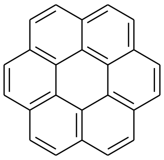

Benzo[g,h,i]perylene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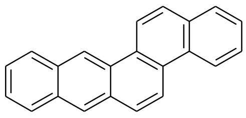
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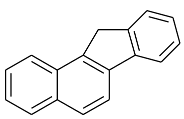
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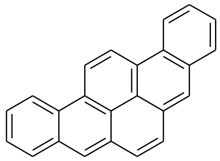
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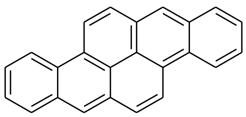
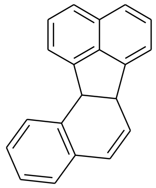

Dibenzo[a,h]pyrene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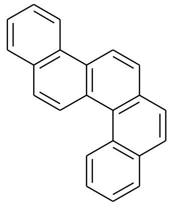
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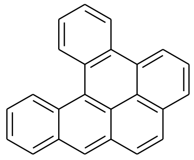
Dibenzo[a,l]pyrene

Source; (Patel *et al.*,2020; Koelmel *et al.*,2022; X. Xu *et al.*,2020).

2.0 METHODOLOGY

Using a narrative literature review technique, the data for this study were collected from original, peer-reviewed studies published in scientific journals that focused on PAHs, their biodegradation, and source apportionment. We conducted a thorough search of electronic literature databases, such as Research Gate and Google Scholar, among other reliable sources, to locate the publicly available peer-reviewed data using keywords like "source apportionment of PAHs," "Proposed biodegradation pathways of PAHs," and "environmental formation of PAHs." We checked the data we had read and/or downloaded, and we resolved any discrepancies that surfaced throughout the draft write-up by having a lengthy conversation that was governed by the review's guidelines. Taking into account the information from the evaluated literature, the conclusion was drawn.

3.2.2 Chemical properties of polycyclic aromatic hydrocarbons

PAHs, or polyhydroxy acids, have an aromatic structure due to their delocalized π-electron system, which provides stability and influences their reactivity (Thacharodi *et al.*,2023). This makes them resistant to chemical and biological degradation, ensuring their persistence in the environment. PAHs can undergo various chemical reactions, including oxidation, reduction, electrophilic addition, and photochemical reactions, influenced by factors like aromatic rings and substituents. Oxidation reactions can lead to more polar and potentially toxic metabolites (Liu *et al.*,2024).

PAHs have a strong tendency to adsorb to organic matter, such as soil, sediments, and suspended particulates, influenced by factors like organic carbon content, pH, and ionic strength of the environment (Radomirović *et al.*,2023). Adsorption affects the bioavailability, mobility, and persistence of PAHs in the environment (Patel *et al.*,2020). PAHs can be degraded by microorganisms like bacteria and fungi through enzymatic processes, with rates and pathways varying based on the compound, environmental conditions, and microbial metabolic capabilities (Wang *et al.*,2022). PAHs can also be bioaccumulated in living organisms due to their hydrophobic nature, with bioaccumulation influenced by factors like lipid content, metabolism, and trophic level (Gondwal & Mandal, 2023). Biomagnification can occur when PAHs are transferred and concentrated through the food web, posing a risk to higher-level consumers (Cara *et al.*,2022).

3.3 Formation of Polycyclic Aromatic Hydrocarbons in the Environment

PAHs are formed in the environment through various processes, including incomplete combustion of organic matter, pyrolysis and thermal degradation, petroleum and oil spills, and natural geological processes (Praveenkumar *et al.*,2024). The incomplete combustion of fossil fuels and biomass produces PAHs like benzo[a]pyrene, fluoranthene, and pyrene (Honda & Suzuki, 2020). The industrial processes like coke production, metal smelting, and power generation also generate PAH emissions. Pyrolysis and thermal degradation of organic matter at high temperatures can lead to the formation of PAHs, such as charcoal production, wood burning, and waste treatment (Praveenkumar *et al.*,2024). The PAH profile in these cases is influenced by factors such as organic matter composition, temperature, and oxygen presence (Yang *et al.*,2019).

Petroleum and oil spills release PAHs into the environment during oil spills or the weathering of petroleum products. The specific PAH profile depends on the composition of the original petroleum source and weathering processes (Guma *et al.*,2021). Weathering of crude oil can release lighter PAHs, while heavier PAHs like benzo[a]pyrene may be more persistent (Qiao *et al.*,2021). Natural geological processes, such as the thermal maturation of organic matter in sedimentary rocks, can also produce PAHs in certain geological formations like coal and shale deposits (Yilmaz *et al.*,2023). The PAH profile in these sources is influenced by the composition of the original organic matter and the thermal history of the geological formation (Nakajigo *et al.*,2023).

3.3.1 Hydrogen abstraction and acetylene or carbon addition (HACA)

The best standard reaction mechanisms for polycyclic hydrocarbon formation in HACA involve hydrogen abstraction and acetylene addition (Zhao *et al.,* 2018). This 2-step route involves continuous hydrogen abstractions to initiate the aromatic grain, followed by acetylene addition to a radical site formed in the hydrogen abstraction step (Kusumawati & Mangkoedihardjo, 2021).

The HACA mechanism is a process that involves the sequential addition of acetylene or other small carbon-containing species to aromatic molecules, coupled with hydrogen abstraction steps. This leads to the growth and formation of larger particulate air (PAH) structures (Khan *et al.,* 2024). The key steps in the HACA mechanism include hydrogen abstraction, where an aromatic molecule is transformed into an aromatic radical (Asiwaju *et al.*,2023). This radical then reacts with acetylene or other small carbon-containing species, resulting in the addition of the carbon-containing species to the aromatic structure (Asiwaju *et al.*,2023).

The adduct formed in the previous step may undergo rearrangement and cyclization reactions, leading to the formation of a new aromatic ring or the expansion of the existing aromatic structure (Bauer *et al.*,2022). The process of hydrogen abstraction and acetylene or carbon addition can repeat, allowing for the sequential growth of the PAH structure and the formation of larger and more complex PAHs (Mallah *et al.,*2022). Understanding the HACA mechanism is crucial for developing strategies to mitigate the formation of harmful PAHs and soot in combustion systems and designing clean and efficient combustion technologies (Verma *et al.*,2023). The best standard reaction mechanisms for polycyclic hydrocarbons formation in HACA involve hydrogen abstraction and acetylene addition (Khan *et al.,* 2024). This 2-step route involves continuous hydrogen abstractions to initiate the aromatic grain, followed by acetylene addition to a radical site formed in the hydrogen abstraction step (Zhao *et al.,* 2018).

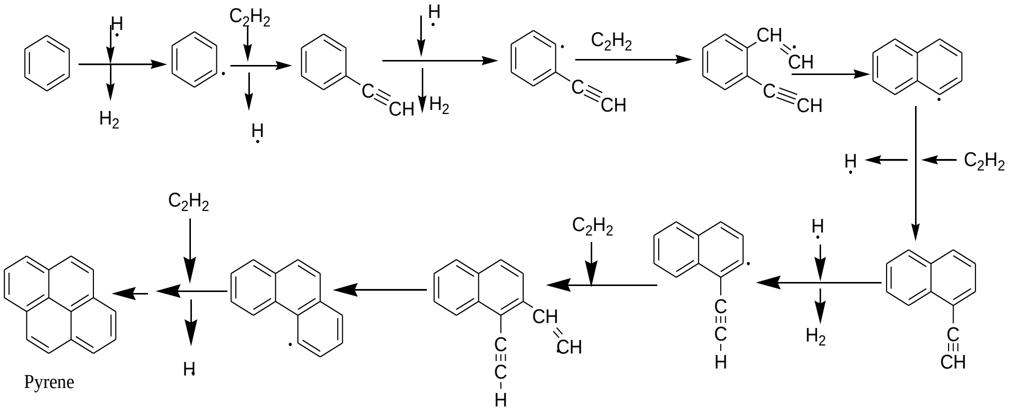

Figure 3.1: *Showing HACA reaction path representation of the HACA reaction mechanism* (Reizer *et al.,* 2022)

3.3.2 Bittner Howard's reaction route

The Bittner-Howard reaction is a process that involves the addition of acetylene to an aromatic radical, resulting in the formation of a linear, unsaturated intermediate (Kislov *et al.*,2005). This intermediate then undergoes cyclization, forming a new carbon-carbon bond, leading to the closure of a new aromatic ring (H. Jin *et al.*,2021). The cyclic intermediate then undergoes hydrogen abstraction, resulting in the loss of hydrogen and the formation of a fully aromatic PAH structure. This sequence can repeat, allowing for the growth and formation of larger PAH structures (Altarawneh & Altarawneh, 2022).

The acetylene addition step is fast and exothermic, providing a driving force for the reaction (Y. Wang *et al.*,2014). The cyclization step is often rate-limiting due to the need to overcome kinetic barriers and form new carbon-carbon bonds (Kislov *et al.*,2013). The dehydrogenation step stabilizes the aromatic structure and drives the reaction forward. The Bittner-Howard reaction route is particularly relevant for the formation of larger PAHs, such as pyrene, benz[a]anthracene, and chrysene, which are important soot precursors in combustion systems (Kislov *et al.,*2005). Its ability to efficiently convert linear or open-chain aromatic intermediates into more stable, condensed aromatic structures makes it an important pathway for soot formation (Bao *et al.,*2023).

Understanding the Bittner-Howard reaction route is crucial for developing strategies to mitigate the formation of harmful PAHs and soot in combustion systems (Yilmaz *et al.*,2023). Extensive experimental and computational modeling studies have provided valuable insights into the kinetics, thermodynamics, and importance of the Bittner-Howard reaction route in the formation and growth of PAHs and soot in combustion environments (Mancera *et al.*,2020).

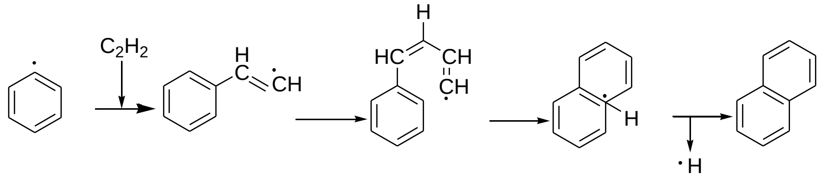

Figure 3.2: *Showing the reaction of acetylene with benzene to form a two-benzene ring PAH* (Khan *et al.,* 2024)

3.3.3 Diels-Alder mechanism

The Diels-Alder reaction is a crucial organic chemistry reaction that plays a significant role in the formation of polycyclic aromatic hydrocarbons (PAHs) and soot in combustion processes (Wu *et al.*,2023). The process involves the cycloaddition of a conjugated diene and an alkene (dienophile) to form a cyclohexene derivative (Matamba *et al.*,2021). The key steps in the Diels-Alder mechanism include diene activation, dienophile addition, cyclization, aromatization, and dehydrogenation (Hernández-Mancera *et al.*,2023).

In combustion processes, the Diels-Alder mechanism can lead to the formation and growth of PAHs, particularly larger, more condensed structures (Wu *et al.*,2023). For example, the Diels-Alder reaction between a conjugated diene and an alkene can result in the formation of cyclic intermediates that can be further reacted with to produce PAHs like naphthalene, anthracene, or phenanthrene (Altarawneh & Altarawneh, 2022). The Diels-Alder mechanism is often considered in conjunction with other PAH formation pathways, such as the Hydrogen Abstraction and Acetylene or Carbon Addition (HACA) mechanism and the Bittner-Howard reaction route (Vaitheeswaran *et al.*,2013). Experimental and computational studies have investigated the kinetics, thermodynamics, and importance of the Diels-Alder mechanism in various combustion environments, including flames, engines, and industrial processes (Vermeeren *et al.*,2020).

The Diels-Alder mechanism is essential for developing strategies to mitigate the formation of harmful PAHs and soot in combustion systems and designing cleaner and more efficient combustion technologies (Medvedev *et al.*,2017). Factors such as the nature of the diene and dienophile, the presence of substituents, and reaction conditions can influence the kinetics and thermodynamics of the Diels-Alder reaction (Gancedo *et al.*,2022).

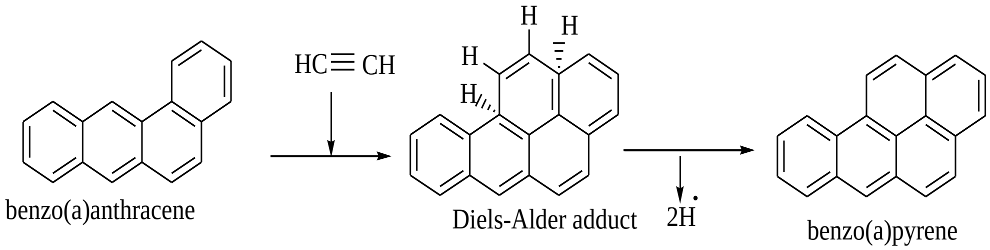

Figure 3.3: *Showing the reaction of acetylene with a five-membered ring* (Kislov *et al.*,2013)

Summary for Physical and Chemical Properties of Polycyclic Aromatic Hydrocarbons

Name	Formula	Molecular weight (g/mol)	Solubility in water (mg/L)	Phase distribution	Melting point (^0C)	Boiling point (^0C)	Vapour pressure (mmHg)	Log Kow	Log Koc	Toxicity as per IARC
Naphthalene	$C_{10}H_8$	128.17	31.00	Gas	80.26	218	0.087	3.29	2.97	2B
Acenaphthene	$C_{12}H_{10}$	154.21	3.800	Gas	95	96	4.47×10^{-3}	3.98	3.66	3
Acenaphthylene	$C_{12}H_8$	152.20	16.10	Gas	92-93	265-275	0.029	4.07	1.40	3
Anthracene	$C_{14}H_{10}$	178.23	0.045	Particle gas	218	340-342	1.75×10^{-6}	4.45	4.15	3
Phenanthrene	$C_{14}H_{10}$	178.23	1.100	Particle gas	100	340	6.8×10^{-4}	4.45	4.15	3
Fluorene	$C_{13}H_{10}$	166.22	1.900	Gas	116-117	295	3.2×10^{-4}	4.18	3.86	3
Fluoranthene	$C_{16}H_{10}$	202.26	0.260	Particle gas	110.8	375	5.0×10^{-6}	4.90	4.58	3
Benzo(a)anthracene	$C_{20}H_{12}$	288.29	0.011	Particle	158	438	2.5×10^{-6}	5.61	5.30	2B
Chrysene	$C_{18}H_{12}$	288.29	0.0015	Particle	254	448	6.4×10^{-9}	5.90	No data	2B
Pyrene	$C_{16}H_{10}$	202.26	0.132	Particle gas	156	393-404	2.5×10^{-5}	4.88	4.58	3
Benzo(a)pyrene	$C_{16}H_{10}$	252.32	0.0038	Particle	179	495	5.6×10^{-9}	6.06	4.58	1
Benzo(b)Fluoranthene	$C_{20}H_{12}$	252.32	0.0015	Particle	168.3	No data	5.0×10^{-7}	6.04	6.74	2B

Benzo(k)Fluoranthene	$C_{20}H_{12}$	252.32	0.0008	Particle	215.7	480	9.59×10^{-11}	6.06	5.74	2B
Benzo(g,h,i)perylene	$C_{22}H_{14}$	278.36	0.0006	Particle	262	No data	1.0×10^{-10}	6.84	6.52	2A
Dibenz(a,h)anthracene	$C_{22}H_{12}$	276.34	0.00006	Particle	273	550	1.03×10^{-10}	6.50	6.20	3
Indenol(1,2,3-c)Pyrene	$C_{22}H_{12}$	276.34	0.06200	Particle	163.6	530	10^{-10} - 10^{-18}	6.58	6.20	2B

Table 3.1. *Chemical and physical properties of the 16 SEPA priority pollutant PAHs. abbreviations: Kow - octanol-water partitioning coefficient, Koc - organic carbon partitioning coefficient*

3.4 Polycyclic aromatic hydrocarbons emission pathways

The evaluation of emission pathways involves identifying and quantifying industrial sources of pollutants, such as heavy metals, organic compounds, and nutrients (Kaur *et al.*,2022). This literature aims to assess the treatment and disposal methods used by industries, as well as the effectiveness of pollution control measures, which can provide insights into the potential for industrial discharges to contribute to environmental contamination. Regulatory compliance and enforcement measures play a crucial role in mitigating industrial emissions (Wang *et al.*,2024).

Urban runoff from urban areas can transport a wide range of pollutants, including sediments, heavy metals, hydrocarbons, and nutrients, into surface water bodies and groundwater (Ouro-Sama *et al.,*2023). The evaluation of the sources and loading of pollutants in urban runoff is necessary to understand their impact on the environment (Stephansen *et al.*,2020). The effectiveness of stormwater management practices, such as green infrastructure, detention basins, and constructed wetlands, in reducing pollutant loads should be assessed to guide possible exposure pathways (Yan *et al.*,2023). Atmospheric deposition is another important aspect of environmental pollution that facilitates the movement of PAHs. It is also important to identify the sources of atmospheric pollutants, such as industrial emissions, transportation, and agricultural activities, in understanding their contribution to environmental contamination (Machate *et al.*,2022). The modeling of atmospheric transport and deposition patterns can help in quantifying the impact of atmospheric deposition on different environmental compartments (Cousins *et al.*,2022).

3.6 Factors influencing biodegradation rates include environmental conditions, microbial communities, and co-contaminant interactions

The biodegradation rates of polycyclic aromatic hydrocarbons (PAHs) can be influenced by three main factors: environmental conditions, microbial community composition, and co-contaminant interactions. Environmental conditions, such as temperature, pH, oxygen availability, and moisture content, affect the solubility, bioavailability, and activity of PAH-degrading enzymes (Zoppini *et al.,*2014).

Aerobic biodegradation of PAHs generally proceeds faster than anaerobic pathways due to more efficient metabolic processes. Microbial diversity, community structure, and adaptation can enhance the overall biodegradation potential (N. Zhou *et al.,*2024). Co-contaminant interactions, such as the presence of additional carbon sources or nutrients, can stimulate microbial growth and cometabolic degradation of PAHs. Inhibitory effects from other contaminants or substances can also affect PAH biodegradation processes (Jiménez-Volkerink *et al.*,2023). Competition for resources or degradation pathways among microorganisms can also influence overall PAH biodegradation rates. Overall, these factors contribute to the efficient and effective biodegradation of PAHs (Shahsavari *et al.*,2021).

The biodegradation rates of compounds like PFAS can be influenced by three main factors: environmental conditions, microbial community composition and dynamics, and co-contaminant interactions(J. Lu *et al.*,2023). Environmental conditions, such as temperature, pH, oxygen availability, and moisture content, affect microbial activity and enzymatic reactions. Aerobic degradation pathways generally proceed faster than anaerobic ones, as they involve more efficient metabolic processes (Hidalgo *et al.*,2020).

Microbial diversity, community structure, and adaptation can enhance the overall biodegradation potential (S. Bolan *et al.*,2024). Co-contaminant interactions, such as the presence of additional carbon sources or nutrients, can stimulate microbial growth and cometabolic degradation of target contaminants (Geng *et al.*,2022). Inhibitory effects from other contaminants or substances can also affect the biodegradation processes. Competition for resources or degradation pathways among microorganisms can also influence the overall biodegradation rates. Overall, these factors contribute to the effective degradation of PFAS (Farouk, 2023).

3.7 Biodegradation of Polycyclic Aromatic Hydrocarbons

PAHs undergo various degradation pathways, including aerobic and anaerobic processes (S. Liu *et al.*,2024). Aerobic degradation involves the initial oxygenation of PAHs, which introduces reactive functional groups into the aromatic structure (Genitsaris *et al.*,2024). Dioxygenases, such as naphthalene dioxygenase, phenanthrene dioxygenase, and pyrene dioxygenase, form cisdihydrodiols and monooxygenases, producing aromatic hydroxylated intermediates (Jiménez-Volkerink *et al.*,2023). These intermediates undergo further oxidation and ring-cleavage reactions, resulting in aliphatic or cyclic intermediates that can be further degraded (Zhang et al., 2022).

Central metabolic pathways integrate these intermediates into central metabolic pathways, allowing for the complete mineralization of PAH compounds to carbon dioxide and water (Berhanu *et al.*,2023). Anaerobic degradation involves the addition of a substituent, such as fumarate, to the aromatic ring, which is catalyzed by enzymes like naphthyl-2-methyl-succinyl-CoA synthase or phenyl-phosphate synthase (Kislov *et al.*,2013). The activated PAH intermediates undergo a series of reduction and hydrolysis steps, transforming the aromatic structure and preparing the compound for subsequent ring-cleavage (Zhang *et al*., 2022).

Factors influencing microbial PAH degradation include bioavailability and adsorption, nutrient availability and co-substrates, and microbial community interactions (Thacharodi *et al.*,2023). Bioavailability is a critical factor in determining the accessibility of PAHs to microbial degraders, while nutrient availability and co-substrates can influence the growth and activity of PAH-degrading microorganisms. The diversity and composition of the microbial community can significantly impact the efficiency and rate of PAH biodegradation (Thacharodi *et al.*,2023).

3.7.1 Naphthalene biodegradation

Naphthalene biodegradation involves the initial oxidation of aromatic rings, followed by ring cleavage and aliphatic intermediate formation, primarily by bacteria like Pseudomonas and Rhodococcus species (Z. Zhang *et al.*,2020). It involves the initial oxidation of naphthalene to 1,2-dihydroxynaphthalene, which is catalyzed by the enzyme naphthalene dioxygenase (Ghafari *et al.*,2024). This process adds two oxygen atoms to the naphthalene molecule, forming the cis-dihydrodiol intermediate, 1,2-dihydroxynaphthalene (Umar *et al.*,2017). The cis-dihydrodiol intermediate is dehydrogenated by an enzyme to form the corresponding dihydroxy compound, 1,2-dihydroxynaphthalene (Umar *et al.*,2017). The ring cleavage of 1,2-dihydroxynaphthalene by 1,2-dihydroxynaphthalene dioxygenase results in the formation of salicylaldehyde and pyruvate (Lyu *et al.*,2014). The salicylaldehyde can be further metabolized through the catechol pathway, converting it to catechol and eventually the Krebs cycle intermediates. Pyruvate can also be utilized in central metabolic pathways to generate energy and biomass for bacterial cells (Chang *et al.*,2002).

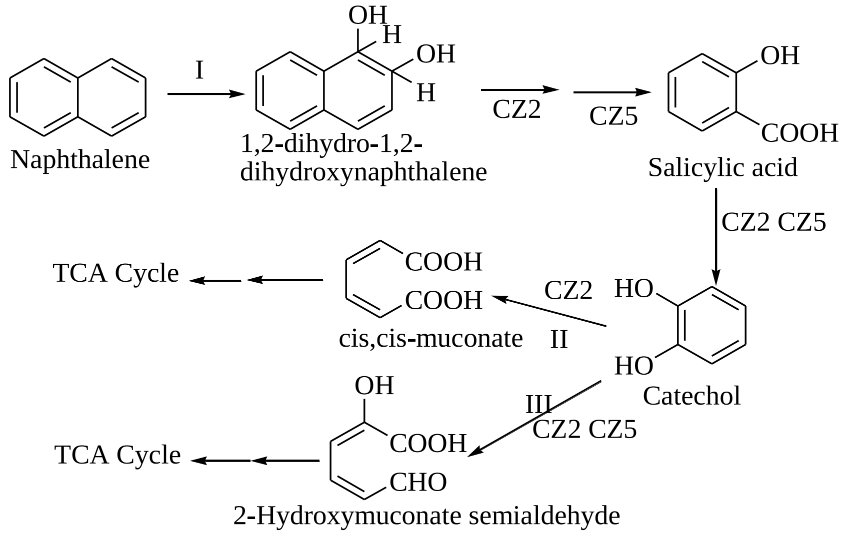

Figure 3.4: *Showing Naphthalene biodegradation using Pseudomonas sp* (Novianty *et al.*,2022; Cai *et al.*,2023)

3.7.2 Naphthalene biodegradation using *Rhodococcus sp*

Naphthalene, a common environmental pollutant, can be degraded by Rhodococcus bacteria (Rodríguez *et al.*, 2022). These bacteria can take up naphthalene through membrane transport systems, undergo initial oxidation to 1-naphthol or 2-naphthol, and undergo ring cleavage to form dihydroxy-naphthalene compounds (Tomás-Gallardo *et al.*, 2014). These compounds are further degraded by enzymes, yielding central metabolites such as pyruvate and acetyl-CoA. These metabolites can be mineralized to CO2 and H2O through the cell's normal metabolic pathways. Rhodococcus sp. is known for its ability to degrade various organic compounds, including PAHs such as naphthalene (H. Zhou *et al.*, 2023).

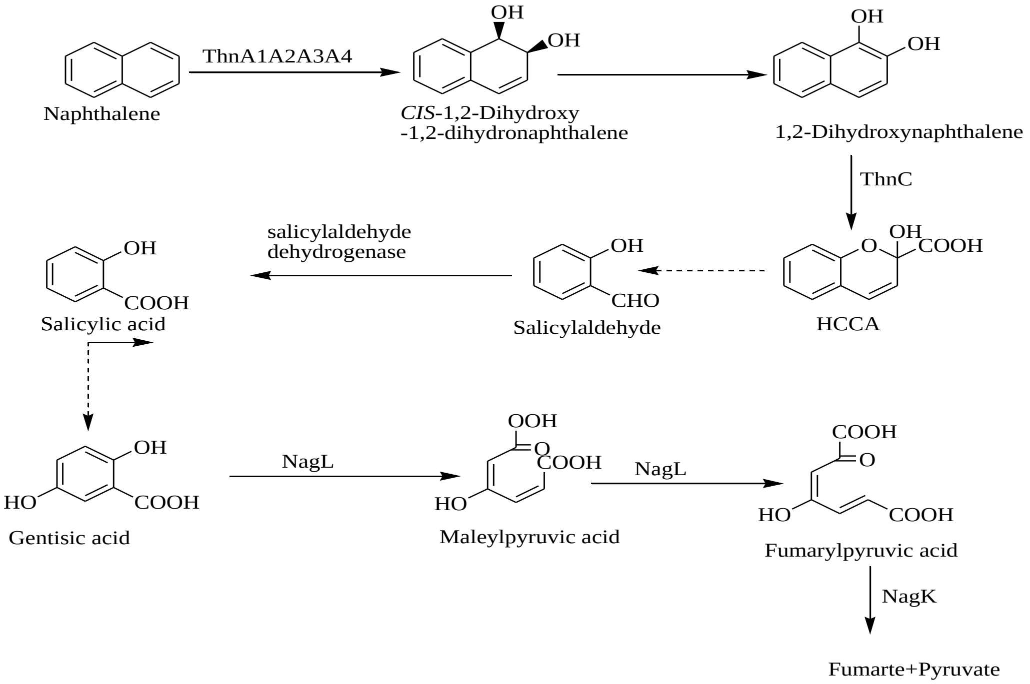

Figure 3.5: *Showing Naphthalene degradation using Rhodococcus sp*. (Rodríguez *et al.*,2022; Jegan *et al.*,2018; Krivoruchko *et al.*,2023)

3.7.3 Phenanthrene biodegradation

Phenanthrene biodegradation involves the oxidation of aromatic rings, resulting in the formation of dihydrodiols and dioxygenase-catalyzed ring cleavage, and is primarily carried out by bacteria (H. Yang *et al.*,2024).

Phenanthrene, a polycyclic aromatic hydrocarbon, is a common contaminant found in contaminated environments (X. Chen *et al.*, 2024). Bacteria can degrade phenanthrene as a carbon and energy source. The biodegradation pathway involves initial oxidation by a multicomponent phenanthrene dioxygenase enzyme system, resulting in the formation of cis-9,10-dihydroxy-9,10-dihydrophenanthrene (M. Liu *et al.*,2024). This is dehydrogenated by a dehydrogenase enzyme to form 9,10-dihydroxyphenanthrene. The ring-cleaving dioxygenase enzyme cleaves the aromatic ring structure, forming aliphatic intermediates that can be further metabolized through central pathways (Sharma *et al.*,2023; Yuan *et al.*,2023).

3.7.4 Proposed biodegradation of phenanthrene using *pseudomonas turukhanskesis*

Phenanthrene, a polycyclic aromatic hydrocarbon, can be degraded by microorganisms like Pseudomonas turukhanskensis. The biodegradation process involves phenanthrene uptake, initial oxidation, ring cleavage, further degradation, and mineralization (Sharma *et al.*, 2023). P. turukhanskensis can transport phenanthrene into the cell through membrane transport systems, using it as a sole carbon and energy source for growth. The phenanthrene cis-9,10-dihydrodiol intermediate undergoes ring cleavage, resulting in 2-hydroxy-1-naphthoic acid (Korshunova *et al.*, 2016). This intermediate is further metabolized through enzymatic reactions, converting the aromatic intermediates into central metabolites like pyruvate and acetyl-CoA. The central metabolic intermediates are then mineralized to CO2 and H2O through the cell's normal metabolic pathways. The specific genetic organization and regulation of the phenanthrene degradation pathway in P. turukhanskensis may vary compared to other Pseudomonas strains. Environmental factors like temperature, pH, oxygen availability, and other carbon sources can also influence the efficiency and kinetics of phenanthrene biodegradation by P. turukhanskensis (Sharma *et al.*, 2023).

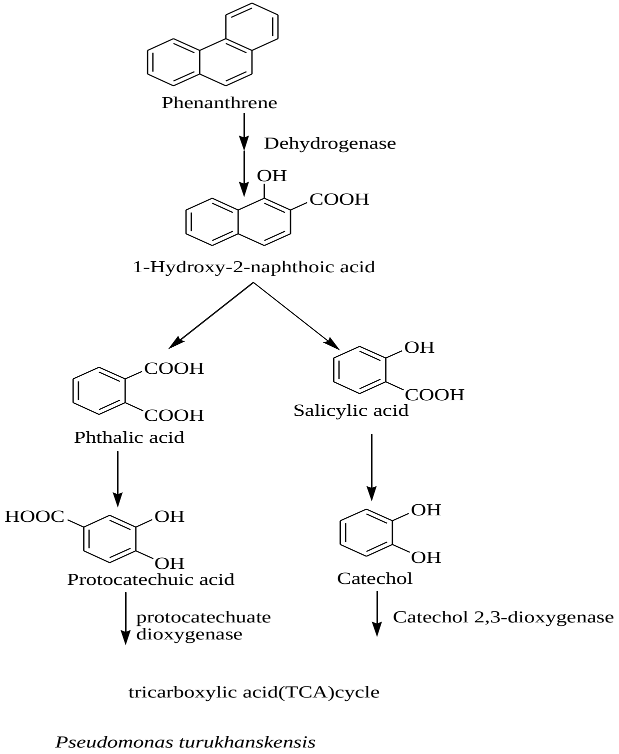

Figure 3.6: *Showing Proposed biodegradation of phenanthrene using Pseudomonas turukhanskesis* (Sharma *et al.*,2023; Izawa *et al.*,2021; Chen *et al.*,2023; Z. Zhang *et al.*,2021)

3.7.5 Anthracene biodegradation using *Mycobacterium sp*

Anthracene, a recalcitrant polycyclic aromatic hydrocarbon (PAH), is difficult to biodegrade. However, several bacterial species can degrade it as a carbon and energy source (Haritash & Kaushik, 2009). The biodegradation pathway involves initial oxidation by a multicomponent anthracene dioxygenase enzyme system, resulting in the formation of cis-1,2-dihydroxy-1,2-dihydroanthracene. This is then dehydrogenated by a dehydrogenase enzyme to form 1,2-dihydroxyanthracene (Mehetre *et al.*,2019). The ring-cleaving dioxygenase enzyme cleaves the aromatic ring structure, forming aliphatic intermediates that can be further metabolized (Lyu *et al.*,2014). Several bacterial genera and species, including Pseudomonas, Bacillus, Mycobacterium, Sphingomonas, and Arthrobacter, have been reported to degrade anthracene (Marzuki *et al.*,2021).

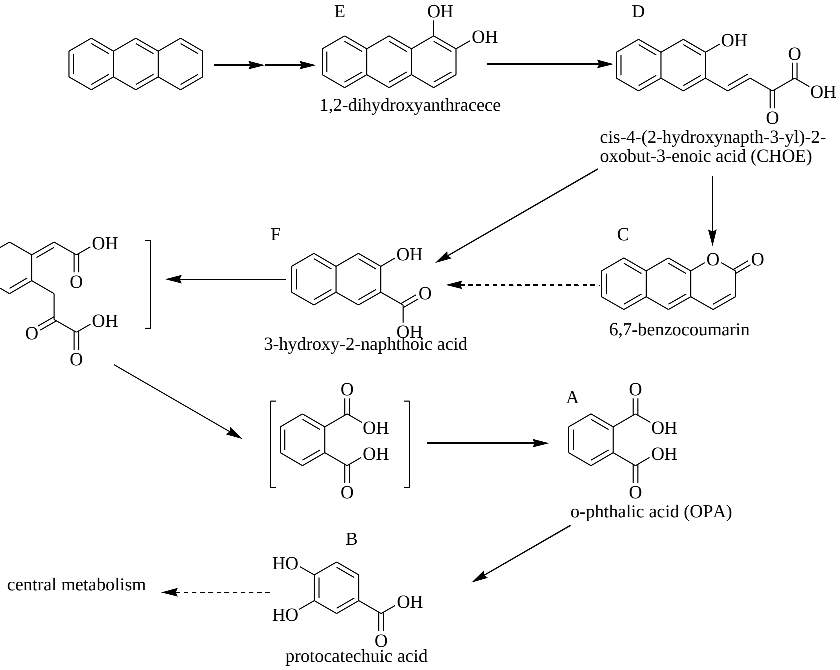

Figure3.7: *Showing Anthracene biodegradation using Mycobacterium sp*. Strain LB501T (X. Gong *et al.*,2015; Marzuki *et al.*,2021; F. Li *et al.*,2023)

3.7.6 Benzo[a]pyrene biodegradation by *Pannonibacter sp*

Benzo[a]pyrene biodegradation involves the oxidation of aromatic rings, forming dihydrodiols and dioxygenase-catalyzed ring cleavage, and is facilitated by bacteria like Mycobacterium and Burkholderia species (Yang *et al.*,2024).

Bacteria typically use a complex and multi-step pathway to biodegrade benzo[a]pyrene, a higher-molecular-weight poly(hydroxy)pyrene (PAH) with a stable structure. The process begins with the initial oxidation of benzo[a]pyrene by a multicomponent benzo[a]pyrene dioxygenase enzyme system, resulting in the formation of cis-7,8-dihydroxy-7,8-dihydrobenzo[a]pyrene (Rodríguez *et al.*,2022). This is then dehydrogenated by a dehydrogenase enzyme to form 7,8-dihydroxybenzo[a]pyrene. The ring-cleaving dioxygenase enzyme then cleaves the dihydroxy compound, forming aliphatic intermediates that can be further metabolized through central pathways (Zhang *et al.*,2024).

Compared to other PAHs, benzo[a]pyrene's biodegradation is more challenging due to its higher molecular weight, increased stability, and presence of bay and K-regions. Bacterial strains like Mycobacterium, Sphingomonas, Rhodococcus, and Pseudomonas species have been reported to degrade benzo[a]pyrene, but their degradation rates are generally slower and less efficient (Goveas *et al.*,2023).

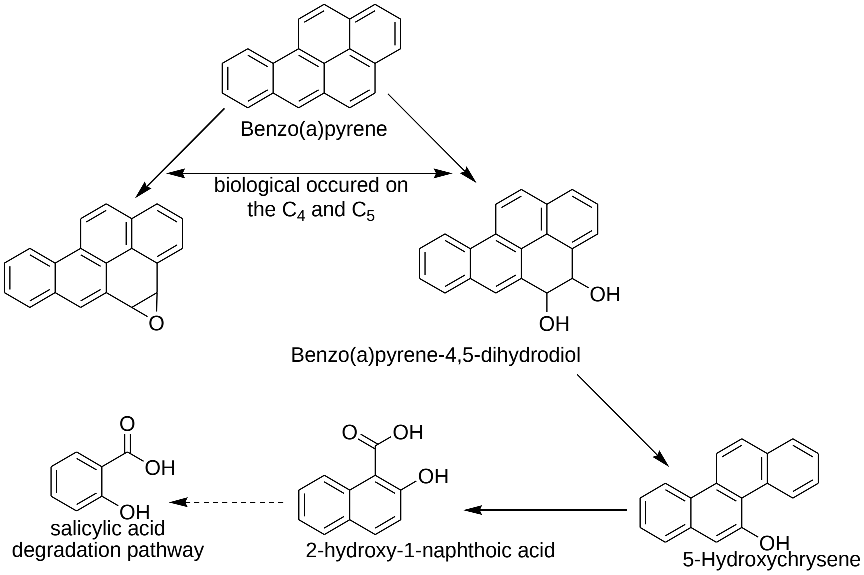

Figure 3.8: *Showing Biotransformation of benzo[a]pyrene by Pannonibacter sp. JPA3* (J. Jin *et al.*,2023; Zokm *et al.*,2022*;* Izawa *et al.*,2021).

3.7.7 Fluoranthene biodegradation *using Pseudomonas*

Fluoranthene biodegradation involves the oxidation of aromatic rings, resulting in the formation of dihydrodiols and ring cleavage, and is facilitated by bacteria like Sphingomonas and Pseudomonas species (Jiménez-Volkerink *et al.*,2023).

Fluoranthene, a polycyclic aromatic hydrocarbon (PAH), can be biodegraded by various bacterial species. The general biodegradation pathway involves initial oxidation by a multicomponent fluoranthene dioxygenase enzyme system, resulting in the formation of cis-2,3-dihydroxy-2,3-dihydrofluoranthene, a dihydrodiol intermediate (Patel *et al.*,2022). This is dehydrogenated by a dehydrogenase enzyme to form 2,3-dihydroxyfluoranthene. The dihydroxy compound is then cleaved by a ring-cleaving dioxygenase enzyme, opening the aromatic ring structure and forming aliphatic intermediates (Méndez-García & García de Llasera, 2024). Several bacterial genera and species have been reported to degrade fluoranthene, including Mycobacterium, Sphingomonas, Burkholderia, Pseudomonas, and Arthrobacter. Mycobacterium vanbaalenii PYR-1 has been extensively studied for its fluoranthene biodegradation capabilities, with key enzymes and reactions involved (Haritash & Kaushik, 2009). Other bacterial strains, such as Sphingomonas paucimobilis strain EPA505 and Burkholderia cepacia strain C3, have also been studied for their fluoranthene biodegradation capabilities (X. Zhou *et al.*,2024).

Biodegradation pathways of fluoranthene ***using Pseudomonas***

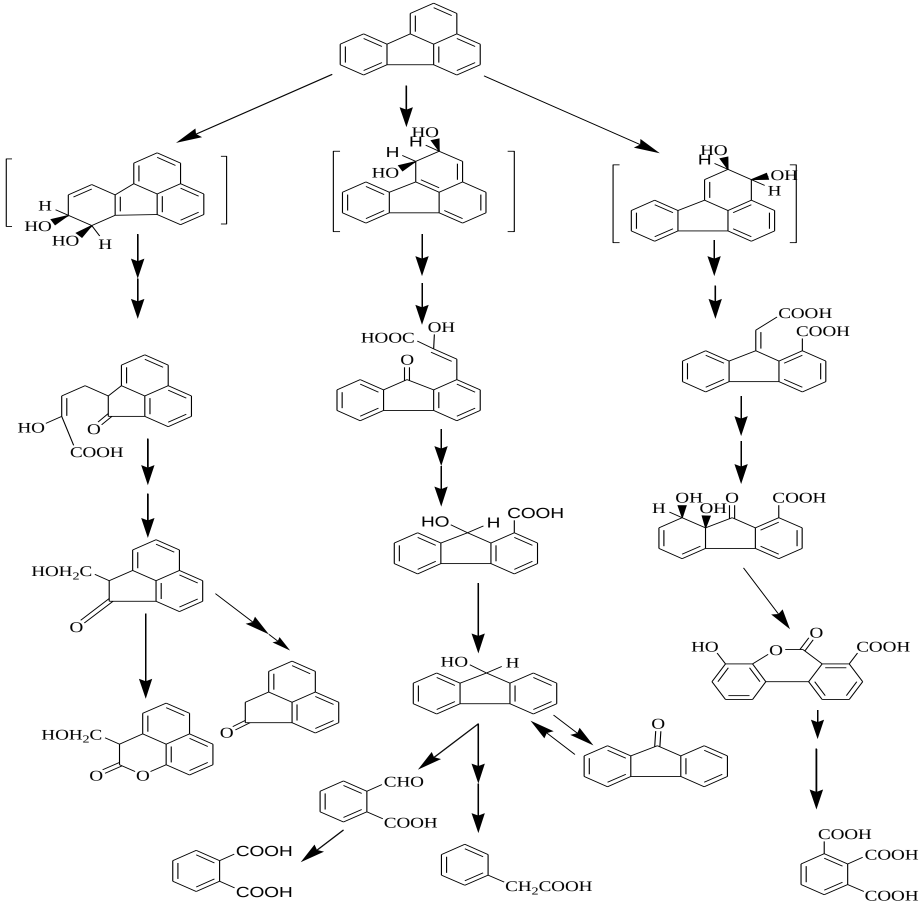

Figure 3.9: *Bacterial fluoranthene biodegradation pathways, illustrating microbial metabolic diversity concerning high-molecular-weight PAHs. Intermediates in brackets have not yet been identified (Geng et al., 2022).*

3.8 Risk assessment methodologies of PAHs

The USEPA Integrated Risk Information System (IRIS) provides toxicity assessments for individual polycyclic aromatic hydrocarbons (PAHs), such as benzo(a)pyrene, by determining cancer slope factors and reference doses (Kimmel, 2001). The Agency for Toxic Substances and Disease Registry (ATSDR) develops comprehensive toxicological profiles, summarizing the health effects of exposure to PAHs (Abugu *et al.*,2023). The International Agency for Research on Cancer (IARC) evaluates the carcinogenicity of PAHs and classifies them based on evidence strength (De Faria & Della Rosa, 2004).

The Benzo(a)pyrene Equivalency Approach uses benzo(a)pyrene as a marker compound for toxicity of PAH mixtures, using toxicity equivalency factors (TEFs) to scale the toxicity of individual PAHs relative to benzo(a)pyrene (Gondwal & Mandal, 2023). The World Health Organization (WHO) has established guidelines for drinking water quality, considering the carcinogenic potential of PAHs and aiming to limit exposure through contaminated drinking water consumption (Mechal *et al.*,2024). The EPA Relative Potency Factor (RPF) Approach scales the toxicity of individual PAHs relative to benzo(a)pyrene, enabling risk assessment of complex PAH mixtures in environmental and occupational settings (Samburova *et al.*,2017).

3.9 Some of the regulatory guidelines on PAHs

The USEPA has developed soil screening levels (SSLs) for polycyclic aromatic hydrocarbons (PAHs) to identify areas requiring further investigation or remediation. These SSLs are based on risk-based concentrations and consider both human health and ecological receptors (Montuori *et al.*,2020). The Canadian Council of Ministers of the Environment (CCME) has established soil quality guidelines for PAHs to protect human health and the environment (Akiner *et al.*,2024). The EU Directive 2008/105/EC on Environmental Quality Standards sets environmental quality standards for priority PAHs, including benzo(a)pyrene, in surface waters to protect aquatic life (Gikas *et al.*,2020). OSHA Permissible Exposure Limits (PELs) aim to limit worker exposures and minimize the risk of health effects, including cancer, associated with PAH exposure (Lee et al., 2015).

The World Health Organization has set guideline values for PAHs in drinking water to protect public health, considering the carcinogenic potential of PAHs (Karyab *et al.*,2013). The EU Water Framework Directive regulates PAHs in surface water, groundwater, and sediment to protect aquatic ecosystems. The ASTM E1739 Standard Guide for Risk-Based Corrective Action (RBCA) provides a framework for applying RBCA principles to the management of PAH-contaminated sites, considering both human health and ecological risks (International, 2009). The Netherlands has established intervention values for PAHs in soil and groundwater, addressing unacceptable risks based on ecological and human health impacts (Gkotsis *et al.*,2022). Australia's National Environment Protection Measure (NEPM) for the Assessment of Site Contamination includes guidelines for the investigation and remediation of PAH-impacted sites. Remediation approaches include soil washing and solvent extraction, bioremediation, thermal desorption, phytoremediation, and adsorption and stabilization (Marsden & Ashe, 2006).

4.0 Remediation targets on Polycyclic Aromatic Hydrocarbons

The USEPA has developed Regional Screening Levels (RSLs) for Particulate Air Pollutants (PAHs) in soil to identify areas requiring further investigation or remediation (Cline, 2001). The Canadian Council of Ministers of the Environment (CCME) has established soil quality guidelines for PAHs to protect human health and the environment (Akiner *et al.*,2024). The Netherlands has set intervention values for PAHs in soil, which serve as remediation targets based on ecological and human health impacts. USEPA Maximum Contaminant Levels (MCLs) are legally enforceable standards for certain PAHs in drinking water to protect public health (Ackah *et al.*,2014). The World Health Organization has set guideline values for PAHs in drinking water to limit exposure risk. The Netherlands has also established intervention values for PAHs in groundwater (Harmsen *et al.*,2007).

The EU Directive 2008/105/EC Environmental Quality Standards sets environmental quality standards for priority PAHs in surface waters to protect aquatic life. The CCME has developed sediment quality guidelines for PAHs to protect aquatic ecosystems and benthic organisms (Gikas *et al.*,2020).

4.1 Research gaps and areas requiring further investigation on PAHs

A review of 41 articles found high levels of PAH pollution in fruits, vegetables, and fish species in Africa. The highest levels were found in fish, pumpkin leaf vegetables, and papaya fruit. Health risk assessments revealed low to high risks associated with PAH consumption. The review emphasized the need for regulation of PAHs in Africa and recommended further research from experts from different African countries (Ezugwu *et al.,* 2024). Another comprehensive review of Lake Victoria's environmental dynamics from 2000 to 2022 reveals significant variations in water quality, heavy metal concentrations, zinc, and chromium levels. Organic pollutants, particularly dichlorodiphenyltrichloroethane (DDT) and its derivatives, are also a concern, which leaves most of the POPs unknown. The review highlights knowledge gaps in research, particularly in the northwestern, western, and southwestern lake basins, and suggests areas for further investigation (Ndunda & Wandiga, 2020). Another study investigated 16 polycyclic aromatic hydrocarbons (PAHs) in Lake Ulansuhai's waters and sediments, revealing no significant seasonal differences in concentrations. The northern part of Lake Ulansuhai had higher PAH content. PAHs are primarily derived from combustion sources and pose no significant carcinogenic risk to humans (Zhang *et al.,* 2024).

Polycyclic Aromatic Hydrocarbons (PAHs) are a significant environmental pollutant with over 100 compounds, accumulating in aquatic sediments and causing mutagenic and carcinogenic effects on humans and aquatic life. A comprehensive study is needed to effectively manage PAHs, focusing on inland aquatic ecosystems and fish biodiversity, which is a major food source for the global population. This could lead to new collaborative approaches to protect aquatic biodiversity from PAHs-induced ecotoxicity (Behera *et al.,* 2018).

4.2 PAHs source apportionment techniques

Source apportionment is a method in environmental science and air quality management that quantifies the contributions of different sources to a pollutant's concentration. It involves collecting data, analyzing it using mathematical models, identifying potential sources like atmospheric sources, vehicle emissions, or industrial processes, and estimating the contribution of each source to the overall pollutant concentration at the monitoring site (H. Li *et al.,* 2023; Kaur *et al.,* 2022).

Several approaches have been used to identify and quantify the contributions of different sources to the overall contamination, for example;

4.2.1 Principal component analysis and Multiple linear regression

Principal Component Analysis (PCA) and Multiple Linear Regression (MLR) are effective tools in source apportionment studies. PCA is used to explore receptor site data and identify major source types contributing to pollutant concentrations (Gholizadeh *et al.,* 2016). It extracts principal components (PCs) that represent underlying source types based on the data's correlation structure. These PCs provide valuable insights into dominant sources and their characteristics, guiding subsequent analysis (Peng *et al.,* 2022).

MLR is used to relate receptor site measurements to PCs obtained from PCA analysis. PCs are used as independent variables, while receptor site measurements are dependent variables in the regression model (Chen *et al.,* 2023). The regression coefficients from the MLR model can be used to estimate the relative contributions of different source types to the receptor site. The PCA-MLR approach simplifies the subsequent MLR analysis by reducing data dimensionality and identifying dominant source types. The orthogonal PCs obtained from PCA improve the stability and interpretability of the MLR model. The PCs can overcome issues of multicollinearity when using original source variables directly (Hansen *et al.,* 2024).

The combined PCA-MLR approach provides both qualitative insights and quantitative estimates of source contributions (Gholizadeh *et al.,* 2016). However, limitations include subjective interpretation of PCs and their association with specific source types, careful choice of PCs for MLR analysis, and assumption of linear relationships between receptor site measurements and source contributions (Li *et al.,* 2022). The PCA-MLR approach relies on the availability and quality of receptor site data and can be affected by uncertainties in measurements (Radomirović *et al.,* 2023).

4.2.2 Cluster analysis

Cluster analysis is an unsupervised machine learning technique used in source apportionment studies to group similar observations into distinct clusters or groups (An *et al.,* 2021). It can be applied to receptor site data, such as concentrations of chemical species measured at the receptor site, to identify groups of samples with similar chemical compositions, which may correspond to different source types. Clustering algorithms, such as k-means, hierarchical clustering, and Gaussian mixture models, can be used depending on the data's characteristics, desired number of clusters, and interpretability level (Wang *et al.,* 2023).

Cluster analysis can be applied in conjunction with other receptor modeling approaches, such as Positive Matrix Factorization (PMF) or Chemical Mass Balance (CMB), to validate source types identified by other models. The clusters identified by the cluster analysis can be used as a starting point or to validate source types identified by other models (Hello *et al.,* 2023). Advantages of cluster analysis include its data-driven nature, ability to identify unknown or mixed sources, and its ability to be sensitive to the choice of clustering algorithm, number of clusters, and data pre-processing (Kumari *et al.,* 2017). Careful data preparation, including handling missing values, normalization, and feature selection, is crucial for the success of cluster analysis (Moussa *et al*., 2021).

4.2.3 Factor analysis

Factor analysis is a statistical technique used in source apportionment studies to identify underlying source types contributing to observed pollutant concentrations at receptor sites (Haji Gholizadeh *et al.,* 2016). It is a data reduction technique that identifies a smaller set of unobserved variables (factors) that explain observed variation in a larger set of observed variables. There are two main types of factor analysis: Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) (Hox, 2021).

Factor analysis is applied to receptor site data, such as chemical species concentrations, to estimate the contributions of different source types to the measurements (Herwin & Nurhayati, 2021). Factor scores for each sample can be used to estimate the contributions of different source types. However, factor analysis is data-driven, can handle multicollinearity among observed variables, and can be subjective in interpretation. The number of factors retained in the analysis can significantly impact results (Gholizadeh *et al.,* 2016). Factor analysis can be integrated with other receptor modeling approaches, such as Positive Matrix Factorization (PMF) or Chemical Mass Balance (CMB), to provide a more comprehensive understanding of source contributions. However, careful data preparation, choice of factor extraction and rotation methods, and validation of factor analysis results are crucial for assessing the reliability and interpretability of the factors (An *et al.,* 2021).

4.2.4 Partial least square discriminative analysis

Partial Least Squares Discriminant Analysis (PLS-DA) is a statistical technique used in source apportionment studies to identify and discriminate between different source types. It is a multivariate regression method that identifies the chemical markers or "fingerprints" characteristic of different source types. The process involves two main steps: model building and model application (Chen *et al.,* 2024).

PLS-DA is supervised, requiring prior knowledge of source types or categories. It can handle multicollinearity and high-dimensional data, but can't identify the chemical species or combinations of species most important for discrimination (Chen *et al.,* 2024). Interpretation of the model can be challenging, and its performance can be sensitive to the quality and representativeness of the training data and the choice of model parameters (Filatova *et al.,* 2024). PLS-DA can be used in source apportionment to identify source types contributing to receptor site measurements based on the chemical composition of the samples. It can be trained using a dataset of known source profiles and corresponding receptor site measurements. The model can be integrated with other receptor modeling approaches, such as Chemical Mass Balance or Positive Matrix Factorization, to inform and validate the results (Mattias *et al.,* 2022).

4.2.5 Diagnostic ratios

Diagnostic ratios are a crucial tool in source apportionment studies to identify and differentiate between different source types (Barhoumi *et al.,* 2019). They are calculated by dividing the concentrations of two chemical species with different characteristic ratios across different source types. Examples of diagnostic ratios include benzene/toluene ratios for vehicular emissions, metal ratios for industrial emissions, biomass burning ratios for biomass burning, and hopanes/steranes ratios for fossil fuel combustion (Pănescu *et al.,* 2022). Diagnostic ratios can be used to qualitatively identify different source types in receptor site samples, comparing observed ratios with the characteristic ratios of known source types. They can also be used in conjunction with other

receptor modeling techniques like Chemical Mass Balance or Positive Matrix Factorization to provide additional information and support the source identification process (An *et al.,* 2021).
However, diagnostic ratios are most effective when source types have distinct and well-characterized chemical signatures (Li *et al.*, 2023). The validity of diagnostic ratios depends on the assumption that the relative proportions of the marker species remain constant during atmospheric transport and transformation processes. Changes in source characteristics over time, mixing of sources, or secondary formation of species can affect diagnostic ratios and introduce uncertainties in source apportionment (Singh *et al.*, 2023). Diagnostic ratios are essential in source apportionment studies to accurately assess the contribution of different source types to pollutant concentrations.

4.2.6 Minimization of PAHs exposure in the environment

The U.S. government has established standards for controlling the concentration of polychlorinated aromatic hydrocarbons (PAHs) in the workplace and the environment. These standards include those for PAHs in drinking water and the workplace. The Occupational Safety and Health Administration (OSHA) has established standards for PAH exposures under OSHA's Air Contaminants Standard, which covers coal tar pitch volatiles (CTPVs) and coke oven emissions. The OSHA PEL for PAHs in the workplace is 0.2 mg/m3 for an 8-hour time-weighted average.
The National Institute for Occupational Safety and Health (NIOSH) recommends setting the workplace exposure limit for PAHs at the lowest detectable concentration, which is 0.1 mg/m3 for coal tar pitch volatile agents for a 10-hour workday, 40-hour workweek. The EPA established ambient water quality criteria in 2000 to protect human health from the carcinogenic effects of PAH exposure. The EPA developed a maximum contaminant level (MCL) for benzo(a)pyrene (BaP), which is the most carcinogenic PAH. The World Health Organization (WHO) has set the unit risk of lung cancer of BaP at 8×10 $^{-}$6 ng m^{-}3 for lifetime exposure. The European Commission sets a target annual average concentration of 1 ng m−3 in the PM10 fraction, but this target has been exceeded in many locations, particularly in eastern countries. The Egyptian Environmental Association Affairs (EEAA) limits benzo(a)pyrene (BaP) at 0.7 µg/L.

5.0 DISCUSSION, CONCLUSION, AND RECOMMENDATION

5.1 Discussion

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds with multiple aromatic rings, primarily resulting from natural processes and anthropogenic activities. Understanding their source apportionment is crucial for effective environmental management and remediation strategies. Key sources of PAHs include fossil fuel combustion, vehicular emissions, industrial discharges, and biomass burning. Source apportionment techniques like principal component analysis and multivariate techniques, factor, and cluster analysis, Partial least squares discriminative analysis, and diagnostic ratios help quantify contributions from these sources, enabling targeted interventions. Biodegradation of PAHs relies on microbial communities capable of metabolizing these compounds. Both aerobic and anaerobic biodegradation pathways exist, with specific microbial taxa demonstrating varying efficiencies. Factors such as oxygen availability, temperature, and co-contaminants significantly influence biodegradation rates. Recent biotechnology advancements have introduced promising bioremediation strategies, including bioaugmentation and bio-stimulation. However, gaps remain in understanding the interplay between source apportionment and biodegradation, including the influence of environmental conditions on microbial community dynamics and the persistence of high molecular weight PAHs in certain environments. Future research should integrate source apportionment data with biodegradation studies to develop comprehensive models.

5.2 Conclusion

The review emphasizes the importance of identifying sources of polycyclic aromatic hydrocarbons (PAHs) contamination, such as industrial activities, vehicular emissions, and natural processes, for effective environmental management and policy formulation. Biodegradation, a natural remediation strategy, offers promising avenues for reducing PAH levels in contaminated sites. By utilizing microbial and some phytoremediation techniques, we can enhance PAH degradation, alleviating its harmful effects on ecosystems and human health. A multifaceted approach combining source identification and advanced biodegradation strategies is crucial for mitigating PAH pollution.

5.3 Recommendations for environmental and ecosystem protection

This review proposes several strategies to address the issue of particulate matter (PAHs) in the environment. These include strengthening regulatory frameworks, enhancing monitoring and assessment, public awareness and education, promoting cleaner technologies, implementing remediation strategies, restoring affected ecosystems, investing in research and development, and fostering interagency and community collaboration. Regulatory frameworks should be comprehensive, establishing stringent regulations targeting PAH emissions and discharges from industrial sources, transportation, and waste management. Compliance requirements should be enforced, and penalties for non-compliance should be imposed. Monitoring programs should be robust, using advanced analytical techniques for accurate detection and quantification of PAHs. Public awareness campaigns should be conducted to inform communities about PAH pollution sources and their effects.

Cleaner production methods should be encouraged, and alternative energy sources should be promoted. Remediation strategies should be implemented, including bioremediation techniques and soil and water treatment. Ecosystem restoration initiatives should be undertaken, and ecosystem health should be regularly assessed to evaluate recovery efforts and remediation strategies. Investing in research and developing innovative solutions for PAH detection, monitoring, and remediation can facilitate rapid response to contamination incidents. Interagency and community collaboration should be encouraged, and local communities should be involved in monitoring efforts and decision-making processes related to PAH management.

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