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Removal of Petroleum Derivative Pollutants from the Environment: Techniques and Methods

**Usuwanie zanieczyszczeń ropopochodnych ze środowiska -
stosowane techniki i metody**

The increasing use of petroleum derivatives as a result of industrial development and urbanization has a negative impact on the natural environment. Due to their toxic and carcinogenic effects, these compounds have a negative impact on living organisms and plants, and also contribute to changes in soil properties and composition, and the abundance of microorganisms present in this soil. Sources of pollution with petroleum derivatives to the soil environment are mostly refinery and petrochemical plants, crude oil extraction sites, storage and distribution sites for petroleum products, transport of crude oil, and traffic accidents. Remediation of an area polluted with petroleum derivatives can be done by their decomposition, transformation into less toxic reactive and mobile forms, or by total elimination. Chemical, physical and biological methods are used for this purpose. In the biological methods, the most important role is played by microorganisms capable of using hydrocarbons as a source of carbon and energy.

Keywords: wastewater, sewage sludge, separators, petroleum derivatives, bioremediation

1. Pollution to the environment by petroleum substances

The development of the industry and increasing urbanization lead to the devastation of the industrial environment. The increase in consumption of petroleum products poses a greater risk of leakage during their transport, production, processing or storage. The presence of these compounds in the environment poses a direct threat to living organisms. Petroleum products adversely affect plant production, modify soil composition and properties and change the number of microorganisms in the soil [1]. Petroleum and its derivative contain mainly aliphatic and aromatic hydrocarbons. Crude oil also contains biogenic elements: carbon (83÷87%), hydrogen, sulphur, oxygen, nitrogen and heavy metal ions, e.g. lead, arsenic, mercury, and tin [2]. The risk is posed by such hydrocarbons as: aromatic hydrocarbons,

alkanes, cycloalkanes, which are the main components of fuels [3]. Aromatic hydrocarbons (toluene, benzene, xylene, phenol) are very harmful to humans due to their mutagenic, carcinogenic and cytotoxic effects. They are characterized by a high capability to accumulate in plants and to be passed to the subsequent links in the food chain [4]. These compounds, due to their high solubility in water, easily get into groundwater and then into water intakes. Their unfavourable impact contributes to the deterioration of groundwater quality by increasing the likelihood of poisoning humans and animals [5].

Currently, petroleum derivatives are becoming more and more popular. Crude oil is the basic material of the petrochemical industry, which is used to obtain, among others, diesel and fuel oils, gasoline, kerosene, lubricants, and asphalts. It is also used for the production of explosives, dyes, cosmetics, and insecticides [6].

The main sources of soil contamination with petroleum derivatives include fuel stations, refineries, reloading stations, storage facilities, industrial areas, and motor vehicles. Petroleum products from these locations get to the environment mainly as a result of pipeline leakages, tank cracking, improper handling of distributors, erosion of tanks, faulty systems for collecting and managing used lubricants and oils, and also as a result of fuel leakage due to traffic accidents [4].

Furthermore, the intensive development of transport and road construction leads to ecological transformations, which are to a large extent caused by pollution from road traffic. In 2007-2015, an increase in the number of expressways and motorways reached ca. 200%, whereas in the following years, this value is expected to have increase by 100% by 2025. The development of roads is followed by building the accompanying infrastructure, e.g. parking lots, sidewalks, petrol stations, roadsides, where various types of waste, chemical substances and waste coming mainly from public transport are discharged. Wastewater formed in these areas results from rainwater flushing [7]. Next, together with rainwater, the pollutants get into the surface water through rainwater drainage. An important role is played by pre-treatment of wastewater discharged from e.g. the areas of petrol stations to the receiver [8]. It was demonstrated that rainwater discharged from road infrastructure areas is mainly contaminated with petroleum derivatives, heavy metals, suspensions, and biogenic compounds. According to the Ordinance of the Minister of Environment as of 18 December 2014 on the conditions to be met for the discharge of waste to waters or to soil and on the substances which are particularly harmful to the aquatic environment, wastewater should meet the qualitative and quantitative conditions. The ordinance stipulates that the amount of the total suspended solids in the treated rainwater must not exceed 100 mg/l, and petroleum hydrocarbons must not exceed 15 mg/l [7].

2. Physical and chemical methods of removal of petroleum derivatives from the environment

The choice of an appropriate technology of rainwater treatment depends on the degree of sensitivity and spatial conditions of the catchment area and the type

of receiver. Therefore, the devices for the protection of receivers of rainwater flow can be divided into four basic groups according to the principle of operation or function:

- biological treatment plants (ditches, grass surfaces, retention and filtration ponds, root zone wastewater treatment plants),
- retention devices (increasing the retention of the outflow, e.g. small longitudinal slopes in ditches and drainage channels, retention tanks),
- mechanical pre-treatment plants (petroleum derivative separators, settling tanks, retention and filtration tanks or retention-sedimentation tanks),
- devices for shutting off the discharge of hazardous substances from the receiver (transverse partitions in ditches, alarm signalling systems for separators, automatic shut-off systems at the inlet or outlet from the separator) [9].

In the case of wastewater treatment containing petroleum derivatives, the most important role is played by sedimentation and floatation devices, commonly known as separators, which are defined in the standards such as PN EN 858-1:2005 and PN EN 858-2:2005. The standards specify the principles of dimensioning, construction, definition of equipment, principles of operation and control tests of separators and settling tanks preceding separators.

These standards divide separators into two basic groups:

- Class 1 separators, where, during laboratory tests conducted in accordance with the standards, the maximum volume of oil in the treated wastewater is 5 mg/l.
- Class 2 separators, where the maximum amount of oil in treated wastewater is 100 mg/l.

According to their functions, separators can be divided into gravitational, lamella and coalescence separators.

The operation of gravity separators is based on the separation of substances of different densities as a result of gravity forces. Consequently, drops of light liquids, e.g. oil or petrol, flow out and accumulate on the surface of rainwater [9].

The lamella separators are used to separate petroleum derivatives from the water flowing in the separating rainwater drainage system. The separation of pollutants occurs through the horizontal flow of wastewater through the lamellar sections due to the phenomena of floatation and sedimentation. This leads to the separation of petroleum compounds from water as a result of petroleum products remaining on the surface in the separation chamber. The remaining pollutants are deposited in the sludge part. Due to their high throughput, lamella separators are used in the areas of petroleum facilities or very large fuel stations [8].

Coalescence separators provide a higher degree of separation than gravity separators. In the coalescence process, tiny droplets are collected on the coalescence material, are enlarged by combining with each other to form larger drops. The resulting droplets can be separated from wastewater based on gravity forces. The coalescence material can be provided by, among others, grids, filter mats or sponges, and adjusted bevels causing hydraulic coalescence [9].

In the Piekutin's study, where 4 separators located in Białystok were selected for the study, it was demonstrated that at maximum concentrations of petroleum hydrocarbons, the efficiency of treatment ranged from 80 to 87%. A reduction of suspensions from 40 to 60% was also observed at the maximum concentration of suspensions from 130 to 205 mg/l [10].

Remediation of the contaminated area, including treatment and removal of pollution caused by industry or as a result of failures and accidents, may be achieved by decomposition, transformation into less toxic, reactive and mobile forms, or total elimination [11].

Physical methods refer to techniques where physical processes are used to force the transport of contaminants from the contamination site. Physical methods include the use of sorption materials, insulating barriers, cutting out and removing contaminated vegetation, washing with hot/cold water under high pressure, combustion or suction into tanks [6].

Chemical methods have also been used to remove petroleum derivatives from the environment. These methods are based on the dosage of specific chemical reagents at specific concentrations into the purified medium. Chemical treatment methods include:

- chemical oxidation,
- methods using gelation processes,
- methods based on the use of dispersing agents [12].

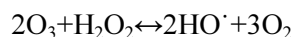
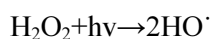
In chemical methods, the chemical structure of petroleum derivative compounds changes, and, as a consequence, their behaviour in the environment changes through various chemical reactions. The process usually generates substances with lower toxicity than the initial contamination [13].

One of the methods used to remove petroleum derivatives from the soil and water environment is chemical oxidation. The strong oxidants used in this method include H_2O_2 and ozone. Chlorine compounds such as chlorate(I), chlorine dioxide and potassium permanganate are also used as oxidants. Chemical oxidation enables the removal of hydrocarbon compounds with double bond e.g. polycyclic aromatic hydrocarbons (PAHs), phenols, trichloroethane (TCE), BTEX (benzene, toluene, ethylbenzene and xylenes), organic volatile components and cyanides [14]. The efficiency of chemical oxidation depends on the oxidant used, physicochemical properties of pollutants, pH and temperature [15].

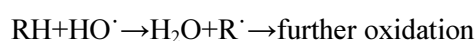
Petroleum pollutants can be removed from the soil through:

- effect of oxidants that can directly react with organic molecules which are oxidized to carbon dioxide, water, and chlorides. The oxidants used may be ozone or H_2O_2 ,
- photochemical dissociation leading to tearing of chemical bonds in molecules of organic compounds,
- UV radiation that causes the breakdown of ozone or H_2O_2 , resulting in the formation of a hydroxyl radical ($HO\cdot$). The resulting hydroxyl radical is a stronger oxidant than ozone and H_2O_2 [14].

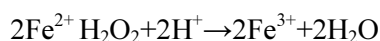
The use of hydroxyl radicals increases oxidation efficiency, for which the potential is 2.8 V. For comparison, ozone has a potential of 2.08 V, KMnO_4 - 1.68 V, H_2O_2 - 1.78 V, chlorine - 1.36 V, oxygen - 1.23 V [15]. The mechanism of the free radical reaction can be represented by the following equations:



In the last Fenton's reaction, whose catalyst is Fe^{2+} , the dissociation of the oxidant and formation of hydroxyl radicals is observed. They cause the formation of organic radicals characterized by high reactivity and the possibility of further oxidation:



With the right amount of reagent, organic compounds are completely broken down into carbon dioxide, water, and inorganic salts. The Fenton's reaction can be given by:



The acidic environment with the pH range from 2 to 5 is the most optimal for the course of the reaction. With hydroxyl radicals, the excess Fe^{2+} and low pH, these radicals can be attached to heterocyclic or aromatic compounds. The reaction depends on the ratio of $\text{Fe}^{2+}/\text{H}_2\text{O}_2$. The course of degradation is faster at the $\text{Fe}^{2+}/\text{H}_2\text{O}_2 \geq 2$ ratio, which is affected by coagulation occurring after the oxidation reaction [14, 15].

Coagulation is a process commonly used in petrochemical plants for the treatment of water and wastewater contaminated with petroleum derivatives in a dispersed form. Most petroleum derivatives, due to their hydrophobic properties, have low energy affinity to water. The effectiveness of coagulation increases significantly with the use of specific substances characterized by high affinity to petroleum derivatives. The salts used as coagulants include Al_2SO_4 , FeCl_3 , AlCl_3 and CaCl_2 [16]. The factors affecting the coagulation process, mainly the removal of organic matter, include dosage of coagulant, concentration and nature of dissolved organic carbon, pH and alkalinity of water [12].

In the paper presented by Piekutin et al. [12], the coagulation process was preceded by aeration of sewage. This process led to the breakdown of long hydrocarbon chains into smaller chains by introducing oxygen molecules into free hydrocarbon bonds. Next, using the coagulation process, these bonds were again combined into larger aggregates, which were subjected to either sedimentation or flotation. The coagulant used was $\text{Al}_2(\text{SO}_4)_3 \cdot 18 \text{H}_2\text{O}$ 5% with the doses of 25, 50, 75, and 100 mg. Based on the study, it was found that the dose containing 25 mg of coagulant was the most effective in removing petroleum derivatives from the tested

model water, while higher doses of aluminium sulphate decreased the effectiveness of removal [12].

In the study presented by Puzzkarewicz et al., the researchers used $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ and $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ salts with the doses of from 30 to 300 mg/l. The research showed that with the use of ferric chloride(III), the highest removal of Mixol engine oil was obtained for the dose of 150 mg/l, where the oil content in the post-coagulation solution was 40 mg/l and the initial concentration was 360 mg/l. In the case of aluminium sulphate, compared to ferric chloride(III), the results were much worse, with the best oil removal observed for 180 and 85 mg/l. However, according to the ordinance, the maximum content of petroleum derivatives discharged to the receiver should not exceed 15 mg/l. For this reason, the adsorption properties of activated carbons for the treatment of oily aqueous solutions were used in further research and the coagulation and adsorption processes were combined [16].

Adsorption is a process of binding molecules, atoms or ions on the surface or in adjacent phases, causing local changes in concentration [17]. The effectiveness of the sorbent depends on its physicochemical properties and the optimal choice of the absorbing materials compared to the absorbed medium. When selecting a sorbent, the following parameters must be taken into account: absorbency, grain size, chemical passivity, bulk density for bulk sorbents and buoyancy for sorbents used on water surfaces [11].

Natural organic and inorganic sorbents can absorb petroleum substances in quantities ranging from 3 to 15 or 4 to 20 times their weight, respectively. Compared to e.g. synthetic fibres, organic fibrous sorbents, due to their relatively high sorption capacity, high biodegradability and density lower than in inorganic or synthetic sorbents, are particularly attractive sorption materials [18]. Fibrous materials such as coconut husks, barley straw, rice husks, sawdust, nut shells, cellulose fibre and cotton fibre have been commonly used in the sorption processes. In the work of Puzzkarewicz et al., coagulation and adsorption processes were combined, where the adsorbents in the form of activated carbons significantly reduced the amount of oils from aqueous solutions. The application of the coagulation process in the form of ferric chloride alone resulted in the removal of oil in 89%, while in combination with activated carbon (hard coal) - the reduction in oil content was 94%. In the case of activated carbon (charcoal type), a dose of 0.2 g/l and 150 mg/l Al_2SO_4 resulted in a 97% oil reduction [16].

3. Biological methods of removal of petroleum derivatives from the environment

In recent years, there has been a growing interest in the use of biological methods for the treatment of soil and groundwater contaminated with petroleum derivatives. In this method, the most important role is played by microorganisms capable of using hydrocarbons as a source of carbon and energy. The advantages of using these methods include:

- they use metabolic pathways of microorganisms leading to the formation of harmless end products such as H₂O and CO₂,
- they allow for direct degradation of pollutants,
- pollutants are the source of the energy needed for the treatment,
- the cost of treatment is lower compared to other methods,
- there are no side effects in the form of landscape destruction at the location where they are used.

However, the use of biological methods is possible only if their concentration does not exceed the toxicity threshold [19, 20].

The properties and characteristics of the environment largely determine the possibility of bioremediation in a given area, as they have an impact on microbiological activity, and the transport of contaminants into the cells of microorganisms. Table 1 presents the main environmental factors affecting environmental bioremediation with petroleum products [5, 21].

Table 1. **Key factors affecting the biodegradation of petroleum products in a contaminated environment**

Environmental factors	Importance to bioremediation	Treatment increasing the effectiveness of bioremediation
Biogenic elements	Nitrogen and phosphorus are often found in the soil in quantities that limit the growth of microorganisms; petroleum derivatives lead to an increase in the ratio of carbon to nitrogen, which is harmful for bacterial metabolism. It is commonly believed that the best ratio of carbon to nitrogen and phosphorus is 10:1:01	Soil improvement with media containing nitrogen and phosphorus
Humidity	Water enables dissolution of certain hydrocarbons (in this form, they are more easily absorbed by microorganisms) and reduces the adsorption of readily soluble PAHs to the surface of soil mineral particles	Sprinkling of soil with water or introduction of water to the soil
Temperature	It affects the intensity of biodegradation and solubility of aliphatic and polycyclic aromatic hydrocarbons, and, consequently, their bioavailability	Temperature control in the bioreactor; composting
pH	Petroleum products can reduce the soil pH (acids are formed during the degradation of hydrocarbons)	Soil liming to increase pH
Oxygen	The availability of oxygen in the soil can be limited by poor soil permeability or the presence of easily degradable nutrients; petroleum derivatives often create extensive anaerobic zones in the soil	Introduction of oxygen into the soil or ploughing the soil
Availability of electron acceptor	The presence of an electron acceptor is essential for the degradation of petroleum hydrocarbons under anaerobic conditions	Introduction of electron acceptors into soil e.g. nitrates, sulphates

Alkanes, followed by branched alkanes, low molecular weight aromatic hydrocarbons and finally polycyclic aromatic hydrocarbons are easily degradable [22].

Microorganisms that show capability of hydrocarbon biodegradation use them as a source of carbon and energy. The precondition for an effective process is

the availability of organic carbon, catalytic efficiency of enzymes present in cells or induced against specific substrates. Microorganisms showing activity in decomposition of xenobiotics have genes (Table 2) *alkB*, *catA*, *xylE*, *ndoB*, *todC* or *bphA*, which in most cases are located on plasmids [23].

Table 2. Basic genes encoding enzymes involved in biodegradation of petroleum derivatives [24]

Gene	Enzyme	Representatives
<i>alkB</i>	alkane hydroxylase	<i>Pseudomonas sp.</i> , <i>Rhodococcus sp.</i> , <i>Acinetobacter sp.</i>
<i>catA</i>	catechol 2,3-dioxygenase	<i>Pseudomonas sp.</i>
<i>xylE</i>	catechol 2,3-dioxygenase	<i>Pseudomonas putida</i>
<i>ndoB</i>	naphthalene dioxygenase	<i>Pseudomonas sp.</i> , <i>P. putida</i> , <i>P. fluorescens</i> , <i>Sphingomonas</i> <i>paucimobilis</i> , <i>Xanthomonas maltophilia</i>
<i>todC</i>	toluene dioxygenase	<i>Pseudomonas putida</i>
<i>bphA</i>	biphenyl dioxygenase	<i>Pseudomonas pseudoalcaligenes</i>

Biosurfactants are surfactants of biological origin. The main task of surfactants is to facilitate the removal of contaminants, which results from their chemical structure. They consist of a hydrophilic part, soluble in water or polar liquids and a hydrophobic part, soluble in oils and non-polar liquids. The presence of the hydrophilic part is responsible for the dissolution of biosurfactants in water, while the hydrophobic part determines the solubility of biosurfactants in oils and other non-polar liquids and affects their concentration in the space between phases. Increased bioavailability of petroleum products can be achieved by using biosurfactants that reduce surface tension, resulting in a better dispersion of hydrophobic pollutants in water. The most numerous group of extensively studied biosurfactants are compounds of microbiological origin produced by bacteria and fungi. They are present inside or on the surface of microbial cells or are excreted extracellularly [22, 25].

The classification of biosurfactants is based on their chemical structure (Table 3). The following groups of biosurfactants are distinguished:

- glycolipids, composed of lipids and sugar units (sophorose, rhamnose, cellobiose, glucose). They allow microorganisms to absorb weakly polar hydrocarbons,
- liposaccharides, extracellular water-soluble high molecular weight emulsifiers produced by bacteria decomposing hydrocarbons e.g. *Acinetobacter calcoaceticus*,
- lipopeptides are made of fatty acid and a peptide attached. Ornithine lipids and subtilisin produced by *Bacillus subtilis* are the most effective biosurfactants,
- phospholipids are composed of two fatty acid molecules and a phosphate residue attached to the glycerol molecule,
- fatty acids and neutral lipids [22].

Low molecular biosurfactants (glycolipids, lipopeptides, phospholipids and neutral lipids) are more effective in reducing surface and interphase tension, whereas their emulsifying activity is low. Multimolecular biosurfactants (lipopolysaccharides, mannoproteins) effectively stabilize the oil-in-water emulsion, but show a minimal capability to reduce surface tension [26].

Table 3. Main classes of biosurfactants and microorganisms producing biosurfactants [26]

Class	Biosurfactant	Manufacturer
Glycolipids	Rhamnolipids	<i>Pseudomonas aeruginosa</i> BI
		<i>Pseudomonas</i> spp. P-17
	Trehalolipids	<i>Rhodococcus erythropolis</i> .
		<i>Arthrobacter paraffineus</i>
		<i>Nocardia erythropolis</i>
		<i>Nocardia</i> spp. SFC-D
		<i>Mycobacterium</i> spp.
	Sophorolipids	<i>Torulopsis bombicola</i>
<i>Candida (Torulopsis) apicola</i>		
	Glycolipids	<i>Alcanivorax borkumensis</i>
Fatty acids, neutral lipids and phospholipids	Fatty acids	<i>Corynebacteria lepus</i>
	Neutral lipids	<i>Nocardia erythropolis</i>
	Phospholipids	<i>Thiobacillus thiooxidans</i>
Lipopeptides and lipoproteins	Surfactin	<i>Bacillus subtilis</i>
	Streptophactin	<i>Streptomyces tendae</i>
	Subtilisin	<i>Bacillus subtilis</i>
	Viscosine	<i>Pseudomonas fluorescens</i>
	Gramicidin	<i>Bacillus brevis</i>
	Polymyxin	<i>Bacillus polymyxa</i>
	Serravetin	<i>Serratia marcescens</i>
Lichenysin	<i>Bacillus licheniformis</i>	
Polymeric biosurfactants	Emulsan	<i>Acinetobacter calcoaceticus</i>
	Alasan	<i>Acinetobacter radioresistens</i>
	Biodispersan	<i>Acinetobacter calcoaceticus</i>
	Lipomanan	<i>Candida tropicalis</i>
	Liposan	<i>Candida lipolytica</i>
	carbohydrate-protein-lipid	<i>Debaryomyces polymorhpis</i>
	bS29 bioemulsan	<i>Gordonia</i> spp. BS29
Molecular biosurfactants	PM factor	<i>Pseudomonas marginalis</i>
	fimbriae, outer membrane vesicles (OMV)	<i>Acinetobacter calcoaceticus</i>
	whole cells	<i>Cyanobacteria</i>

In studies conducted by Smulek et al., it was found that the surfactants tested increased the rate of degradation of diesel oil by the microorganisms studied: *Microbacterium sp.* and *Achromobacter sp.*, with saponins, surfactants of plant origin, showing higher efficiency. Diesel oil degradation increased fivefold compared to the system without surfactant. The study by Witek demonstrated that rhamnolipids have a positive effect on the biodegradation of crude oil fractions by a mixed culture of bacteria consisting of strains: *Rhodococcus erythropolis*, *Acinetobacter calcoaceticus* and *Pseudomonas putida*. The maximum substrate loss in the presence of rhamnolipid was 40% and was almost twice as high as in cultures without rhamnolipids, in which it was ca. 20%. Śliwka et al. achieved a 35% increase in the efficiency of the biodegradation of residues from atmospheric distillation of the oil fraction of crude oil by a mixed culture of: *Acinetobacter calcoaceticus* H29, *Rhodococcus erythropolis* H45, *Brevibacterium brevis* B1 at 250 mg/l rhamnolipid concentration [22].

One of the techniques of treatment of soil contaminated with petroleum derivatives is phytoremediation. The method uses plants and associated microorganisms to degrade, stabilise or extract contaminants. Phytoremediation techniques are based on processes occurring in plant tissues that are able to absorb harmful substances and stimulate their decomposition in the surrounding environment. When removing petroleum derivatives from the soil, grasses play an important role due to the extensive, bunched root system, which effectively penetrates the surface layers of the soil. Similar efficiency is observed for *Fabaceae* plants. Phytoremediation also uses such plants as corn, mustard, sunflower, alfalfa, willow, poplar. During the phytoextraction process, particular attention should be paid to the management or disposal of the obtained contaminated plant material [27]. A number of studies have been published in the literature concerning phytoremediation of soils contaminated with PAHs. Sverdrup et al. presented the effective contribution of three plant species: red clover (*Trifolium pratense*), perennial rye-grass (*Lolium perenne*) and mustard (*Sinapsis alba*) in the decomposition of PAHs, where a decrease of total 15 PAHs content in soil by about 70÷85% was observed. The use of five plant species in studies on the decomposition of PAHs in areas with long-term PAH contamination (*Panicum bisulcatum*, *Echinogalus crusgalli*, *Astragalus membranaceus*, and *Aeschynomene indica*) significantly reduced the level of pollutants during the three-month phytoremediation process of post-mining sites in Korea. Furthermore, Chen et al. confirmed its mineralization at the level of 37.7 and 30.4% in soil with meadow fescue and sugar cane, respectively, using labelled pyrene 14C, compared to the control without plants, where mineralization was only at the level of approx. 4.3% [28].

Hydrophytic technologies play an increasingly important role in the treatment of rainwater, e.g. from roads and car parks. This technology allows for efficient and economical treatment of rainwater at its source. Studies conducted by Bergier confirmed the usefulness of hydrophytic treatment plants for the treatment of rainwater from petroleum derivatives present in this type of wastewater. The study was performed using a hydrophytic treatment plant planted with common reed

Phragmites australis. The observed concentrations of total aliphatic hydrocarbons in raw rainwater ranged from 96.02 to 6,177.33 $\mu\text{g/l}$ whereas in treated wastewater, from 47.55 to 5011.14 $\mu\text{g/l}$. Mean removal efficiency of total aliphatic hydrocarbons was 48%, with individual values ranging from 19 to 81%. Alkanes with carbon content from 40 to 20 were removed with the lowest efficiency (26÷32%), whereas lighter hydrocarbons - with higher efficiency (39÷68%). However, the highest efficiency was observed for hydrocarbons with the highest number of carbon atoms in the molecule (from 51% for C20 to 92÷93% for C26-C30) [29]. In a study by Bergier et al., the researchers performed tests in model hydrophytic pot treatment facilities using two species: common reed (*Phragmites australis*) and basket willow (*Salix viminalis*). The *Phragmites australis* bed showed the highest efficiency in removing aliphatic hydrocarbons from sewage (98÷100%), followed by the *Salix viminalis* bed (97÷100%) [30].

Conclusions

One of the main environmental problems today is hydrocarbon pollution resulting from petrochemical industry activities. The adverse environmental effect of petroleum substances can be seen through the altered composition and properties of the soil, the abundance of microorganisms in the soil and the negative impact on plant production. This is due to the increase in urbanisation and the development of industry, with their activities related to higher consumption of petroleum products give rise to the likelihood of release of harmful substances into the environment. Petrol stations, refineries and storage facilities are the main sources of contamination of soil with petroleum derivatives. Furthermore, accidental releases of petroleum products also pose a very significant threat to the environment. Hydrocarbon components are known to belong to the group of carcinogenic and neurotoxic organic pollutants. Physical and chemical methods have been used to eliminate the environmental pollution caused by petroleum derivatives. These methods can eliminate the pollution completely, or decompose it or transform it into less toxic forms. The removal of petroleum-derived hydrocarbons in the soil environment is a substantial global problem. It is also possible to treat the soil using biological methods, which have become more and more popular in recent years. It has both advantages and disadvantages, one of the key disadvantages of this method being that they can be used only if the concentration does not exceed the toxicity threshold for microorganisms. When considering issues related to the treatment of soil contaminated by petroleum substances, attention should be paid to biological remediation methods that have the lowest impact on the soil environment and allow for the return to its original condition in the shortest possible time.

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Streszczenie

Wzrost wykorzystania związków ropopochodnych na skutek rozwoju przemysłu i urbanizacji wpływa negatywnie na środowisko przyrodnicze. Związki te ze względu na właściwości toksyczne i kancerogenne wykazują negatywny wpływ na żywe organizmy, rośliny, a także przyczyniają się do zmiany właściwości i składu gleby oraz liczebności obecnych tam mikroorganizmów. Źródłami skażenia związkami ropopochodnymi środowiska gruntowego najczęściej są: zakłady rafineryjne i petrochemiczne, miejsca wydobywania ropy naftowej, miejsca magazynowania i dystrybucji produktów ropopochodnych, transport ropy naftowej, kolizje drogowe. Remediację terenu zanieczyszczonego związkami ropopochodnymi można dokonać poprzez ich rozkład, przekształcenie w formy mniej toksyczne, reaktywne, mobilne lub całkowitą ich eliminację. W tym celu wykorzystywane są metody chemiczne, fizyczne oraz biologiczne. W metodach biologicznych największą rolę odgrywają mikroorganizmy zdolne do wykorzystania węglowodorów w charakterze źródła węgla i energii.

Słowa kluczowe: ścieki, osady, separatory, związki ropopochodne, bioremediacja