

Recent advances in emission, analysis and remediation technique of carcinogenic polycyclic aromatic hydrocarbons: a review

Kothiyal N.C.¹, Abhay¹, Khan L.¹, Kumar V.^{2*}, Saruchi³ and Singh S.⁴

¹Department of Chemistry, Dr B R Ambedkar National Institute of Technology, Jalandhar- 144011 Punjab, India

²Department of Applied Sciences, CTIEMT, CT Group of Institutions Jalandhar, Punjab, India

³Department of Biotechnology, CTIPS, CT Group of Institutions Jalandhar, Punjab, India

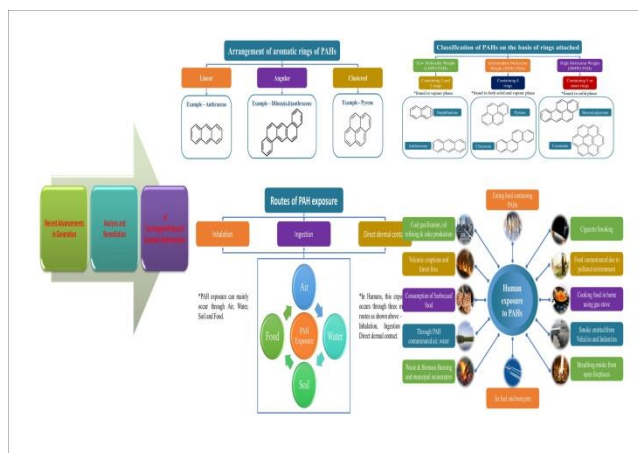
⁴Department of Management Studies, CTIEMT, CT Group of Institutions Jalandhar, Punjab, India

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*to whom all correspondence should be addressed: e-mail: vaneet2106@gmail.com

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Graphical abstract



Abstract

Polycyclic Aromatic Hydrocarbons (PAHs) are aromatic hydrocarbons with three or more fused benzene rings that include carbon and hydrogen. These are thought to be harmful to human health, and we cannot avoid being exposed to them because they are widely disseminated throughout the environment. PAHs enter our bodies through the air, water, food, and soil. The developments in different sources of generation, analysis, and remediation approaches are reviewed in this paper based on recent available literature. The chemistry of PAHs, their exposure routes, and their health implications are also discussed. In this manuscript future scope of work as well as removal and reduction of carcinogenic PAHs are also discussed briefly. PAHs are highly carcinogenic in nature for human being. The brief knowledge of PAHs and its latest reduction method for human being are very important. These types of review article are one of the most promising solutions to reduce air pollution issues from environment. This study could be one of the best studies to reduce carcinogenic pollutants from our environment.

Keywords: Polycyclic Aromatic Hydrocarbons (PAHs), sources, chemistry, human exposure, effects, analysis, control of automobile exhaust, degradation

1. Introduction

PAHs correspond to a class of organic pollutants that are omnipresent in our environment. PAHs are present in crude oil; thus they contaminate the environment as the result of oil exploitation, transport and refinement. PAHs also have a source, as the result of the incomplete burning of organic compound, wood, oil, tobacco, and meats cooking at very high temperature. PAHs mostly survive in our environment as gases phase and deposited to airborne PM_{2.5} (particulate matter). They are generated in our environment as a result of incomplete combustion of fossil fuels and organic materials through different kind of exhaust. A tiny proportion of them primarily exists in the gas phase which may subsequently adsorbed on existing PM_{2.5} (Kothiyal and Kumar, 2011, 2011a).

PAHs can be generally divided in two groups according to the structure, i.e. structures containing a bay region and those without it. Typically, PAHs containing a bay region are considered to be carcinogenic, whereas PAHs without a bay region are comparatively less carcinogenic in nature (Kumar and Kothiyal, 2012). There are more than 100 PAHs are present in our environment but all of them are not carcinogenic in nature for human being. Out of 100 PAHs only 16 PAHs are carcinogenic in nature for human being given in Figure 2.

PAHs (Polycyclic Aromatic Hydrocarbons) are types of Polycyclic Organic Matter (POM). Compounds with three or more fused aromatic rings make up the POM. C, H, O, N, and S can all be found in the structures of these molecules. PAHs, on the other hand, are made up entirely of carbon and hydrogen. PAHs with two to seven fused benzene rings (e.g. naphthalene) are most commonly found in the environment, while PAHs with more rings are also present. PAHs associated with particles are thought to be particularly hazardous to human health. (Choi *et al.*, 2010).

The most common PAH Benzo[a]pyrene (B[a]P) which is highly carcinogenic in nature. Actually, they are a widespread collection of many chemically related molecules that are persistent in the environment, having different structures and toxic effects. They can enter the environment in a number of ways, and they are not present as individual molecules but as the mixtures of contaminants. They can interfere with the cellular membranes disturbing their function and also the particular enzymes connected with the membrane and producing toxic effects in our body (Naushad, 2014; Naushad *et al.*, 2015, 2015a, 2019). That is why PAHs have been shown to have carcinogenic (cancer-causing) and mutagenic (changes occur in the DNA of cells) properties.

PAHs are generated from natural (e.g. forest fires, volcanic eruptions) or man-made (automobiles & industry emission, cigarette smoke) combustion sources. PAHs are widely spread in the environment (whether in air, soil or in water). (Abdel-Shafy *et al.*, 2016). That's why PAH exposure is inevitable. We cannot escape from their harmful effects. They are present everywhere around us, from the food that we cook and eat to the smoke (from vehicles and industries) that we inhale while going outside.

2. Chemistry of PAHs

PAHs are typically colourless, white, or light-yellow solid compounds made up of two or more fused aromatic rings having carbon and hydrogen in them (Figure 1). Aromatic rings can be arranged in space in a linear, angular, or clustered manner (Abdel-Shafy *et al.*, 2016).

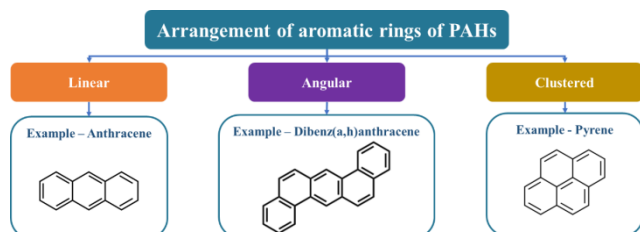


Figure 1. Molecular arrangements of Polycyclic Aromatic Hydrocarbons (PAHs) (Abdel-Shafy *et al.*, 2016).

Based upon these structural arrangements, a variety of PAHs have been identified. The most extensively studied of them are the 16 which are referred to as priority pollutants are shown in Figure 2. Now from the structures, it is clear that there is different arrangement as well as number of rings present in these structures. So, depending upon the ring size and arrangement, the PAHs are of Low Molecular Weight (LMW), Intermediate Molecular Weight (IMW) and High Molecular Weight (HMW) types. LMW PAHs contain two/three fused aromatic rings (e.g. Naphthalene, Anthracene) and are primarily exist in the vapour phase in the environment. IMW PAHs are those containing four aromatic rings (e.g. Pyrene, Chrysene) and are divisible into two phases – solid and vapour, based on air temperature. HMWPAHs are those containing five or more aromatic rings (e.g. Benzo[a]pyrene, coronene) and are mostly linked to the particles. (Patel *et al.*, 2020). PAHs can also be categorized into small and large PAHs. Small ones are those which

contain six fused aromatic rings while large ones are those which contain above six fused aromatic. It is to be noted that Benzene is not a PAH. Depending on their structures, PAHs are differentiated by their low water solubility, low vapour pressure as well as high melting and boiling temperatures. More the molecular weight of PAH, lower is the water solubility and thus higher is the lipophilicity (lipid loving/soluble), which makes them more resistant. They have low vapour pressure, and very low aqueous solubility (Abdel-Shafy *et al.*, 2016).

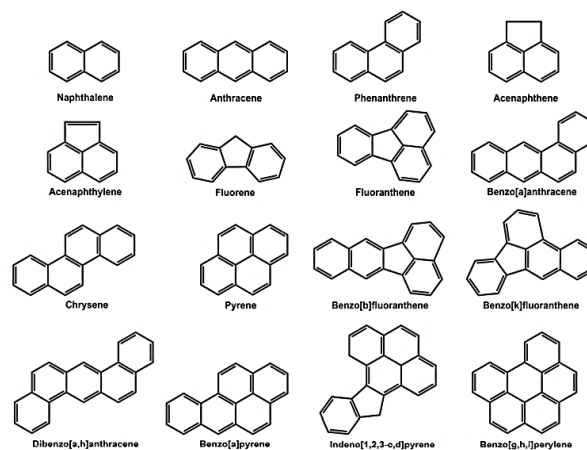


Figure 2. Structures of the 16 PAHs enlisted as priority pollutants by US EPA (Ghosal, Ghosh *et al.*, 2016).

The properties vapour pressure and aqueous solubility are inversely proportional to the molecular weight, but the resistance to oxidation and reduction is directly proportional to it. PAHs water solubility drops with each extra ring. PAHs, on the other hand, are highly soluble in organic solvents as they are highly lipophilic in nature. The UV absorbance spectra of different PAHs are different. Even each isomer has a different UV absorbance spectrum because each ring structure absorbs a different wavelength of UV-light. This is very beneficial while studying different PAHs. The majority of PAHs show the phenomenon known as fluorescence (Figure 3). The PAHs are photochemically decomposed when exposed to UV light. Some bacteria in the soil may also potentially breakdown PAHs (Abdel-Shafy *et al.*, 2016).

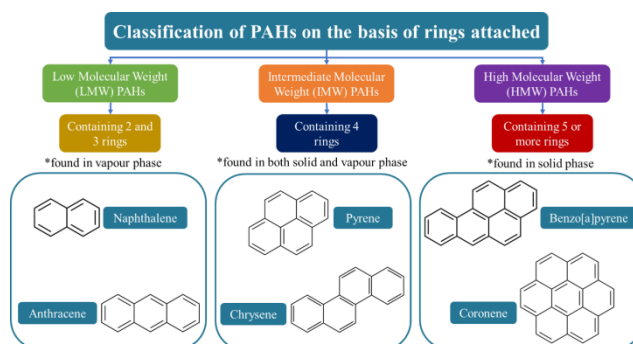


Figure 3. Classification scheme of PAHs based on the rings attached (No. of rings).

Concluding, different PAHs have different physical and chemical properties such as molecular weight, melting point, boiling point, vapour pressure etc. Based on these different properties, different PAHs are characterized and

studied for the research and also they can be categorized on the basis of the harmful effects they produce. It means that not all the PAHs are carcinogenic in nature but only some of them are carcinogenic while other PAHs have different effects on the human body.

3. Sources of PAHs

The PAHs are generated by the incomplete combustion of organic matter. There are different activities during which PAHs are generated. For example – cooking, automobile exhaust (which is the major source of PAH generation), industrial exhaust, cigarette smoke, burning biomass, coil smoke, forest fires, volcanic eruptions, oil processing and various polymer manufacturing tasks all are the major sources of PAH generation. Various nitro PAHs are also generated by incomplete combustion which are again toxic for the humans as well as animals.

The PAH sources therefore can be anthropogenic (man-made) or natural. (Mojiri *et al.*, 2019). Volcanic eruptions, forest fires (not man made), and lightning-caused moorland fires are minor or insignificant sources of natural emissions. The significant predictors of PAH pollution are anthropogenic emission sources, which can be industrial (e.g. coal gasification, polymer manufacturing, pesticides production), mobile (e.g. motor vehicles, trains, aircrafts, ships), household (cooking, using mosquito coils, burning fire in winters, garbage burning and wood burning) or agricultural (spraying pesticides on crops, burning agricultural waste in open).

Domestic and agricultural sources account for the majority of PAH pollution in rural areas, while industrial, mobile, and domestic sources in city areas. PAH concentration also changes with the atmospheric conditions. Its concentration is more in the winter season as compared to other seasons.

PAH sources can also be categorized into pyrogenic, petrogenic, and biogenic depending upon their origin of production as shown in Figure 4. (Mojiri *et al.*, 2019).

Pyrogenic PAHs are generated by burning organic materials unintentionally and incompletely at high temperatures (623–1473 K) in the absence or less amount of oxygen. Pyrogenic PAHs are formed by thermal breakdown of complex molecules of petroleum to the lower hydrocarbons. Pyrogenic PAHs are majorly found in the urban areas. Petroleum and its by-products contain petrogenic PAHs, which are widely distributed due to crude oil storage, transportation, usage, and leakage. HMW PAHs predominate in pyrogenic sources, while LMW PAHs predominate in petrogenic sources. Biological entities such as bacteria, phytoplankton, algae, and plants produce biogenic PAHs during the gradual conversion of different molecules biologically. (Mojiri *et al.*, 2019).

Gaseous PAHs are deposited in the particulate phase in water, soil, and plants via deposition processes (either dry or wet). Because of their low vapour pressure and high hydrophobicity, PAHs which are having three or more fused aromatic rings are highly powerful adsorbents to soil particles. (Abdel-Shafy *et al.*, 2016). PAHs accumulate in soil/sediment and thus pollute the groundwater, plants

and ultimately the food that we are eating. For example – as the soil gets polluted, the roots of plants absorb PAHs and transport them to other plants and thus enter the food chain. In the current environment, PAH exposure is inescapable.

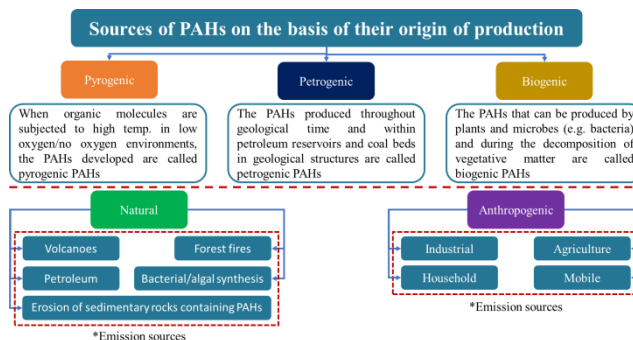


Figure 4. PAHs sources scheme based on their origin of production.

Because the majority of PAH sources are located in the urban areas, their concentration is more in the urban areas than in the rural areas. PAHs are detected in two phases after being discharged into the atmosphere: a vapour phase and a solid phase when adsorb on the particles. PAHs sorb to air particulates more readily than benzene. Individual PAHs are distributed in varying concentrations in the vapour and other physical phases due to the differences in vapour pressures of different PAH molecules (Abdel-Shafy *et al.*, 2016).

4. Routes of PAH exposure and their effects

The air, water, soil, and food are highly contaminated with carcinogenic PAHs. This contamination can occur either through dermal contact or ingestion or inhalation. Its not necessary that the exposure occurs through one route only. It can occur through more than one route also.

Now, based on these routes, different people are exposed to PAHs in different ways. Most commonly cigarette smoking, consuming air from open fireplaces, and cooking food containing PAHs are the general routes of their exposure. Mainly PAH exposure occurs through four routes in the environment: Air, food, soil, and water.

4.1. Air

As suggested by White, Bradshaw *et al.*, 2016, air sources of PAHs are cooking and smoking and also, according to Verma, Patel *et al.*, 2015, mosquito coils, and PAH-containing materials (e.g., petroleum products, synthetic fuels).

For the majority of the worlds population, PAH exposure from solid fuel combustion is a significant public health concern. Individual-level exposures, on the other hand, are still poorly understood. Using stoves in homes and burning fire are major indoor sources of air pollution.

Coming to the outdoor source of air pollution, the primary source is the vehicle exhaust majorly in the urban areas.

4.2. Food

PAHs are found widely in the seafood, meats and also in some fruits and vegetables. The way of cooking food also

affects the generation of PAHs. Different analysis methods have been developed till date to find out the type of PAHs present in different foods. One such example is of analysing coffee samples by using multiple extraction techniques and by using multiple solvents, for example – hexane, cyclohexane, dichloromethane, acetone etc. Most common PAHs found in daily food are benzo[b]fluoranthene, fluoranthene, and benzo[k]-fluoranthene. Also, Chrysene is found in sugar and sweets (De vos *et al.*, 1990).

4.3. Soil

Soil deposition of PAHs is continuously occurring by different mechanism, either dry or wet. Some of these PAHs come from neighbouring sources like automobile emissions from surrounding highways. Other PAHs come from further away and have travelled great distances through the air. As soon as PAHs are deposited in the earth surface, they can become mobile and thus can get transported from one place to another. Now, adsorption process occurs between the soil particles and the PAHs deposited in the soil. The PAHs have the tendency to get adsorbed on the soil particles. So, this adsorption can be used as a parameter for having the information about the mobility of the PAHs.

All surface soils contain carcinogenic PAHs. PAHs, which are carcinogenic, are found in rural soil at concentrations of 10–100 g/kg, primarily due to atmospheric fallout. These values go above 1000 g/kg when it comes to the forest and the agricultural soil. But, in case of the industrial areas, the PAH concentration is even more than agricultural or forest soil because fossil fuel, which is one the major source of PAH emission, its burning occurs continuously in the industrial sector, which in turn generates PAHs.

The vast majority of urban soil concentrations are between 600 and 3000 g/kg. As we move to the heavy transportation and industrial region, these values definitely increase. Higher levels are likely to be found near areas of heavy transportation and industrialization. Upper range is considered to be between 1000–3000 g/kg (Menzie *et al.*, 1992).

A simplified solvent extraction and GC/MS/MS methods can be used for the quick determination of PAHs in the soil. The GC/MS/MS can be used to monitor various reactions in a pseudo-multiple mode (PMRM).

4.4. Water

PAHs are mostly introduced to surface waterways through different sources including sewage water, industrial effluent, pesticide water runoff, oil leakage in industry. The wet and dry deposition of the particles and vapours in the atmosphere is known as atmospheric fallout. PAHs are thought to be deposited in surface waters by atmospheric deposition. About 80 percent of the PAHs to the oceans in the world are only from air sources. Urban run-off contributes a substantial proportion of PAHs to surface waters carried by sewers. Similarly, in ground water PAHs coming either from industries or agricultural processes or solid waste disposal, it gets contaminated and thus acts as

a route of PAH exposure. Also in case of drinking water, higher PAH levels are detected from rainwater collecting basins and water treatment plants. It is to be noted that PAH derivatives (e.g. nitro PAHs, oxygenated PAHs) are more harmful than the parent PAHs. Chlorinated water also one of the sources of PAH exposure. (Manoli *et al.*, 1999).

In this way, we are exposed to PAHs by coming in contact with surface water, ground water and drinking water containing PAHs (Pandey *et al.*, 2020, 2020a, 2021).

4.5. Effects of PAH exposure

The PAHs have very significant effect on the human health. Now, these effects can be either short term (e.g. nausea, irritation in eyes, confusion in mind, vomiting) or long term (e.g. asthma, weakened immune system, jaundice, lung abnormalities). Repeated skin contact can cause redness and inflammation. Also, Naphthalene can cause RBC disintegration, when consumed in high amounts.

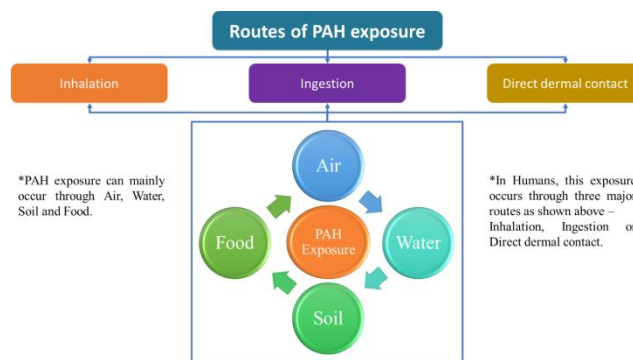


Figure 5. PAH exposure by different kind of routes.

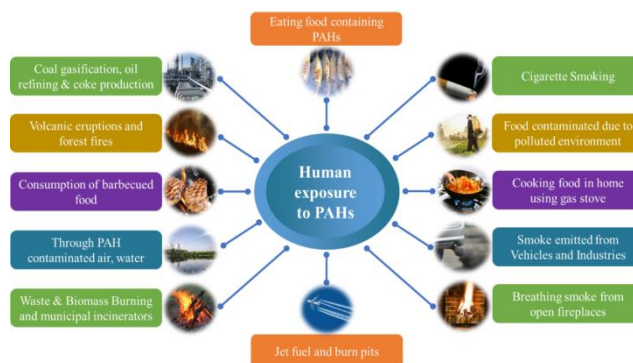


Figure 6. PAH exposure to Human by different kind of routes.

Reduced immune function, cataracts, kidney and liver damage (e.g. jaundice), breathing issues, asthma-like symptoms, and lung function abnormalities are all possible side effects of chronic (long term) PAH exposure. Mutations, developmental malformations, tumours, and cancer are all caused by biochemical disturbances and cell damage. PAH combinations have been shown to be carcinogenic to humans. Animals also get affected by high amounts of some PAHs causing skin irritation, lung cancer and stomach cancer and it is found out that the chemical carcinogen Benzo[a]pyrene is the first PAH responsible for the cancer in animals. Now other PAHs have also been identified. In the meantime, certain PAH-rich mixes have been recognised as human carcinogens. (Abdel-Shafy *et al.*, 2016).

In this way, PAHs are very harmful, toxic as well as carcinogenic to humans.

Based upon the three routes i.e. Inhalation, Ingestion and Direct dermal contact, Humans are exposed to PAHs regularly both on the work and even while sitting at the homes. The routes of PAH exposure are shown in Figure 5. So, we can't escape from coming in contact with PAHs. There are a variety of activities, through which we are exposed to PAHs. Some of them are shown in Figure 6.

5. Analysis of PAHs

Chemical grade used for PAHs analysis was 99.999 (HPLC Grade). A very high purity of chemicals is need on HPLC/GC for PAHs analysis.

5.1. Sampling

To analyse the PAHs in the environment, the very first step is sampling. Now, depending upon the various properties, PAHs exist either in the gas phase or particle

Table 1. Common analytical methods used in analysis of PAHs. (Lawal, 2017)

S/N	Analytical methods	Target PAHs	Reference
1	Synchronous fluorescence spectrophotometry	Water	(Baudot, Viriot et al., 1992; Vo-Dinh, Fetzer et al., 1998)
2	Fluorimetry	Food and environmental sample	(Zhang, Yuan et al., 1998; Wenzl, Simon et al., 2006)
3	IR	Forensic samples	(Douglas, Emsbo-Mattingly et al., 2015; Tommasini, Lucotti et al., 2016)
4	HPLC-fluorescence	Indoor samples	(Liaud, Millet et al., 2015)
5	Gas chromatography-mass spectrometry	Roasted coffee	(Guatemala-Morales, Beltrán-Medina et al., 2016)
6	GC-MS/MS	Petrochemical soil	(Shang, Kim et al., 2014; Zhao, Zhang et al., 2015; Shimada, Takenaka et al., 2016)
7	HPLC and MS	Sludge	(Viguri, Verde et al., 2002)
8	Fluorescence spectroscopy	Waste sludge	(Aemig, Chéron et al., 2016)
9	HPLC-fluorescence	Fire events	(Denis, Toney et al., 2012)
10	LDM (localization-delocalization matrix)	Water	(Sumar, Cook et al., 2015)
11	FT-IR	Soil	(Swaathy, Kavttha et al., 2014)
12	Gas chromatography-triple quadrupole mass spectrometry	Fruit and vegetable	(Banerjee et al., 2012)
13	Near-infrared (NIR)	Air	(Doney, Candian et al., 2016)
14	GC/MS	Sediment	(Retnam, Zakaria et al., 2013; Sanil Kumar, Nair et al., 2016)
15	HPLC-fluorescence	Indoor air	(Liaud, Millet et al., 2015)
16	Miniaturized membrane inlet mass spectrometer (mini-MIMS)	Sand and Soil	(Frandsen, Janfelt et al., 2008)
17	Two-dimensional fluorescence correlation spectroscopy	Water	(Zhou, Zhao et al., 2016)
18	Polythiophene sensors	Air	(Tiu, Krupadam et al., 2016)
19	LC-MS/MS	Waste	(Pitarch, Cervera et al., 2016)
20	HPLC with fluorescence and chemiluminescence detections,	Air	(Hayakawa, 2016)
21	UHPLC-MS/MS	Biological sample	(Han, Sapozhnikova et al., 2016)
22	Graphene nanosensor	Aqueous solution	(Church, Wang et al., 2016)

5.2. Removal and clean up

The extraction of PAHs from airborne particles is mostly accomplished using solvent-based techniques. The most prevalent methods for removing soluble organic materials are Soxhlet and ultrasonic. Different solvent-based

phase. These various properties are temperature, pressure, and concentration play an important role in their differentiation in the environment. (Keller et al., 1984). Small PAHs exist in the gas phase and as the size of PAHs increases, existence of PAHs in solid phase increases. Active samplers are used for measuring PAHs in ambient air.

The samplers contain a sampling module that usually has two parts: a filter for collecting the particles and a solid adsorbent for gas-phase contaminants. The other option is passive samplers, which, unlike active samplers, do not require a pump or energy to gather pollutants. Instead, a free movement from air to collecting medium is used. (Tang et al., 2005).

To summarise, sample equipment selection depends upon the type of the PAHs that are to be analysed and most importantly their compatibility (Kumar et al., 2014).

methods are available for extraction including microwave extraction and rapid solvent interaction. Solid phase extraction method is now modified for the extraction of PAHs from particles of air, specifically for small PAHs. When compared to the other extraction procedures discussed, the key feature of this method is that it utilises

very little solvent. A clean-up process is recommended after liquid extraction to remove various interferences that could compromise PAH detection in chromatographic analysis (Havenga *et al.*, 2000).

5.3. Chromatographic analysis

Once the sampling, extraction (removal) and cleansing steps are done, then chromatographic techniques are used for the analysis of PAH samples collected. Now, different types of chromatographic techniques are available for the analysis of PAHs, depending upon the type of PAHs (their properties). In different chromatographic methods, sensitive detectors are used. For example - In HPLC systems, the most commonly employed detectors are ultraviolet absorption and fluorescence spectroscopy.

Real time exposure of PAHs cannot be detected by the methods available till now. Actually, this has been the focus of some recent research, which has resulted in the creation of several innovative techniques that are directly relevant to the monitoring of dangerous substances in the workplace. The principles of UV absorption, synchronous luminescence and room temperature phosphorescence are used in most promising analysis methods as shown in Table 1. These instruments are extremely sensitive, allowing for the detection of extremely low quantities while also providing information on the PAH content of the sample.

Now, because of the superior selectivity, resolution, and sensitivity, gas chromatography (GC) has traditionally been used to analyse PAHs in environmental samples rather than liquid chromatography (LC). For the chemical investigation of complicated mixtures, GC-MS is one of the most effective analytical techniques available. Mass spectrometry improves gas chromatography's capabilities; the detector is highly specific in nature, giving qualitative as well as structural information about the sample. This selectivity of mass spectrometers can ultimately be used for the determination of structure of the sample under investigation. (Chen *et al.*, 2015).

The most recent generic method of extraction and analysis of PAHs in animal feed and food samples is developed by. In it, acetonitrile and heptane of HPLC grade were used as the solvents. The Water acetonitrile heptane solid phase extraction (WAHSPE) method was used for the extraction of PAHs from the samples. The instruments used for analysis were GC-MS and LC-MS.

This WAHSPE method has its great advantages in the field of food science as multiple compounds can be investigated by the single sample and definitely if one sample is required, then the efforts required are less and the information gathered about the sample is more. (Eyring *et al.*, 2021).

6. PAHs emission from automobile exhaust

In urban areas, the automobile exhaust causes the problem of air pollution. The two main types of pollutants, which is emitted from mobile sources are categorized into two parts. The first is regulated and second is unregulated

by law. Carbon monoxide (CO), nitrogen oxides (NO_x) and unburned hydrocarbons (HC) are considered as regulated pollutants (Westerholm *et al.*, 1988). The exhaust which is not specified by law is the exhaust of unregulated pollutants. The polycyclic aromatic hydrocarbons which are the result of incomplete combustion of fossil fuels are the class of the compound who come under the category of unregulated pollutants (Westerholm *et al.*, 1988). Several authors also tried to investigate the air pollution influence on the people suffering from cancer (Nielsen, 1996). The exhaust emission has different types of unregulated pollutants which are originated from the components present in the fuel (Westerholm *et al.*, 1988). The combustion of gas stoves, diesel, petrol and gasoline all add up to the air pollution containing PAH in addition to the Polycyclic organic matter (POM) (Nielsen, 1996). Due to their carcinogenic nature around 1-10% person became a sufferer of the lung cancer due to air pollution (Doll and Peto, 1981; Speizer, 1986), but it is also a disregarded fact that the content of (POM) with ambient air pollution in year, 1950s and 1960s has a high content of unsubstituted PAH in comparison to air pollution in 1990s and 1980s (Holmberg and Ahlborg, 1983). This is due to the development of effective combustion approach which has led the conversion of PAH into oxygenated PAH and secondly due to the atmospheric transformation of reactive PAH, which is caused by growing of air pollution with NO_x and ozone (Nielsen, 1983).

A large percent of the population, i.e. around 50% spend their life within 100 miles of seashore (Hinrichsen, 1997) and pollutants which mainly released from human activities affects the lives of the creature who lives in coastal regions. The water birds like ducks, geese and swans and 70% of recreational and commercial fishes who spent almost a segment there of the life cycle are largely affected (Dickhut *et al.*, 2000).

Several researchers have investigated the PAH content in densely populated areas and found out that the greatest source of PAH is automobile exhaust (Nielsen, 1996). The traffic contribution is determined in the street of city named Copenhagen and it is investigated that air pollution is at highest in the winter season (Nielsen, 1996). There is also the difference in the concentration of different compounds in the street or in the city area. The BeP is applied as the PAH indicator and the traffic contribution is determined in the street as well as the city area (Nielsen, 1996).

6.1. Diesel as a source of PAHs

The diesel is considered as a heavy fuel which is used for various types of vehicles. They are having the better results and the longevity as compared to gasoline engines (The EPA, 2002). Although, due to some old technology, the emission of hazardous pollutants causes several carcinogenic and mutagenic diseases, but using some advanced technology, the harmful contaminants releasing from the diesel engine reduced up to some extent under government policy to overcome hazardous pollutants. However, the emission control technology can be applied to some old engines which largely reduce toxic pollutants.

Therefore, it is concluded that the effect of level of (PAHs) and (NPAHs) i.e. Nitrated polycyclic aromatic hydrocarbons due to increase in urbanization is largely due to incomplete combustion of the diesel engine (The EPA, 2002).

The composition mainly consists of several types of gaseous mixture. They also contain some elements including carbon, a little amount of sulphate, nitrate, metals and gases like, CO including some trace elements (Schauer *et al.*, 1999). The PAH and NPAH are the main classes that are generally considered important. NPAH are basically the compounds which result from the nitration of PAH due to incomplete combustion of fuel. NPAH are toxic compounds having mutagenic property (can alter the DNA of cell).

In countries like Japan testing shows that more than 99%, the source of 1-NP generates from exhaustion of diesel. Therefore, the study shows that being the chief source of diesel engine as NPAH, the emission from diesel is considered a major source for PAH (Kumar *et al.*, 2014; Kothiyal *et al.*, 2021).

6.2. Gasoline as a source of PAHs

Emissions of PAHs are from several combustion sources which also involves internal combustion engines. The PAH like benzo(α)pyrene and benz(α)anthracene are mainly used as the total PAH emission indicator (concave report no. 98/55, 1998). The levels of PAH in exhaust gas are reported and it is seen that they depend on the type of vehicle, the employed driving cycle and the procedures of sampling and analytical (concave report no. 98/55, 1998). So, it becomes difficult to define the minimum and maximum values (concave report no. 98/55, 1998). The fuel variables which results from the emission of PAHs like fuel aromaticity, the type of aromatic compounds present are also investigated (Zukeran *et al.*, 2017). It is concluded that there is the increase in PAH emission due to the increase in fuel aromaticity, which is leaded gasoline. This effect was not appeared for the equivalent lead – free fuel quality (Zukeran *et al.*, 2017). Due to their reactivity, the aldehydes are proved to be the precursor of photochemical oxidants. In a study it is also found that the levels of gasoline aldehyde emission is about 6 times lower as compared to the level of aldehyde emission (Zukeran *et al.*, 2017).

6.3. Methods to control automobile exhaust

6.3.1. Diesel Particulate Matter (DPM) control technologies

The emission from the diesel engine causes harmful impact on humans and ecology. Therefore, to reduce the harmful impact, government has developed some policies for transportation and designed some regulations for the environment to reduce the negative impact by enhancing the fuel economy and considering the environmental performance of the diesel engine (From Kazuichi Hayakawa, Polycyclic Aromatic Hydrocarbons). The new perspective for improving the engine emission is adopted and allowing the manufacturers of the engine to have enough time for implementing the advancement in

technology which is important to satisfy the new emission standards (Miller and Facanha, 2014). The wide range of emission control technology is applied on the advanced diesel engines and for older diesel engines it is retrofitted (From Kazuichi Hayakawa, Polycyclic Aromatic Hydrocarbons). The technologies which are mainly used for reducing the particulate matter (PM) emissions are diesel particulate filters (DPF), closed crankcase ventilation, diesel oxidation catalysts (DOC) (MECA, 2007; IARC, 2014). The technologies like selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) are used to decrease the NO_x emission (from Kazuichi Hayakawa, Polycyclic Aromatic Hydrocarbons). Generally, these technologies are very helpful in reducing the emission of pollutants like PAHs and NPAHs (Heeb *et al.*, 2008, 2010; Hu *et al.*, 2013; Khalek *et al.*, 2015). It has been found that various biodiesel blends reduce the emissions of PAHs and NPAHs when it replaces the conventional diesel fuel (Bagley *et al.*, 1998; Sharp *et al.*, 2000). The reduction in the PAH emission is seen from biodiesel up to 65 to 85% rather than conventional diesel fuel (Bagley *et al.*, 1998).

6.3.2. Electrostatic precipitator with heat exchanger

The particulate matter like carbon black, soluble organic fraction (SOF) and sulphates are emissions of marine diesels which causes several health problems in humans and coastal environment. ESP (electrostatic precipitator) is made which collect all these particles (Zukeran *et al.*, 2017). ESP has capability to remove the PAHs and it is reported that ESP was able to remove the emission of PAHs from the diesel engine (Phirun *et al.*, 2008). The diesel particulate matter (DPM) which includes sulphates, soluble organic fraction (SOF) and dry soot were removed by ESP having a heat exchanger (Zukeran *et al.*, 2014). Due to the incomplete combustion of fuel, both the soluble organic fraction (SOF) and PAHs are formed. Therefore, the authors were expected that PAHs in gaseous form are absorbed into particulate SOF then condensation takes place in heat exchanger. Thus, there was a collection of PAHs in ESP (Zukeran, 2017) and it was also shown that the PAHs in particulate form, and in gaseous form were removed (Nanjo *et al.*, 2016; Ito *et al.*, 2017).

In an experiment of removing the PAHs in exhaust gas which is emitted from marine diesel, it was found that for eliminating the PAHs in diesel exhaust gas, the electrostatic precipitator with heat exchanger was an effective device (Zukeran, 2017).

7. Recent advancements in removal of PAH

The PAH emitted from various sources has degraded the ecological system at huge extent. Therefore, several methods have been developed to degrade these harmful toxins environmental pollution. The removal of PAH can be done in various ways like biodegradation method (Abdel-Shafy *et al.*, 2014; Perera *et al.*, 2011) chemical degradation and photochemical degradation method. At present by the use of green diesel blending with different diesel we can also reduce carcinogenic PAHs.

7.1. Biodegradation of PAH

Biodegradation is an effective method of PAH degradation around 73% to 92% and requires high temperature in the range of 40 to 45°C (Adeola and Forbes, 2020). Currently, new developments are made in the field of bioremediation which is thenanoparticle based eco-engineered bioremediation method which helps in reducing the compounds like PAH emerging from different sources involving water, soil and sediments (Patel *et al.*, 2020). This technique mainly involves biomolecules like bio-surfactants, humic acids, proteins and enzymes which act as functionalizing agents (Basak *et al.*, 2020). The biodegradation mainly focuses on degrading the PAH present in water sources and soil with the help of several types of plants, microorganisms, and different types of enzymatic reactions (Ghosal *et al.*, 2016., Gouma, Fragoeiro, Bastos and Magan, 2014). Biodegradation is considered as a meticulous field of research. However, there is a need for some advancement for some microbial bioremediation (Ghosal *et al.*, 2016). The PAH affects differently from each process due to the difference in the structure of PAH and their biological, physical and chemical properties (Abdel-Shafy and Mansour, 2016). The removal of PAH from the contaminated environment can also be done by the help of bio functionalized NPs which has properties like catalytic degrading and nano – adsorption (Basak *et al.*, 2020). The silica nanoparticles which are coated with zwitterionic lipid bilayers are used to degrade the benzo(α)pyrene from the contaminated surface and soils subsurface (Wang *et al.*, 2015).

A recent advancement in the field of microbial biology has been achieved. This achievement mainly focuses on identifying conserved sequences, which is found in the particular microorganism's group, mainly 16S rRNA and 18S rRNA genes. They mainly provide the phylogenetic characterization which is present in the habitat of the microbial population (Pace *et al.*, 1986; Amann *et al.*, 1995). This technique proves to be effective in the area of treating PAH through bioremediation approach because it becomes easier to find out the microorganisms which live in those environments by finding the microbiota in the polluting system, and therefore it is possible to predict the biodegradation potential (Ghosal *et al.*, 2016). Currently, it is seen that the bacteria like *Aeromonas hydrophila*, *Serratia marcescens*, *Bacillus megaterium* and *Raoultella* are capable of degrading the PAH like acenaphthene and fluorene up to 90% (Ghosal *et al.*, 2016). The two types of bioremediation approaches involve in situ (or the intrinsic bioremediation) of micro flora dwelling at the place which is having contamination of various pollutants and based on its bioremediation potential (Ghosal *et al.*, 2016). This technique is the most efficient option due to little disturbances and cheap rate, also avoid digging and provides the remediation at its main site (Ghosal *et al.*, 2016). On other side ex situ (or extrinsic bioremediation) involves physically eliminating the polluted material for the treatment to another place (Carberry and Wik, 2001). The fungi and bacterial species can also degrade the PAH in large proportion. The fungi like *Peniophora gigantea*, *Pycnosporus coccineus*, *Phanerochaete chrysosporium* and *Trametes versicolor* (Silva, Grossman and Durrant,

2009) and bacteria are like *Trichocladium sp.*, *Fusarium sp.*, *Pseudomonas* and *Aspergillus* (Quinn *et al.*, 2009; Soleimani, 2012; Sun *et al.*, 2014; Wu, Chen, Tian, Ding and Dick, 2013) effectively degrade the pollutants like PAHs.

The factors like temperature and pH are capable of changing the efficacy in the process of bioremediation. However, due to enhancement in the microbial growth the temperature in the range of 30°C to 38°C are considered as optimum for degrading the PAH. The decrease in the amount of dissolved O₂ which is available in the bioreactor for the microbial growth is seen, when there is a reduction in the solubility of oxygen due to increasing temperature (Alegbeleye *et al.*, 2017; Vinas, Sabate, Espuny and Solanas, 2005). The bioavailability is the main factor for degrading the PAH by bacteria and it becomes bioavailable in the dissolved or vapour phase (Abdel-Shafy and Mansour, 2016). The solubility also plays an important role for bioavailability of PAH (Abdel-Shafy and Mansour, 2016). However, the degradation in the rate of PAH experiences the reduction if the chemical found by the degrading bacteria, which is better used as a food source (Abdel-Shafy and Mansour, 2016).

7.1.1. Degradation by bacteria

The bacteria are considered as the natural scavengers as they are capable of developing the methods for obtaining the energy from virtually each and every compound and evolved around three billion years ago or more (Ghosal *et al.*, 2016). The bacteria can be considered as the remediation for degrading environmental hazards because of their quick flexibility (Ghosal *et al.*, 2016). The bacteria like gram-positive and gram-negative can be easily isolated from soil which have the ability to metabolize naphthalene, anthracene and phenanthrene (Figure 7) (Cerniglia, 1993). It has been seen that the soils with low PAH content contain low PAH utilizers than soils with high total PAH content (10⁵– 10¹⁰ bacteria per gram of soil) (Cerniglia, 1993).

On the basis of oxygen's presence or absence, there are mainly two ways for degrading the bacteria (Ghosal *et al.*, 2016). The aerobic bacterial PAH degradation initiates when the O₂ act as the final electron acceptor and for hydroxylation co-substrate and oxygen-mediated cleavage of aromatic ring (Chen *et al.*, 2016). The anaerobic PAH degradation mainly depend on the alternative final electron acceptor and reductive reaction type for breaking and opening of the aromatic ring (Dhar *et al.*, 2020; Ghosal *et al.*, 2016). The degradation of bacteria mainly initiates from the attack of dioxygenases on the aromatic ring and form a compound named cis-dihydrodiol (Figures 2 and 8). The formation of trans-dihydrodiols by monooxygenases oxidation has been shown (Heitkamp *et al.*, 1998; Kelley *et al.*, 1991). The compound formed by dihydroxylation i.e cis-dihydrodiol intermediate on oxidation to form substrates for ring cleavage enzymes and on doing catabolism generates tricarboxylic acid cycle intermediates (Cerniglia, 1993).



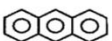
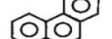
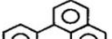
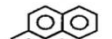
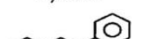

PAH	Solubility mg l ⁻¹	Carcinogenicity
 Naphthalene	31.7	Non-carcinogen
 Acenaphthene	3.9	Non-carcinogen
 Anthracene	0.07	Non-carcinogen
 Phenanthrene	1.3	Non-carcinogen
 Fluoranthene	0.26	Weak carcinogen
 Pyrene	0.14	Non-carcinogen
 Benz[a]anthracene	0.002	Carcinogen
 Benzo[a]pyrene	0.003	Carcinogen

Figure 7. Structural formulas, solubilities and carcinogenicity of polycyclic aromatic hydrocarbons (Cerniglia, 1993).

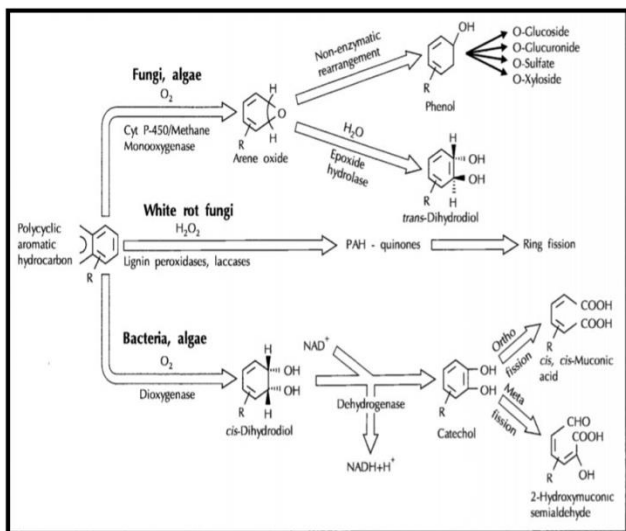


Figure 8. The steps involved in microbial pathways for oxidation of polycyclic aromatic hydrocarbons (Cerniglia, 1993).

7.1.2. Degradation by fungi

For the biodegradation of PAH contaminated soil, the fungi are equally important as bacteria (Cerniglia, 1993). There are very few studies on PAH degradation by fungi as compared to bacteria (Lawal, 2017). Unlikely, fungi do not use PAH as the main source of carbon and energy, but they transform the PAH co-metabolically to the chemical products which are detoxified (Cerniglia, 1993). The fungal transformation by PAH includes different paths initiated by enzymes and also depends on the specific species and growth factor (Ghosal *et al.*, 2016). There are mainly two types of fungi which are involved in PAH biodegradation

(Ghosal *et al.*, 2016). The ligninolytic fungi or white – rot fungi (which have the capability to produce several enzymes like lignin peroxidase (Lip), laccases and manganese peroxidase (MnP) for the degradation of lignin present in wood) and second is non-ligninolytic fungi (which do not have the ability to produce enzymes like peroxidases and laccases, but have the ability to produce enzymes like cytochrome P450 monooxygenases (Hofrichter, 2002; Cerniglia and Sutherland, 2010; Tortella *et al.*, 2005; Li *et al.*, 2010). After the catalytic cleaving of aromatic compounds, the ligninolytic enzymes produce polar products which are water soluble which then available for the soil microflora and the fungal metabolism present in the vicinity (Gupta and Pathak, 2020). Some of the fungal species have the ability to produce the bio surfactants which can reduce the hindrance for high molecular weight PAH which are less soluble, and it results in degradation at maximum level (Ojha *et al.*, 2019).

7.1.3. Degradation by Algae

The biodegradation of PAH by algae has gain less attention as compared to biodegradation with bacteria and fungi (Ghosal *et al.*, 2016). For the aquatic environment, the microalgae are commonly known as the primary producers and play an important role for degrading the PAH in an aquatic environment (Ghosal *et al.*, 2016). The microalgae (Cyanobacteria) which is a freshwater single celled green alga considered as prominent due to its propagating nature, the ubiquitous occurrence and most effective for degrading HMW PAHs (Ke *et al.*, 2010). It has also been shown that under photoautotrophic conditions, in the presence of little amounts of cis – 1,2-dihydroxy – 1,2- dihydronaphthalene and 4-hydroxy-1-tetralone, the cyanobacteria and green, red and brown algae oxidize naphthalene to 1-naphthol (Cerniglia *et al.*, 1980). The cellular biodegradation and bioaccumulation are mainly responsible for the algae-mediated effective PAH removal (Ke *et al.*, 2010).

7.1.4. Degradation by archaea

Harmful pollutants, PAH and petroleum-based pollutants are released by some oil industries mainly in the saline region and requires extremophiles for bioremediation and not the conventional microorganisms (Dastgheib *et al.*, 2012). Recently, there are various reports in which the archaea can degrade the PAH effectively. In a study it is seen that the distribution is mainly in six groups of the archaeal and bacterial strains which are having the catabolic property (Ghosal *et al.*, 2016). The groups are mainly Betaproteobacteria, Alphaproteobacteria, Gammaproteobacteria, Firmicutes Actinomycetes and Archaea (Halophiles) (Ghosal *et al.*, 2016).

7.2. Photodegradation of PAHs

The boiling point of PAHs varies in between 300 to 1000°C. In this method, the degradation of the compound is done in the presence of light (Manahan, 1994). The reactions mainly initiated when there is excitation of electrons by the absorption of light through the PAH within the molecule. However, these types of excitations

generate the arrangements which are not the stable structure (Abdel-Shafy and Mansour, 2016) and they allow various types of processes involving physical and chemical to act on these compounds (Schwarzenbach *et al.*, 1993). Some of the little photodegradation can also occur when the PAHs are stick to the particles present in the atmosphere or in soil which gives the reactions which is more active and having the increment in the particle surface area (Okoro *et al.*, 2020). With the help of the catalyst like TiO₂ (titanium oxide) and UV radiation, the PAH degradation with the help of photocatalysis is investigated (Zhang, Li, Gong and Li., 2008). The PAH like phenanthrene, benzo(α)pyrene and pyrene follow the path of pseudo- first order in the presence of UV irradiation and due to its catalytic activity by adding some amount of TiO₂ the reaction was accelerated (Garg *et al.*, 2019). Under different UV radiation intensities various types of PAHs are degraded to different extents whereas the increase in the dosage of TiO₂ from 0.5 to 3 weight percent has no significant result on the photo degradation of PAH and which is mainly high under the acidic conditions of pH (Zhang *et al.*, 2008). The reactions of photolysis are effective on the particles like silica gel and alumina which are light coloured particles in comparison with the dark colour particles like carbon black. For instance, the half life of anthracene on alumina is 0.5h whereas on carbon black is 310h (Abdel-Shafy and Mansour, 2016). The photo degradation approach is considered as more effective for the low molecular weight compounds like naphthalene because of the high bioavailability and also for a long period of time they can be exposed to sunlight, (Okoro *et al.*, 2020). The PAH photo degradation in the soil mainly depend on hydrocarbon molecular weight, the texture of the soil and the overall exposure time (Marques *et al.*, 2016).

Generally, the angular PAHs like dibenz[α,h]anthracene, anthracene and the phenanthrene show slow process of degradation while the two membered ring and linear and some PAHs which form clusters exhibit fast degradation in the presence of light. This change in the rate of degradation is mainly because they are having the most stable structure (Korfmacher *et al.*, 1980). The composites which are having the photocatalytic properties are synthesized and they applied for the degradation of PAH (e.g like platinum / TiO₂ . SiO₂) (Luo *et al.*, 2015).

7.3. The chemical degradation of PAHs

In various environmental conditions, the chemical oxidation is considered as a little process of PAH degradation (Abdel-Shafy and Mansour, 2016). This technology mainly uses the oxidants like activated persulfate (Huling and Pivetz, 2006), ozone (Lian *et al.*, 2017), Fenton reagent (Zhang, Dong, Zhao, Wang and Meng, 2019) and H₂O₂ (Flotron, Delteil, Bermond and Camel, 2005). There are some species which are greatly responsible for the PAHs aromatic ring breakdown and these techniques involve the generation of some reactive radicals like •OH, O₃ and some of the reactive species like peroxides and persulfate anion (Adeola and Forbes, 2020). The different degradation ways are such that

different oxidation reactions which involves the •OH radical and O₃ are willing to react with aromatic compounds like PAHs at very near diffusion-controlled rates by the abstraction of H-atom or by two fold bonds expansion (Ukiwe *et al.*, 2013). The reaction further proceeds with various complex ways and creating different intermediates (Agrawal *et al.*, 2019). In these types of reaction, the final product involve mixture of quinones, aldehydes, carboxylic acids and ketones for both the oxidants (Reisen and Arey, 2002). O₃ can directly attack double bonds or it can form •OH reactive radical (who can attack on double bonds) by decomposition of water (Legrini, Oliveros and Braun, 1993). It is also investigated that some of the treatments like physical and chemical, have the ability to degrade the PAHs from the surface water in huge extent (Ukiwe *et al.*, 2013). The degradation of PAHs by the photo chemical method involves similar oxidative species that are generated during PAH through pure chemical oxidation (Ukiwe *et al.*, 2013). Due to the presence of high radical reactivity and degradation of in situ contaminants the quality of chemical oxidation in comparison with other conventional methods of remediation involve shorter treatment time and effectiveness for the broad range of PAH remediation (Adeola and Forbes, 2020).

Due to the low aqueous solubility and vapour pressure, the chemical degradation efficiency of PAHs is limited (Luning and Pritchard, 2002). Therefore, the surfactants are considered as an effective tool that are having the properties for removing the problem of low aqueous solubility of PAH (Boonchan, Britz and Stanley, 1998). Different studies also focus on the importance of the surfactants in order to increase PAHs solubility by lowering down the interfacial surface tension between the PAH and water-soil interface (Li and Chen, 2009).

7.4. Phytodegradation of PAHs

The phytodegradation of PAHs is the approach in which the plants and soil microorganisms are used for minimizing the concentration and the hazardous effects of the contaminants like PAHs in the atmosphere (Lawal, 2017). It is in situ and solar energy regulated approach which also minimizes the cost (Haritash and Kaushik, 2009). Many researchers have investigated that several different types of grasses and leguminous plants have a good ability for the phytodegradation (Ukiwe *et al.*, 2013). Several types of categories of grasses like *Bouteloua gracilis*, *Elymus canadensis*, *Festuca rubra*, *Festuca arundinacea*, *Agropyron smithii*, *Melilotus officinalis* and *Cynodon dactylon* etc are commonly studied for degrading the PAHs (McCutcheon and Schnoor, 2003). The sources of energy and carbon which are used by the plants are sunlight and carbon dioxide. The roots of the plants are capable of absorbing a variety of natural and hazardous compounds from human as well as industrial activities and for which several amazing methods of detoxification have developed (Lawal, 2017). In a study it is also found that the grasses like tall fescue (*Festuca arundinacea*) and switch grass (*Panicum virgatum*) have the ability to degrade the PAH like pyrene

about 38% in 190 days (Chen, Banks and Schwab, 2003). Some authors also found the significant enhancement in the PAHs adsorption from the contaminated soil in the presence of vegetation such as corn (*Zea mays*), rape seed (*Brassica napus*) and alfalfa (*Medicago sativa*) (Ukiwe *et al.*, 2013). By releasing enzymes through roots, the plants remove the PAHs in an indirect manner (Agrawal *et al.*, 2019). By catalysing the chemical reactions in soil, the enzymes have the capability for transforming the organic contaminants (Ndimele *et al.*, 2010). Thus, it is considered that phytoremediation is an emerging technology for the degradation of PAHs (Sun, Cang *et al.*, 2010).

7.5. Degradation by adsorption process

The adsorption is considered as the surface phenomenon at which the pollutants are adsorbed onto the surface or the interface through different types of attractive forces like physical, chemical and electrostatic (Adeola and Forbes, 2020). The processes which influence the adsorption of organic compounds are pH, temperature, sorbate concentration, particle and pore size and various adsorbate and adsorbent physicochemical properties (Adeola and Forbes, 2020). The adsorption technique is simple, quick, require a minimum amount of solvent and have high recovery and due to this reason, it is used for the PAH removal from water samples (Ma *et al.*, 2010). In this process, the nature of adsorbent is considered as an important factor of obtaining the best results (Adeola and Forbes, 2020). The materials which act as adsorbents for the removal of PAH and pre-concentration in contaminated water are the porous organoclay composite, polyvinylidene fluoride, bamboo charcoal and matrix-immobilized organoclay (Ma *et al.*, 2010). Although, there is need for the improvement in the recovery of PAHs having high ring (Ma *et al.*, 2010). This technique has various advantages which involves the removal of hazardous compounds produced by processes like oxidation and reduction, rather than broken into harmful metabolites (Okoro *et al.*, 2020). However, for the adsorption treatment of wastewater containing PAHs, activated charcoal is proved to be very effective adsorbent (Okoro *et al.*, 2020).

7.6. PAHs removal through filtration in wastewater

The process which is capable of removing solutes from fluids through a filter which act as a medium and allows the fluid to cross and keep the solutes is called filtration (Akinpelu *et al.*, 2019). The process can be physical, mechanical and biological. The passing fluid through the filter is termed as filtrate (Akinpelu *et al.*, 2019). Recently, for the removal of PAH by the filtration process, the membrane is considered as a common medium. The size of the particles which is retained on the medium (membrane) are the application of different procedures of filtration (Akinpelu *et al.*, 2019). The particle size of PAHs is very small as compared to the microfiltration membranes (MF) pore size, therefore microfiltration is not considered for the removal of PAHs (Smol and Włodarczyk – Makula, 2016). Thus, the procedures like forward osmosis (FO), ultrafiltration (UF), nano filtration (NF), reverse osmosis (RO) are considered as most convenient

procedures for the removal of PAHs which is applied in filtration (Akinpelu *et al.*, 2019).

8. Future prospective

There is a need of research in the area of automobile exhaust which is a major source of PAH. There is a need for advancement in the technologies which are capable of reducing the diesel exhaust. However, the electrostatic precipitator with heat exchanger proved to be effective for the PAHs removal in diesel exhaust, but the removal technologies for PAHs from automobile exhaust could be an appealing topic for near future research (Zukeran *et al.*, 2017). The progress in the field of bioremediation has been made as discussed above. Various technologies and remediation approaches have been developed. Although, several challenges are unresolved and also the remediation of the site of PAHs is an enormous task. From this review, we cannot deny the fact that the bioremediation, photoremediation are the most effective methods which provides a considerable solution of the degradation of PAH. The conventional treatments like phytoremediation are proved to be a refreshing method for PAHs treatment. There is a need for research in the degradation of PAH under soil and the huge problems which have to look upon is the marine environment. There is a need to determine, what is exactly happening in the environment which is contaminated with PAHs. There is very little information on enzymes, genes, and also on the molecular mechanism of the PAHs degradation in the high- salty environment and anaerobic or low- oxygen containing environments (Ghosal *et al.*, 2016).

For the many preceding years, degradation of PAHs by different microorganisms has been studied. However, very limited work has been dedicated to most carcinogenic PAH BaP, and the main purpose is its recalcitrance to biodegradation, as the result of its high stability. However, a few studies have been devoted on BaP biodegradation. For instance, so far, there is no report on a single bacterial strain that can biomineralise BaP when used as a sole source of carbon. More studies are needed on individual PAH according to their carcinogenicity report.

9. Conclusion

The PAH are the compounds which come under the class of unregulated pollutants. Several authors found that the greatest source of PAH is automobile exhaust, which is also responsible for lung cancer in humans. From the literature review it is also found that automobile exhaust which also causes air pollution, is highest in the winter season. The PAH and NPAH are the main class of compounds and are largely emitted from the incomplete combustion of diesel engine. However, the diesel particulate matter technologies (DPM) are helpful in reducing the PAH contaminant by increasing the fuel economy. Several technologies like diesel particulate filters, diesel oxidation catalysts (DOC) and closed crankcase ventilation is used for reducing the particulate matter (PM) emission. The electrostatic precipitator with heat exchanger is helpful in removing the PAH emitted from marine diesel up to a large extent. The advancement

in the biodegradation of PAH is also shown and it is found by several authors that this technique is effective with the degradation up to 72 to 92%. The phytoremediation is considered as cost-effective technique. The adsorption and photoremediation also proved to be a productive one. The adsorption processes are having a lot of advantages and involves removal of harmful compounds rather than broken into metabolites. The advancement in several PAH degradation techniques is helpful in degrading the PAH up to a maximum level while phytoremediation can be a revolutionized topic for near future research.

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