



# Green Technologies for the Decontamination of Polycyclic Aromatic Hydrocarbons

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Shubhangee Agarwal, Priyanka Rani, and Himanshu Gupta

## Abstract

Polycyclic aromatic hydrocarbons (PAHs) are dangerous microscopic contaminants which are organic in nature and characterized by the presence of two or more phenyl rings, which are notably resistant to degradation. PAHs originate from man-made as well as natural sources including volcanic eruptions forest fires, petroleum, coal, and oil-based products such as gasoline, as well as improper disposal of industrial and domestic waste, crude oil extraction, and spills. They are potentially a threat to human health, plants, animals, and the environment as a whole. Environmental scientists are exploring numerous methods for treating PAH-contaminated water and soil, which encompass biological, chemical, physical, and thermal technologies. The conventional approach to PAH decontamination typically involves the use of harsh chemicals and a process that consumes significant energy, leading to a push for more sustainable and eco-friendly alternatives. This chapter reviews recent progress in green technologies for PAH decontamination, including bioremediation, electrokinetic remediation, phytoremediation, adsorption (utilizing adsorbents like zeolites, biomass derivatives, geosorbents, silica, and graphene-based materials), advanced oxidation processes, enhanced remediation through biocatalysts, and nanotechnology.

## Keywords

Polycyclic aromatic hydrocarbons (PAHs) • Environment • Remediation • Green • Nanomaterials

S. Agarwal (✉) · P. Rani · H. Gupta  
Department of Chemistry, School of Sciences, IFTM University, Moradabad, Uttar Pradesh, India  
e-mail: [shubhangeearwal79@gmail.com](mailto:shubhangeearwal79@gmail.com)

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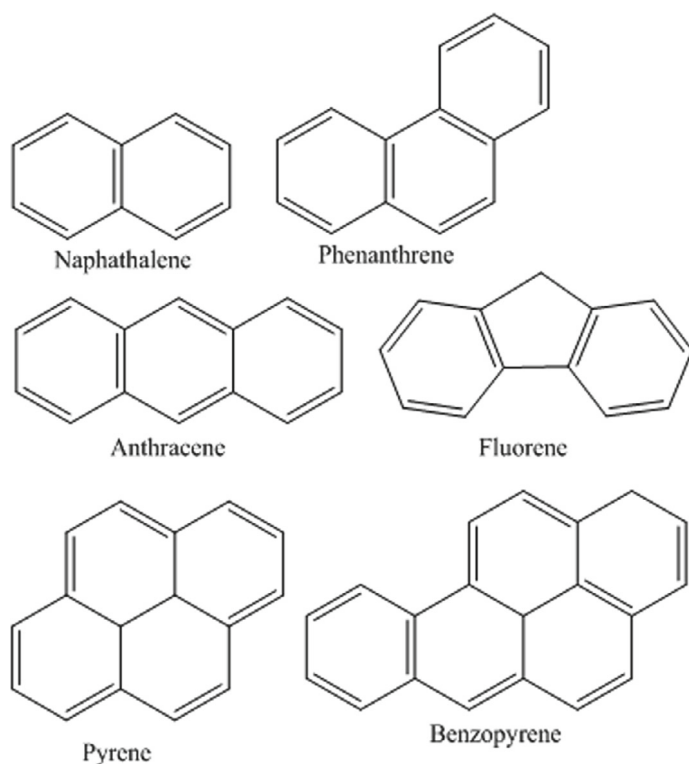
## Introduction

In recent years, the environmental existence of the pervasive organic contaminants PAH has come to an attention. PAHs are widely distributed, resilient, and hazardous organic pollutants, consisting of two or more fused phenyl rings arranged in clustered, angular or linear formations, and characterized by less solubility in water (Johnsen and Karlson, 2005; Gupta and Gupta, 2016). They primarily originate from the incomplete burning of carbon-based materials. PAHs can be present in variety of environmental matrix structures, including air, water, and soil (Ansari et al., 2023; Gupta and Dhiman, 2023). PAHs are categorized into two groups: lower molecular weight (LMW) compounds having two or three ring structures that are generally less hazardous, such as phenanthrene, naphthalene, anthracene, and fluorene, and higher molecular weight (HMW) compounds with four to seven ring structures that are less susceptible to deterioration, mutagenic, and capable of causing tumors, such as pyrene, benz[a]pyrene, and chrysene (Kuppusamy et al., 2016) (Fig. 13.1). The potential for carcinogenicity in persistent organic compound increases with their molecular weight (Eisler, 1987). PAHs that are bound to particles pose significant health risks to humans. Benz[a]pyrene contributes significantly to the total carcinogenic potential, accounting for 51–64% (Ohura et al., 2004). While they exhibit less solubility in water, PAHs are more soluble in organic solvents. Their partial volatile and lipophilic characteristics lead to a strong tendency for absorption and capture by biological matter and soil minerals, resulting in reduced mobility for microorganisms and other degrading agents in the upper layer of soil (Shanker et al., 2017). When PAHs are released into the atmosphere, they experience a variety of mechanisms including physical, chemical, and biological reactions through metabolic and microbial pathways, which are commonly referred to as weathering or degradation processes (Ossai, 2020). These weathering processes are significantly influenced by two non-biotic factors: the ecological characteristics and the composition of the contaminants. These persistent pollutants can adsorb on the upper layer of the soil, volatilize into the surroundings, and dissolve in water (Schwarzenbach et al., 2016). The physicochemical components of each organic pollutant affect their fate, behavior, and movement within the environment. The distribution of these organic hydrocarbons across different environmental matrices will differ substantially based on their molecular characteristics and the surrounding environmental conditions (e.g., temperature). Consequently, the amount of PAHs in the environment changes depending on the place of origin (Chen et al., 2020).

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## Sources of PAHs

PAHs are common environmental contaminants that are produced when carbon-based materials burn at high temperatures. Both naturally occurring and man-made sources emit PAHs. PAHs from natural sources are negligible in comparison to those produced by humans (Charlesworth et al. 2002; Ravindra et al. 2008; Witt



**Fig. 13.1** Chemical structure of few PAHs with lower and higher molecular weights

1995). Oil seeps, volcanic eruptions, thermal geological reactions, and fires in natural forests and prairies are examples of natural sources (Wright and Welbourn 2002; Hidayat et al. 2019; Hall et al. 2009; Gupta, 2018). Household waste burning, processing of agricultural products, automobile exhaust, armed forces operations, fossil fuel conversion, emissions from coal tar, and shale formation, petroleum based products processing, manufacturing of steel and iron, aluminum manufacturing, coke production, and partial combustion are all examples of human-induced sources of PAH emissions (Gupta and Gupta, 2018). These contaminants are extensively utilized in the manufacturing of pigments, dyes, insecticides, resins, wood maintenance, grease, and pharmaceutical and agricultural products (Abdel-Shafy and Mansour, 2016). The main ways that PAHs reach the aquatic system are by polluted debris, precipitation absorption, and accidental leakage. They are present in tar sands, coal, and oil (Blanchard et al. 2004). Humans come in contact to these persistent aromatic hydrocarbons through a variety of routes, including atmospheric deposition, and even at low quantities, they can cause cancer. Inhalation, water (from home and recreational activities), food, and work environments are among the exposures. One of the main ways

that humans are exposed is through contaminated water (Wang et al., 2009; Wu et al., 2011). The harmful consequences of PAHs necessitate constant and careful monitoring of human intake. According to their sources, PAHs can also be categorized as biogenic (originating from biological sources), pyrogenic (originating from combustion processes), or petrogenic (originating from petroleum products) (Merhaby et al., 2019).

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## Pathways of Exposure

PAHs are a class of chronic toxic substances that linger in many environments, such as the air, soil, and water, for a considerable amount of time. Their endurance is explained by their high thermal stability and poor water solubility (Na et al., 2021; Kim et al., 2013). Humans are exposed to PAH through a variety of routes, through breathing in particles that are in air and re-suspended contaminants, ingesting and drinking, and getting into contact with dirt and other substances through the bare skin (Menzie et al., 1992). The formation and destiny of these pollutants have become a major concern because to their mutagenic, carcinogenic, and teratogenic properties.

### Air

Natural events such as volcanic eruptions and bushfires send PAHs into the surrounding air. However, the main causes of these volatile organic pollutants in the surrounding air are activities brought on by high temperatures, such as partial combustion of biomass from wood, garbage from municipalities, and combustion of petroleum based products (Lammel, 2015). Additionally, chewing tobacco or employing high-temperature cooking techniques like grilling, deep-frying, roasting, or baking near or directly over a flame might cause it (Wróbel et al., 2022).

### Soil

In terms of soil quality, agricultural productivity, and other aspects, the ecosystem has suffered from the wet or dry accumulation of atmospheric PAHs on upper layer of soil (Balmer et al., 2019). Forest fires, volcanic eruptions, the degradation of sedimentary rocks that contain petroleum based chemicals, and the production of bacteria and algae are all natural sources of organic pollutants. PAHs level in upper layer of soil is also influenced by human activities including the pyrolysis of organic matter and inadequate burning of carbon-based fuels. Because of PAHs' hydrophobic properties and stable chemical composition, which lead to their build

up in soil, they have mutagenic, teratogenic, and carcinogenic qualities. Additionally, surface soil in crowded urban areas contains a significant concentration of PAHs (Bortey-Sam et al., 2014).

## Water

PAHs primarily enter water sources through leaching from creosote-impregnated wood, road drainage, waste water from factories, burning petroleum and other fossil fuels, and wet or dry accumulation (Karyab et al., 2013). Groundwater, wastewater, potable water, water bodies like lakes and rivers, and wreckages have all found to contain volatile organic compounds (Mojiri et al., 2019).

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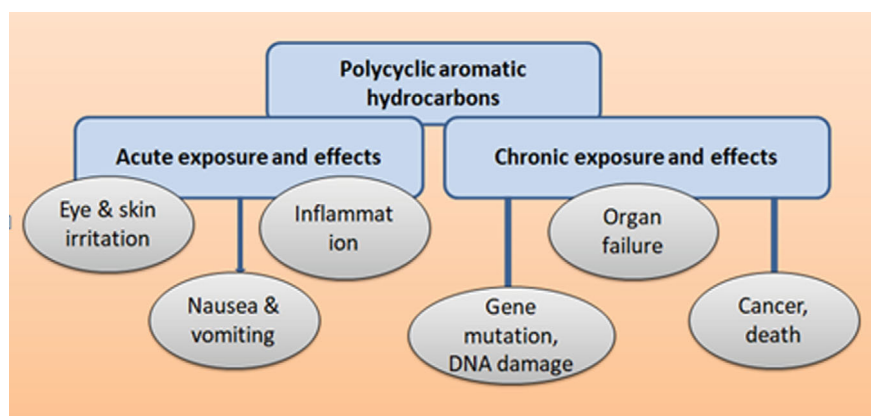
## Effect of PAHs on Health

Both short-term and long-term health impacts are possible with PAHs. Signs of asthma, respiratory difficulties, pulmonary problems, kidney and liver impairment, glaucoma, and immune system suppression are among the long-term complications (Abdel-Shafy and Mansour, 2016). Short-term or immediate side effects include gastrointestinal stress, diarrhoea, vomiting, discomfort and pain in eyes, anxiety, and more (Abdel-Shafy and Mansour, 2016). Air, plants, animal tissues, water reservoirs, soil, and rocks have also been found to contain a number of PAHs (Chang et al. 2004a, 2004b; Balati et al. 2015; Liu et al. 2014; Vane et al. 2014). Due to their persistence and lack of biodegradability, PAHs can penetrate into the food chain through the soil and reach humans through the respiratory, food, and skin systems (Abdel-Shafy and Mansour, 2016). The immune system transforms PAH into epoxide hydrolase and diolepoxides, which react with genetic material and stop its synthesis, when they reach the human body and may successfully pass through the plasma membrane and be absorbed by the cells (Kaya et al., 2013) (Fig. 13.2).

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## PAH Derivatives and Their Fate

PAHs penetrate into the environment through the air and water, travel through the marine environment and eventually make their way into the food chain of humans through marine foods. The amount of time PAHs stay in the atmosphere depends on a number of factors, including the chemical makeup, pollutant-degrading microorganisms, their concentration, dispersion, bioavailability, pH, oxygen levels, soil type, temperature and the availability of nutrients. PAHs are pervasiveorganic pollutants that have serious negative impact on human beings and environment (Cai et al., 2017). In spite of their greater mobility and substantial risk of harm, polar PAHs are less known and are not often studied. Many types of cancer, including those of the skin, bladder, and lungs, are brought on by these carcinogenic



**Fig. 13.2** Schematic representation showing the acute and chronic exposure to PAHs

compounds. They can also cause genotoxicity (damaging non-transmissible DNA), nephrotoxicity (damaging kidney), cytotoxicity (damaging cells), ocular toxicity (damaging eye disorders), cardiotoxicity (damaging heart muscles), hepatotoxicity (damaging liver), hemotoxicity (destroying RBCs), teratogenicity (causing malformation of the embryo or fetus), neurotoxicity (damaging brain and nervous system), immunotoxicity (damaging immune system), and mutagenicity (causing transmissible genetic alterations) in both animals and human beings (Ossai et al., 2020). Researchers are very interested in the destination and removal of all those ubiquitous substances from the atmosphere. Since their presence increases the potential impact of health risk. According to numerous research factors including population density, economic development, and meteorological conditions affect both the concentration and geographical distribution of PAH in the surrounding atmosphere (Peng et al., 2016; Zhang and Chen, 2017). The concentration of PAH varies by area, just as these factors do. Therefore, effective measures are needed to limit the negative effects of prolonged exposure on local residents due to the elevated PAH burden in diverse parts.

## Decontamination Techniques of PAH

Concern over the immediate and long-term hazards linked with PAH emissions has spread around the world due to the fact that their presence might result in irreparable harm to the environment and living things. In last few decades, numerous decontamination techniques have been created to detect and handle these environmental contaminants. To maintain a sustainable ecosystem, the cleaning methods should be both inexpensive and effective (Abdel-Shafy and Mansour, 2016). Both the qualitative and quantitative content, as well as the degree of contamination, influence the technique (Cunningham, 1996). Chemical and physical procedures

are among the different approaches used for decontamination. However, these methods are expensive and introduce a number of harmful substances into the chemical, physical and biological treatments are among the various methods used to degrade PAH (Ossai et al., 2020). Every treatment has pros and cons, but choosing the best one for a contaminated site requires a thorough case analysis that takes into account the features of the site, the pollutants' characteristics, and the possible treatment method. In 2018, Gitipour et al. Therefore, the best course of action is to employ green technologies, which are more appropriate, sustainable, effective, and economical. Physical therapy techniques such as electrokinetic remediation and solvent extraction are simple to use and typically require non-toxic materials. However, the requirement for follow-up care is the primary drawback of this kind of treatment. Degradation of high molecular weight (HMW), persistent and hazardous pollutants is the primary benefit of chemical interventions like catalytic degradation and oxidation via chemicals. The most environmentally friendly method that produces no trash is biological treatment. These methods are the most effective, but they take longer. This chapter goes into great length into a number of green and traditional (physical, thermal, and chemical) methods, including advanced oxidation processes (AOPs), bioremediation, phytoremediation, and hybrid green technologies.

### **Physical Degradation**

Pollutant transfer throughout geochemical cycles and pollutant accumulation on soil or water is examples of physical processes (Ansari et al., 2023). While pollutant transit can happen by condensation or dispersion, retention can happen through adsorption or aggregation in the intergranular area. Numerous variables, such as soil media, temperature, moisture content, soil salinity, or water pH, influence these interactions.

### **Thermal Degradation**

Because of their speed and effectiveness, thermal technologies and incineration are regarded as excellent remediation methods for PAH-contaminated areas. High total petroleum hydrocarbon elimination efficiency is the outcome of the thermal process. Despite these benefits, thermal treatment necessitates elevated temperatures, which may result in several problems. High temperatures at contaminated sites need a lot of energy, which is expensive (Vidonish et al., 2016). High temperatures have the capacity to completely destroy organic matter or site composition and leading to structural degradation that makes it difficult to return the environment to its initial state. Although it's evident that thermal approaches are capable of efficiently eliminating pollution, little is known about how high temperatures affect ecosystems, including soil and sediment organisms, and restoration initiatives (Buttress et al., 2016). As a result, the necessity to develop a approach to

maximize thermal treatments with sustainable objectives like ecosystem preservation and energy saving is developing. A thorough approach to thermal treatment is necessary to guarantee that environmental cleanup initiative programs do not unnecessarily damage our planet but rather support worldwide endeavors to enable a sustainable development in the future. According to research, one of the most effective thermal techniques for quickly and affordably cleaning up PAH-contaminated areas is microwave irradiation (Falciglia et al., 2013; Robinson et al., 2012; Buttress et al., 2016).

## Chemical Oxidation Degradation

Another popular technique for breaking down resistant organic contaminants (such PAHs) is chemical oxidation. PAHs can be eliminated from contaminated water using standard chemical oxidation techniques such ozonation, photolysis, and chlorination. More harmful by-products, however, may result from the actual treatment. For instance, natural organic matter in water can react with the classic oxidant chlorine to form harmful halogenated hydrocarbons (Amor et al., 2019). Ozonation has been proposed by a number of authors as a way to eliminate PAHs from water (Ates and Argun, 2018). Ozone can oxidize the pollutant in two ways: (a) the pollutant is directly oxidized by ozone via chemical bonds between electrons or atomic nuclei. (b) By generating radicals that oxidize pollutants to minuscule molecules, metal oxides or organic materials indirectly destroy ozone. pH plays a major role in these degradation processes. Basic pH facilitates the indirect pathway for the breakdown of  $O_3$  and the generation of OH radicals. A direct approach is preferred because ozone becomes more stable and deteriorates the contaminants in an acidic pH. The benzene ring is cleaved by chemical reactions between ozone and PAHs, producing intermediate molecules that are like carboxylate and hydroxylated benzene. Subsequently, intermediate chemicals may directly or indirectly compete with the pollutants being targeted for  $O_3$  and  $OH^-$  radicals (Rubio-Clemente et al., 2014). Oxidation limits, such as the existence of  $OH^-$  scavengers in water that is contaminated and the generation of hazardous products, may adversely impact PAH decomposition (Miller and Olejnik 2001).

## Green Technologies for Decontamination of PAHs

### Biodegradation

Biodegradation is a remediation technique that enables organic contaminants to be eliminated through the substrate's natural biological activity (Ghosal et al., 2016; Ansari and Rafatullah, 2023; Sivasamy et al., 2025; Gupta et al., 2025). Microorganisms, plants, and enzymatic reactions are used to detoxify or degrade environmental pollutants (Ansari and Rafatullah, 2023; Kaur et al., 2023). The microorganisms used for biodegradation are bacteria, algae, fungi and yeast (Al-Hawash et al., 2018). The microbes utilized for biological degradation ought

to be native to the site or contaminated area (Das and Chandran, 2011). In order to accelerate the biodegradation process, it is crucial to consider the bioavailability of the contaminant to microbial attack, the availability of microbial consortia can degrade the pollutant, and particular environmental factors (oxygen level, soil type, soil nutrient content, pH, electron acceptor agents and temperature) that encourage microbial growth (Moghaddam et al., 2024). Many scientists believe that certain bacterial isolates can degrade PAHs. Under aerobic conditions, PAHs can be broken down by microorganisms belonging to the genera *Mycobacterium* and *Pseudomonas* (Motteran et al., 2024). A recent study found that *Serratiamarcescens*, *Bacillus megaterium*, *Raoultellaornithinolytica*, and *Aeromonashydrophila* decomposed PAHs with above 90% efficiency for acenaphthene and fluorene. The effectiveness of bioremediation methods was found to be significantly impacted by a few environmental factors, including pH and temperature. According to Moscoso et al. (2013), temperatures between 30 and 38 °C, which are higher than room temperature, were found to be ideal for the breakdown of PAHs due to increased microbial proliferation. Nevertheless, as demonstrated by a study that was carried out at a slightly higher temperature between 40 and 45 °C and showed a notable decrease in PAH degradation from 92% (37 °C) to 74%, bioremediation is not a rigorous and reliable method. As a result of decreased oxygen solubility brought on by rising temperatures, bioreactors have less dissolved oxygen available for microbial Restoring the soil's capacity to operate as intended should be the ultimate goal of any remediation operation, in addition to eliminating contaminants from contaminated substrates (Punnapayak et al., 2009). The application of laccase, an enzyme obtained from a *Genodermalucidum* isolate that causes white rot. It was found that, with or without the use of a redox mediator, *G. lucidum* totally breaks down anthracene. Additionally, it was discovered that *Thiobacterisubterraneus*, *Alcoligenes* sp., and *Escherichia coli* were effective isolates used for breaking down anthracene and phenanthrene (Abd-Elsalam et al., 2009).

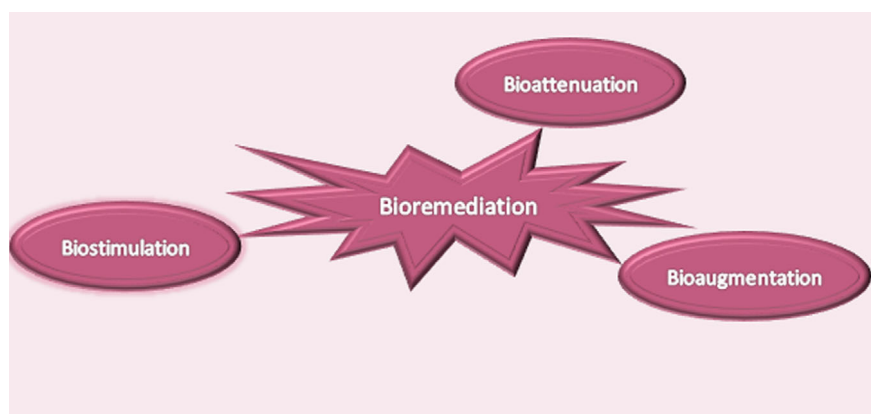
Three main elements influence the pace of the bioremediation process: the contaminants being degraded, the form of microorganisms, and the natural habitat. Inherent bioremediation may result from natural decrease or bioattenuation, however this process may take years (Carolin et al., 2021). Therefore, by altering various parameters, a number of approaches have been proposed to improve the natural microbial digestion of all these kind of contaminants. To boost microbial metabolism of PAHs, biostimulation or bioaugmentation have been employed (Mohapatra and Phale, 2021). According to Zhou et al. (2022), biostimulation is the process of increasing the metabolic activities of endogenous microorganisms by electron acceptors, adding nutrients or biosurfactants. In order to remediate oil-contaminated soil, bioaugmentation technology—which involves introducing specific functional microorganisms into the intended environment—has been used repeatedly (Wu et al., 2016). In order to enhance the breakdown of PAHs by making them more soluble in water and more accessible to microorganisms, many researchers employ biosurfactants, which are surface-active molecules made

by microorganisms (Cameotra, 2008). Amphiphilic compounds with both water-resistant and water friendly components are known as biosurfactants. While the hydrophilic portion comes in a variety of forms, the hydrophobic portion is usually a hydrocarbon chain. Molecular weight is used to categorize the microbial surfactants into two groups. Polysaccharides and lipoproteins are classified as high molecular weight (HMW), whilst lipopeptides and glycolipids are classified as low molecular weight (LMW). Biosurfactants' structural variations also affect how functional they are (Johnson et al., 2021). LMW biosurfactants are utilized far more often than HMW biosurfactants due to their significant reduction in surface tension (Carolin et al., 2021). Because of their numerous functional properties, such as dispersion, surface activity, foaming, emulsification, wetting, cleansing, stability under pH, extreme temperature, and salinity conditions, and more, biosurfactants are a promising choice for biotechnological applications such as biological remediation, emulsion stabilization, and microbial enhanced oil recovery (MEOR) (Adetunji and Olaniran, 2021). Table 13.1 lists the often researched biosurfactants along with the microbes that produce them. Despite the environmental advantages, the main drawback of producing biosurfactants is their high cost in comparison to producing synthetic ones. Since synthetic surfactant synthesis uses proven procedures rather than microbial culture, it is believed to be more cost-effective and efficient (Fig. 13.3).

In situ and ex situ are the two categories of bioremediation approaches. Langenbach (2013) further investigated bioremediation methods including composting, land farming, bioslurry, bioventing, and biosparging. In order to accelerate the in-situ degrading process, air is injected into a contaminated area, a procedure known as bioventing. In the saturated zone, bio-sparging is employed to raise the oxygen content, which improves the biological performance of native microorganisms. In a controlled bioreactor, contaminated locations can be treated using bioslurry. In order to achieve maximum removal effectiveness, these bioreactors are designed to monitor, manage, and adjust a number of parameters, including temperature and nutrients. The practice of land farming involves sprinkling contaminated soil over a region. Because the pollutant's biodegradation takes place at the oil-water interface, oxygen, moisture, and nutrients—such as fertilizers—had to be added.

**Table 13.1** List of types of biosurfactants and the microbes that produce them

Microorganism	Biosurfactant type	References
<i>Bacillus licheniformis</i> LRK1	Lipopeptide	Nayak et al., (2020)
<i>Acinetobacter</i> sp.	Alasan	Uzoigwe et al., (2015)
<i>Acinetobacter calcoaceticus</i> PTCC1318	Emulsan	Amani and Kariminezhad, (2016)
<i>Bacillus subtilis</i> - RSL2	Lipopeptide	Sharma et al., (2020)
<i>Bacillus tequilensis</i> MK 729,017	Surfactin	Dutta et al., (2020)
<i>Brevibacillus brevis</i>	Surfactin	Krishnan et al., (2019)

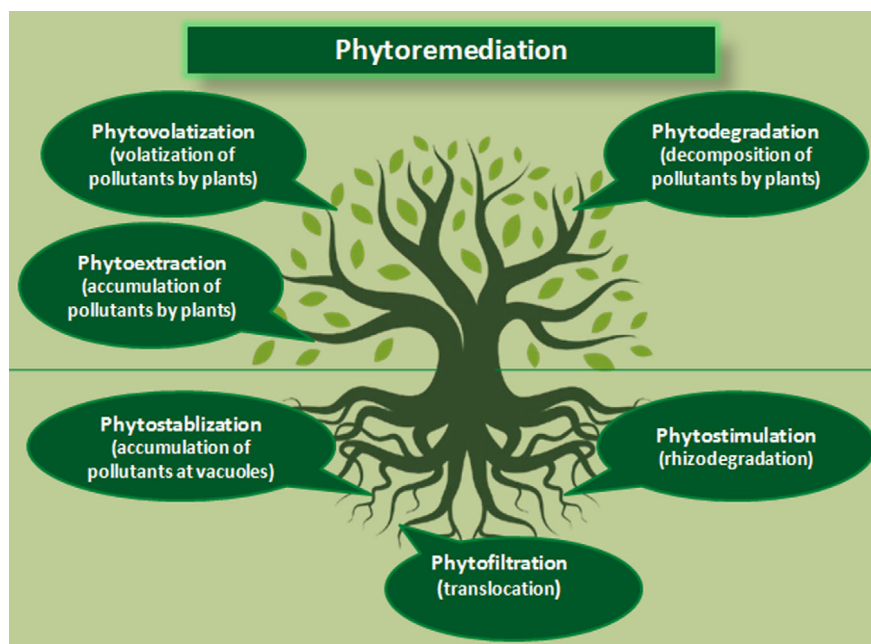


**Fig. 13.3** Biodegradation of organic contaminant

Organic wastes can be turned into compost, a humic substance that can be applied as soil fertilizer, through a controlled natural microbial degradation process (Ossai et al., 2020).

### Phytoremediation

Phytoremediation also referred to as phytodegradation. It is an ecologically friendly and economical approach that utilizes plants to reduce soil contamination through processes such as removal, digestion, assimilation, or absorption (Wu et al., 2016). The phytoremediation process encompasses various subgroups aimed at extracting organic compounds and metals from contaminated soil. These subgroups include phytoextraction, phytodegradation, phytostabilization, phytofiltration, phytovolatilization, and phytostimulation, as shown in Fig. 13.4. Phytoextraction involves using hyper accumulator plants to gather pollutants from the soil (Mani and Kumar, 2014). Phytodegradation serves as an effective secondary treatment for eliminating PAHs from composted soils (Parrish et al., 2004). Pollutants that enter plant cells frequently undergo enzymatic transformations that decrease their toxicity (Kvesitadze et al., 2009). Phytostabilization employs plant cell compartments to sequester toxic substances from critical cellular regions, including the mitochondria, plastids, cytoplasm, and nucleus. Unlike mammals, plants possess different excretory mechanisms and lack a conjugated excretory system. Instead, they store toxic substances within organelles like cell membrane and vacuoles (Kvesitadze et al., 2009). In the process of phytofiltration, the root areas and lipophilic discharges help in translocation, mobilization, or adsorption PAHs in the rhizosphere. Additionally, they promote biodegradation by stimulating microbial activity and metabolic pathways triggered by compounds released from roots, as well as direct plant uptake and metabolism (Hussein et al., 2022). Research indicates that plants are more prone to accumulate low molecular weight



**Fig. 13.4** Phytoremediation: the green approach

(LMW) PAHs (Tian et al., 2018). These compounds can exist in vapor form, allowing for easier entry into plants via stomatal openings. This phenomenon explains the higher occurrence of PAHs in the above ground parts of the plant. LMW PAHs may volatilize and travel to the leaves (Tian et al., 2018). The leaves are significant sites for excretion and volatilization processes, contributing to the detoxification of harmful substances, while leaf space index plays a role in biomass growth by affecting photosynthesis (Sun et al., 2011). This method utilizes both plants and soil microbes to remove PAHs at a low cost with least environmental impact. Phytostimulation, or rhizodegradation, is considered the most effective solution for eliminating PAHs from soil. Plants naturally synthesize organic substances such as organic acids, sugars, and secondary metabolites that promote microbial growth. These microorganisms associated with plant roots aid in breaking down PAH compounds (Rohrbacher and St-Arnaud, 2016).

### Adsorption via Nanomaterials

The use of nanomaterials in technologies aimed at remediating environmental compartments like air, water, and soil has been explored (Oluwasanu et al., 2019). Various types of nanomaterials have been used as nanosorbents to improve the removal of PAH contamination prior to their reuse (Russo et al., 2020). An effective adsorbent exhibiting a high adsorption capacity possesses certain characteristics related to its surface area and pore size (Nethaji et al., 2013). Adsorbing

materials can be divided into natural adsorbents, which include both organic and inorganic types, and synthetic adsorbents. Natural adsorbents can originate from biological or earth-based resources, such as food wastes or materials derived from plants, including vegetable fibers, clay minerals, graphene, straw, sawdust, and date palm. In comparison to other adsorbents, these natural organic options are advantageous due to their low cost and easy availability. They have been utilized to enhance adsorption capabilities and transform waste into valuable substances known as sorbents (Ndimele et al., 2018). However, a significant drawback of their use is the challenge in separating the adsorbent for reuse or disposal after it has been applied in oil spill water (Crini and Lichtfouse, 2019). Synthetic sorbents, frequently produced in laboratories or available commercially, include materials like activated carbon, zeolites, graphene, silica, and those based on nanotechnology. According to the USEPA, one of the best remediation techniques is activated carbon (AC) adsorption. According to Okiel et al. (2011), the use of AC for oil-contaminated water treatment is generally acknowledged as a technically viable technique for eliminating a variety of organic compounds. However, this adsorbent is thought to be costly, particularly in developing nations. The oleophilic and hydrophobic characteristics of these synthetic adsorbents enable them to absorb oil media weighing up to 100 times the weight of media (Ndimele et al., 2018). The diverse scientific applications of graphene and its composites can be attributed to their extensive specific surface area, high tensile strength, conductance, thermal stability, chemical durability, thin film width flexibility, and charge mobility (Novoselov et al., 2012). Owing to their fundamental physicochemical characteristics, including adsorption, high ion exchange capacity, mechanical and thermal stability, and specific surface area—both naturally occurring and synthesized materials exhibit these characteristics (Fletcher et al., 2017). Zeolites play an essential role in the removal of contaminants from soil and water by functioning as molecular sieves, ion exchangers, membranes, and adsorbents. This necessary modified clay substance has proved to be a practical, affordable and readily available sorbent (Lee and Tiwari, 2012). Zeolite and its improved forms were used in a sorption process to extract pyrene, phenanthrene, and benz(a)pyrene from water (Zhang et al., 2017). Benz(a)anthracene, pyrene, fluoranthene, phenanthrene, and fluorene were all removed from water with an average removal rate of 98% using organo-zeolite as an adsorbent (Lemić et al., 2007).

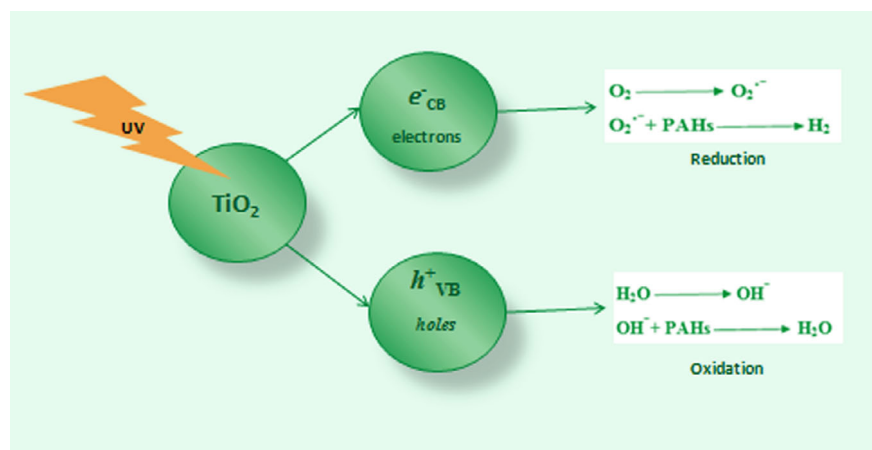
### **Advanced Oxidation Processes (AOPs)**

AOPs are chemical oxidative methods employed for addressing PAH contamination in soil and various types of landfills, including industrial and municipal. These advanced chemical techniques can degrade approximately 90% of PAHs. The oxidising agents such as activated peroxodisulphate (Huling and Pivetz, 2006), hydrogen peroxide (Flotron et al., 2005), Fenton's reagent (Zhang et al., 2019; Gupta and Gupta, 2015; Gupta, 2016), and ozone (Lian et al., 2017) are utilized in this process. These methods generate highly reactive radicals like OH, O<sub>3</sub>, SO<sub>4</sub>, along with other activated species such as peroxides and persulfate anion, which facilitate the disintegration of the aromatic rings in PAH compounds. AOPs

present several advantages over conventional remediation methods, including the in situ degradation of contaminants, a relatively shorter treatment time, and the ability to effectively remediate a diverse array of PAHs due to their highly reactive radicals. Nonetheless, the oxidation of components which are not target such as particulate organic matter or dissolved can complicate the use of these highly reactive oxidizing agents, and their corrosive nature makes them unsuitable for treating potable water (Amor, et al., 2019). AOPs are divided into photochemical and non-photochemical processes, based on the method used to produce OH radicals. The photochemical process employs a source of light—specifically UV light in conjunction with oxidising agents or catalysts. The production of OH<sup>-</sup> can be initiated by oxidisers like H<sub>2</sub>O<sub>2</sub>, O<sub>3</sub>, and UV light, as well as by catalysts. The effectiveness of AOPs is affected by various variables, which include the type and amount of oxidant used the intensity and type of light, pH levels, the rate at which free radical are generated, the level of contamination and characteristics of the contaminants, and the composition of the water (Rubio-Clemente et al., 2014). TiO<sub>2</sub> is a unique metal oxide semiconductor which has high photocatalytic decomposition property, high efficiency and extremely low price so, it is selected as photocatalyst. Its catalytic reaction starts in the presence of UV light. When the material absorbs UV light it causes formation of electrons and positive holes in the valence and conduction band. In contrast, electrons can directly oxidize organic pollutants, such as PAHs, by consuming oxygen molecules through a reduction reaction. Conversely, holes can either directly react with PAHs or form an OH radical that can oxidize PAHs. AOPs represent the most promising approach and offer economic advantages when leveraging a solar light source. AOPs are associated with relatively high operating costs due to the expensive nature of chemicals like H<sub>2</sub>O<sub>2</sub> and the significant energy utilization is involved. Furthermore, OH radicals are highly non-selective and can react with non-target pollutants found in the contaminated water (Comminellis et al., 2008). Innovative techniques that merge ultraviolet photo-Fenton and Fenton oxidative-coagulation processes have also demonstrated considerable effectiveness in removing PAHs from leachates and solid waste (Li et al., 2016) (Fig. 13.5).

### Hybrid Green Technologies

Recent findings indicate that bioremediation and adsorption are currently effective and cost-efficient remediation methods. Nevertheless, bioremediation has its limitations, including the potential accumulation of harmful metabolites or degradation byproducts. For instance, dichlorodiphenyltrichloroethane (DDT) and its metabolic product, dichlorodiphenyldichloroethylene (DDE), can accumulate over time (ATSDR, 2000). In order to overcome these obstacles integrated technologies or hybrid methods have been proposed. In the context of treating drinking water, bioaugmentation is an integrated approach that can be used to clean PAH-polluted water, given that the bacteria employed are safe for human health or can be effectively removed through standard chlorination processes. Phytoremediation, also referred to as plant-aided bioremediation, is one strategy capable of tackling PAH contamination on a large scale. Plants can absorb, store, and chemically



**Fig. 13.5** Mechanism of photo catalytic degradation of PAHs using TiO<sub>2</sub>

alter pollutants, making research into PAH degradation in water valuable. They can produce enzymes that function as surfactants, which enhance the pollutant's availability in solution (Capello et al., 2019). The electrokinetic approach employs electrical current to decontaminate contaminated soils, and integrating bioremediation with an electrokinetic process enhances the holistic effectiveness of soil contaminant remediation. Nanoremediation is an emerging tool for soil remediation, effectively removing contaminants when combined with other methods such as bioremediation (Ansari et al., 2023). To fully utilize the substantial potential of nanoremediation in the removal of PAHs, research should be done on the creation and application of nanofertilizers (biostimulation and bioaugmentation), nanominerals (biostimulation), or green-synthesized nanooxidizers (for PAH oxidation) (Kuyukina et al., 2021). Furthermore, nanoremediation can be utilized alongside established PAH bioremediation techniques to enhance remediation efficacy and facilitate quicker PAH decomposition in practical applications.

### Electrokinetic (EK) Remediation

This method has the ability to eliminate non-biodegradable persistent pollutants like PAHs from soil. It employs electric current to extract contaminants from the affected soil. A small electric current is applied at the contaminated location to create an electric field. The main mechanisms by which the electric field facilitates the movement and mobilization of pollutants towards the electrodes (anode and cathode) during the EK process are electromigration and electroosmosis (Gill et al., 2014). However, the difficulty in dissolving PAHs in water, along with their hydrophobic nature and low dispersal rate, poses challenges to their removal. The use of a combination of surfactants can effectively extract hydrophobic organic compounds from soil with contaminants (Boulakradeche et al., 2015). Integrating the biological restoration process with the electrokinetic process enhances the

effectiveness of soil contamination remediation. It represents a physical detoxification method that works well for non-biodegradable organic contaminants like PAHs (Capello et al., 2019). This integration makes nutrients, pollutants and both electron acceptors and donors easily exposed to active microorganisms that break them down, thus addressing the limitations of bioremediation and improving its effectiveness (Capello et al., 2019).

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## Conclusion

PAHs can originate from both human activities and natural processes. These contaminants are dangerous and present serious risks to the ecosystem and human well being. This study examines the origin, transport mechanisms, dispersion processes and fate of PAHs in the environment. Several remediation technologies, including traditional, advanced, and hybrid or integrated methods, are explored, such as physical, chemical, thermal, electrokinetic, AOPs, phytoremediation, and bioremediation. Bioremediation stands out as a promising method for extracting PAHs. This method evacuates PAHs from the atmosphere by using various kinds of microorganisms, which involves bacteria, fungi, and algae. Microbes like *Serratia marcescens*, *Bacillus megaterium*, *Raoultellaornithinolytica*, and *Aeromonashydrophila* decomposed PAHs with above 90% efficiency for acenaphthene and fluorene. Similarly, *Thiobactersubterraneus*, *Alcoligenes* sp., and *Escherichia coli* are effective isolates used for breaking down anthracene and phenanthrene. Moreover, phytoremediation seems to be among the most economical and environmentally friendly techniques for lowering PAHs in substrates. Recently, there has been a trend toward using integrated or combined treatment technologies to maximize their effectiveness. This approach is a green degradation method that produces no waste, thus preventing further environmental contamination. Zeolites also proved to be very important in a adsorption process. Benz(a)anthracene, pyrene, fluoranthene, phenanthrene, and fluorene were all removed from water with an average removal rate of 98% using organo-zeolite as an adsorbent. Integrated methods represent environmentally friendly green degradation processes with no waste generation that might lead to further pollution. To determine the most appropriate treatment techniques, site characteristics are also critical. The criteria for selection are usually based on site attributes, costs, challenges, advantages, and the type and concentration of pollutants present. Addressing PAH contamination at sites usually presents significant challenges and high costs; therefore, opting for methods that are adaptable, sustainable, eco-friendly, efficient, rapid, and economical is a wise choice.

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