

BIOTECHNOLOGICAL ASPECTS OF HYDROCARBONS BIODEGRADATION

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In review the present situation of petroleum pollution, its consequences and basic oil composition are described. The up-to-date survey of hydrocarbon degradation microbiology and major strains are presented with respect to following practical introduction of obtained data. A general characteristic of oil hydrocarbons biodegradation is done. Biodegradation metabolism of petroleum products different categories and its biochemistry are described. Principal biochemical pathways are indicated. Biotechnological properties of hydrocarbon degrading microorganisms including that of industrial significance are investigated. Much attention is given to biological and environmental factors that influence completeness and rate of hydrocarbons biodegradation. It was established that microorganisms consortium biodegradation is faster and more complete than single species ones. The effects of hydrocarbons presence in medium on biochemical and cytological levels of microbial metabolism are also analyzed. The major methods of microbial resistance to petroleum products toxic influence are described. It is shown that one of the most important among them is metabolic processes shifting towards surfactants.

Key words: hydrocarbons, petroleum pollution, biodegradation, microorganisms.

Petroleum Pollution Characteristics

A problem of environmental pollution by oil and petroleum products is very serious today. Many areas with excess of maximum allowable petroleum products concentrations in soils and water are found in Ukraine. Most often this fact applies to regions near the airfields, fuel depots, oil storage depots, refineries, oil wells, parking lots, gas stations, etc. Pollution has become so critical in some regions that oil products in soils and groundwater are not only toxic, but fire hazardous [1].

World oil production increased by 1.8 million barrels/day and was 3913.7 million tons in 2010 [2]. Environmental pollution by oil and refined products is negative consequence of such intensification of oil production. Oil and petroleum products are released into the environment due to violations of technology, various emergency situations. The components of gas streams are deposited on the surface of plants, soil and water bodies. Part of hydrocarbons is returned to the earth's surface with precipitation leading to secondary contamination of land and water. Microbial and chemical hydrocarbons degradation causes their evaporation, which may serve as a source of soil and air pollution.

Hydrocarbons form a gas areola in the aeration zone during evaporation from the oil-contaminated ground water surface. Having a property of explosive mixture formation at certain vapor and air ratio they can explode if high-temperature source is introduced into this mixture. Oil and petroleum products vapor have a toxic effect on human organisms. Sulfur crude oil and petroleum products fumes are particularly toxic, as well as leaded gasoline [3].

Interactions of oil and petroleum products with soils, microorganisms, plants, surface water and groundwater have their own characteristics depending on the type of oil products.

The principal effects of oil pollution are the danger of fire, the toxic effect of the oil, and the physical coating of the environment. Their relative importance depends on the type and amount of oil, and where it is spilled. The danger of fire is greatest with light oils, and with crude oil. The extent and amount of toxic damage depend on the season of the year, and the stage of life that the various organisms have reached at the time of the pollution. Whereas adult fish may be able to swim away, and avoid the toxic area, larvae, and less mobile creatures, may have no such escape. They may be killed, or may have experience

changes in their feeding or reproductive cycles that may materially affect fish stocks size and species composition. Physical coating of the sea surface is not as much problem as physical coating of the shore [4].

Oil element and qualitative composition

Oil includes a large range of complex and diverse products. «Crude» or unrefined oil is a natural substance, produced over millions of years by the decomposition of vegetable matter. Crude oils is a «dirty» oil, since it contains tars and waxes, and it evaporates rapidly, since it also contains petrol, kerosene, and other «light fractions», and this makes it highly dangerous. Refined oils range from petrol and kerosene, to diesel fuel and heavy oils such as lubricating and boiler oil. The light oils are highly volatile, and so present a high fire danger. They are also highly toxic. The heavy oils are much less dangerous, but they may be very dirty and persistent [5].

Oil or petroleum is natural disperse system of liquid organic compounds, the main parts of which are hydrocarbons of various molecular weights. It is a mixture of about 1000 individual substances [6]. Oil in common usage includes all liquid, gaseous, and solid (e.g., paraffin) hydrocarbons. Lighter hydrocarbons as methane, ethane, propane and butane occur as gases, while pentane and heavier ones are in the form of liquids or solids [7].

The proportion of light hydrocarbons in the petroleum mixture varies greatly among different oil fields, ranging from as much as 97% by weight in the lighter oils to as little as 50% in the heavier oils and bitumens. The hydrocarbons in crude oil are mostly alkanes, cycloalkanes and various aromatic hydrocarbons while the other organic compounds contain nitrogen, oxygen and sulfur, and trace amounts of metals such as iron, nickel, copper and vanadium. The exact molecular composition varies widely from formation to formation but the proportion of the most chemical elements varies over fairly narrow limits as follows shown in table 1 [6].

Sulfur components are mostly mercaptans, cyclic and acyclic sulfides and thiophenes. Nitrogen compounds are included in composition of heterocycles and aromatic amines such as pyridine, aniline, pyrrole and their analogues. The major part of oxygen components are acids, phenols, alcohols, ketones, ethers. Vanadium and nickel compounds are the most common among organometallic compounds of petroleum [6].

Table 1. Element composition of petroleum by weight

Element	Percent range
Carbon	33–87%
Hydrogen	10–14%
Nitrogen	0.1–2%
Oxygen	0.05–1.5%
Sulfur	0.05–6%
Metals	< 0.1%

Four different types of hydrocarbon molecules appear in crude oil. The relative percentage of each varies from oil to oil, determining the properties of each petroleum type. Average content and range of hydrocarbon molecules different types are given in table 2 [7].

Table 2. Qualitative composition of petroleum by weight

Hydrocarbon	Average	Range
Paraffins	30%	15–60%
Naphthenes	49%	30–60%
Aromatics	15%	30–60%
Asphaltics	6%	remainder

Alkanes are a significant portion of oil, most of them are naphthenes. Commonly, they are cyclopentane and cyclohexane with 1–3 radicals, decalin, bicyclohexane, norbornane and their alkyl derivatives. Aromatics of petroleum are represented with benzene, its derivatives and polycyclic aromatic compounds. Heteroatomic compounds include resin-asphaltene substances [7].

Thus, oil pollution common feature is high variation in the contaminant composition in each case and its complex content unlike most other anthropogenic pollutants.

Petroleum Degrading Microorganisms

A lot of the experimental evidence for petroleum microbiology is a result of the pioneering work of Claude ZoBell. Beginning in the 1930s and extending through the late 1970s, ZoBell's research established that bacteria are important in a number of petroleum related processes [8].

Nowadays it is known, that hydrocarbons in the environment can be decomposed mainly by bacteria, algae, yeast and fungi [9, 10]. Despite the fact that these organisms in terrestrial and aquatic ecosystems are ubiquitous, number of heterotrophic microorganisms that can utilize hydrocarbons is very

variable: from 6% to 82% of soil fungi, from 0.13 to 50% of soil bacteria, from 0.003 to 100% of marine bacteria [11]. Some microorganisms can metabolize only a limited number of hydrocarbon substrates. A set of different microorganisms with all possible enzymatic pathways can more efficiently break down a complex mixture of hydrocarbons in soil, fresh and sea water than single microorganism can. Thus complete mineralization of substrate can be achieved [12].

Bacteria that utilize gaseous hydrocarbons, particularly propane, are representatives of the genera *Corynebacterium*, *Mycobacterium*, *Nocardia*, *Rhodococcus*. Microorganisms that can use butane as the unique source of carbon and energy are of the *Arthrobacter*, *Brevibacterium*, *Pseudomonas* spp. [13].

Strains capable to utilize polycyclic aromatic hydrocarbons are *Beijerinckia* sp., *Pseudomonas* spp. (*P. paucimobilis*, *P. fluorescens*, *P. putida*), *Alcaligenes denitrificans* WW1, *Mycobacterium* spp. (e.g. *M. flavescens*), *Rhodococcus* spp. (e.g. *R. rhodnii*), *Athrobacter* sp., *Aeromonas* sp., sea *Cyanobacteria*, *Streptomyces flavovirens*, *Synechococcus* sp. [14, 15].

Fungi *Penicillium* and *Polisporum* can grow on nutrient agar medium with crude oil heavy fractions. *Penicillium* and *Mortierella* sp. can be used for conversion of crude oil high molecular fractions [16].

The most important bacteria in hydrocarbons biodegradation in soils and sea water are *Achromobacter*, *Acinetobacter*, *Alcaligenes*, *Arthrobacter*, *Bacillus*, *Corynebacterium*, *Flavobacterium*, *Nocardia* and *Pseudomonas* spp. Among sea water yeasts and fungi that decompose hydrocarbons the most significant are *Aureobasidium*, *Candida*, *Rhodotorula*, *Sporobolomyces* spp., species obtained from soils are *Trichoderma* and *Mortierella* ones [17–22].

B. subtilis was proved to be a better hydrocarbon degrader than other isolates [22]. In another study, strains were isolated from petroleum polluted soil and identified as *Pseudomonas pseudoalcaligenes*, *Bacillus firmus*, *Bacillus alvei*, *Penicillium funiculosum*, *Aspergillus sydowii* and *Rhizopus* sp., and they removed 79%, 80%, 68%, 86%, 81% and 67% of total petroleum hydrocarbon correspondently. Genera *Stenotrophomonas*, *Bacillus*, *Brevibacillus*, *Nocardiodes* and *Pseudomonas* were used in combination and give a degradation rate of 67% after only 12 days of treatment [23]. It has been proved that the mixed consortium effectiveness was significantly superior to that obtained by individual strains [12, 24–28].

Petroleum Products Aliphatic Component Microbial Degradation

Various classes' hydrocarbons decomposition mechanisms are essentially different. This fact results in individual spectrum of hydrocarbons consumption for different microorganisms. n-Alkanes, isoalkanes, naphthenes, polycyclic aromatic hydrocarbons and adjacent heteroaromatic hydrocarbons have specific metabolic pathways [29].

Aliphatic hydrocarbons are demonstrative example of organic substances that are biodegradable. Alkanes are the easiest to be ruined, alkenes and alkynes are following [30]. The components consisting of straight chains degrade easier than those with branched chains [31]. Biodegradation of straight chain alkanes occurs through β -oxidation. Oxygen binds to the end of the hydrocarbon chain during this process leading to the formation of carboxyl group (Fig. 1).

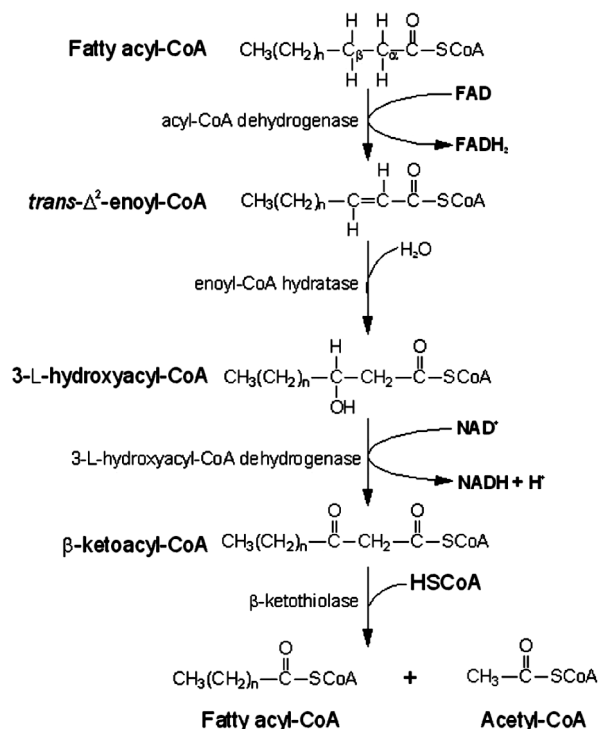


Fig. 1. β -Oxidation of hydrocarbons [32]

Two carbon compound (acetyl) splits off from fatty acid formed. This process is repeated as many times as necessary for the splitting of the whole molecule. β -Oxidation stops when it reaches branched position in the hydrocarbon molecule.

Alkanes biodegradation is the best for components, which have 10 carbon atoms in the chain. Shorter structures have tendency to show high toxicity to many organisms. Very

short alkanes (methane, ethane, propane and butane) are present as gases and can be used as primary substrates or degradation cometabolites [33].

Rhodococcus spp. absorb n-alkanes through passive diffusion by solubilization them in thick lipophilic cell wall. In contrast, *Pseudomonas* spp. solubilize n-alkanes in the environment [34]. An increase of cytochromes group, as well as the high content of ATP, increased cellular respiration, increased number of flavins is characteristic for microorganisms growing on media with n-alkanes. The number of mitochondria increases and endoplasmic reticulum development is enhanced in eukaryotes [29].

Natural isoalkanes with saturated isoprenoid structure are oxidized through citronellol pathway. Initially, the terminal CH_3 groups are oxidized to COOH groups, then C_2 or C_3 fragments are evolved through consecutive reactions; acetoacetate and acetyl-CoA are formed (Fig. 2). Some *Rhodococcus* strains that can grow on isoprenoid hydrocarbons are known [35].

Petroleum Products Aromatic Component Microbial Degradation

Aromatic hydrocarbons can be degraded during aerobic and anaerobic biological processes [30, 37]. Oxygen binds to the benzene ring. This eventually leads to the formation of catechol, that is characteristic for aerobic degradation. Catechol molecule is then broken up in ortho- or meta- position. Final products of this process are used in cell anabolic pathways [12].

In such aromatic compounds as benzoates and phenols, benzene ring double bonds are initially reduced by hydrogen adding to the molecule, then the ring is splitted of and modified, and saturated fatty acids or dicarboxylic acids are formed [38]. Phenol can also be degraded by binding carboxyl groups to the ring with subsequent reducing to cyclohexanone and splitting of the ring. Benzene is mono aromatic compound; it degrades extremely slowly under anaerobic conditions [30].

Many bacteria strains are capable of heteroaromatic hydrocarbon compounds degradation (mainly sulfur compounds) [39].

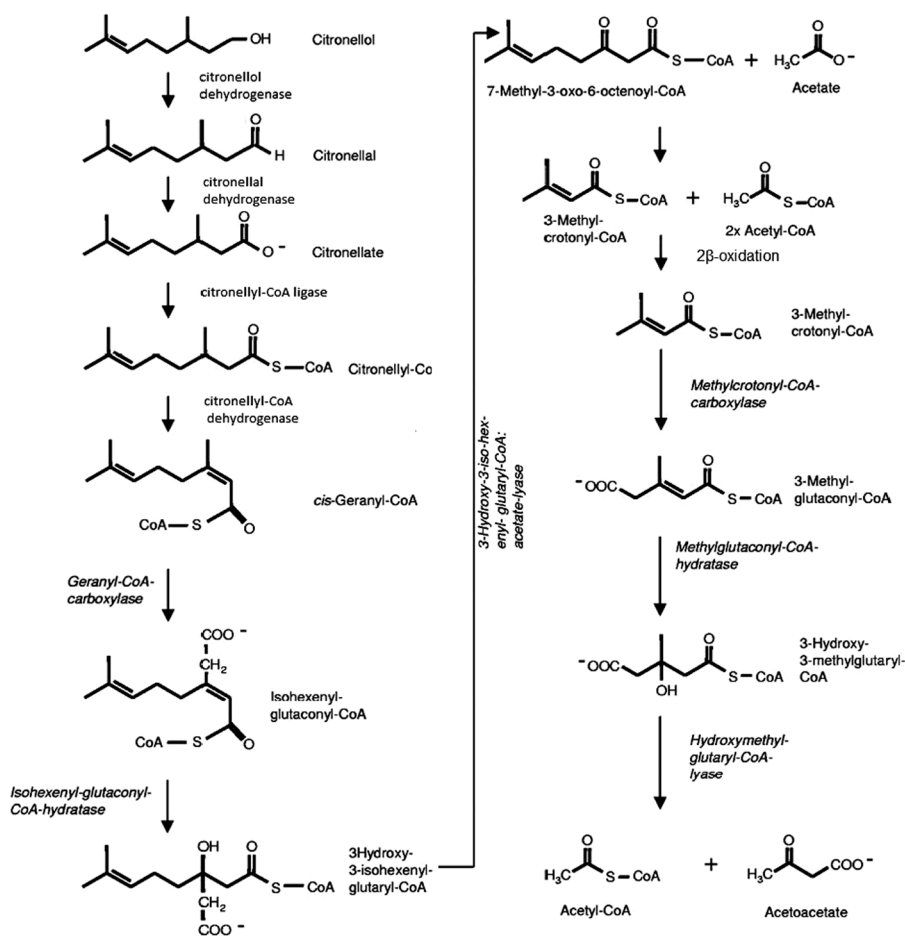


Fig. 2. Citronellol pathway [36]

Aromatic hydrocarbons with heteroatoms biodegradation is often accompanied by denitrification, sulfate reduction or methane production in anaerobic conditions. Benzene and toluene anaerobic transformation is accompanied with methane production. This process can be characterized as enzymatic one. There are partial oxidation and partial reduction of the substrate with methane and carbon dioxide formation as end products. In addition, trivalent ferrum and manganese oxides may be alternative electron acceptors in appropriate anoxic conditions [40].

One methyl group in the aromatic hydrocarbon fundamentally changes the process of primary oxidation and further metabolism of compounds. Either aromatic ring or radical is oxidized. Many microorganisms need energy co-substrates to transform complex hydrocarbons. Hydrocarbon decomposition is often accelerated in their presence [34, 41].

Polycyclic aromatic hydrocarbons (PAHs) consist of two or more aromatic rings. Compounds' resistance to microbial degradation increases with an increase of ring number. PAHs can be subjected to aerobic and anaerobic biodegradation.

Aerobic decomposition is more common for the destruction of PAHs with two or three rings (naphthalene, anthracene, phenanthrene) [42]. Degradation of PAHs begins when hydrogen reduces double bonds in a ring or when water oxygen binds to the aromatic ring similarly to compounds that consist of one aromatic ring. Oxygen binds directly to one of the rings, which then splits, as in the case of benzene and its derivatives. This process is repeated as many times as necessary for the whole molecule splitting. In addition to aerobic bacterial biodegradation some fungi and algae have the ability to decompose PAHs. *Phanerocheate chryso sporium* produces lignin-specific enzymes that are to destruction PAHs having from two to five ring [43]. Microbial association combined metabolic action is very important for degradation of compounds with benzene rings large number.

Biodegradation of highly-condensed PAHs with large molecular masses is very slow, therefore requires a long time to complete cleavage. It is known that half lifetime of these compounds is 6 months or more during biological pathways [44]. Microorganisms capable of decomposing PAHs with cycles' number up to seven are known [45].

Solid hydrocarbons transport efficient mechanism in the cell is important for intensive growth in addition to the presence of bac-

terial enzymes that catalyze PAHs oxidation. Surfactants usage increases PAHs solubility and promotes their further biodegradation [42].

Influence of Hydrocarbons on Microbial Organisms

Possibility of microbial growth on hydrocarbon medium is provided by combination of two factors: biochemical complementarity of organism and resistance to hydrocarbon toxic action. It is obvious these two factors should be optimal. Considering polycomponent character of petroleum pollution, microorganism (association of microorganisms) should be able to grow on most components of pollutant and be resistant to their toxic action for complete mineralization of oil products [29].

Oil at low concentrations has a stimulating effect for soil biota because it is an energy substrate for a large group of microorganisms. Significant petroleum soil pollution, which occurs at emergency spills, is accompanied by acute toxic oil effects on organisms [46]. Microorganisms' reaction to the effect of any toxic substance depends on the toxic agent nature, its concentration, contact time, perceiving system properties, state and other properties of the organisms exposed. The toxic effect of oil is shown through the transformation of microorganisms' environment by physical, chemical, agronomic and other characteristics of contaminated soils [46, 47].

Light oil fractions partially inhibit heterotrophic microorganisms but act also as a substrate for hydrocarbon degrading microorganisms. Heavier fractions are less toxic to microorganisms, but they are not actively metabolized [47].

Petroleum hydrocarbons are characterized by strong antibacterial effect and can cause cell lysis. However, some bacteria show a high resistance to these substances. Toxicity of hydrocarbons is mainly determined by their ability to damage the membrane of microorganisms [48]. The interaction of oil hydrocarbons with cell membranes occurs at the level of lipid-lipid and lipid-protein interactions. The thickness of a phospholipid bilayer, its fluidity, asymmetric distribution of membrane components, activity of enzymes and proteins transport in the membrane are changed as a result. These changes, in turn, lead to membrane barrier properties disruption, protons and other intracellular ions passive flux increasing across membranes. All of this leads to a decrease cell viability [48, 49].

Various cell structures damage is observed during contact with the hydrocarbons.

Cytoplasmic membrane integrity interruption, cell wall and membranes damage of the *Pseudomonas* genus bacteria occur, accompanying with myeloid-like structures formation in the disruption place and nucleoid condensation in the central part of the cells. Finally, the cell wall losses rigidity, that leads to cell lysis [50].

Hydrocarbons toxic effect may also be caused by intermediates. Negative impact on hydrocarbon degrading microorganisms' development. Butyric acid has is an intermediate product of hydrocarbons and carbohydrates metabolism. It does not lead to the bacteria death, but has an inhibiting effect on their dissimilative activity and acts as growth inhibitor [46]. Acetate, as well as butyric acid, is a factor that has significant influence on active microflora development. Unlike butyric acid, acetate increased concentration accelerates the development of the microflora, and its deficiency can lead to microbial population anabiosis [35].

Hydrocarbon various classes metabolism leads to a huge number of different intermediates, accumulation of these substances leads to cell growth inhibition in the case of incomplete oxidation.

Hydrocarbons degrading bacteria have developed special mechanisms of resistance to hydrocarbons in evolution process that are expressed in the metabolism peculiarities and cell structure. These features include ultrastructural cell displacement (inclusions of different density formation, cytoplasm fragmentation, membrane unit enhanced development, an overgrowth of the cell wall), capsules formation, metabolic activity changing.

The special changes in cell structure organization are increased content of fatty acids in the cell wall, synthesis of specific lipids, intracellular inclusions of various purposes formation [29].

Rhodococcus, *Arthrobacter* and *Acinetobacter* genera transform hydrocarbons excess into neutral lipids — triglycerides and waxes that serve as an extra carbon source for energy supply, whereas *Pseudomonas* don't form the extra lipids [34].

50% of *Rhodococcus* and *Arthrobacter* general species contain wax in smaller contents than triglycerides. Lipophilic cell wall formation provides solubilization and passive transport of the hydrophobic substrate into the cell [34, 41]. Thus, hydrocarbons transfer into the lipids may serve as a mechanism for toxic effect, fall-offing, a way of extra carbon and energy accumulation and contribute to the hydrocarbons controlled transport into the cell.

Changing the fatty acid composition provides resistance to hydrocarbons. For example, unsaturated fatty acids with odd number of carbon atoms are typical for representatives of the *Rhodococcus* genus. The prevalence of these acids is characteristic for microorganisms living at low temperatures. At the same time the cell wall is a hydrocarbon acceptor. This allows microorganisms to grow actively on hydrocarbons [34, 41].

Representatives of *Arthrobacter*, *Pseudomonas* and *Acinetobacter* genera have trehalose containing phospholipids which are synthesized in response to the n-alkanes addition to the medium for hydrocarbons mobilization and complete degradation. They contribute to the membrane stabilization in extreme conditions. Trehalose also can be part of surfactants. Emulsifiers are synthesized by some strains of slimy *Rhodococcus*, especially *Rhodococcus ruber* [34, 51]. Thus, the synthesis of hydrocarbons emulsifiers and concomitant substances can be either a way of cells protection from exposure to liquid hydrocarbons or a factor necessary for successful hydrocarbons degradation, as well as perform other protective functions.

One of the key mechanisms for the suppression of the hydrocarbons toxic effect is hydrocarbons oxidizing enzymes synthesis. The same mechanism provides the cell with carbon and energy for biosynthetic processes [29].

Biotechnologically Important Properties of Petroleum Degrading Microorganisms

High specificity of microorganisms' enzymes causes strains specialization to certain hydrocarbons, so it is necessary to make a search of strains capable to degrade wide range of petroleum pollutants. Lots of methods to assess the characteristics of hydrocarbon degrading communities are used. For example, isolation of microorganisms from contaminated environment on different media. This allows to estimate bacteria of different physiological groups and to obtain pure cultures, among which we can select the promising hydrocarbon degrading strains.

To determine the number of different microorganisms colony-forming units, the method of serial dilution with following seeding and counting colonies of microorganisms on plates with nutrient agar is used. This approach has been used for long and is now almost a standard. Subculturing on dense nutrient medium (potato agar and nutrient agar) is used to obtain pure cultures of hydrocarbon

oxidizing microorganisms from media with the hydrocarbons [52]. Use of limiting dilutions in liquid Chapeck's medium with hydrocarbons (diesel fuel) and in medium with glucose as the unique source of carbon and energy allows to set the number of degrading microorganisms and to obtain microorganisms of this group pure culture [53]. One of the methods for the selection of hydrocarbon degrading microorganisms may be usage of the modified Raymond's medium. In the same time the method of serial dilutions helps to establish the fact of a successful introduction of degrading microorganism [54].

Alternative ways to search for microorganisms utilizing oils and their components were recently developed. The activity of each strain can be assessed visually by the formation of clearing zones when grown on porous oils impregnating mineral carrier.

It has sense to pay attention to nocardioform actinomycetes for selection a group of microorganisms among which it is supposed to find strains for bacterial preparations. One of the advantages of *Actinobacteria* is the absence of pathogenic species. Most of them belong to a group of saprophytic microorganisms. This fact has important practical value for creating safe commercial bacterial preparations. The choice of this group of microorganisms at an early stage of the selection by using simple methods avoids working with pathogenic bacteria [29].

Microorganisms of this group are able to adapt to multiple stress factors simultaneously (e.g. high salinity of medium, extreme values of acidity, low concentration of nutrient substrates). These capabilities are due to the peculiarities of the actinobacteria physiology [34].

A strain supposed for creation of the bacterial preparation often must have several properties simultaneously (e.g. to be oil destructor and biosorbent). Many representatives of the *Rhodococcus* genus (Fig. 3) have destructive, emulsifying and sorbing activity relative to hydrocarbons combined in one strain [55].

To create bacterial preparations intended for cleaning petroleum pollutions the search and selection of bacteria oil degrading strains

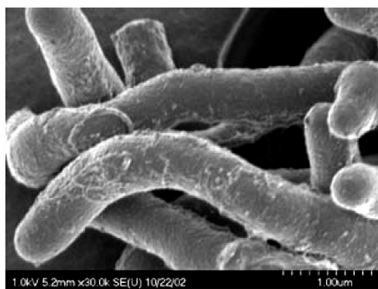


Fig. 3. A micrograph image of *Rhodococcus* sp. [56]

are conducted with the help of certain criteria. Strains should possess biodegradability of crude oil, fuel oil, light oil (kerosene, diesel fuel), growth at high and low temperatures, at high medium salinity and extreme values of acidity. The main peculiarity and disadvantage of such approach is specialized study of specific strains relative to certain petroleum products [29]. Strain that is effective for one oil type biodegradation may be inefficient relative to other petroleum products. Thus, it is necessary to specify the hydrocarbon orientation of the strain, when creating a universal preparation.

One of the urgent tasks is the bioremediation of complex contaminants such as oil pollution followed by heavy metals co-contamination [57]. Therefore, strains of bacteria used for the detoxification of oil pollutants, should be stable with respect to heavy metals.

Since the hydrocarbons are not soluble in water, one of the important properties of strains capable to utilize hydrophobic substrates is their ability to synthesize bioemulsifiers [58].

A problem of environmental pollution by oil and petroleum products is very serious today. The common feature of oil pollution is high variation in contaminant composition in each case and its complex content unlike most other anthropogenic pollutants. The one of the promising directions of petroleum contamination elimination is microbial degradation.

Hydrocarbons in the environment can be decomposed mainly by bacteria, algae, yeast and fungi. Microorganisms can metabolize only a limited number of hydrocarbon substrates. A set of different microorganisms with all the possible enzymatic pathways can more efficiently break down a complex mixture of hydrocarbons than single microorganisms can.

Decomposition mechanisms of hydrocarbon various classes differ significantly. There is specialization of metabolic pathways for n-alkanes, isoalkanes, naphthenes, aromatic hydrocarbons, polycyclic aromatic hydrocarbon and the adjacent heteroaromatic compounds.

Hydrocarbon presence in medium causes corresponding response in microorganisms' metabolism. Petroleum products generally have toxic action and microorganisms develop the resistance mechanisms. PAHs have the most toxic impact and are the most resistant to biodegradation.

It is necessary to make a search of strains capable to degrade wide range of petroleum pollutants considering such their properties as stability, resistance to different toxic effects, ability to synthesize bioemulsifiers, etc. The nocardioform actinobacteria are considered to be a promising group of microorganisms used for the detoxification of oil pollution.

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БІОТЕХНОЛОГІЧНІ АСПЕКТИ БІОДЕГРАДАЦІЇ ВУГЛЕВОДНІВ

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В огляді наведено характеристику нинішньої ситуації забруднення нафтою, його наслідків та базового складу нафти. Розглянуто біодеградацію вуглеводнів, основні штамми-нафтодеструктори та можливість подальшого практичного застосування отриманих даних. Подано загальну характеристику біодеградації нафтових вуглеводнів, а також описано метаболізм мікробного розкладання нафтопродуктів різних категорій із зазначенням біохімічних шляхів деградації. Досліджено біотехнологічно важливі властивості мікроорганізмів-нафтодеструкторів, зокрема промислового значення. Велику увагу приділено біологічним та екологічним чинникам, що впливають на ступінь і швидкість біодеградації вуглеводнів. Установлено, що розкладання нафтопродуктів консорціумами мікроорганізмів відбувається швидше та повніше, ніж окремими штамми. Проаналізовано вплив присутності вуглеводнів у середовищі на метаболізм мікроорганізмів як на біохімічному, так і цитологічному рівні. Описано основні методи резистентності до токсичної дії нафтопродуктів. Виявлено, що одним з найважливіших серед них є зміщення метаболічних процесів у бік синтезу поверхнево-активних речовин.

Ключові слова: вуглеводні, нафтове забруднення, біодеградація, мікроорганізми.

БИОТЕХНОЛОГИЧЕСКИЕ АСПЕКТЫ БИОДЕГРАДАЦИИ УГЛЕВОДОРОДОВ

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В обзоре дана характеристика нынешнего нефтяного загрязнения, его последствий, а также базового состава нефти. Рассмотрены биодеградация углеводородов, основные штаммы-нефтедеструкторы и возможность дальнейшего практического применения полученных данных. Представлена общая характеристика биодеградации углеводородов нефти, а также описан метаболитизм микробного разложения нефтепродуктов различных категорий с указанием биохимических путей деградации. Исследованы биотехнологически важные свойства микроорганизмов-нефтедеструкторов, в том числе промышленного значения. Большое внимание уделено биологическим и экологическим факторам, влияющим на степень и скорость биодеградации углеводородов в промышленных масштабах. Установлено, что разложение нефтепродуктов консорциумами микроорганизмов происходит быстрее и в большей степени, чем отдельными штаммами. Проанализировано влияние присутствия углеводородов в среде на метаболитизм микроорганизмов как на биохимическом, так и цитологическом уровне. Описаны основные методы резистентности к токсическому действию нефтепродуктов. Выведено, что одним из самых важных среди них является смещение метаболитических процессов в сторону синтеза поверхностно-активных веществ.

Ключевые слова: углеводороды, нефтяное загрязнение, биодеградация, микроорганизмы.