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Biogeochemical Engineering: Technologies for Managing Environmental Risks

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Abstract

This research aims at one of the most important economic and environmental problems - the elimination of the consequences in case of emergency spills while cleaning petroleum products. The objectives of the study include the development and production of new biological products and biosorbents based on carbon-oxidizing microorganisms, testing the developed technologies for environmental risk management to eliminate the consequences of emergency petroleum product spills, creating an algorithm for conducting preliminary studies in vitro for their subsequent use in situ. A biological product and a biosorbent were developed to clean soils and water from hydrocarbon pollution were developed based on the developed consortiums of strains of carbon-oxidizing microorganisms. Biogeochemical technologies for producing and applying new biological products and biosorbents have been developed. The natural biogeochemical structure of the ecosystems is restored, and this is revealed by studying the species composition of the microbiocenosis or by analyzing the enzymatic activity of the microorganisms in soil or water. Finally, the effectiveness of the risk management method based on biogeochemical and, in particular, microbial engineering methods under conditions of oil pollution has been proven.

Keywords
Biogeochemical technologies; petroleum products; biosorbents; bioremediation; oil pollution; environmental risks; peat; soil self-purification

1. Introduction

For more than 100 years, biogeochemistry has developed as one of the most important scientific disciplines. The rapid development of the field can be attributed to the extensive research being carried out at many universities and research centers around the world. Priority scientific directions of biogeochemistry development are based on the ideas expressed by the outstanding Russian scientist Vladimir I. Vernadsky who worked on the universality of biogeochemical cycles. V. Vernadsky also revealed the role of these cycles in the movement of chemical elements between living organisms and the biosphere. These concerns are related to the most important component of the biosphere – the soil [1-5]. It should be emphasized that a quantitative understanding and a model of the biogeochemical cycles are necessary for the quantitative parameterization of the multi-scale local, regional, and global changes occurring in the biosphere. These changes can be attributed to natural and anthropogenic influences. This seems to be one of the fundamental directions of modern science. The study of the fundamental mechanisms associated with the quantitative parameterization of the ecosystem biogeochemical cycles allows us to identify several new directions for the development of biogeochemical research. These new trends lie at the junction of fundamental and applied studies. A new field of research – engineering biogeochemistry - meets such demands. Innovative biogeochemical technologies are being developed within the framework of engineering biogeochemistry. Biogeochemical technologies are technologies and technological processes based on modeling, understanding, and managing biogeochemical cycles. The use of such technologies is aimed at preserving and, if necessary, restoring disturbed biogeochemical cycles to their natural states. Natural variations are taken into account. Consequently, these technologies are natural, again underlines their importance in the face of increasing risks of environmental pollution. Areas of application include mining, biofuel production, biogeochemical standards, and risk management.

Several of our previous publications have already considered the use of such technologies protected by patents from the Russian Federation [6-8].

Presented below are examples of several such technologies that are directly related to the management of environmental and geoecological risks.

The development of biogeochemical technologies to manage geoecological risks in oil and gas complexes involves the study of fundamental biogeochemical mechanisms for the generation of geoecological risks. The interdependent influence of the oil and gas industry on the environment, as well as the impact of the environment on the functioning of industry and the health of workers, result in geoecological risks. As the natural conditions in the promising and active regions associated with the development of the Russian oil and gas industry (the Yamal Peninsula, the regions of Eastern Siberia, the shelves of the Arctic and northeastern seas) present a very high diversity, it is necessary to take into account geoecological factors of soil. The biogeochemical, cryological, sedimentation, geodynamic, and geophysical nature of soil are also taken into account. Ultimately, the development of biogeochemical research data will allow the development of fundamental and applied risk management tasks, including system analysis, quantitative assessment, and management of geoecological and environmental risks.

Technology for determining the environmental risks in the field of development of gas condensate fields in polar regions [6-9]. Methods involve the calculation of critical loads (CL) of pollutants and their exceedances. The critical load is an indicator of ecosystem sustainability. It reflects the maximum permissible load of a pollutant which reduces the risk of damage to the biogeochemical cycling and structure of an ecosystem. The sensitivity of the biogeochemical cycle and ecosystem structure can be calculated by measuring or estimating certain links of biogeochemical cycles of sulfur, nitrogen, heavy metals (HM), persistent organic pollutants (POPs), etc.

The critical load methodology has been used as a scientific basis for implementing the guidelines provided at the UN long-range transboundary air pollution convention. These have been implemented in various regions of the world, particularly in Europe.

The probabilities of exceeding CL (or the probabilities of exceeding the permissible exposure levels) are calculated to assess (geo) environmental risks. This can be expressed as follows:

$$Risk(X) = P(Ex(CL) > 0) = \mathrm{P}([X]_{dep} - CL(\mathrm{X}) > 0),$$

where *Risk(X)* is the environmental risk to the ecosystems associated with the impact of a particular pollutant (*X*), *CL(X)* is the permissible level of receipt of this pollutant, *[X]dep* is the existing or projected level of receipt of the pollutant, *Ex(CL)* is the excess of the permissible level of receipt *(CL)*, and *P(Ex(CL)* is the probability of exceeding the permissible level *(CL)*.

However, in the case of large-scale environmental pollution, for example, when oil products are spilled during their transportation, risk calculations are carried out to assess the specific impacts of the spill on the biogeochemical food chain (starting from microbes and ending with humans as the final consumers). In the first stage, it is important to eliminate the excess amount of pollutants (petroleum products) in the spill area.

Technologies of recultivation of disturbed and polluted tundra soils for the management of (geo)environmental risks. These technologies are aimed at preserving the biogeochemical structure of the natural tundra and polar ecosystems. A closed type of a biogeochemical cycle associated with various biophilic elements and their deposition on the biogeochemical barrier of most zonal soils, usually in the peat horizon, described the process. As established in experimental works conducted with natural carbon and nitrogen isotopes, peat formation occurs in a time range spanning 50 to more than 400 years. Therefore, peat, as a natural resource, is technologically non-renewable. The method is protected by the Russian Federation [10-13].

Peat can be used as a sorbent in the process of recultivation of polluted ecosystems (for example, at oil spills). The consequences of oil spills in the event of accidents at industrial facilities are serious. The effectiveness of sorption methods for eliminating such spills has been proven. Spilled petroleum products present on the water and soil surface have been treated using these methods [14].

The process of sorption of petroleum products exploits the force of attraction between the molecules of oil and the sorbent at the boundary of the contact phases. It is obvious that the surface properties and the area of the sorbent affect the extent of adsorption.

There are various powdered hydrophobic materials that absorb oil from the surface of water and land [15]. This method is used to treat petroleum products of low film thicknesses. Powdered hydrophobic sorbents play the role of thickeners during the cleaning of surfaces with a large amount of contaminants. This results in an increase in the viscosity of the suspension and the formation of dense conglomerates.

Peat is a multi-component natural substance containing various mineral and organic compounds. In terms of chemical composition, peat occupies an intermediate position between vegetable raw materials and solid fuels. It belongs to the group of caustobolites.

SiO_2, CaO, MgO, Fe_2O_3, Al_2O_3, K_2O, P_2O_5, and SO_3 are the main constituents of the mineral part of peat. These elements account for approximately 99% of ash.

The organic part of peat consists of organic residues (that have not lost their natural structure) and humus. Humus is a complex of relatively stable, usually dark-colored organic compounds formed as a result of biological and biochemical transformations of the remains of dead plants and animals. The group composition of organic matter of peat and soil is diverse. It primarily consists of the following compounds:

- nitrogenous substances (proteins, chlorophyll, alkaloids);
- carbohydrates (fiber, hemicellulose, starch, chitin, pectins);
- lignin;
- lipids (fats, wax);
- resins, tannins, ash.

One of the indicators characterizing the potential sorption capacity of substances is the moisture capacity (the ability of a substance (in this case, peat) to retain the maximum amount of water at a given time). This property depends on the state of moisture, the environmental conditions, and the chemical composition of the peat.

On the one hand, the high moisture capacity (sorption capacity) of peat, the cost-effectiveness of the material, the ease of accessibility, and the abundance of reserves make it a unique raw material for the production of sorbents. On the other hand, the high moisture capacity of the substance also limits the application prospects of the material. The moisture capacity of peat should be controlled to develop an effective sorbent. The moisture capacity can be regulated following the hydrophobization process.

It has been shown [16, 17] that peat-based sorbents are effectively used to prevent the migration of petroleum products into groundwater. This can be attributed to the porous surface and the presence of carbon-oxidizing microorganisms, which ensures the sorption and partial destruction of petroleum products.

Researchers have proposed [18, 19] the method of bioremediation of sorption based on the introduction of optimal doses of natural sorbents. The reduction in soil toxicity is achieved following the sorption of pollutants and by improving the soil structure. Furthermore, the use of sorbents ensures the localization of pollutants in the soil. This helps avoid expensive stages of excavation and transport of soil. It also promotes the in situ reclamation work.

The use of sorbents results in a decrease in phytotoxicity and microbotoxicity. This can be attributed to the sorption of hydrocarbons. A decrease in hydrophobicity and an increase in soil moisture capacity and porosity are achieved [20].

Carbon-oxidizing microorganisms are abundant in nature and thrive under certain temperature, humidity, and pH conditions. They promote the self-purification of soils contaminated with hydrocarbons. However, the actions of native microbes are inhibited at high concentrations of hydrocarbons (>5%), and this hinders the self-purification process [21].

The effectiveness of sorbents has previously been reported [9].

Biogeochemical technologies help restore biogeochemical cycles at the microbial link. A quantitative assessment can be made either by analyzing the microbiological (enzymatic activity of soils and other media) properties or by assessing the degradation mechanism of pollutants. The development of biogeochemical technology helps develop biosorbents that are used to eliminate the consequences of hydrocarbon pollution in oil and gas facilities [22].

Emergencies in the form of accidents at oil and gas facilities and subsequent oil spills endanger people's health and present considerable environmental and economic losses. Therefore, it is important to address these issues.

Risk management involves the development and justification of effective programs that help in the implementation of security solutions. The process of optimal allocation process of resources to reduce various types of risks should be focused on. The maximum possible level of safety should be achieved. In other words, risk management ensures the implementation of various ways that help reduce risks to a minimum level based on a preliminary risk assessment [23].

The control functions used to analyze the problems of risk management in the case of emergency spills can be divided into two categories: active and passive. Active measures involve preventive measures aimed at reducing the likelihood of emergencies (using automated controls) and measures that help reduce potential damage (technologies). Passive measures are designed solely to eliminate the consequences of possible accidents. The degree of damage control realized depends on the methods used to eliminate accidental oil spills [24].

Herein, the results obtained during the assessment of environmental risk management methods have been presented. The developed hydrophobized peat- and hydrocarbon-oxidizing microorganism-based biosorbents and other biosorbents were studied.

We aim to develop biogeochemical technologies for addressing oil pollution and manage environmental risks associated with soil and groundwater contamination.

The objectives of the study included: the development and production of new biological products and biosorbents based on carbon-oxidizing microorganisms, testing the developed technologies for environmental risk management to eliminate the consequences of emergency spills of petroleum products, and developing an algorithm for conducting preliminary studies in vitro for their subsequent use in situ.

2. Materials and Methods

2.1 Biosorbent Development

Biosorbents are biological systems consisting of a sorbing part (a carrier) and a biochemically active part (carbon-oxidizing microorganisms). The technology for obtaining a biosorbent includes:

- obtaining a biological product based on carbon-oxidizing microorganisms;
- obtaining a sorbent carrier,
- immobilization of microorganisms in the pores of the sorbent,
- thickening of biomass,
- drying of the finished product to preserve the viability of microbes.

Figure 1 presents a general scheme for obtaining a biosorbent based on hydrophobized peat. The important technological stages are also depicted.

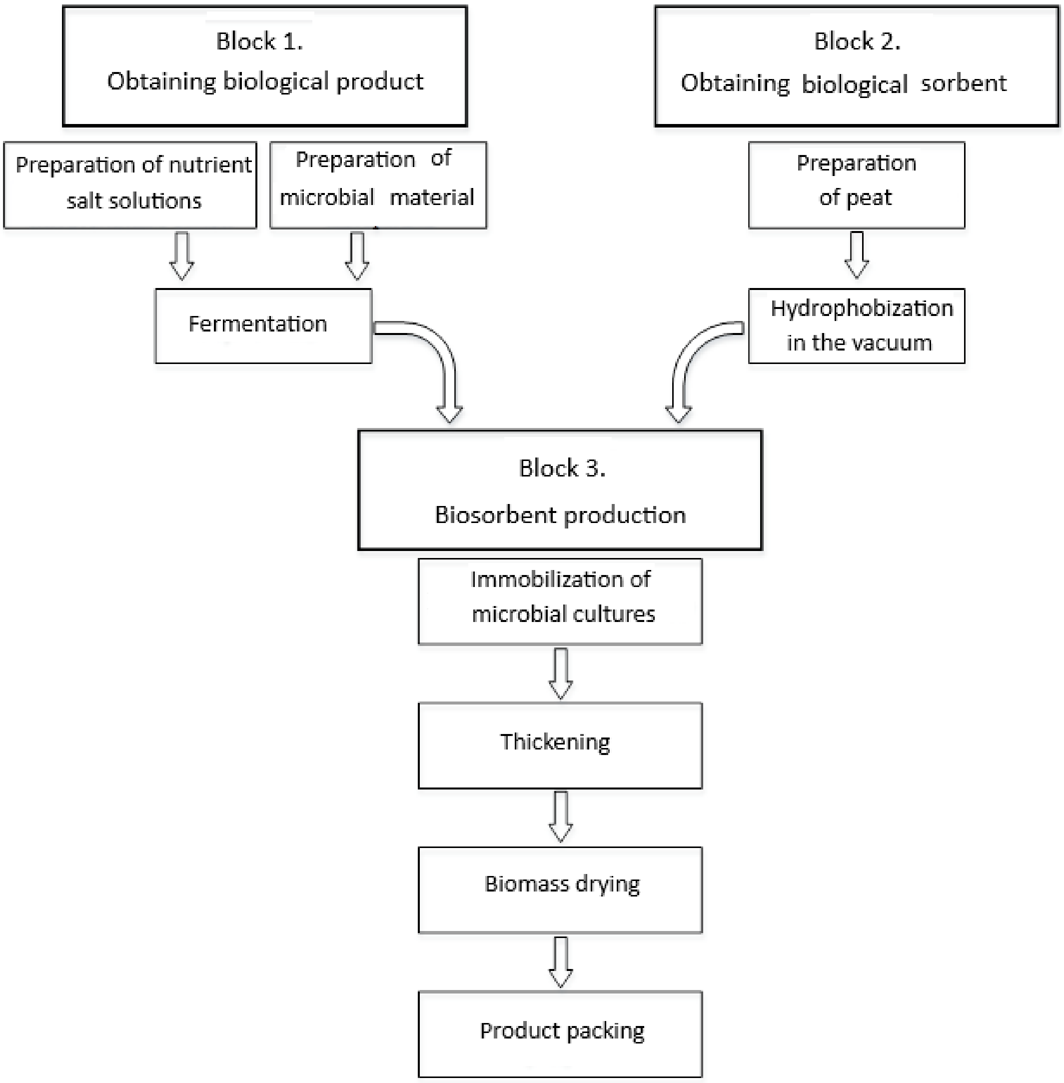

Figure 1 Schematic illustration of the process of biosorbent production process.

2.2 Development of an Experimental Batch of Biosorbent

The production of a pilot batch of biosorbent was carried out in accordance with the developed "Technological instructions for obtaining biosorbent." The process was carried out in an experimental facility for the production of biological products under non-sterile conditions (exception: laboratory stages associated with the growth of carbon-oxidizing microorganisms involved the use of sterile conditions).

2.2.1 Block 1– Obtaining a Biological Product

Two types of microorganisms were selected for the production of biosorbents containing yeast *Candida maltosa* VKPM Y-3446 and bacteria *Dietzia Maris* VKPM Ac-1824. These microorganisms effectively oxidize hydrocarbons. The process of biomass production of each crop was carried out on paraffin-class hydrocarbons [21]. Solutions of the following salts were used as a source of mineral nutrition:

- macronutrients (K_2SO_4, H_3PO_4, $MgSO_4.7H_2O$, and $FeSO_4.7H_2O$)
- microelements ($CoSO_4.xH_2O$, $Na_2MoO_4.2H_2O$, potassium iodide (KI), $CuSO_4.5H_2O$, $ZnSO_4.7H_2O$, and $MnSO_4.5H_2O$).

A pure culture of carbon-oxidizing microorganisms was culture over 2 days using a laboratory thermostat at a temperature in the range of 34–36 °C. The microbial biomass was transferred from the jamb under sterile conditions to rocking flasks (750 mL) containing 100 mL of the sterile nutrient medium. Immediately before sowing, liquid paraffin was added to the nutrient medium (1%; 1 ml). Subsequently, the sample was sterilized in a boiling water bath for 30–40 min. Subsequently, it was cultivated for 24–48 h. The resulting culture was transferred to a fermenter, pre-sterilized, and filled with a nutrient medium containing tap water and a solution of macro and microelements. Liquid paraffin (2% by vol) was also added.

The primary process parameters were automatically maintained during fermentation (time: 36 h):

- pH = 6.8–7.2 (for bacterial culture) and 4.0–4.2 (for yeast culture)
- Medium temperature: 32–34 °C;
- air consumption amount 0.6 m^3/h.

After fermentation, a suspension of microbial biomass was obtained for the subsequent immobilization of cultures in the pores of the sorbent.

2.2.2 Block 2 − Obtaining a Sorbent

The partially decomposed peat was dried to an air-dry state. Subsequently, it was sifted through a sieve with a mesh size of 1 mm. The prepared peat was placed in a heat-resistant dish and kept at a temperature of 220 °C for 2 h in a dry-burning cabinet under a vacuum.

2.2.3 Block 3 − Obtaining a Biosorbent

The resulting hydrophobic sorbent was used as a carrier for the immobilization of carbon-oxidizing microorganisms. The immobilization of microbial cells was carried out on the sorbent when it was introduced into the medium at the stage of the slow growth of the culture.

A suspension of paraffin (90 g) was introduced into the fermenter (7 L). The weight of the suspension of the sorbent was calculated on the basis of the sorption capacity of paraffin (3.1 units). The amount of sorbent introduced was 29 g.

The sorbent was introduced following a decrease in the dissolved oxygen content in the culture medium. This indicated the activation of the growth of microorganisms. The biomass and sorbent were cultivated together for 30 min. The resulting mass was drained from the apparatus and passed through a filter to remove excess liquid.

The biosorbent was dried following a lyophilic method using a dryer (GZL-0.5 type). The process of drying was allowed to proceed for 36 h. The biosorbent containing yeast and bacterial culture was dried separately.

The dried biosorbent was collected from trays and packed in separate paper bags.

2.3 Laboratory tests Conducted for the Analysis of Biosorbents

2.3.1 Tests with Water

Dechlorinated tap water was used to conduct laboratory tests for the analysis of the biosorbents.

The prepared water (1000 mL) was poured into containers suitable for testing (72 pieces in total).

Appropriate amounts of hydrocarbon (HC) were added (50, 100, and 150 g) to each container. Light-colored petroleum products were added in the first 36 containers, and dark petroleum products were added in the next 36 containers. The petroleum products were poured in a thin stream into the center of the tank.

The amount of biosorbent to be applied was 50, 100, and 150 g per sample (based on the pollutant/biosorbent ratio of 1:1). The measured amount of biosorbent was evenly distributed over the contamination spot in the samples (exception: the control samples).

The mass of the biosorbent with sorbed hydrocarbons was collected from the water surface after 3 h.

Water samples were collected to determine the residual concentration of HC in the contaminated samples, including the control samples.

The tanks were shaken on a rocking chair for 5 min to determine the residual concentration of HC. Further, water samples were collected from the middle of the liquid volume. The hydrocarbon film was removed from the control variants, and the containers were shaken on a rocking chair for 5 min. Subsequently, the samples were collected from the middle of the liquid volume.

The concentration of hydrocarbons in the selected samples was measured using the IR spectrometry technique (concentrator: IKN-025).

The samples were extracted twice in 25 mL portions of CCl_4 for 10 min on a rocking chair. After each extraction, the sample was defended until the emulsion was completely delaminated. The lower organic layer was drained from the dividing funnel into a conical flask. The combined extract was drained with 10 g of calcined sodium sulfate (time: 30 min).

The dried extract was passed in portions through a column with aluminum oxide and collected in a volumetric flask (50 mL).

The volume of the eluate was adjusted to the CCl_4 mark, after which the flask was closed and shaken well.

The IR spectra of the resulting solution were recorded using a cuvette with (layer thickness: 50 mm; IKN-025 concentrator). The optical density was measured at wave number 2962 cm^{-1}.

2.3.2 Conducting Soil Tests

The soil sample was collected from the upper, 10–20 cm-thick fertile layer. Large organic residues in the form of roots, the above-ground parts of plants, grasses and shrubs, stones, and solid household waste were removed from the soil samples.

Soil sampling was carried out according to previously reported methods [25] at 5–6 points of the tank.

The soil sample (100 g) was weighed on a scale and placed in each of the prepared containers (72 in total) for testing.

The pollutant was introduced evenly over the entire volume of soil. Light petroleum products were introduced into the first 36 containers, and dark petroleum products were introduced into the next 36. The final concentrations of petroleum products in the soil were 5, 10, and 15% (that is, 5, 10, and 15 g per soil sample). The soil was thoroughly mixed to evenly distribute the pollutant.

The amount of biosorbent to be applied was 5, 10, and 15 g per sample (based on the pollutant/biosorbent ratio of 1:1). The required amount of biosorbent was weighed on a scale, and it was applied evenly over the entire area of each container. Subsequently, the soil was mixed again.

The biosorbent was not added to the control variants.

Sampling was done weekly until the end of the experiment.

The concentration of HC in the selected samples was measured using the IR spectrometry technique.

2.3.3 Conducting Tests for the Recultivation of Oil-contaminated Soils

In vitro recultivation of oil-contaminated soil was carried out using a representative averaged sample of heavy loamy gray forest soil (Moscow region, 55°37' N, 33° 44° E). The soil contamination was simulated by treating the sample with oil in quantities of 50 and 100 g/kg. The "Piksa" biocompost [8] was introduced in 50 and 100 g/kg doses. Further, the soil samples were incubated in plastic containers (volume: 250 mL) at a constant humidity of 70%. The samples were incubated at a temperature of 8 °C for the first 20 days, and the samples were cultivated at a temperature of 18 °C over the next 20 days. The process helped model the annual variation in temperature in the soil layer (period: May–July) in this region. On the 10 and 40th days, the content of petroleum hydrocarbons in the soil was analyzed using the IR spectrometry technique (concentrator: IKN-025). For this purpose, 1 g of the soil sample was extracted with 50 mL of CCl_4 over 5 min. The Ekros-8000 extractor was used for extraction. Following the settling process (10 min), the extract was passed through a chromatographic column packed with aluminum oxide (Al_2O_3). The content of petroleum hydrocarbon was analyzed using a concentrator. The activities of catalase and dehydrogenase were determined on the 40th day to confirm the microbiological nature of the decomposition of petroleum hydrocarbons. Data on the petroleum hydrocarbon content were used to calculate the complete decomposition (99% decomposition; T_{99}). This was obtained as follows:

$$y = e^{-kt},$$

where y is the residual hydrocarbon content at time t, and it is related to the initial y_0. The symbol e denotes the base of the natural logarithm, and k is the rate constant of decomposition of hydrocarbons. The corresponding formula for the calculation is as follows:

$$\mathrm{T}_{99} = \ln 100/\mathrm{k},$$

where $k = \ln(y_0/y)/t$.

3. Results

3.1 Laboratory Tests for Biosorbents

The oil capacity of commercial peat (wet) ranges from 0.94 to 2.11, and that of the dry sample ranges from 1.11 to 2.29 kg/kg. However, for each test batch of peat, an increase in oil capacity is accompanied by a decrease in the moisture content. Studies have been conducted to determine the degree of influence of moisture on the sorption properties of peat. A clear dependence of the capacity of peat oil on the moisture content was observed. The results are presented in Table 1.

Table 1 Influence of peat humidity on oil capacity.

Relative humidity, %	**Oil capacity, kg/kg**
80.2	0.5
62.5	0.8
59.9	0.9
38.5	1.1
7.8	1.9

The ash content in peat has a significant effect on the degree of absorption of oil. A decrease in ash content from 23.2 to 8.8% results in an increase in the oil capacity by 50%. A decrease in the ash content from 8.8 to 3.9% further decreases the oil capacity by 33%. The results are presented in Table 2.

Table 2 Influence of the peat ash content on oil capacity.

Ash content of peat, %	**Degree of decomposition, %**	**Oil capacity, kg/kg**
23.2	60	1.8
8.8	40	2.4
8.8	40	2.6
3.9	20	3.3
3.9	20	3.8

The size of the peat particles affects the amount and rate of oil absorption from the water surface. A 10 mm peat fraction absorbs the maximum amount of oil in 15 min. An hour after the start of the experiment, 3 to 5% of free oil and some unreacted peat remained on the water surface. A 5 mm peat fraction adsorbed 98% of oil in 5 min, and a 1 mm fraction adsorbed 100% of oil in just 3 min. When the peat was ground to form particles no larger than 5 mm, the oil capacity increased by 12%. When the sample was ground to form particles no larger than 1 mm, the oil capacity increased by 41%. The results are presented in Table 3, and the data on the rate of oil absorption from the water surface is shown in Table 4.

Table 3 Influence of peat particle size on oil capacity.

Peat particle size, mm	**Oil capacity, kg/kg**
<10	1.7…1.9
<5	2.5
<1	4.4

Table 4 Influence of particle size on oil absorption rate.

Peat particle size, mm	Absorption time, min.	Oil absorption, %
<10	15	95...97
<5	5	98
<1	3	100

An algorithm was obtained for developing a model of an effective sorbent based on peat. It was observed that hydrophobic, low-ash, slightly decomposed peat, dried to 6–9% and ground to particles of size 1 mm, was characterized by the maximum oil capacity.

The relevant data are presented in Table 5.

Table 5 Degree of water purification achieved under laboratory conditions.

Variants of experiments	Crude oil Initial concentration of HC, %			Diesel fuel		
	5	10	15	5	10	15
Biosorbent *Candida maltosa*	97.2	96.8	92.8	83.5	82.9	80.5
Biosorbent *Dietzia maris*	97.8	97.1	93.2	82.7	82.1	80.2
Biosorbent *C. maltosa* + *D. maris*	98.5	97.4	94.6	84.1	83.6	81.8
Control	58.2	46	31.3	32.2	26	21

Generalized data on the effectiveness of the use of biosorbents are presented in Table 6.

Table 6 Degree of soil purification achieved under laboratory conditions.

Variants of experiments	Crude oil Initial concentration of HC, %			Diesel fuel		
	5	10	15	5	10	15
Biosorbent *Candida maltosa*	58	60.7	54.6	65.8	62.9	57.8
Biosorbent *Candida maltosa*	57.2	63.9	58	64.2	64.1	61.2
Biosorbent *Candida maltosa*	64.8	64.6	63.6	69.4	65.5	65.4
Control	15	24.8	8.6	20.4	29.8	13.87

The results obtained indicate the efficiency of the light and heavy fractions of HC pollutants. However, the studied biosorbents are characterized by a slightly lower efficiency than the biosorbents prepared following biological methods. This can be explained by a decrease in the total number of immobilized microbial cells in the pores of hydrophobized peat. The number of immobilized microbial cells was lower than the number of immobilized cells recorded under conditions of biological preparation.

The best results were obtained when a biosorbent (5%) was used with two cultures of *Candida maltosa,* and *Dietzia maris* microorganisms was used for cleaning diesel fuel from the soil. The degree of purification achieved over a 28-day period was 69.4%, and the degree of purification achieved using the control was 20.4%. This can be explained by the activation of the native microflora and the natural evaporation of volatile fractions during testing.

The best results were obtained when a biosorbent with two cultures of *Candida maltosa* and *Dietzia maris* was used to remove petroleum oil from the soil. When the initial oil contents were 5 and 10%, the degrees of purification were 64.8 and 64.6%, respectively. For control samples with an oil concentration of 5 and 10%, the degree of purification was 15 and 24.8%, respectively.

When the pollutant concentration was 15%, the degree of HC purification achieved using the variants of concentrations 5 and 10% was lower than that achieved using the control samples. This is explained by the toxic effects of high concentrations of hydrocarbons on microorganisms.

The degree of soil purification achieved when biosorbents with microorganism monocultures were used to purify samples containing 10% hydrocarbons was slightly higher than that achieved when the initial hydrocarbon concentration of the hydrocarbon was 5%. This can be explained by the fact that at a 5% concentration of hydrocarbons, the purification process takes place only under the influence of cultures of microorganisms immobilized on hydrophobized peat. This suppresses the activity of the native microflora. The native microflora influences the purification process when the concentration of hydrocarbons increases to 10%. This results in an increase in the purification efficiency, and the efficiency achieved under these conditions is better than that achieved under conditions of 5% contamination.

3.2 In Vitro Cultivation of Oil-contaminated Soil

Studies on the decomposition of petroleum hydrocarbons under the action of biocompost were conducted. The time required for the complete decomposition of hydrocarbons in the presence of biocomposts of amounts 50 and 100 g/kg was lower by 1.8 and 4.8 times, respectively, than the time required for the complete decomposition when the control was used. The relevant data are presented in Table 7. The efficiency of the decomposition process was determined by analyzing the catalase and dehydrogenase activities. The results revealed that the control variants were characterized by the minimum biochemical parameters (Table 8). However, when the biocompost dosages were 50 and 100 g/kg, catalase activity in soil contaminated with 50 g/kg of oil increased by 15 and 27 times, respectively, and activity in soil contaminated with 100 g/kg of oil increased by 9 and 22 times, respectively. The comparisons were made with respect to the control variant. The dehydrogenase activity in soil samples contaminated with 50 g/kg of oil increased 5.7 and 10.6 times when the biocompost dosages were 50 and 100 g/kg, respectively. Activity in the soil contaminated with 100 g/kg of oil increased 4.7 and 15.6 times when the biocompost dosages were 50 and 100 g/kg, respectively. The comparisons were made with respect to the control variant.

Table 7 Time of almost complete decomposition of petroleum hydrocarbons (T_{99}) in polluted soil under the action of the "Piksa" biocompost (Moscow region).

Variant	T_{99}, days	Variant	T_{99}, days
Oil-contaminated soil (50 g/kg)	329	Oil-contaminated soil (100 g/kg)	1150
The same + “Piksa” biocompost (50 g/kg)	184	The same + “Piksa” biocompost (50 g/kg)	658
The same + “Piksa” biocompost (100 g/kg)	69	The same + “Piksa” biocompost (100 g/kg)	288

Table 8 Enzyme activity recorded during the recultivation of polluted soil using the "Pix" biocompost (Moscow region).

Variant	Catalase activity, ml O_2/(min·g)	Dehydrogenase activity, mg $C_{19}H_{16}N_4$/(g·d)
Oil-contaminated soil (50 g/kg)	0,1	0,13
The same + “Piksa” biocompost (50 g/kg)	1,5	0,74
The same + “Piksa” biocompost (100 g/kg)	2,7	1,38
Oil-contaminated soil (100 g/kg)	0,1	0,15
The same + “Piksa” biocompost (50 g/kg)	0,9	0,71
The same + “Piksa” biocompost (100 g/kg)	2,2	2,34

4. Discussion

We aimed to address one of the most important economic and environmental problems. The aim was to address the cases of emergency spills during the cleaning of petroleum products in the environment. A biological product and a biosorbent for removing hydrocarbons from soils and water bodies were developed on the basis of the developed consortia of strains of carbon-oxidizing microorganisms. Biogeochemical technologies for the development of new biological products and biosorbents have been developed. The effectiveness of the risk management method using microbial engineering methods has been proven.

A laboratory method was tested to estimate the bioremediation technology for subsequent use in the field during bioremediation. This approach will determine the necessary technological parameters (peat doses, necessary consortium of carbon oxidizing microorganisms, temperature, etc.) in a short time (2 to 3 months).

The results reveal that the developed biosorbent exhibits sufficient sorption properties and high destructuring ability.

The residual concentration of petroleum products in the contaminated environment was monitored using the widely used IR spectrometry method to assess the environmental risks arising from emergency conditions and to determine the effectiveness of the management process during remediation to eliminate the consequences of contamination of water and soil surfaces. A test system was developed for the preliminary verification of the feasibility of using bioremediation technology and the environmental risk management system for the management of soil and water pollution. The emergencies were modeled as an emergency spill of petroleum products.

It should be noted that, in addition to the sorption bioremediation method, various technological methods are used for the purification and remediation of soils, natural surfaces, and wastewater [26-33]. The type of pollution determines the efficiency of the prevalent methods and the technological conditions prevalent. Thus, many technologies can be successfully used under industrial conditions for removing heavy metals and various petroleum products. These techniques can also be used for the desulfurization of diesel fuel. Using these technologies can significantly reduce the risk of environmental pollution. However, not all of them can be used to eliminate oil and petroleum product spills, especially in the Arctic, where oil and gas production and transportation are carried out.

In the harsh conditions of the Arctic, it is necessary to use nature-like technologies that can restore the default conditions of the disturbed biogeochemical cycles [6-8]. Hence, it is necessary to develop the described biogeochemical technologies that can be potentially used for restoring biogeochemical cycles in the microbial link. The use of such technologies for sorption bioremediation of natural objects contaminated with petroleum products (under conditions of spills, leaks, and emissions of oil and condensates) helps decrease the concentration of petroleum products. The decomposition of these substances is induced in the presence of the introduced microorganisms. As the concentration of the pollutant decreases, the natural microorganism-destructors of hydrocarbons get activated. In the end, the natural biogeochemical structure of these ecosystems is restored, and this is validated by studying the species composition of the microbiocenosis. The results are also verified by analyzing the enzymatic activity in soil or water [8].

It is important that these biogeochemical technologies can be applied to manage environmental risks. This can be done by following at least two technological approaches. Firstly, it is possible to simulate technological processes under experimental conditions in a relatively short time interval, and the results can then be applied to address the cases of emergency spills. Second, the decomposition time of petroleum products (50 or 99% of the initial content; t_{50} or t_{99}) can be calculated based on experimental data.

Natural biogeochemical technologies can be used to address the problem of environmental pollution. These can also be used to advance the field of biogeochemical engineering.

5. Conclusions

Methods have been developed for the bioremediation of oil-contaminated media and environmental risk management using developed biogeochemical technologies based on consortiums of strains of carbon-oxidizing microorganisms. The obtained results revealed positive dynamics in the process of cleaning the prototypes. The results indicate the high efficiency of the developed biosorbents that can be used to address the problem of oil spills. The developed method can help in the significant reduction of the environmental risks associated with in situ remediations of contaminated media.

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Author Contributions

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Competing Interests

The author has declared that no competing interests exist.

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