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BIODEGRADATION OF POLYCYCLIC AROMATIC HYDROCARBONS: A REVIEW

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ABSTRACT

This review paper is devoted to polycyclic aromatic hydrocarbons (PAHs, arenes), high molecular organic compounds, in the structure of which benzene rings are present. PAHs are considered to be priority pollutants, since many of them possess carcinogenic and mutagenic activity and pose a danger to human health. The paper discusses the technologies for the removal of PAHs from the environment, in which bioremediation is one of the most promising and safest options. Various genera of bacteria, fungi and algae that are capable of highly efficient biodegradation of PAHs are characterized. In addition, the review discusses the extent and mechanisms of action of PAHs on various components of the environment. The information is provided on the main sources of PAHs, role of abiotic and biotic factors in the biodegradation of PAHs in the environment, and mechanisms for the degradation of PAHs by microorganisms are considered.

Key words: polycyclic aromatic hydrocarbons (PAHs), sources of PAHs, biodegradation of PAHs.

INTRODUCTION

At the present stage, a concern for the nature conservation consists not only in the development and observance of legislation on the protection of the Earth and its subsoil, forests and waters, atmospheric air, flora and fauna, but also in understanding the patterns of cause-effect relationships between different types of human activity and changes occurring in the natural environment. Data are needed on how certain chemicals that enter the biosphere are behaving, what transformations they are going through, and what consequences they will have. It is necessary to proceed from the statement of the changes taking place in nature to their forecasting and habitat quality management.

One of the acute environmental problems of our time is the contamination of ecosystems by polycyclic aromatic hydrocarbons (PAHs), which are organic compounds of the benzene series, differing in the number of benzene rings and characteristics of their attachment. The major sources of technogenic PAHs emission into the environment include energy complex enterprises, motor transport, chemical and oil refining industries. The thermal processes associated with the burning and processing of organic raw materials (oil products, coal, wood, garbage, food, tobacco, etc.) form the basis of practically all technogenic sources of PAHs. Large industrial clusters and urban soils are particularly contaminated by such substances [1, 2].

PAHs are now widely used in the manufacture of plastics, resins, pigments, dyes, pesticides, and pharmaceuticals. In general, the scope of detection and concentrations of PAHs in environmental objects have increased over the past 30 years, especially in the industrialized regions of the world, and these indicators will grow over the next few years due to an increasing number of anthropogenic emissions.

Despite the widespread availability of a large number of PAHs, most of the existing data and regulations are concentrated only on a limited number of the most examined PAHs.

In Kazakhstan, there are no methodological bases for monitoring of environmental contamination by PAHs. Meanwhile, many countries, in particular the European ones, have accumulated and summarized long-term experience in monitoring of PAHs in the environment [3].

The relevance of the study into the behavior of PAHs in the environment is due to the increased danger and scope of the soil and vegetation contamination by these supertoxicants.

Polycyclic aromatic hydrocarbons (PAHs) and characteristics of their chemical structure

Polycyclic aromatic hydrocarbons (PAHs) are a large group of organic compounds with two or more single or condensed benzene rings.

PAHs and their hybrid forms are part of the complex carbonaceous materials of the Earth's crust and landscape envelope in the form of dispersed bituminous substances, oils, bitumens, soil humus components, air aerosols, plant and animal tissue lipids [4]. These are high-molecular organic compounds containing in their structure several benzene rings connected together or separated by a pair of neighboring carbon atoms between adjacent rings (fig. 1) [5, 6].

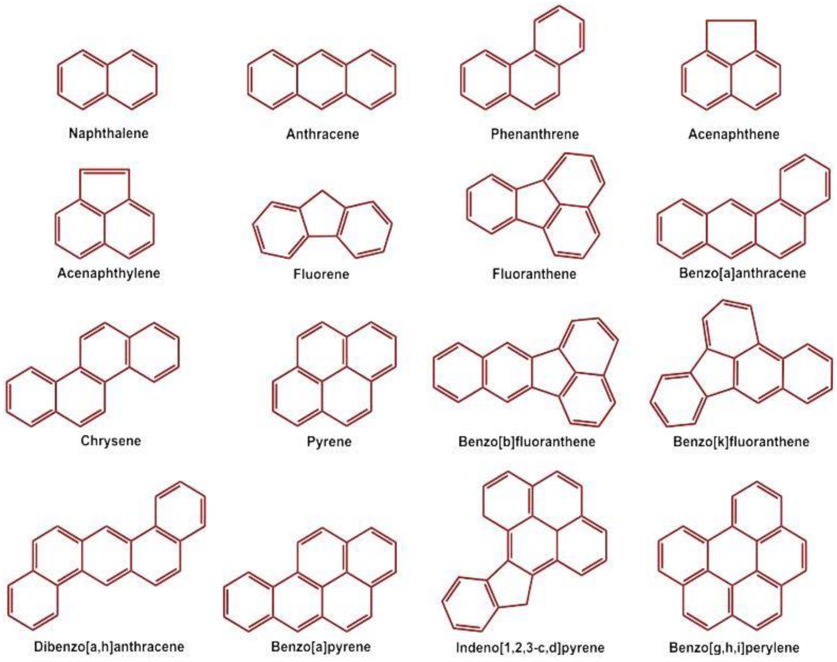

Fig. 1. Chemical structure of the 16 PAHs included in the US Environmental Protection Agency (EPA) Priority Pollutant List

The solubility of PAHs in pure water is low and varies considerably for different hydrocarbons (0.1-1.0x10^4 μg/L). The solubility in organic solvents decreases with increasing molecular weight of the compound and depending on the relative position of the condensed benzene rings in the molecule. The water solubility of pyrene is 1 μg/L, which is about a thousand times higher than that of 3.4-benzpyrene. The most important chemical property of PAHs is their readiness for substitution reactions. They relatively easily replace hydrogen atoms, attached to the aromatic rings, with other atoms or groups. As a result of such reactions, alkyl-substituted PAHs are formed, as well as halogen-, nitro-, amino-, sulfo-derivatives, phenols and aromatic alcohols, quinones, aromatic aldehydes, and aromatic acids. Under sufficiently “hard” conditions, PAHs can undergo the addition reactions. For example, the attachment of halogen to an aromatic ring can occur under the ultraviolet irradiation, and hydrogenation is possible at high temperatures in the presence of catalysts. PAHs can be oxidized to form quinones and carboxylic acids. “Acene” structures or hydrocarbons that contain them are more reactive than “phens” with the same number of rings or hydrocarbons consisting of them [7].

Geochemical processes occur in the earth's crust, which lead to the formation of PAHs in the form of resinous, bituminous, and carbonaceous substances [8]. One of the mechanisms for the formation of natural PAHs in modern and ancient sediments as well as in soils is the effect of the Earth's deep heat on the organic matter buried in it [7]. The natural factors affecting the formation of PAHs in sedimentary deposits and soils may include forest fires, both in the current and past geological epochs. In addition, PAHs formation is possible as a result of biogeochemical transformation of substituted and unsubstituted hydrocarbons, peptides, lipids, carbohydrates.

According to the US Environmental Protection Agency (EPA, https://www.epa.gov/), 16 of the most stable PAHs were included in the Priority Pollutant List.

PAHs suit the main characteristics of organic pollutants: acute and chronic toxicity, bioaccumulation, long-range transboundary transport in the environment. PAHs are included in the biospheric cycle, they move from one environment to another, and there is a continuous transfer of these substances along food chains and their accumulation in the final links, to which a human being belongs. PAHs are toxic, possess potential mutagenic, carcinogenic and teratogenic effects and pose a hazard to living organisms [9].

It has been shown that low molecular weight PAHs, such as naphthalene, fluorene, phenanthrene and anthracene, have significantly lower toxicity than PAHs with 4-7 rings (from chrysene to coronines). The latter are particularly persistent and carcinogenic to humans [2, 9].

Sources of contamination by PAHs in the environment

PAHs are found almost everywhere, but about 90% of the environmental load caused by PAHs falls on soils [10].

The natural and technogenic origin of PAHs in various soils is the subject of scientific discussions and a methodological tool for studying their evolution and genesis. Contamination by PAHs occurs from a variety of sources, and changes in emission sources can affect the qualitative soil distribution profiles of PAHs. Certain material has been accumulated in the literature about the sources of PAHs entry into soil [11]. The authors consider their technogenic origin in soil horizons as a result of burning coal, oil, wood, coke production, and operation of internal combustion engines.

The sources of PAHs entry are divided into natural and anthropogenic. The natural sources include forest and steppe fires, volcanic eruptions, oil. For example, oil contains 10% of PAH homologues of pyrene, perylene, fluorene, chrysene, benzfluorenes. There are practically no unsubstituted PAHs. Anthropogenic sources include incomplete combustion of organic raw materials (oil, shale, coal, peat), which originate from the stationary (thermal power stations, heating stations, manufacturing) and mobile (automobile and water transport, aviation) facilities, industries (metallurgical, coke chemical, cellulose, and oil ones). For example, in the places where the wood combustion, gasification or liquefaction of fossil fuel, production and use of carbon took place, the contamination by high concentrations of fluorothene, pyrene, chrysene and benzo[a]pyrene occurs [12]. Due to open burning of tires, coal, various household and industrial wastes, soil becomes contaminated by phenanthrene, fluorophthene, pyrene, chrysene and benzo[a]pyrene.

However, PAHs were detected even in the areas that are far from industrial activity. These include tropical and polar regions that are contaminated by PAHs due to atmospheric transport of these substances over long distances. In many tropical soils, naphthalene, phenanthrene, and perylene are the most prevalent and present at very high concentrations, even higher than in the temperate soils of the continent. The high-molecular PAHs, such as benzo[a]pyrene, fluoranthene often predominate in moderate soils [13].

Role of abiotic and biotic factors in biodegradation of PAHs in the environment

The degradation of PAHs in nature, including soil, can occur due to abiotic and biological processes. It was shown that during the first day in the summer period up to 80% of technical gasoline, 22% of kerosene, 2-15% of crude oil, and about 0.3% of volatile components of fuel oil evaporates from the oil slick on the soil surface [8]. In air, PAHs can undergo abiotic degradation through interaction with free radicals [14]. As a result of oxidation and photolysis, the initial PAHs are capable of forming more toxic compounds.

A 25-year monitoring of the biodegradation of polycyclic aromatic hydrocarbons and total amount of petroleum hydrocarbons in sedimentary rocks and soil under field conditions showed that three levels of biodegradation can be distinguished for PAHs: 1) rapid degradation during the first year, 2) slow degradation during the subsequent 6 years, and 3) very slow degradation after 7 years until 25 years. In addition, 2 -, 3- and 4-ring PAHs, also 5- and 6-ring PAHs were degraded. As a result of this kind of long-term experiments, the biodegradation process for all types of PAHs could be modelled [3].

According to M. Malawska and B. Wiołkomirski [15], soil is considered to be non-contaminated if the standard concentration of PAHs is <0.2-0.6 mg/kg. If the total concentration of PAHs is in the range of 0.6-1, 1-5, 5-10, and >10 mg/kg, soil is considered to be weakly contaminated, contaminated, heavily contaminated, and very heavily contaminated, respectively. Depending on the source of contamination, soil may contain PAHs in the concentration range of 0.001 to 300,000 mg/kg of total hydrocarbons [16].

After analyzing the global picture of PAHs concentrations in soil (0.004-186 mg/kg), W. Wilcke [17] concluded that Central Europe (Germany and the Czech Republic) are more contaminated by PAHs than other countries such as China, Russia, Thailand, America, Brazil, and Ghana. B.G. Loganathan and P.K.S. Lam [18] found higher concentrations of PAHs in soils in India compared to those in Africa, Iran, Brazil, Russia, Canada, and Australia. The European Environment Agency (EEA) identified about 1.5 million contaminated sites in Europe, including 200,000 sites contaminated by PAHs [19].

Soils often act as the ultimate depositary of PAHs, in particular because of their hydrophobicity [1]. When examining mountain meadow soils of different degree of development and age of the profile, it was established that in soil with a low content of organic matter (1.6%), the total content of PAHs was 11 μg/kg, and in soil with a high content of organic matter (5.8-11.1 and 9.3-11.5%), the concentration of PAHs was higher (45-104 and 69-218 μg/kg, respectively).

Concentration of PAHs rises with increasing age of soils [20]. In this case, the qualitative composition of PAHs in soils also changes. In the young mountain meadow soils (about 100 years old) only relatively simple trinuclear fluorene molecules were detected, while PAHs of complex composition were absent.

A large number of individual PAH compounds (fluorene, phenanthrene, acenaphthene, tetraphene, chrysene, anthracene, naphthalene, pyrene, and 3.4-benzpyrene) were found in the medium developed soil (about 300 years old). The PAH molecules are strongly associated with a finely dispersed organomineral fraction in this soil. In the developed soil (about 1000 years old), a high total concentration of PAHs was recorded, but a less diverse individual composition compared to medium developed soil. PAHs contained 5- and 6-ring compounds and 1.12-benzperylene.

The content of PAHs also varies according to the soil profile. A concentration of PAHs in the upper layer of the humus-accumulative horizon of chernozem soil was of 713 μg/kg and in the illuvial horizon (80 cm depth) of 201 μg/kg. Moreover, 4-7 nuclear polyarenes were accumulated mainly in the upper layer (0-9 cm), and at a depth of 9-13 cm their concentration decreased 10 times. On that basis, the authors concluded that heavy multinuclear PAH molecules have predominantly technogenic origin in the examined chernozem soil [20].

Biodegradation of PAHs in nature

The degradation of PAHs in nature can occur through photooxidation, chemical oxidation, leaching, biodegradation, bioaccumulation [21]. Each of these processes is carried out in different ways with respect to different PAHs, because of the uniqueness of their structure and properties.

The greatest number of studies in the field of PAHs degradation is devoted to their biodegradation, including anaerobic and aerobic bacterial degradation.

A variety of living organisms (bacteria, fungi, algae, higher animals and plants) are capable of transforming PAHs. And only bacteria oxidize PAHs with the subsequent assimilation of the formed products. Transformations of PAHs in nature occur through chemical photooxidation, interaction with oxidants, thermal reactions, etc. Physical removal of PAHs from the natural environment and transition to another environmental compartment occurs by leaching, weathering, etc.

The most important factor controlling the concentration of free PAHs in nature is an interaction with humic acids. Humic acids can be considered as detoxicants of PAHs. When analyzing the transfer of PAHs along food chains, we can record their movement from soil to plants, further to animal feed and later to human food. According to the literature, the content of benzo(a)pyrene in the grass is less than 1 μg/kg, in some plant species up to 20-30 μg/kg. In wheat grains its concentration ranges from 0.68 to1.44 mkg/kg, in dried fruits it reaches 23.9 μg/kg, in marine fish is in the range of 0.1-0.2 μg/kg. Meanwhile, MPC in food products is 1 μg/kg.

Plants and their rhizosphere microorganisms can participate in the biodegradation of hydrocarbons (phytoremediation) [22].

Since soil is the major PAH-depositing landscape component, plants are considered as the most vulnerable biotic component. Being constantly subjected to the effects of global and local pollution, they play a major role in the absorption of a variety of soil pollutants. The study of PAHs in the soil-plant system allows determining the mechanisms of their formation, estimate the probability of absorption by plants, establish the biological effects caused by PAHs in plant organism and soil, which in future will make it possible to use the plants as indicators of contamination by PAHs [23].

Microorganisms represent one of the major agents involved in the degradation of PAHs [24]. Biodegradation of oil hydrocarbons is an energetically beneficial process for microorganisms [25]. Some microorganisms have the ability to degrade alkanes and/or aromatic compounds [26]. Microorganisms in contaminated ecosystems adapt to the environment and, as a result of genetic mutations, subsequent generations also have the ability to degrade even larger concentrations and types of contaminants. Studies carried out by R.M. Atlas [27] showed that hydrocarbon-degrading microorganisms make up less than 0.1% of the microbial community in uncontaminated ecosystems, but this number can increase to 1-10% of the total population in oil-contaminated environments. However, in the contaminated ecosystems, the total microbial diversity decreases. Aboriginal hydrocarbon-oxidizing microorganisms play a significant role in the process of bioremediation [28].

The process of degradation of PAHs is carried out by microorganisms, including bacteria, fungi, algae [29-31]. Nevertheless, bacteria are the major active agents in degradation of PAHs. Bioavailability to microorganisms is crucial to the biodegradation of PAHs in soi.

Bacteria-destructors possess a huge variety of enzyme systems and a great lability of metabolism, which perform the process of biodegradation of PAHs [13, 32]. In this regard, there is an urgent need to search for new bacterial strains for the reclamation of ecosystems, which would be resistant to the conditions of the restored areas and could provide destruction of PAHs in significant quantities.

The ability to degrade PAHs is neither a species nor a generic sign of microorganisms. The spectrum of microorganisms used for the destruction of oil hydrocarbons in soil, in particular PAHs, includes microorganisms of the genera *Acidovorans, Acinetobacter, Agrobacteriun, Aeromonas, Arthobacter, Bacillus, Brevibacterium, Comamonas, Gordona, Flavobacterim, Galomonas, Micrococcus, Micobacterium, Nocardia, Pseudomonas, Rhodococcus , Rhodotorula, Sphingomonas, Streptomyces, Vibri, Azotobacter* and many others.

Microorganisms exhibit selectivity towards various hydrocarbons. This ability is determined by the difference in the structure of hydrocarbons, as well as by the number of carbon atoms that make up this structure. In natural conditions, microorganisms join in consortia, composing a single oil hydrocarbon oxidation chain. Each of the microorganisms which form the consortium, has specific enzyme systems aimed at a certain substrate (both hydrocarbons themselves and their derivatives), and uses this substrate in the metabolism. Consequently, the catabolic cooperation between different microbial groups during biodegradation is very important. Therefore, extraction of both a larger quantity and a wider range of oil hydrocarbons takes place through the joint action of microorganisms forming a consortium.

Microbial biodegradation is a widely used method for removal of PAHs in both terrestrial and aquatic ecosystems. Many studies on the microorganism-assisted biodegradation of PAHs were carried out in the last decade [25, 33, 34]. Many reviews have been published outlining the general mechanisms and pathways of oil hydrocarbon degradation by microorganisms and where the pathways for degradation of PAHs are considered separately [35, 36].

Factors affecting biodegradation of hydrocarbons

At the present time, a huge experimental material has been accumulated on the influence of various factors on the biodegradation of hydrocarbons. These factors include the physical and chemical properties of PAHs: molecular weight, aqueous solubility, lipophilicity, evaporation capacity, concentration in a natural object, availability of functional groups and others [37]. When getting into the soil, low-molecular PAHs (LHW PAHs), become more mobile and rapidly decompose. High-molecular PAHs (HMW PAHs) are more resistant to degradation.

Microbiological factors include the type and size of the microorganism-destructor population, bioavailability of PAHs, their cellular metabolic pathways and structural changes (from simple inclusions to complex extracellular polymer spheres) [26]. The most constant factors that have a significant effect on the biodegradation of PAHs are as follows: pH, temperature, oxygen concentration, salt composition of water or soil, availability of nutrients and co-substrates, light intensity [2, 38]. In addition, biodegradation of PAHs depends on the physical and chemical properties of soil, density, moisture and texture, etc. [39]. To select the hydrocarbon degradation routes, it is important to study all these factors before choosing any alternative to the rehabilitation process. Thereby, the degree of hydrocarbon biodegradation on contaminated soils depends critically on optimal environmental conditions for stimulating biodegradation.

Temperature fluctuations affect the metabolism of microorganisms and composition of the microbial community [37]. High temperatures can have an adverse effect on biodegradation. Thus, at temperatures above 40^0C, the toxic effect of PAHs on cell membranes is manifested. J. Aislabie et al. and A.I. Okoh reported that elevated temperatures increase the solubility of hydrocarbon contaminants, reduce viscosity and transfer long-chain n-alkanes from the solid phase to the aqueous phase [40, 41]. A low temperature reduces the evaporation of toxic substances (for example, naphthalene), decreases the solubility of PAHs in water. Low temperatures are the limiting factor for degradation of PAHs in marine sediments and fresh water from lakes. M. Thamer et al. reported that salinity and high temperatures inhibit the growth of microbes [42].

The availability and ratio of nutrients in the water body and soil play an important role in the degradation of PAHs. An unbalanced ratio of carbon, nitrogen, and phosphorus in sediments and groundwater, sea water limits the biodegradation of PAHs. The introduction of nitrogen and phosphorus fertilizers accelerates the biodegradation of PAHs.

J.H. Leahy and R. Colwell [43] have shown that although oil hydrocarbons are a rich source of carbon and energy, they do not contain significant concentrations of other nutrients (such as nitrogen and phosphorus) necessary for the growth of microorganisms. The carbon/nitrogen/phosphorus/potassium ratio (C-N-P-K) can be adjusted by adding fertilizers such as urea, phosphate, ammonium and phosphate salts, which accelerate the biodegradation of oil hydrocarbons [24, 38].

An acidophilic *Stenotrophomonas maltophilia* strain AJH1 (KU664513) could degrade polycyclic aromatic hydrocarbons (PAHs) at acidic pH (=2). Strain AJH1 was isolated from a soil sample taken in the mountainous area in the presence of PAHs as the sole source of carbon and energy. Strain AJH1 is able to degrade low molecular weight (LMW) PAHs (anthracene, phenanthrene, naphthalene, fluorene) and high molecular weight (HMW) PAHs (pyrene, benzo(a)pyrene and benzo(k)fluoranthene). In the medium at pH 2, the removal rate is up to 95% (LMW PAH) and 80% (HMW PAH), respectively [44].

The concentration of salts also affects the microbial degradation of PAHs. The relationship between the naphthalene mineralization rate and content of NaCl in the sediments of Hudson River, which has an unstable salt regime, was recorded. The degradation rate of PAHs in the river water decreased with an increase in the concentration of sodium chloride in water (3%) and almost completely disappeared at 28% [45]. The degradation rate of PAHs in soil may also decrease due to the lack of moisture necessary for growth and metabolism of microorganisms. The optimum soil moisture for biodegradation of PAHs should be at least 30% of the field moisture capacity. Концентрация солей также влияет на микробную деградацию ПАУ.

Mechanisms for degradation of PAHs by microorganisms

Aromatic hydrocarbons are less biodegradable than saturated hydrocarbons. This is due to the presence of benzene rings in PAHs, which are difficult to undergo bacterial decomposition, the presence or absence of enzymes involved in various pathways of biodegradation. Therefore, the cleavage of benzene ring is a key step in the degradation of aromatic hydrocarbons. Simpler crude oil compounds can be degraded by a wide range of bacteria, but the ability to degrade complex compounds (such as PAHs, resins, and asphaltenes) occurs in very few species.

The degradation of PAHs by bacteria has been well examined, and the metabolic pathways have been elucidated [25, 26]. For a long time it was believed that the degradation of oil hydrocarbons, including PAHs, takes place under strictly aerobic conditions. However, recent studies have shown that these processes also occur under anaerobic conditions [25, 26, 46]. Usually aerobic biodegradation proceeds much faster than anaerobic one [25, 26]. Various reactions including oxidation, reduction, hydroxylation, and dehydrogenation are common for aerobic and anaerobic pathways for microbial degradation of PAHs [29]. Anaerobic degradation of PAHs was examined later. Therefore, today there is much less information available on the genes and enzymes involved in these pathways. BTEX compounds (benzene, toluene, ethylbenzene, xylene) are usually degraded at about the same rate as in aerobic and anaerobic metabolism [25]. In anaerobic metabolism, these aromatic compounds are first oxidized to phenols or organic acids, and further transformed into long-chain volatile fatty acids, which in turn are metabolized to CH_4 and CO_2 [25, 29].

Various electron acceptors are commonly used in the anaerobic degradation of PAHs, namely nitrate, iron, manganese, and sulfate [47]. U. Jaekel et al. reported about anaerobic degradation of propane and butane by sulfate-reducing bacteria isolated from sea water. They found that the isolated cultures form a special phylogenetic cluster affiliated with the *Desulfosarcina-Desulfococcus* group within the δ-*Proteobacteria* [48].

Bacterial degradation of aromatic compounds commonly involves the diol formation, followed by the ring cleavage and dicarboxylic acid formation. Fungi and other eukaryotes normally oxidize aromatic compounds by monooxygenases to form trans-diols (fig. 2) [49].

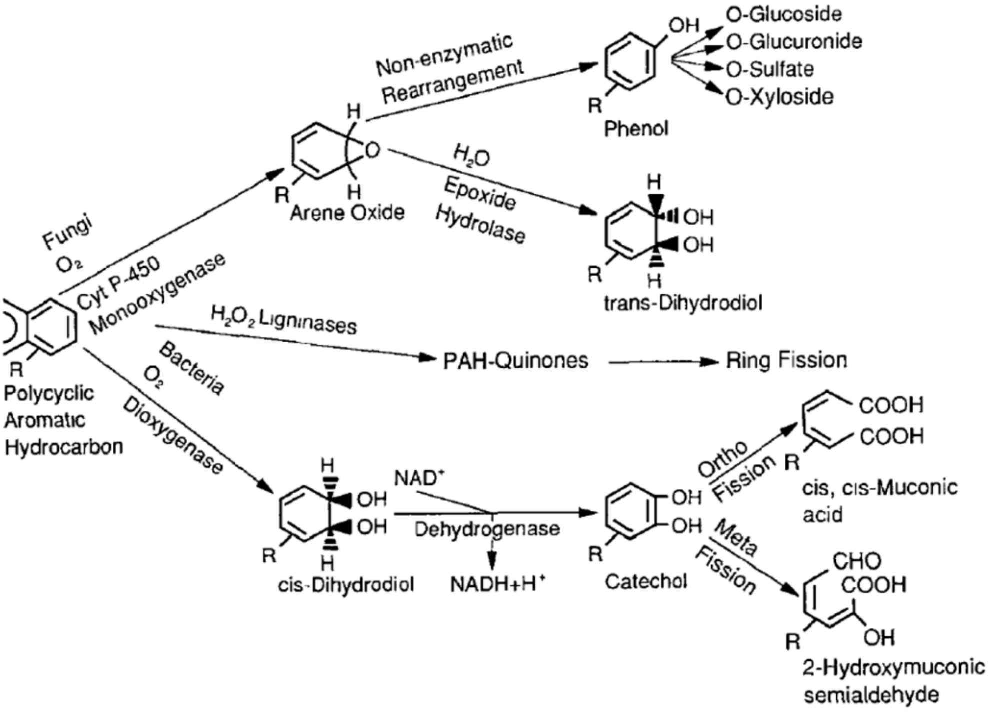

Fig. 2. Mechanism for degradation of polycyclic aromatic hydrocarbons by bacteria and fungi [45]

The predominant pathway of initial oxidation of PAHs involves the formation of *cis*-dihydrodiols by the incorporation of oxygen atoms and formation of catechins [25]. The benzene ring is cleaved by microorganisms with participation of appropriate enzymes along the ortho- or meta-cleavage pathways, leading to the formation of central intermediate products such as protocatechins and catechins, which are further converted to intermediate compounds of the tricarboxylic acid cycle [25]. The meta-cleavage genes are located on plasmids. The ortho-cleaved genes are located on a chromosome, while genetically modified orthogenes on catabolic plasmids.

Various KEGG (Kyoto Encyclopedia of Genes and Genomes) and NCBI (National Center for Biotechnological Information), GenNet, etc. databases describe gene networks for metabolism of a large number of aromatic hydrocarbons. Gene networks and metabolites of many reactions in the degradation of oil monoaromatic hydrocarbons by microorganisms are presented in the KEGG database. Enzymes involved in each stage of the reaction and bonds with other degradation chains, for instance benzoate, are shown as an example. The enzyme benzoate/toluate dioxygenase cleaves cyclic hydrocarbons such as camphor, toluene, salicylate, naphthalene, and degrades toluene to 3-methylcatechol, which further enters the network of xylene metabolism.

There are fundamental differences in the mechanisms for cleavage of polycyclic aromatic molecules carried out by various classes of microorganisms (139). Bacteria and some green algae oxidize polycyclic aromatic hydrocarbons (PAHs) using both atoms of molecular oxygen (the reaction is catalyzed by dioxygenase), and producing *cis*-hydrodiol, which undergoes further hydrogenation to form a catechol.

Some fungi are able to oxidize PAHs via a cytochrome P-450 monooxygenase by incorporating one atom of the oxygen molecule into the PAH (fig. 3) [50].

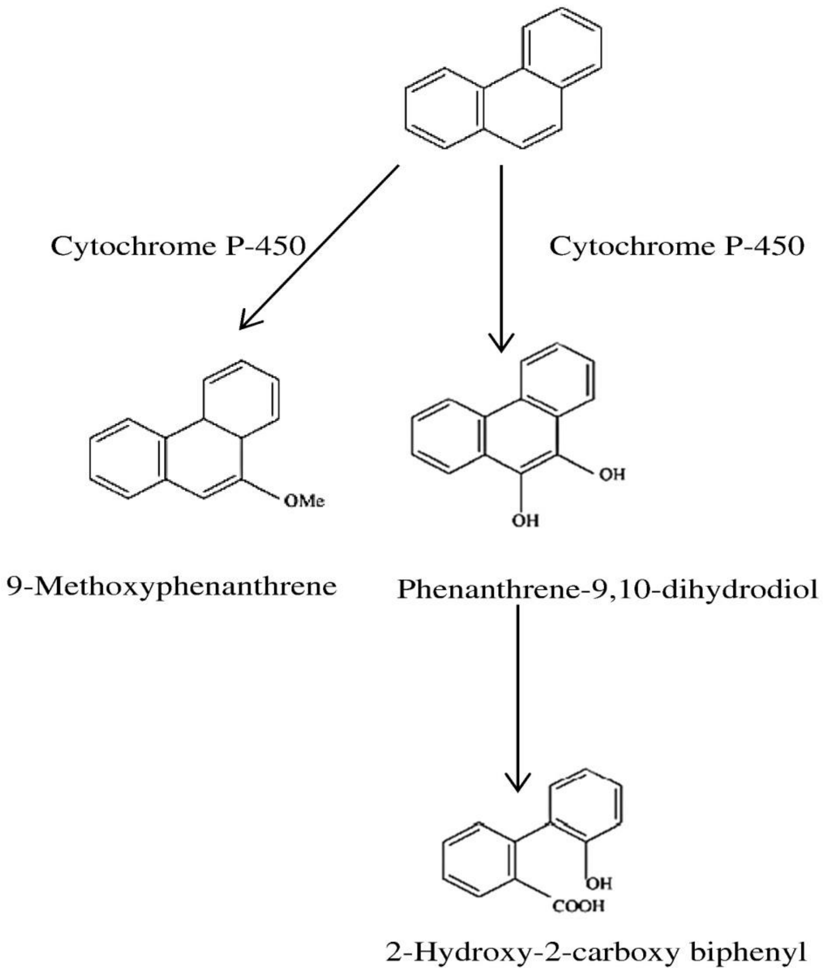

Fig. 3. Pathway for degradation of phenanthrene by the fungus *Irpex lacteus*

The rate of degradation of PAHs is inversely proportional to the number of rings in the molecule. This is due to the low water solubility, which decreases with increasing number of aromatic rings. Enzymatic PAH-ring cleavage proceeds only under aerobic conditions (140) [51].

CONCLUSION

Polycyclic aromatic hydrocarbons are widely distributed in environmental objects contaminants possessing mutagenic, carcinogenic, and teratogenic properties. Their resistance to degradation due to low reactivity poses an extremely serious threat to the environment and human health, and determines high relevance of the studies on the mechanisms for transformation and degradation of PAHs, as well as the search for approaches to developing effective strategies for remediating the environment contaminated by PAHs.

The greatest number of studies in the degradation of PAHs is devoted to anaerobic or aerobic biodegradation by various groups of microorganisms. Other pathways for degradation of PAHs, such as photolysis or oxidation, have been examined to a lesser degree, and a comprehensive study can also contribute to an understanding of the mechanisms for transformation and degradation of PAHs.

The use of microorganisms for biodegradation of PAHs has been recognized as an effective, economically advantageous method and is a universal alternative to physicochemical methods for bioremediation of ecosystems. Understanding of the factors that affect the biodegradation of PAHs, study of catabolic processes involved in the biodegradation (aerobic/anaerobic) of PAHs by microorganisms, will help develop effective strategies of the environmental bioremediation.

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