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A review on the occurrence, fate and remediation of Polycyclic Aromatic Hydrocarbons

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Abstract

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic pollutants characterized by fused aromatic rings and low aqueous solubility, making them highly resistant to environmental degradation. Informal electronic waste (e-waste) dismantling has emerged as a significant source of PAHs, particularly in developing countries where open burning and uncontrolled thermal recovery are common practices. These activities release a complex mixture of low- and high-molecular-weight PAHs into soils, sediments, and air, resulting in contamination hotspots with profound ecological and human health implications. PAHs are lipophilic, strongly adsorb to organic matter, and bioaccumulate through trophic levels, increasing their carcinogenic and mutagenic risks. Their distribution and persistence in various environmental matrices are influenced by molecular structure, hydrophobicity, and environmental conditions. This review incorporates current knowledge on the occurrence, fate, and environmental behaviour of PAHs. It also includes detection and characterization techniques, including GC-MS, HPLC, and other methods, essential for risk assessment. Furthermore, the paper examines remediation strategies—physical, chemical, and biological approaches. The review mentions limitations, like low bioavailability of high-molecular-weight PAHs and site-specific variability, and proposes integrated remediation frameworks combining chemical and biological processes. Addressing these challenges is crucial for mitigating PAH contamination and sustainable management of e-waste recycling hotspots worldwide.

Keywords: Polyaromatic hydrocarbon, bioremediation, e-wastes, pollution

Introduction

Polycyclic aromatic hydrocarbons (PAHs) are a group of hydrophobic organic compounds composed of two or more fused benzene rings (Sahoo *et al*. 2020) [42]. They are formed due to incomplete combustion of organic matter and anthropogenic activities like fossil fuel burning, biomass incineration, and industrial processes. Electronic waste (e-waste) dismantling is a major contributor to PAH contamination in soils, sediments, and air, particularly in developing countries where informal recycling practices are common (Ackah 2017) [2]. Manual dismantling, open burning of cables, and uncontrolled thermal processes release a complex mixture of low- and high-molecular-weight PAHs into the surrounding environment, leading to sites with persistent organic pollution near e-waste processing sites. The environmental interactions of PAHs is determined by their chemical properties like low aqueous solubility, high hydrophobicity, and strong sorption to organic matter which lead to accumulation in soils and sediments. These compounds exhibit remarkable stability, resisting natural degradation and leading to long-term effects in terrestrial and aquatic ecosystems., PAHs are known to have carcinogenic, mutagenic, and hormone-disrupting potential, posing significant risks to human health. Epidemiological and ecotoxicological studies link elevated PAH concentrations at e-waste sites to increased cancer risk, respiratory disorders, and genotoxic effects.

PAH remediation requires effective remediation strategies that are feasible, environmentally sustainable, and adaptable to heterogeneous site conditions. Traditional physical methods such as soil excavation and thermal desorption provide rapid pollutant removal. However, these techniques are costly and energy-intensive. In contrast, chemical oxidation, photocatalysis, electrokinetic treatment, and bioremediation offer promising alternatives

Properties of PAHS

PAHs are organic compounds with two or fused aromatic rings. they are generally colourless These molecules can be arranged in linear, angular or clustered manner. PAHs with four or more aromatic rings are large molecules with low vapour pressure and high hydrophobicity (Suman *et al*. 2016) [46]. They act as powerful adsorbents in soil. Their abundance in ground affects the water quality. The PAHs are up taken by the plant roots and are translocated to various parts of the plant. Exposure to PAH can occur through various routes like breathing, absorption and dermal contact.

Sources of PAHs

Various medical, agricultural and industrial processes emit harmful and toxic hydrocarbons. Polyaromatic Hydrocarbons are formed when the organic compounds are partially damaged at high temperature are cooled at a low temperature for an extended period of time (Stogiannidis and Laane 2015). These compounds are also emitted by petroleum and fossil fuel combustion, effluents from waste water treatment plant, aluminium industries, waste incineration and also electricity generation (Abdel-Shafy and Mansour 2016) [1]. Natural processes like forest fires, oil seeps, volcanoes, plants, bacteria and fungi also contribute to the global occurrence of PAHs (Alegbeleye *et al*. 2017) [3]. The significant proportion of nucleic acids found in various PAHs from sediments indicate that combustion of biomass and fossil fuels are primary sources of these chemicals.

The increase in demand for petroleum and other fossil fuels have led to elevated levels of polyaromatic hydrocarbons. the transport, collection and use of heavy petroleum and crude oil products have massively increased the chances of environmental disasters caused due to hazardous PAHs (George *et al*. 2024) [22]. Oil spills that contaminate the surface water and maritime ecosystems, tank leaks from underpass and above-ground holdings and buildup due to minor leaks of fuels, and other organic compounds associated with transportation are a primary source of petrogenic PAHs. These compounds are known to be formed due to incomplete combustion of substance of biological origin. The PAHs can also be formed by plants and bacteria and can also be generated during decomposition of vegetative matter. So, PAH can be generated from both natural and anthropogenic sources. PAHs are also found in soil samples. The concentration of PAHs can vary from 25 to 37,000 ng/g. Soil contaminated with e-wastes are found to have higher concentrations of these hazardous chemicals. One of the highest concentrations of PAH has been found from soil samples of a de-waste demolishing site in northern Vietnam. Dismantling electronic waste is one of the major reasons of soil pollution with polycyclic aromatic hydrocarbons (PAHs). Research shows that the average levels of total PAHs in soils from older e-waste sites in China are generally lower than those from newer sites in countries like Pakistan, India, and Ghana (Chakraborty *et al*., 2019) [14]. This difference suggests that PAHs at older sites may have broken down, evaporated, or moved around over time. Also, PAHs in these places have not yet reached equilibrium in all of the environmental compartments, like soil, water, and air. So, the apparent rise in the relative amount of high molecular weight (HMW) PAHs may be due to the fact that low molecular weight (LMW) PAHs are lost because they are more volatile and break down faster (Beriain *et al*. 2024) [8]. Also, finding PAH homologs with similar structures at different depths in soil profiles suggests vertical migration. This means that PAHs move through the soil column as a group instead of staying in the top layers (Huang *et al*. 2014) [25].

Occurrence and Fate of PAHs

These chemicals contaminate the environment during dismantling and recycling of informal electronic waste (e-waste). PAHs are formed from burning cables, printed circuit boards, and plastic parts in the open for the purpose of metal recovery (Qin *et al*. 2022) [39]. These processes release PAHs into the air, soil, sediments, and water bodies near dismantling sites.

PAHs are hydrophobic, and bind with organic matter. Airborne PAHs can be found in both vapour and particulate forms. Low molecular weight (LMW) compounds like naphthalene, phenanthrene, and anthracene are mostly in the gaseous phase, while high molecular weight (HMW) congeners like benzopyrene, chrysene, and dibenz(a,h)anthracene are mostly found bound to .in soil and water. Atmospheric deposition, surface runoff, and leaching from contaminated soils lead to PAH accumulation in aquatic ecosystems (Kieta *et al*. 2022) [29]. Sediments act as long-term reservoirs because they have less oxygen, which slows down degradation. Studies from sites where e-waste is taken apart show that soils have very high levels of PAHs, often between tens and hundreds of mg/kg, which is much higher than the levels found elsewhere.

The molecular weight of PAHs and their properties, like vapour pressure, water solubility, and octanol-water partition coefficient, have a big impact on how they behave in the environment (Suresh *et al*. 2025) [47]. LMW PAHs (2–3 rings) are more volatile and have moderate water solubility, which makes them easier to move around in the environment and easier to remove through volatilisation and leaching. HMW PAHs (4–6 rings), have low volatility and very low solubility, which means they bind to soil organic matter and sediments. This makes them last longer and have a higher probability of bioaccumulation. The loss of LMW congeners through volatilisation, microbial degradation, or photolysis leads to a relative increase in the amount of more stable and toxic HMW PAHs in contaminated sites (Singh and Singh 2025) [44].

These compounds are constantly exchanged through atmospheric transport, deposition, and surface runoff. HMW PAHs that are bound to particles can move long distances in the air before they deposit, which adds to pollution in distant places (Liu *et al*. 2022) [32]. PAHs are not found only in the top layers of soil. Studies have found that these compounds also occur at different depths in soil profiles, which suggests that they move down through processes like infiltration and colloid-facilitated transport (Cheng *et al*. 2024) [15]. This downward movement raises concerns about groundwater contamination, especially at sites where dismantling activities have been going on for a long time.

Chemical stability and slow pace of degradation lead to PAHs having a long half-lives in the environment. There are three main ways through which the PAHs break down: photolysis, microbial metabolism, and chemical oxidation (Kumari and Das 2023) [30]. Photodegradation is efficient for breakdown of LMW PAHs when they are exposed to sunlight, but HMW congeners don't react as much because their particles stick together strongly. Microbial degradation, mostly through monooxygenase and dioxygenase enzymes, breaks down PAHs into intermediate metabolites like dihydrodiols, quinones, and carboxylic acids. However, the rates of degradation decreases as the number of rings increases. Microbial degradation is difficult in anaerobic conditions, like those found in sediments. Some oxidative transformation products, like oxygenated PAHs, might be more harmful and cause mutations than the original compounds.

Distribution and Characterization of PAH Pollution

The distribution of Polycyclic Aromatic Hydrocarbons (PAHs) in the environment is dependant on their physicochemical properties, sources of the pollutant, and how they interact with the environment. PAHs that are released into the air, land, and water during incomplete combustion, pyrolysis, and waste incineration, including those from breaking down electronic waste, are dispersed over a wide area (Dutta *et al*. 2025) [19]. Their distribution varies over time and space, and is affected by chemical and environmental conditions of each site.

PAHs exist in two states in air: as gas and as particulate. Low Molecular Weight PAHs, like naphthalene, acenaphthylene, and fluorene, are volatile and make up most of the vapour phase. High Molecular Weight PAHs, like benzopyrene and indeno[1,2,3-cd]pyrene, strongly bind to particles (Rodríguez *et al*. 2022) [40]. This phase partitioning affects how things move through the air and deposit. As these compounds do not dissolve well in water and bind to organic matter, clay particles, and black carbon, PAH concentrations increase in soil and sediments. PAHs dissolve into aquatic systems through runoff, atmospheric fallout, and leaching. They bind to suspended particles and eventually settle in sediments, where they stay for an extended time. Sediments indicate PAHs were deposited in the past, which shows how human activities have changed over time. Urban and industrial areas have the highest levels of PAHs, caused by cars, coal burning, and burning trash. Informal e-waste recycling centres in Asia and Africa have levels of contamination that are higher than the global average. Vertical distribution studies show that PAHs can leach into soil profiles, and are found in subsoils at detectable levels (Bandowe *et al*. 2021) [7]. This suggests that they move downwards through colloidal transport or water infiltration. Seasonal changes also affect the distribution of PAHs. Studies have shown there are higher concentrations of PAH in winter because there is more combustion and little photodegradation (Jia *et al*. 2023) [28].

To characterise PAH pollution, chemicals are classified on the basis of individual congeners, abundance ratio relative to each other, and composition to differentiate between sources. PAHs are grouped by molecular weight: LMW (2–3 aromatic rings) are more volatile, mobile, and are more prone to break down, while HMW (4–6 rings) are more stable, hydrophobic, and toxic (Ali and Wang 2021). The octanol-water partition coefficient and vapour pressure are two very important factors that affect how things interact with the environment. HMW PAHs have log K_ow values greater than 5 and very low vapour pressures, which means they are strongly adsorbed and bioaccumulate. When characterising a source, diagnostic ratios like phenanthrene/anthracene and fluoranthene/pyrene are often used to distinguish between petrogenic (oil-derived) and pyrogenic (combustion-derived) origins. PAH profiles at e-waste dismantling sites usually show that HMW chemicals are the most common. This happens as plastics and circuit boards are burned at high temperatures. Gas Chromatography-Mass Spectrometry (GC-MS) is a common method for analytical characterisation. It can be used to separate and identify individual PAHs with high resolution. Other methods, like High-Performance Liquid Chromatography (HPLC) with fluorescence detection and Fourier Transform Infrared (FTIR) spectroscopy, are also used to confirm and measure the chemical constituents. Some samples have alkylated PAHs and oxygenated derivatives, which suggests that secondary transformation processes may happen, which make them more toxic (Cao *et al*. 2022) [12].

Detection of PAHs

It is important to detect and quantify Polycyclic Aromatic Hydrocarbons (PAHs) with accuracy in environmental samples. As these chemicals do not dissolve freely in water, are not very volatile, these chemicals are found in complicated materials like soil, sediments, water, and air particles (Wang *et al*. 2023) [49]. Identifying PAHs requires a series of steps, like collection, extraction, cleansing, and analysis using various tools and techniques.

The aim of the study determines how samples are collected. To keep soil and sediment samples from breaking down and evaporating, they are usually collected with stainless steel corers or augers and kept at low temperatures. PAHs that are bound to particles are caught on quartz fibre filters, and PAHs that are in the air are caught on polyurethane foam or XAD-2 resins. To concentrate trace-level compounds, water samples are often collected in large amounts and then solid-phase extraction (SPE) method is used. After collection, samples are freeze-dried or dried with a solvent before being extracted.

Extraction techniques: Extraction is one of the first steps for PAH analysis because these chemicals bind very well to soil, sediment, and other small particles.

Soxhlet extraction, is widely used to isolate PAHs using non-polar or semi-polar organic solvents like dichloromethane or hexane-acetone mixtures. This method is reliable, but it takes a long time and needs a lot of solvents (Gea *et al*. 2024) [21].

Ultrasonic-assisted extraction (UAE) uses high-frequency sound waves to disrupt the sample matrix, which makes it easier for the solvent to penetrate and speeds up the extraction process (Bhadange *et al*. 2024) [9].

Accelerated solvent extraction (ASE) utilizes at higher temperature and pressure, which makes solubility and extraction kinetics better and uses much less solvent than Soxhlet.

Solid-phase microextraction (SPME) is a solvent free method of extracting volatile PAHs in air and water because they are easy to use and. After extraction, it is important to clean the silica gel or alumina columns to get rid of contaminants, like lipids and pigments that could interfere with analysis (Temerdashev *et al*. 2021) [48].

Instrumental analysis: Gas chromatography (GC) and high-performance liquid chromatography (HPLC) are used to detect PAHs because they separate the PAH and can work with complicated matrices (Ekner *et al*. 2022) [20]. GC-MS, combines gas chromatography with mass spectrometry, is one of the most common method because it gives both qualitative and quantitative data. When separating PAH congeners, non-polar capillary columns like DB-5 or HP-5 are often used (Chung *et al*. 2024) [16]. Electron impact ionisation and selected ion monitoring (SIM) make it easier to detect trace amounts. GC used with a flame ionisation detector (GC-FID) for quantification is easy to use and use but is not as specific as mass spectroscopic methods. For PAHs that are thermally unstable or have a high molecular weight, HPLC coupled with fluorescence detection (HPLC-FLD) or UV detection is the best choice. Fluorescence detection is very sensitive technique that is perfect monitoring PAHs that are required by law (Qazi etal. 2021) [38]. Some, spectroscopic methods like UV-Vis and Fourier-transform infrared (FTIR) spectroscopy are used for rapid screening, but they aren't usually good enough for detailed profiling studies.

Newer analytical methods have made it possible to use high-resolution methods to detect PAHs with more accuracy in complex environmental samples. Comprehensive two-dimensional gas chromatography (GCGC) with time-of-flight mass spectrometry (TOF-MS) gives better separation of co-eluting PAHs. This makes it easier to resolve complex mixtures that are often found at e-waste dismantling sites. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) are also a powerful way to identify the presence of oxygenated and nitrated PAH derivatives, which are generally more toxic than the original compounds (Jeong *et* *al*. 2024) [27]. Fluorescence spectroscopy and immunoassays are two examples of field-based screening methods that are increasingly used to detect pollutants on site, in large-scale surveys. These methods although not as accurate as GC-MS or LC-MS/MS, give quick results that help with more in-depth lab analysis (Cutillas *et al*. 2025) [17].

Accurate detection of PAHs along with strict quality assurance and quality control (QA/QC) protocols gives results that are reliable and can be repeated. This includes using procedural blanks to check for contamination. Standard protocols that use deuterated PAHs to check recovery efficiency, and matrix spikes help to check method accuracy (Yang *et al*. 2025) [50]. Calibration with certified reference materials is very important for getting the correct results, especially in regulatory settings. Detection limits for instruments depend on the method and the type of sample. Advanced techniques like GC-MS and HPLC-FLD generally have detection limits in the sub-ng/L range for water and µg/kg levels for soils and sediments. Following QA/QC protocols closely not only improves the accuracy of the analysis, but it also helps to compare results between laboratories and meet international monitoring standards (Balaram and Satyanarayanan 2022) [5].

Effects of PAHs

In Soil

PAH produced by degradation of crude oil are toxic, mutagenic and carcinogenic to plants, animals and human beings (Brzeszcz *et al*. 2024) [10]. The leaching of carcinogenic PAHs to groundwater endangers environment and human health. Plants being producers in the food chain, take up carcinogenic PAHs and cause them to be transferred across the trophic levels. PAHs are classified as hazardous toxins that pose serious risks to the environment, and can accumulate in large quantities in soil. This results in the soil ecosystem acting as a sink for the PAH chemicals (Rusănescu 2024) [41]. These pollutants accumulate in the environment. This leads to an increase in the toxic effects on soil dwelling microorganisms, plants, animals and even humans. The high levels of PAH often exceed the threshold levels. This negatively affects the environmental quality harming all organisms. Prolonged exposure to these chemicals causes cancer, respiratory and neurodegenerative disorders. PAH also negatively affect the soil dwelling microorganisms. Research has shown exposure to high molecular weight PAH like pyrene inhibits microbial dehydrogenase activity (Lipinska *et al*. 2021). Naphthalene and phenanthrene inhibit urease and dehydrogenase activities. Increased pyrene levels of have been found to depress phosphatase activities.

In Aquatic Environment

PAHs are also toxic to aquatic organisms. These chemicals enter waterbodies through various pathways like runoff from contaminated soil and precipitation causing long term damage to aquatic ecosystems (Nawrot *et al*. 2022). The toxicity if PAHs in water depend on the concentration, duration of exposure and the chemical nature of the PAH present. PAHs like benzopyrene are known to have teratogenic effects on aquatic organisms. Additionally, they also cause reproductive failure and suppressed immune functions in fish and aquatic invertebrates.

Remediation of PAHs

Physical remediation methods

Physical remediation is the use of engineering-based methods to physically remove, separate, or immobilise PAHs from contaminated environments like soil, sediments, and water. These methods are usually used as primary or temporary measures because they work efficiently to quickly lower pollutant levels, especially in areas with high concentrations of PAH pollutants, like e-waste dismantling sites. Physical processes don't usually degrade PAHs like biological or chemical remediation methods. Instead, they try to lower exposure and stop PAHs from moving further (Samanth 2024) [43].

One of the most common methods is excavation and off-site disposal. This means physically removing contaminated soils or sediments and transporting them to secure landfills made for hazardous waste containment. This method works well in small, localised hotspots with high PAH levels. However, it uses a lot of energy, costs a lot of money, and only transfers the contamination problem instead of solving it. Digging of landfill sites can pose short-term risks because it creates dust and lighter PAHs evaporates when they are handled (Bamtora *et al*. 2025).

Using water-based solutions or surfactant-based washing fluids, soil washing separates fine particles that are contaminated with PAHs from coarser soil fractions. Because PAHs binds strongly to organic matter and fine silts or clays, washing concentrates the contaminants into a smaller part of the soil, which can then be safely treated or disposed off. Key factors that influence washing efficiency include particle size distribution, organic matter content, and surfactant properties. Soil washing gets rid of some of the contaminated material, but it also makes secondary waste streams that needs to be treated.

Thermal desorption is another common physical method for removing PAHs. In this method PAHs are desorbed and volatilised by heating contaminated soils or sediments to temperatures between 200°C and 600°C, depending on how volatile the target compounds are. The desorbed vapours are later collected and processed using condensation or combustion units. This method works best for removal of PAHs with low and medium molecular weights, but it needs higher temperatures for high-molecular-weight chemical compounds that stick around. Thermal desorption lowers the concentration of contaminants significantly in a short amount of time. However, it is both energy and cost-intensive.

Soil Vapour Extraction (SVE) is a good way to clean unsaturated soils that have volatile and semi-volatile PAHs. It involves using vacuum to pull PAH vapours and trapped air out of the vadose zone through extraction wells. SVE is suitable for lighter PAHs that have higher vapour pressures, but it is not suitable for compounds that are strongly sorbed or have a lot of molecules (Cao *et al*. 2021) [13]. Before being released back to the environment, the extracted vapours are cleaned up with activated carbon filters or thermal oxidation systems.

Electrokinetic remediation is a recent in-situ technique for purifying soils and sediments contaminated with polycyclic aromatic hydrocarbons (PAHs), by applying a low-intensity direct current (1–2 V/cm) across electrodes placed within the contaminated matrix to induce electroosmosis, electromigration, and electrophoresis. As PAHs are neutral and hydrophobic, their transport is facilitated by using surfactants, where micelles formed by added surfactants or cyclodextrins solubilize PAHs and allow movement along electroosmotic flow towards the collection wells. Operational setups involve maintaining pH gradients caused by electrolysis reactions that prevent soil clogging and ensure effective pollutant mobilization. Strategies involving coupling electrokinetic processes with oxidizing agents like Fenton's reagent or persulfate and integrating bioremediation, have been explored to increase efficiency and achieve simultaneous degradation of PAHs. Electrokinetic remediation is particularly advantageous for low-permeability soils where conventional flushing or excavation is difficult, offering a minimally invasive approach (Dehghan Abkenar *et al*. 2024) [18].

PAHs are covered with impermeable layers like geosynthetic liners or clean soil in places where digging or treating a site isn't possible. This prevents PAHs from contaminating the environment. This method keeps contaminants from getting into groundwater and reduces direct exposure, but it doesn't get rid of or destroy them.

Chemical remediation methods

Chemical remediation involves the use of chemicals that degrade, transform, or immobilize polycyclic aromatic hydrocarbons (PAHs) in contaminated soils, sediments, or water systems (Patel *et al*. 2020) [37]. It converts persistent hydrophobic PAHs into less toxic, more soluble, or biodegradable compounds, thereby reducing environmental risk and enhancing subsequent treatment processes. Since PAHs are stable and have low solubitily, chemical remediation often relies on strong oxidants, catalysts, or co-solvents for remediation.

Oxidation: Chemical oxidation is one of the most widely used techniques, where powerful oxidants react with the aromatic rings of PAHs, leading to the opening of the ring structure and forming an open-chain structure. Finally, the compound are converted into carbon dioxide, water, and inorganic salts. Fenton's reagent is a mixture of hydrogen peroxide (H_2O_2) and ferrous iron (Fe^{2+}). It is widely used for in-situ chemical oxidation (ISCO). The reaction generates hydroxyl radicals that can degrade both low- and high-molecular-weight PAHs. Its efficiency is influenced by soil pH, as acidic conditions favour radical formation. To solve pH limitations, modified Fenton systems incorporating chelating agents or stabilizers have been developed. Permanganate oxidation is a technique where potassium permanganate ($KMnO_4$) acts as a strong oxidant that is particularly effective for breaking down aromatic compounds through electron transfer reactions. Persulphate-based oxidation, activated by heat, alkaline conditions, or transition metals, are increasingly being used for PAH degradation due to its ability to produce sulfate, which have high redox potential and longer lifespans than hydroxyl radicals, allowing deeper penetration into soil matrices.

Ozonation: Ozone is a powerful oxidizing gas, that is used for the degradation of PAHs in both aqueous and soil systems. Ozonation involves direct electrophilic attack on the π-electron system of aromatic rings and forming secondary radicals under alkaline conditions (Song *et al*. 2019) [45]. Ozonation is highly effective for low molecular weight PAHs. The application of ozone in heavily contaminated soils is challenging due to its low solubility and rapid decomposition, Ozonation is combined with hydrogen peroxide to form peroxone systems for better oxidation.

Chemical remediation techniques are faster when compared to biological methods and is particularly suitable for sites with high PAH pollution or mixed contaminants. However, incomplete oxidation, potential formation of toxic intermediates, and the need for careful management of chemical reagents to prevent secondary pollution are challenges often faced when using chemical techniques. Additionally, reaction efficiency is strongly influenced by soil texture, moisture content, and pH, requiring site-specific optimization.

Photocatalysis: Photocatalysis is an oxidation process that uses light energy: ultraviolet (UV) or visible light, in the presence of a semiconductor catalyst to degrade persistent organic pollutants like polycyclic aromatic hydrocarbons. The most commonly used photocatalyst is titanium dioxide (TiO_2) due to its strong oxidative potential, chemical stability, non-toxicity, and low cost. When TiO_2 is irradiated with photons of energy equal to or greater than its bandgap, electron–hole pairs are generated on the catalyst surface. These charge carriers participate in redox reactions, with the holes oxidizing water or hydroxide ions to produce highly reactive hydroxyl radicals, and the electrons reducing oxygen to form superoxide anion radicals. These reactive oxygen species react with aromatic rings of PAHs, initiating hydroxylation, ring opening, and conversion into CO_2 and H_2O (Liu *et al*. 2024) [33] .

Photocatalysis offers several advantages, including the ability to achieve complete mineralization without producing harmful secondary waste. Its efficiency can be determined by catalyst deactivation, recombination of electron–hole pairs, and the low solubility of PAHs, which restricts mass transfer to the catalyst surface.

Biological remediation

Biodegradation of PAHs occurs through aerobic oxidation, which is faster and more efficient than anaerobic pathways. The process begins with activation of aromatic ring of PAHs by dioxygenase enzymes. These enzymes incorporate molecular oxygen into the PAH structure, forming cis-dihydrodiols. The intermediates undergo dehydrogenation leading to the formation of catechols or other dihydroxylated compounds. These compounds undergo ring cleavage via ortho- or meta-cleavage pathways. The final products are aliphatic acids that enter metabolic pathways like tricarboxylic acid (TCA) cycle, leading to complete oxidation to CO_2 and H_2O.

Under anaerobic conditions, degradation of PAHs is slower and often proceeds through reductive mechanisms. Microorganisms activate PAHs by carboxylation, methylation, or addition to fumarate, forming intermediates that are ultimately metabolized to simpler compounds (Gupta *et al*. 2015) [24]. Sulphate-reducing, nitrate-reducing, and methanogenic bacteria have can breakdown PAHs in hypoxic environments, at a much slower pace than aerobic systems.

Bacteria belonging to the genera *Pseudomonas*, *Mycobacterium*, *Sphingomonas*, and *Rhodococcus* play critical roles in PAH biodegradation (Huang *et al*. 2023) [26]. These bacteria has ring-hydroxylating dioxygenases that initiate aromatic ring activation. Fungal species, like

Phanerochaete chrysosporium, can degradae high-molecular-weight PAHs through extracellular oxidative enzymes such as laccases and lignin peroxidases. These enzymes generate free radicals capable of cleaving complex aromatic structures.

The rate and extent of PAH biodegradation depend on multiple environmental factors like bioavailability. PAHs exhibit low solubility and strong sorption to soil organic matter. This limits the microbial access to the PAHs. Various techniques like adding surfactants, biosurfactants, or co-metabolic substrates are used to enhance bioavailability. Temperature, pH, nutrient availability (nitrogen, phosphorus), and oxygen concentration influence microbial activity. Aerobic biodegradation of LMW PAHs occurs at a more rapid pace compared to HMW PAHs require prolonged exposure and co-metabolic conditions (Ghoshal *et al*. 2016).

Biodegradation is environmentally friendly, cost-effective, and capable of achieving complete remediation of PAHs without generating hazardous secondary pollutants (Mekonnen *et al*. 2024) [34]. However, the degradation of HMW PAH is slow, dependant on environmental conditions. These limitations can be solved by adopting integrative approaches that use biological processes with physical or chemical methods for complete remediation.

Discussion

Polycyclic Aromatic Hydrocarbons (PAHs) are one of the most persistent and hazardous classes of environmental pollutants, particularly in regions impacted by e-waste dismantling, industrial emissions, and petroleum-based activities. Their hydrophobicity, chemical stability, and strong affinity for organic matter result in long-term accumulation in soils and sediments, posing significant ecological and human health risks through bioaccumulation and carcinogenicity. Understanding the occurrence, distribution, and fate of PAHs is therefore crucial for designing effective remediation strategies. PAHs can be detected using chromatographic and spectroscopic techniques, enabling trace-level quantification and structural elucidation in complex environmental matrices (Mogashane *et al*. 2024) [35]. Conventional physical methods such as excavation, soil washing, and thermal desorption offer rapid reduction of contamination are not cost-effective and often displace rather than destroy pollutants. Chemical treatments, like oxidation using Fenton's reagent, persulfate oxidation, and photocatalysis, are used for degrading PAHs into less toxic products. Biological approaches, particularly microbial biodegradation and plant-assisted remediation, represent sustainable alternatives by exploiting metabolic pathways to neutralize PAHs. These methods, are plagued by slow degradation rates because of hydrophobicity and environmental variability. Strategies like combining electrokinetics with bioremediation or coupling oxidation processes with microbial treatments achieve higher efficiency and minimize residual toxicity (Cameselle and Reddy 2022) [11]. Integration of green chemistry principles, nanotechnology-based catalysts have significantly enhanced PAH remediation efficiency while reducing ecological footprints. A shift toward integrative frameworks that combine physical, chemical, and biological methods tailored to site-specific conditions is needed for large-scale implementation. Effective management of PAH contamination requires a multidisciplinary approach that aligns with sustainability goals, ensuring environmental protection and human health in a rapidly industrializing world.

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