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Influence of petroleum products on the state of microbiocenosis of soil during short and medium terms of pollution

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Abstract. Bioremediation by autochthonous microbial communities is currently considered the main and most environmentally secure way how to remove petroleum products from contaminated soils. To study the possibilities to control the processes of biodegradation of aviation kerosene by indigenous communities of the soil together with plants and in the presence of a cometabolite (glucose), a model experiment was carried out with concentrations of aviation fuel from 0 to 20%. Soil without the addition of petroleum products served as reference. The state of the microbial community was studied 1 and 21 days after the addition of the petroleum products. It has been established that the soil contamination with petroleum products within one day leads to quantitative and qualitative changes in the state of the microbial cenosis, and the phytotoxicity of the soil significantly increases. At low concentrations of the petroleum products (1%) the occurrence of microbiological processes in the soil slows down, and at high concentrations (20%) they intensify. It has been shown that an increase in the number of polysaccharide-synthesising bacteria increases not only the absolute amount of degraded petroleum products from 0.240 to 1.88 g kg^{-1}, but also their relative share from 6.33%. Growing plants and adding easily accessible substrates to the soils contaminated with petroleum products ensures more active destruction of pollutants (by 63.6 and 45.5%, respectively) compared to the soils without phytocenosis and the addition of exogenous substrates.

Key words: microbiocenosis, ecological and trophic groups, mineralization, humus, toxicity, pollution with petroleum products.

INTRODUCTION

Pollution with crude oil and petroleum products poses a great danger to the normal functioning of the soils. It manifests itself in changes in their physicochemical properties, inhibition of the intensity of biological processes, a decrease in the solubility of most micro and macroelements, and a sharp increase in the ratio between carbon and nitrogen (Hawrot-Paw, 2020; Hu, 2020; Krainiukov et al., 2022; Haider & Ejaz, 2021). Oil pollution interferes with normal heat and gas exchange in the soil. At high doses the mechanical elements and structural aggregates of the soil are covered with an oil film, which isolates the nutrients from the root systems of the plants. The soil particles stick together, and with aging and partial oxidation of the oil components the latter thickens, and the soil layer turns into an asphalt-like mass, which becomes unsuitable for the plant growth. The soil structure deteriorates, the reaction of the soil solution shifts to the alkaline side, the total carbon content increases by 2–10 times, and the amount of hydrocarbons by 10–100 times (Haghsheno & Arabani, 2022). The total number and species diversity of the soil microorganisms undergo significant changes, and the composition of the dominant species changes (Shi et al., 2022; Zhuang et al., 2023). Thus, in unpolluted loess soil of *Yan'an* Province (China), the dominant genera of the soil microorganisms were *Pantoea, Sphingomonas*, *Thiothrix* and *Nocardioides*. After oil pollution the abundance of the representatives of the genera *Pseudomonas, Pedobacter, Massilia, Nocardioides* and *Acinetobacter* in the soil increased, while the abundance of *Thiothrix, Sphingomonas* and *Gemmatimonas* decreased significantly. It has been shown that a decrease in the richness and phylogenetic diversity of microorganisms in the oil-contaminated soils is associated with disruption of the nitrogen cycle, while the number of species and functional genes, involved in nitrification, has significantly decreased (van Dorst et al., 2014).

Violation of the ecological purity of the soils leads to deterioration in the quality of the food products since soils are the main accumulators of organic pollutants (Xu et al., 2018). Basic methodologies have been developed for cleaning the soils from the oil pollution. But the most modern method is a combination of two approaches: phytoremediation and bioaugmentation, which leads to rhizoremediation (Kuiper et al., 2004; Sui et al., 2021). During rhizoremediation the plant exudates can help stimulate bacterial survival and action, which subsequently leads to more efficient degradation of the contaminants. The root system of plants can allow bacteria to spread through the soil and penetrate into the impervious layers of the soil. Inoculation of pollutant-degrading bacteria on the plant seeds can be an important additive to improve the phytoremediation or bioaugmentation efficiency. Evidence has been obtained that the autochthonous oil-degrading bacteria are more efficient in soil bioremediation than a preparation, based on a microbial consortium, and are active even in soils, supersaturated with oil (Wu et al., 2020; Ali & Al-Awadhi, 2022). The autochthonous bacteria are widely used to decompose the waste, produced by the petroleum, agricultural, chemical and pharmaceutical industries, due to the low cost and ecological friendliness of this technology (Guerra et al., 2018; Xu et al., 2018). Microbial remediation technologies play an indispensable role in ensuring ecological safety when working with environments, contaminated with petroleum hydrocarbons, due to their low cost, positive effect, insignificant impact on the environment and the absence of secondary pollution (Dvořák et al., 2017).

The purpose of this work is to conduct research into the regularities of influence of increased concentrations of petroleum products upon microbial communities in the soils without plants, with phytocenosis and under conditions of introducing an easily accessible cometabolite, as well as the ability of native microbial communities to decompose introduced petroleum products.

MATERIALS AND METHODS

A model experiment was carried out using soil of the monitoring site of the National Scientific Centre of the Institute of Agriculture of the National Academy of Sciences, Ukraine in collaboration with the Ulbroka research centre of the Latvian University of Life Sciences and Technologies, Latvia.

The 0–20 cm soil layer contained: humus 2.74%, easily hydrolysable nitrogen 933 mg, mobile phosphorus 368 mg and mobile potassium 153 mg kg of soil, pH (KCl)-5.6. The fallow phytocenosis was formed as a result of spontaneous overgrowth over 28 years and is represented mainly by cereal grasses. The soil was sampled in autumn, and before the model experiment; its biological activity was restored by moistening and thermostating at 25 °C for 20 days. The oil products were introduced in concentrations from 0 to 20% in the form of an aqueous emulsion. The aviation fuel TS-1 was used as an oil product. 8 days before the introduction of the oil products into a part of the vegetation vessels, seeds of a cereal grass mixture were sown, and a day before, a sterile solution of glucose (1%) was added as a cometabolite. Soil without introduction of oil products served as the control.

The state of the microbial community was studied 1 and 21 days after the introduction of the oil products. The number of microorganisms of the main ecological-trophic, functional and systematic groups was estimated by the method of sowing the soil suspension on the appropriate nutrient media (Nannipieri et al., 2003). The indicators of the intensity of the mineralization processes, the probability of formation of bacterial colonies (FBC), the coefficient of the specific phosphate-dissolving activity, the total biological activity, and phytotoxic properties of the soil were determined as described earlier (Malynovska, 2019; Krainiukov et al., 2022).

The residual amount of the oil products was determined by a modified method of extraction concentration of the oil products from soil with carbon tetrachloride, purification of the extract on a chromatographic column with aluminium oxide, followed by IR spectroscopy at a wavelength of 3.42 μm on a KM-2 concentrator.

Statistical assessment of the data obtained for the reliability and error of the experiments was determined according to the generally accepted methodology (Welham et al., 2014; Bulgakov et al., 2022). To assess the significance of the differences, we calculated the error of the mean (Table 6) and the least significant difference (HCP_{05}) between the results of the studies (Tables 1–5), which has a statistical reliability of 95%. It is used to assess the significance of the difference selective sample averages. When comparing two selected averages, the difference between them is equal to or greater than the HCP, such a difference is the significant difference, and any difference less than the HCP is the insignificant difference.

RESULTS AND DISCUSSION

Incubation of soil, polluted with the oil products for 21 days, leads to significant changes in the number and physiological activity of the soil microorganisms, the results are shown in Tables 1–4. Thus, the number of ammonifiers one day after the introduction of oil products decreased at concentrations of the oil products of 5–20% (Table 2), and after 21 days their number decreases only at a concentration of oil products of 20% (Table 4). At concentrations less than 20% the petroleum products stimulate an increase in the number and physiological and biochemical activity of ammonifying microorganisms. The functioning of hydrocarbon-degrading bacteria is mainly dependent on hydrocarbon-degrading enzymes, whose expression and activity are closely related to the physiological activity of the bacteria (Mukherjee et al., 2017; Song et al., 2017).

One day after the introduction of the petroleum products the number of oligonitrophils, nitrifiers, and prosaccharide-synthesizing bacteria decreases several times, compared to the reference (Tables 1 and 2).

Table 1. The number of microorganisms of the carbon cycle in the soil 24 hours after the introduction of oil products, mln CFU * g^{-1} of absolutely dry soil

Variant	Pedotrophs	Cellulose-decomposing	Polysaccharide-synthesizing	Autochthonous	Streptomycetes	Micromycetes	**Total number**
Control, without petroleum products	49.0	26.5	7.05	11.0	11.2	0.22	**383.9**
1% oil products	76.8	68.5	5.16	9.98	16.9	0.22	**710.2**
5% oil products	64.4	80.4	4.07	9.09	19.0	0.20	**773.7**
10% oil products	58.9	73.3	4.14	11.0	15.2	0.21	**557.9**
20% oil products	50.7	77.6	3.52	9.48	12.8	0.14	**456.7**
Phytocenosis (control)	780.4	500.1	199.7	48.8	6.01	0.19	**2,973.8**
Phytocenosis + 5% oil products	588.0	577.2	72.0	15.5	26.1	0.38	**2,850.4**
Glucose (1%) + oil products (5%)	198.0	165.2	20.1	13.0	18.4	0.19	**1,209.5**
HCP_{05}	8.77	9.42	1.07	0.94	0.74	0.04	

Note: CFU * – colony forming unit.

After 21 days the number of oligonitrophils exceeds the reference value at a concentration of the petroleum products of 1% by 3.74 times, 5% by 3.48, and 20% by 1.69 times (Table 4). During 21 days of soil incubation the amount of immobilizers of mineral nitrogen also increases, and at the same time the inhibitory effect of high concentrations of platanum can be traced. The number of pedotrophs increases during incubation at a concentration of the petroleum products of 1% by 7.28 times, 5% by 7.98, 10% by 9.49 and 20% by 6.43 times (Table 4). As for microorganisms of other ecological-trophic groups, the negative effect of high pollutant concentrations is manifested: the number of pedotrophs at a concentration of 20% is reduced by 13.2%, compared to the number of these microorganisms at 1% (Table 3).

Table 2. The number of microorganisms of the nitrogen and phosphorus cycle in soil 24 hours after the introduction of oil products, million KUO * g^{-1} of absolutely dry soil

Variant	Ammonifiers	Immobilizers of mineral nitrogen	Oligonitrophils	Azotobacteria,% of soil clods infestation	Denitrifiers	Nitrifiers	Mobilizers of mineral phosphates	Mobilizers of organophosphates
Control, without petroleum products	90.4	63.3	54.3	6.67	52.0	1.09	9.88	1.03
1% oil products	173.3	121.8	25.2	0.00	177.2	0.82	32.2	2.13
5% oil products	115.0	216.5	55.6	0.00	180.4	0.77	22.8	5.44
10% oil products	65.6	77.9	45.6	0.00	183.4	0.76	20.9	0.99
20% oil products	40.0	74.9	36.7	0.00	140.2	0.44	10.1	0.09
Phytocenosis (control)	230.2	698.9	255.1	0.00	188.1	0.67	25.8	39.8
Phytocenosis + 5% oil products	498.5	488.8	165.9	3.13	197.8	1.44	187.1	28.5
Glucose (1%) + oil products (5%)	190.3	250.6	140.5	5.67	177.0	0.90	23.9	5.75
HCP_{05}	10.8	10.2	7.84	0.06	10.9	0.04	4.17	0.54

The number of polysaccharide-synthesizing bacteria during short-term pollution decreases by 36.6–100.3% compared to uncontaminated soil (Table 1), but after 21 days the opposite pattern is observed: the number of polysaccharide-synthesizing bacteria increases compared to the control at a concentration of the oil products of 1%–8.60 times, 5%–9.33, 10%–34.3, and 20%–14.7 times (Table 3).

Table 3. The number of microorganisms of the carbon cycle in the soil 21 days after the introduction of the oil products, mln. CFU* g^{-1} of absolutely dry soil

Variant	Pedotrophs	Cellulose-decomposing	Polysaccharide-synthesizing	Autochthonous	Streptomycetes	Micromycetes	**Total number**
Control, without petroleum products	39.7	89.2	8.08	4.45	27.8	0.19	**533.2**
1% oil products	289.1	255.6	69.5	26.3	15.0	0.04	**1,490.3**
5% oil products	316.8	182.3	75.4	29.5	12.2	0.16	**1,484.1**
10% oil products	376.9	180.8	277.4	52.5	13.0	0.15	**1,880.9**
20% oil products	255.4	202.6	118.9	64.6	11.9	0.22	**1,350.0**
Phytocenosis (control)	62.9	244.5	25.0	7.54	9.54	0.22	**948.5**
Phytocenosis + 5% oil products	315.3	488.6	180.1	21.9	5.48	0.23	**1,956.2**
Glucose (1%) + oil products (5%)	154.7	326.7	111.6	17.8	13.9	0.25	**1,343.2**
HCP_{05}	10.4	11.3	5.30	2.05	1.88	0.003	

Note: CFU* – a colony-forming unit.

A possible reason for the decrease in phytotoxicity is the higher rate of destruction of the petroleum products by the more powerful microbial community of the rhizosphere soil (Table 6), namely, in the soil without a phytocenosis, 5.82% of the applied amount of the petroleum products was destroyed, and in the soil with a dead phytocenosis- 9.23%. The high concentration of easily accessible organic substances in the rhizosphere as a result of the intravital release of the root exudates and the decay of the remains of the root system of dead plants is a pool of metabolites that can be cometabolites during the degradation of the petroleum products and toxins.

Introduction of glucose into the soil also made it possible to form a microbiocenosis, which differs from the soil with 5% oil products in the number of microorganisms, namely, it contains more: mineral nitrogen immobilizers-by 25.9%, nitrifiers - 13.8, cellulolytics - 79.2, polysaccharide-synthesizing - 48.0, micromycetes - 56.3, streptomycetes -13.2, mobilizers of organophosphates-by 18.8% (Tables 3 and 4). Thus the addition of glucose increases the number of microorganisms of both the carbon cycle and the nitrogen cycle. Addition of glucose also leads to a significant increase in the physiological and biochemical activity of the microorganism cells, mainly of the carbon cycle: pedotrophs, 2.18 times; cellulose-destroying - 3.94, micromycetes-1.63, organophosphate mobilizers - 4.95, polysaccharide-synthesizing - 1.24 times (Table 5).

After 21 days, with an increase in the concentration of the petroleum products from 1 to 10%, the number of ammonifiers increases by 73.8%, and their physiological and biochemical activity-by 69.5% (Tables 4, 5). In addition, at a concentration of the petroleum products of 1%, the ammonifiers are more numerous and active than in the reference soil, which is consistent with the literature data (Gamzaeva, 2021). Thus, during the incubation period, the ammonifiers overcame the state of stress at all studied concentrations of the petroleum products (except for 20%) and used them as a substrate for growth.

Table 4. Nitrogen and phosphorus cycle microorganisms in dark gray podzol soil 21 days after petroleum product application, million CFU*/g absolutely dry soil

Variant	Ammonifiers	Immobilizers of mineral nitrogen	Oligonitrophils	Azotobacter,%	Denitrifiers	Nitrifiers	Mobilizers of mineral phosphates	Mobilizers of organophosphates
Control, without petroleum products	90.4	53.1	40.2	7.87	132.4	1.16	32.6	6.02
1% oil products	172.3	301.2	150.2	1.05	165.3	0.55	22.5	24.4
5% oil products	265.9	216.2	139.8	1.00	175.8	0.94	50.5	17.6
10% oil products	299.4	323.5	99.4	0.00	180.4	0.96	60.5	16.0
20% oil products	199.2	212.6	68.1	0.00	180.4	0.94	22.3	12.8
Phytocenosis (control)	155.0	48.2	98.4	0.00	195.8	1.01	70.1	30.3
Phytocenosis + 5% oil products	295.4	166.7	143.8	7.33	211.0	1.54	60.3	58.8
Glucose (1%) + oil products (5%)	180.6	272.2	81.5	0.00	133.2	1.07	28.8	20.9
HCP_{05}	10.4	8.32	9.95	0.45	9.28	0.08	5.44	2.02

Thus introduction of the oil products significantly affects the abundance of the soil microorganisms, especially carbon cycle microorganisms (the group of organophosphate mobilizers can be considered as related to both the phosphorus cycle and the carbon cycle).

After 21 days of incubation, nitrifiers continued to experience the toxic effect of the pollutant - their numbers were reduced by 20.8–110.9% compared to the control (Table 4).

The persistent negative impact of the petroleum products upon the nitrifier cells may be associated with the creation of anaerobic conditions in the soil, and the nitrifiers belong to the group of obligate aerobes and feel a lack of oxygen, which is also manifested in a decrease in the physiological and biochemical activity of their cells by 20.6–141.2% (Table 5).

Table 5. Probability of formation of colonies of microorganisms (λ_1, year^{-1} 10^{-2}) in soil 21 days after application of the oil products

Variant	Ammonifiers	Immobilizers of mineral nitrogen	Oligonitrophils	Pedotrophs	Cellulose-decomposing	Polysaccharide-synthesizing	Autochthonous	Mobilizers organophosphates	Micromycetes	Nitrifiers
Control, without petroleum products	0.58	0.18	2.17	1.77	7.15	0.33	0.67	1.12	3.44	0.41
1% oil products	2.39	0.50	5.18	1.99	4.95	0.37	0.93	0.26	4.15	0.22
5% oil products	2.98	0.30	3.07	0.45	0.51	0.49	0.94	0.38	2.47	0.17
10% oil products	4.05	2.11	1.99	0.88	4.11	0.44	1.11	1.88	1.86	0.30
20% oil products	2.98	0.71	1.05	2.13	0.48	0.61	1.30	1.02	3.22	0.34
Phytocenosis (control)	5.85	0.53	2.33	3.77	7.88	0.38	1.11	2.64	6.77	0.27
Phytocenosis + 5% oil products	6.07	2.01	0.99	2.00	5.16	0.62	0.52	2.92	6.58	0.30
Glucose (1%) + oil products (5%)	3.11	0.41	2.66	0.98	2.01	0.59	0.77	1.88	4.03	0.28
HCP05	0.25	0.04	0.07	0.04	0.03	0.03	0.08	0.03	0.11	0.02

The reason for the decrease in the number and physiological and biochemical activity of nitrifiers may also be their high sensitivity to water-soluble organic substances in the soil solution, the concentration of which increases significantly as a result of microbial degradation of the aviation kerosene molecules. The number of denitrifiers in the contaminated soil exceeds the number of these microorganisms in the reference soil by an average of 32%. The azotobacter, both in the first day after contamination and after 21 days, experiences strong inhibition by the petroleum products: it completely disappears in the contaminated soil within 24 hours, and appears in minimal quantities at low concentrations of the petroleum products after 21 days, which confirms the possibility of using it as a diagnostic group for oil pollution.

Considering the fact that bacterial exopolysaccharides are able to emulsify molecules of hydrophobic pollutants and increase their availability for biodegradation (Krasowska & Sigler 2014; Varjani & Upasani 2017), it can be concluded that an increase in the number of polysaccharide-synthesizing microorganisms is an indicator of the intensification of the process of destruction of the petroleum products. The data from Table 6 indicate that, with an increase in the number of polysaccharide-synthesizing bacteria, not only the absolute amount of the degraded oil products increases from 0.240

to 1.88 mg, but also their relative share from 6.33% (at an initial concentration of oil products of 1%) to 9.64% (at an initial concentration of oil products of 20%).

Table 6. Degradation of petroleum products by native microflora of the soil 21 days after application, g kg^{-1}

Variant	The content of oil products in the soil, mg g^{-1} of soil	
	0 days	21 days
Control, without petroleum products	0	0
1% oil products	3.79 ± 0.40	3.55 ± 0.41
5% oil products	18.9 ± 1.78	17.8 ± 2.22
10% oil products	40.0 ± 4.42	36.0 ± 4.11
20% oil products	77.8 ± 8.42	71.3 ± 8.66
Phytocenosis + 5% oil products	19.5 ± 2.02	17.7 ± 1.95
Glucose (1%) + oil products (5%)	19.0 ± 2.03	17.4 ± 1.88

An even closer relationship was revealed between the physiological and biochemical activity of cells of polysaccharide-synthesizing bacteria and the amount of degraded oil products ($r = 0.631$), with the proportion (%) of the degraded oil products, the correlation coefficient is 0.704.

After 21 days of incubation of the polluted soil the direction and intensity of the mineralization processes in it change. The data of the Table 7 show that, if a day after pollution the mineralization coefficient of the nitrogen compounds increases with an increase in the concentration of the oil products, then after 21 days it decreases from 1.75 (1% oil products) to 1.07 (20% oil products). Similar trends are observed for the pedotrophy index and the oligotrophy coefficient: one day after the introduction of the oil products, they increase with increasing pollutant concentration, after 21 days, on the contrary, they decrease from 1.68 to 1.28 (pedotrophy index) and from 0.872 to 0.342 (the oligotrophy coefficient). The regularities of changes in the activity of humus mineralization were revealed to be the same in a day and 21 days: the activity increases by 63.8 and 180.8%, respectively, with an increase in the level of pollution (Table 7).

After 21 days of incubation, the phytotoxicity of the polluted soil decreases: at a concentration of the oil products of 1%, by 9.02%; at a concentration of oil products of 5%, the growth of the test plants appears, while one day after pollution the seeds of the test culture did not germinate in this variant of the experiment (Table 7). At higher concentrations of the pollutant (10 and 20%), the phytotoxicity of the soil remains so high that the seed germination process of the test culture is inhibited.

Introduction of 5% oil products into vessels with a vegetative grass mixture led to death of the plants in three days; at the same time the remains of the dead phytocenosis made it possible to form a more powerful microbial cenosis than in the variant without plants. So the number of microorganisms in the variant with a dead phytocenosis exceeds the number of soil microorganisms without plants: azotobacter, by 7.3 times; polysaccharide-synthesizing, by 2.39 times; organophosphate mobilizers, by 3.34 times; ammonifiers by 11.1%, nitrifiers by 5.43, celluloselitics by 91.2% (Table 3, 4). The total biological activity of this soil has the maximum value among the studied variants; it exceeds the total activity of the soil without phytocenosis by 53% and the activity of the soil with the addition of glucose by 39.6%.

In this soil the processes of mineralization of the soil organic matter are significantly slowed down-by 12.3%, podsalization-by 8.23, nitrogen and humus mineralization-by 2.52 and 1.34 times, respectively (Table 7). The phytotoxicity of the soil after the death of the phytocenosis is significantly reduced-by 2.84 times, compared with the phytotoxicity of the soil without phytocenosis.

Table 7. Indicators of the intensity of the mineralization processes and phytotoxicity of the soil 21 days after the introduction of the oil products

Variant	Pedotrophy index	Oligotrophy coefficient	Immobilization coefficient of nitrogen	Humus mineralization activity,%	Total biological activity	Specific phosphate mobilizing activity	Mass of 100 test culture plants-winter wheat, g
Control, without petroleum products	0.439	0.445	0.587	11.2	514.1	1.35	14.5
1% oil products	1.68	0.872	1.75	9.01	680.2	1.30	13.3
5% oil products	1.19	0.526	0.813	9.31	712.5	1.12	3.26
10% oil products	1.26	0.332	1.08	16.5	927.6	0.91	**
20% oil products	1.28	0342	1.07	25.3	741.3	0.96	**
Phytocenosis (control)	0.406	0.634	0.311	12.0	700.3	0.66	11.9
Phytocenosis + 5% oil products	1.06	0.486	0.564	6.95	1,089.8	1.96	9.25
Glucose (1%) + oil products (5%)	0.857	0.451	1.51	11.5	780.9	1.06	4.15
HCP05	0.34	0.15	0.22	0.55	82.0	0.18	1.01

**– due to high toxicity, the seeds of the test crop did not germinate.

The influx of glucose slows down assimilation of the soil organic matter by 38.8%, the activity of destruction of humic substances - 23.5, the process of soil podsalization by 16.6%, and accelerates the mineralization of nitrogen compounds by 85.7% (Table 7). Soil phytotoxicity decreases as a result of the introduction of an exogenous substrate by 27.3%. Due to the higher activity of microorganisms in the variant with glucose the amount of the degraded oil products was by 45.5% higher, compared to the soil without cometabolite application (Table 6).

CONCLUSIONS

Short-term (24 hours) contamination of the soil with the petroleum products leads to a decrease in the number and physiological and biochemical activity of the microorganism cells of the most studied groups, a change in the direction and intensity of mineralization processes. Addition of glucose (1%) to the oil-contaminated soil leads to an increase in the number of carbon cycle microorganisms, an increase in the intensity of mineralization of organic matter and nitrogen compounds, and a 2.2 - fold slowdown in the humus destruction.

On the 21st day of incubation of the contaminated soil at concentrations of the petroleum products from 1 to 10%, the number and physiological and biochemical activity of microorganisms of most of the studied groups exceeds those in the uncontaminated soil (reference). The total number of microorganisms exceeds the reference indicator at a concentration of the petroleum products of 1% by 2.79 times, 5% by 2.78 times, 10% by 3.53 times, and 20% by 2.53 times.

An indicator of intensification of the process of destruction of the petroleum products is the number and physiological and biochemical activity of cells of the polysaccharide synthesizing bacteria, whose exoglycans increase the availability of pollutant molecules for biodegradation. There is a close correlation between the number of polysaccharide-synthesizing bacteria and the proportion (%) of the degraded petroleum products (r = 0.632). Between the physiological and biochemical activity of cells of the polysaccharide-synthesizing bacteria and the amount of degraded petroleum products, the correlation coefficient is r = 0.631, with the share (%) of the degraded petroleum products - 0.704.

The cereal plants, producing root exudates, form a powerful microbial cenosis in their own rhizosphere, which has high biochemical activity, and destroys the petroleum product molecules more intensively than the soil microbiocenosis without phytocenosis.

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