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Efficient cleaning up of oil-polluted bottom sediments of water bodies using geotube technology

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Abstract – The article is devoted to the currently relevant issue of cleaning up bottom sediments of water bodies polluted with hydrocarbons as a result of accidental leakage of oil and oil products or oil spills during routine operations of oil production. One of the promising ways of their recovery is the geotube technology recently introduced in Russia, which involves removing bottom sediments from the site of pollution with their subsequent dehydration in geocontainers and cleaning up the soil quality to the established standards. Geocontainers are made of a special fabric, capable for transmitting water with the dissolved substances with safely retaining solid particles of various sizes. The results of a case study of using of geocontainer technology for remediation of bottom sediments of three lakes heavily contaminated with oil in Western Siberia, Khanty-Mansi Autonomous Okrug - Ugra (Nizhnevartovsk) are presented. In 2013, forty-four geotubes were filled up with pulp from the bottom sediments of three lakes, then placed on an oil well platform and left for two years. After that, samples from 14 geotubes were randomly selected and tested for changes in physicochemical properties, biological activity, and phytotoxicity compared to the initial oil-polluted samples. A significant decrease was found in the concentration of total petroleum hydrocarbons, i.e. by 81–98%. Purified soils from geotubes contained a noticeable amount of oil-oxidizing bacteria, heterotrophic and autotrophic microorganisms, and exhibited high biological activity without acute phytotoxicity. The proposed technology is characterized by high efficiency, simplicity and environmental friendliness and can compete with the known cleaning procedures used for the same purposes.

Keywords: bottom sediments, oil pollution, geotubes, remediation.

Эффективная очистка донных отложений водоемов от нефтяного загрязнения с помощью геоконтейнерной технологии

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Аннотация – Статья посвящена актуальной в настоящее время теме очистки донных отложений водоемов от их загрязнения углеводородами, произошедшего в результате аварийных утечек нефти и нефтепродуктов или в процессе эксплуатации нефтяных скважин. Одним из перспективных способов их очистки является недавно появившаяся в России геоконтейнерная технология, суть которой состоит в изъятии донных отложений для их последующего обезвоживания в геоконтенерах и доведения качества почвы до установленных нормативов. Геоконтенеры изготовлены из специальной ткани, способной пропускать воду и растворенные в ней вещества, но хорошо задерживать твердые частицы различных размеров. Приведены результаты исследования применения геоконтейнерной технологии для ремедиации донных отложений трех озер, сильно загрязненных нефтью, в Западной Сибири, Ханты-Мансийском автономном округе - Югре (Нижневартовск) в 2013 году. Сорок четыре геотубы были заполнены пульпой донных отложений трех озер, размещены на платформе нефтяных скважин и оставлены на два года в естественных климатических условиях. После этого случайным образом были отобраны пробы из 14 геотуб и проведена оценка изменений физико-химических свойств, биологической активности и фитотоксичности проб по сравнению с исходными загрязненными пробами. Показано, что за два года произошло значительное снижение концентрации общих нефтяных углеводородов на 81–98%. Очищенные почвы из геоконтейнеров содержали большое количество нефтеокисляющих бактерий, гетеротрофных и автотрофных микроорганизмов и обладали высокой биологической активностью при отсутствии острой фитотоксичности. Данная технология отличается высокой эффективностью, простотой и экологичностью и может конкурировать с другими способами очистки, используемыми для данных целей.

Keywords: донные отложения, загрязнение нефтью, геокотейнеры, ремедиация.

INTRODUCTION

Currently, Russia is one of the largest oil producing countries in the world [1]. Unfortunately, it is impossible to completely avoid accidental oil spills. In 2018, the territorial authorities of the Russian Federal Agency for Oversight of Natural Resource Usage recorded 3,053 facts of the spill of oil and oil products in the Russian Federation with the total volume of oil products released into the environment estimated as 11214,807 m^3 [2]. Most recently, in May 2020, a huge accident occurred in Russia's Arctic region with the leak of more than 20,000 tons of diesel fuel spilled into the local river after a fuel tank collapsed at the Norilsk Nickel plant threatening to inflict significant damage to the Arctic environment [3].

Therefore, the environmental issues related to oil production and transportation are of paramount concern in our country. In general, the largest oil and oil product spills occur during the transportation of oil through pipelines, as well as during the transportation of hydrocarbons through water bodies [4].

In fact, the oil spills into water stop oxygen supply and lead to the death of water body inhabitants. The toxic effects of hydrocarbons on living organisms have been well studied [5], and are usually explained by the degradation of the lipid layer of the cytoplasmic membrane in the presence of petroleum hydrocarbons [6].

As a rule, oil spilled over the surface of the water is contoured with booms, pulled to the oil collectors and skimmed off [7]. To completely eliminate the accidental spill of oil products after mechanical collection of hydrocarbons, a wide range of sorbents are usually used, as well as bacterial preparations of oil destructors immobilized on floating carriers [7].

While the problem of water surface pollution from oil and oil product spills can be fairly solved, the issues of the water bottom pollution are of less concern though the bottom pollution is equally important since it ultimately worsens the environmental and sanitary conditions of water bodies [8].

To clean up bottom sediments from oil, air compressors are used, the pop-up oil is collected, and then active booms are built to collect the oil film floated up to the surface [9] or bacterial oil destructors are used [10]. A procedure is also known of using *Limnodrilus hoffmeisteri* worms for *in situ* cleaning bottom sediments from oil and oil products [11, 12]. Nevertheless, the proposed methods for cleaning up bottom sediments can't be applied for water bodies in certain cases due to inappropriate climatic conditions or due to the risk of secondary pollution of the reservoir with heavy metals [13].

More recently, in Russia, a geotube technology for purifying bottom sediments of reservoirs with natural or anthropogenic pollution was put into practice which is based on the removal of polluted bottom sediments with their subsequent dehydration and cleaning up to the established purity standards [8, 14–16].

Geotextile containers have long been widely used in many countries for dewatering sand, sapropels, peat, excess activated sludge from urban aeration stations, agricultural and industrial wastes, along with cleaning up the bottom of water bodies from various contaminants, including pollution by oil products, heavy metals and polyaromatic hydrocarbons, as well as for reinforcement of the coastline of water bodies [17–22]. Geocontainers of the required size are made of special fabric, capable for transmitting water with the dissolved substances with safely retaining solid particles of various sizes. In addition, the most recent studies have been carried out focusing at developing biodegradable materials for geotube filtering fabric [23].

The use of geocontainers does not require special conditions: the operating temperature can be varied in the range from -40 to +60°C, without shelter from direct sunlight and atmospheric precipitation. When filling a geotube, flocculants are often added, which provides a fast and complete exit of moisture from finely dispersed suspensions such as sludges, sediments and slurries. In some cases, disinfectants are also added to the pulp, such as lime or hydrogen peroxide, to prevent the growth of pathogenic microflora [24, 25]. In due time, the geotube content is shrinked transforming into dehydrated purified soil [26].

The use of geocontainer technology for cleaning up bottom sediments from oil pollution of water reservoirs in oilfield regions looks promising. However, before starting to implement the technology by environmental service companies in the harsh climatic conditions of Western Siberia and Arctic region, a comprehensive evaluation is required.

A few years ago, EcoVek company developed a technological scheme and applied geotube technology to clean up bottom sediments of three oil-polluted Siberian lakes (Khanty-Mansi Autonomous Okrug-Yugra, Western Siberia). A ground site was prepared with a gravel layer and a layer of waterproof film isolating geotubes from the ground. Leaking water was collected in special ponds with natural purification of water, which was then dumped onto the relief. Geocontainers were filled with the pulp of oil-polluted bottom sediments followed by two years of keeping in the environment [27].

This paper analyzes changes in the physicochemical properties, biological activity and phytotoxicity of the bottom sediments of the lakes previously contaminated with oil, after applying the EcoVek geotube dehydration technology in comparison with the starting level of oil pollution of the bottom sediments.

EXPERIMENTAL PART

Three oil-polluted lakes were located in the Yuzhno-Agansky licensed area near oil production platform no. 14, the Tyumen region, Nizhnevartovsk district, Khanty-Mansi Autonomous Okrug-Yugra, Western Siberia [27]. These lakes (hereinafter numbered as nos. 1, 2 and 3) had been polluted as a result of oil spills during the drilling procedures and subsequent exploitation of oil wells along with accidental oil spills. The exact time of accidental spills, the volumes of spilled oil and spill site locations were unknown. The lakes were either round or oblong shaped; the water surface area varied from 8837 m^2 to 22724 m^2; the shores were low and peat-forming; the depth of the lakes varied from 0.5 m near the shore to 1.5–2 m in the deepest places. The water volume of these lakes varied from 7511 m^3 to 34086 m^3. The lakebeds were cup shaped; the topography of bottom was smooth. Lake bottoms were formed of perhumid damp peat. Bottom sediments were up to 1.0–1.2 m thick. The subsoil of the bottom sediments was loam, according to the engineering-geological reportbog of SibNIPIRP [27].

Lake waters penetrated into a peat deposit via infiltration. The results of engineering-geological report suggested a hydrologic connection between the three-lake complex and the peat bog, which was particularly evident in the spring-summer period, when water levels raised both in the lakes and in the bog massif. No riverbed tributaries or drains, including hidden ones, were found in the mentioned lakes (nos. 1, 2 and 3). These geographical features could prevent contamination of the adjacent water bodies with oil products during remediation the lakes from oil.

The adjoining territory of these three lakes was subjected to anthropogenic influence: e.g. deforestation, exploration and drilling of oil wells, accumulation of drilling slimes, followed by operation of oil wells and construction of interfield roads, water ducts, pipelines for pressure retention and removal of extracted oil, creation of the electric power lines, etc.

In the summer of 2013, the works were conducted to clean up the bottom sediments of the lakes. The nearly full excavation of bottom sediments of lakes nos. 1, 2, 3 from a depth of ~1 m was carried out by a suction dredge; the total volume of excavated excessively damp peat was 45441.6 m^3. The oil that rose to the water surface during the dredging of bottom sediments was collected, removed and utilized.

The excavation of bottom sediments by the suction dredge resulted in the formation of working pulp (the mixture of solid-phase organic, organo-mineral and mineral particles with water), which was pumped under pressure into geotextile tubes for dewatering. In total, 44 geotubes were filled, the length of the tubes varied in the range 17.5 m to 55 m. Two types of flocculating agents, i.e. Praestol 852 and Praestol 655 with the optimal effective dose of 1.6–2.0 kg/ton were added to the pulp, to compact the pulp with the high content of oil products.

Figure 1 presents the technological scheme of the remediation procedure. The geotubes were placed in two rows above one another for space saving and facilitating the leakage of the released water from geotubes in the bottom row. The water flowing out from the geotubes was collected in a specially constructed pool where natural remediation of oil products proceeded.

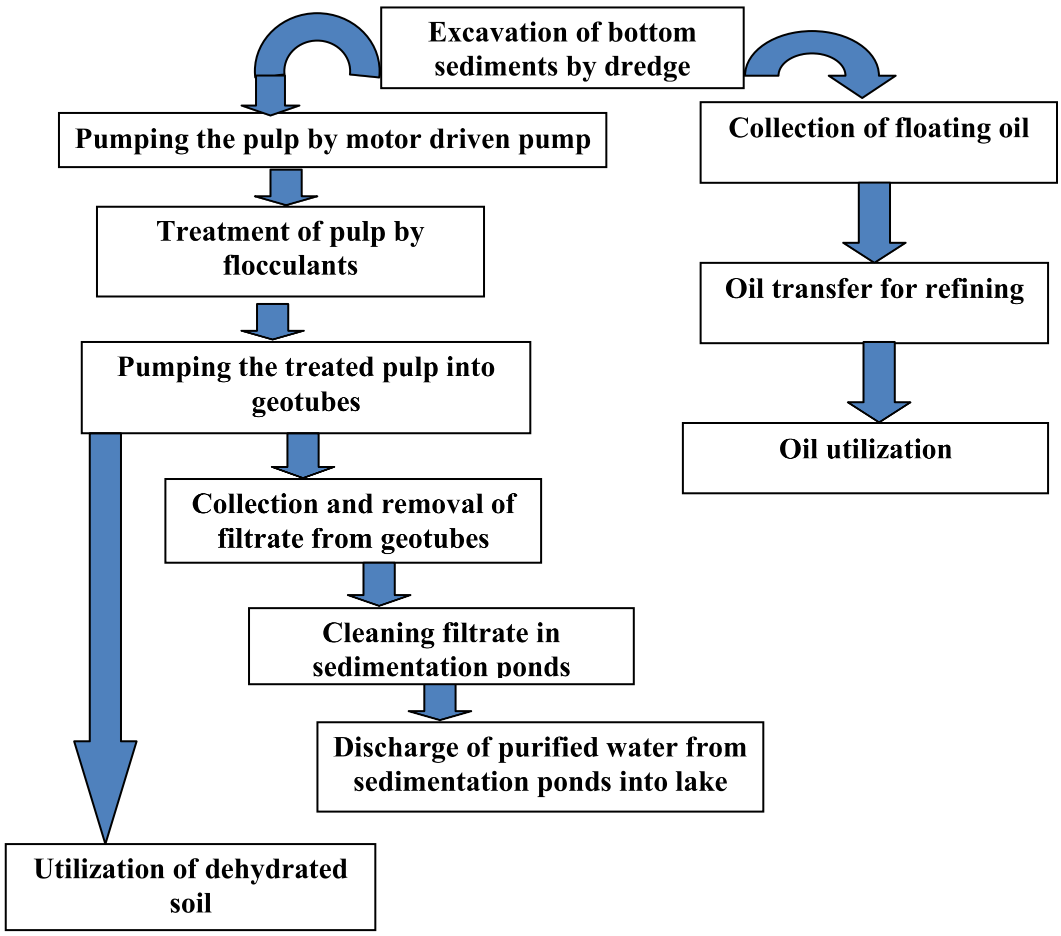

Fig. 1. Technological scheme for remediation of bottom sediments of three lakes polluted with oil.

A bacterial biopreparation MD-dry (with total bacterial count of 10^{11} CFU/kg) was added in the amount of 22.5 kg into geotube no. 1 to accelerate oil degradation. Then, all the geotubes filled with the pulp containing oil-polluted bottom sediments from the three lakes were kept for 2 years, being exposed to freezing and thawing cycles following the change of seasons in the Nizhnevartovsk district, KhMAO-Yugra. In late September, 2015, 14 out of 44 geotubes were randomly selected for sampling from both top and bottom rows to evaluate the quality of dewatering and remediation of bottom sediments in the geotubes. The samples were found to be quite representative; therefore, the results of careful examination of bottom sediments from 14 geotubes were extrapolated to those from all other geotubes. The averaged samples of dried bottom sediments (hereinafter, soil) were taken from 4 points (2 top and 2 bottom samples) using a 2-m screw sampler out of the 14 geotubes (Fig. 2).

1 2 3

Fig. 2. (1) Geotubes placed on treating area; (2) and (3) Non-uniformly distributed oil pollution in the soils from geotubes.

The residual oil content, pH value, humidity level, the content of soluble nitrogen and phosphorus forms, the total count of microorganisms, biological activity and phytotoxicity of soils were measured in soil samples collected from the geotubes.

The soil was pulled out of the geotubes and taken from the middle of each portion at three points (the total amount of ~1–1.5 kg), then thoroughly mixed and ≈500 g of each sample was picked out for analyses. The soil samples from geotubes represented compacted peat of brown and dark brown color, with a weak petroleum odor. A part of each sample was air-dried, mixed by a mixer, and used for chemical and agrochemical analysis. Smaller samples were taken from the remaining part of the soil for microbiological, agrochemical and biochemical analyses; larger samples of the remaining part were taken for testing soil phytotoxicity.

The quantitative analysis of hydrocarbons (HC) in the soils after dewatering and in the initial bottom sediments contaminated with oil was carried out by the gravimetric method. Each sample was dried up at 75°C, milled to shallow particles, and adjusted to a constant weight at 105°C. Then, the samples (≈3 g) were extracted in the Soxhlet with boiling chloroform. Chloroform extracts were dried in weighed containers. Each sample of the dried chloroform extract (≈20 mg) was fractioned on a mini-column with silica gel cartridges (BioKhimMak, Russia) at normal atmospheric pressure by sequential washing (4 times, 1 mL) with hexane, benzene and ethanol-benzene mixture (1 : 1). Each fraction from the column was collected in the vial and evaporated at 75°C, then adjusted to the constant weight at 105°C and weighed on the analytical balance. The content of total petroleum hydrocarbons (TPH), aromatic HC and resinous-asphaltene fractions was calculated from percentage of the dried chloroform sample. The amount of non-HC fraction (the oxidized complexes) remaining on the column was calculated as a difference of weights of final fractions and the initial dried chloroform extract.

Gas chromatographic (GC) analyses of the hexane fractions obtained by column chromatography were performed with a CrystalLux 4000m gas chromatograph (MetaKhrom, Russia) using the NetChrom V2.1 program, with a OV-101 column, of 50 m in length and 0.22 mm internal diameter, with a phase thickness of 0.50 microns and FID detector, at the temperature of the detector and the evaporator of 300°C and 280°C, respectively. The gradient was from 80 to 270°C and the rate of temperature elevation was 12°C/min. The carrier gas was nitrogen, the analysis time was 45 min. Injected sample volume was 1 ml. The concentration of the used solutions of reference compounds (undecane, dodecane, tetradecane and hexadecane) was 5 μg/μL for each compound.

HPLC analyses were carried out using Knauer HPLC instrument (Knauer, Germany) with an ultraviolet detector and a Diasphere 110-C18 reversed phase column for HPLC (250 mm length, 4 mm diameter, grain size 5 microns). The samples for HPLC analysis were prepared after drying of hexane fractions, followed by extraction with 1 mL of acetonitrile during 20 min under shaking, and then analyzed. Phenanthrene, pyrene and benzo(e)pyrene were used as external standards in concentrations of 10 μg/μL for each substance in acetonitrile.

The pH and humidity of soil samples were determined by the standard methods. The quantitative determination of soluble nitrogen and phosphorus in salt extractions from the soils was performed by the colorimetric method using a Shimadzu UV-1202 spectrophotometer (Shimadzu, Japan) at the wavelengths of 578 nm and 860 nm, respectively. The fermentative activities of the soils after dewatering the geotubes and the initial bottom sediments polluted with oil (towards dehydrogenase, peroxidase urease and cellulase) were determined by the colorimetric method using the Shimadzu UV-1202 spectrophotometer.

Microbiological analyses were performed by the classical methods using elective solid nutrient media in Petri dishes with ten-fold dilutions for the identification of ammonifying microorganisms, actinomycetes, pseudomonas, oligotrophic bacteria and micromycetes. The most probable number of microorganisms (MPN) was determined on aerobic count plate Petrifilm^{tm} (3M, USA) and the amount of HC oxidizing bacteria (HCO) was determined in the modified liquid medium (pH = 7.0) with crude oil as the sole carbon source (g/l):

Na_2CO_3 – 0.1;	$CaCl_2·6H_2O$ – 0.01;	$MnSO_4·7H_2O$ – 0.02;
$FeSO_4$ – 0.01;	$Na_2HPO_4·12H_2O$ – 4.0;	KH_2PO_4 – 1.0;
$MgSO_4·7H_2O$ – 0.2;	NH_4Cl – 2.0;	NaCl – 5.0.

The experiments to determine soil phytotoxicity after using the geotube technology for remediation of oil-polluted bottom sediments from the three lakes were carried out under laboratory conditions.

The analyses were performed with obligatory statistical processing of the results, to obtain reliable information about the remediation of bottom sediments polluted with oil in the geotubes which was compared to the data for the initial oil-polluted bottom sediments.

The samples collected from the appropriate geotubes are designated as Tube 1, Tube 2, etc. in the tables and figures.

RESULTS AND DISCUSSION

The chemical analysis of the soil samples under study demonstrated a 10–11-fold decrease in the Total Extractable Material (with Chloroform) (TEM) in the geotubes compared to the initial oil pollution.

The estimation of degradation rate of each hydrocarbon fraction of the samples from the geotubes, (both by indigenous microorganisms initially presented in the sediments and by the microorganisms that propagated in the soils for 2 years), showed that the content of TPHs, aromatic hydrocarbons, resin and asphaltene fractions in dehydrated bottom sediments (the soil samples from the geotubes) decreased by 80.6–97.5%, 64.6–92.5%, and 45.2–77.1%, respectively. The content of oxidized substances (unrelated to hydrocarbons) decreased by 48.4–86.5% (Fig. 3).

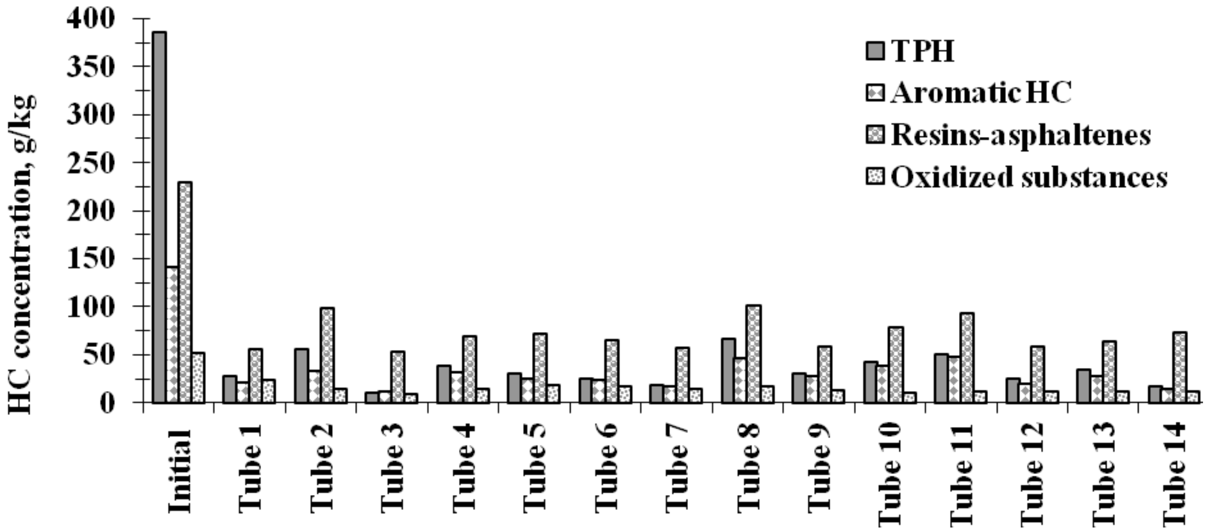

Fig. 3. Changes in fraction composition of the soil samples after 2-year period of geotube-assisted dewatering procedure of bottom sediments from three lakes.

The results demonstrate an intensive degradation of TPHs resulting from dehydration of bottom sediments in the geotubes. This process is apparently induced by indigenous microorganisms, as well as caused by the removal of relatively light water-soluble hydrocarbon fractions released through the geotube fabric and leaked out into sedimentation ponds. The process of HCs degradation was active in all geotubes, especially in geotubes nos. 3, 7 and 12.

Unfortunately, degradation of oil pollution proceeded nonuniformly in various geotubes, probably, because of the non-uniform distribution of bottom sediments that were pumped from the lake bottoms into the geotubes. Most likely, it was impossible to mix them thoroughly and uniformly by applying the filling procedure. Figure 2 shows the non-uniform distribution of oil pollution in soils in the geotubes.

The GC-analysis of the hexane fractions of hydrocarbons from geotube soils confirmed the results of gravimetry (Fig. 4).

The HPLC analyses of polyaromatic hydrocarbons (PAHs) possessing carcinogenic activity revealed their almost complete absence in the soils from geotubes, except for the soil from geotube no. 1. All samples from this geotube, where the MD bacterial biopreparation was added, demonstrated a peak with the retention time similar to that of benzopyrene. Its concentration was low and the emergence of this peak is not found to be something special. Benzopyrene is occasionally revealed in bioremediated soils when biopreparations are applied for the remediation of soils polluted with oil, but this compound can be later utilized by microorganisms.

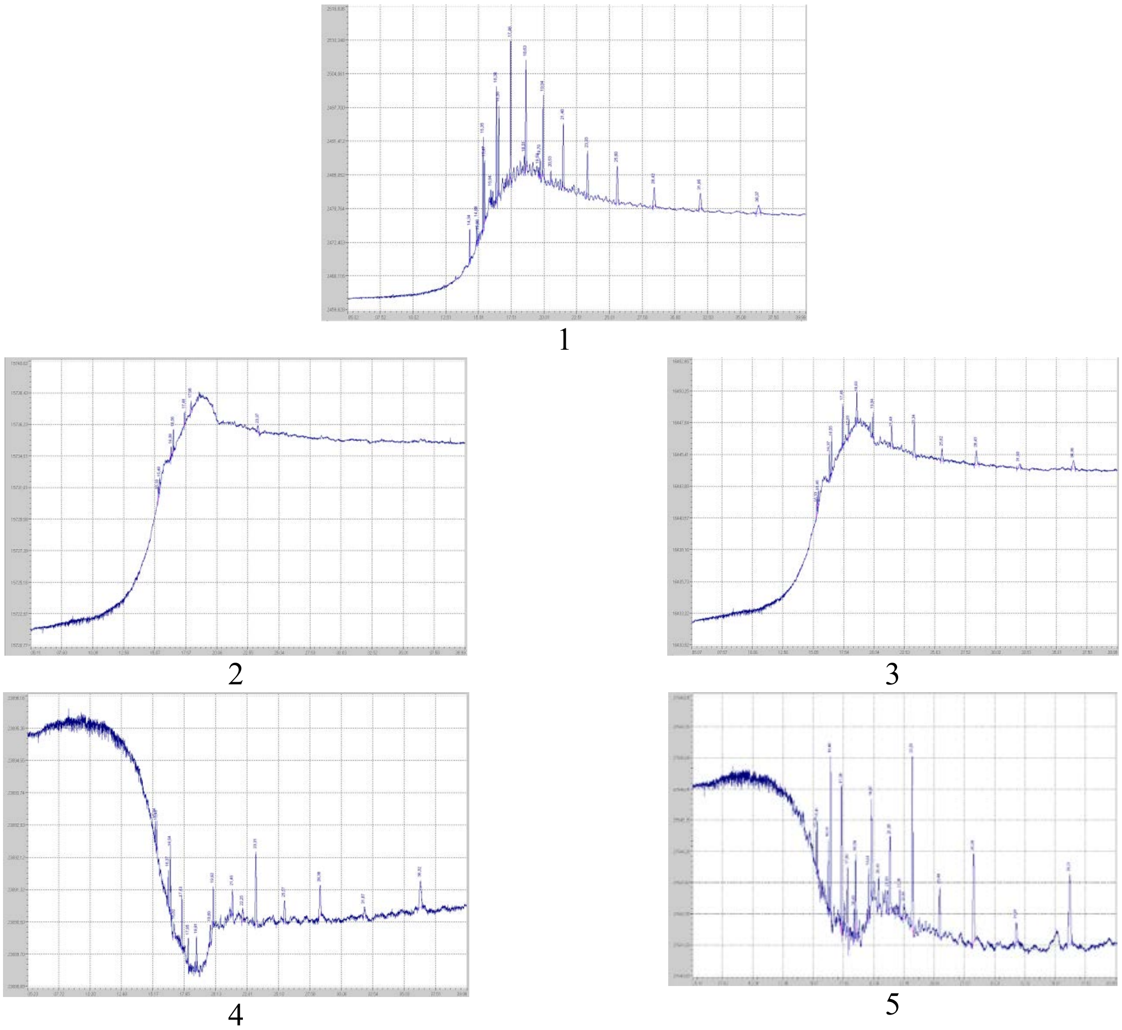

Fig. 4. The GC-analysis results for TPHs: TPHs in the initial bottom sediments (1); TPHs in the soil samples from geotube no. 1 (2 – top, 3 – bottom); TPHs in the soil samples from geotube no. 7 (4 – top, 5 – bottom).

The agrochemical analysis (Fig. 5) of the initial bottom sediments and geotube soil samples showed acidic pH values (from 4.69 to 5.90) for nearly all samples. The average humidity of soils after 2 years of dewatering in geotubes was 80.0–87.9%.

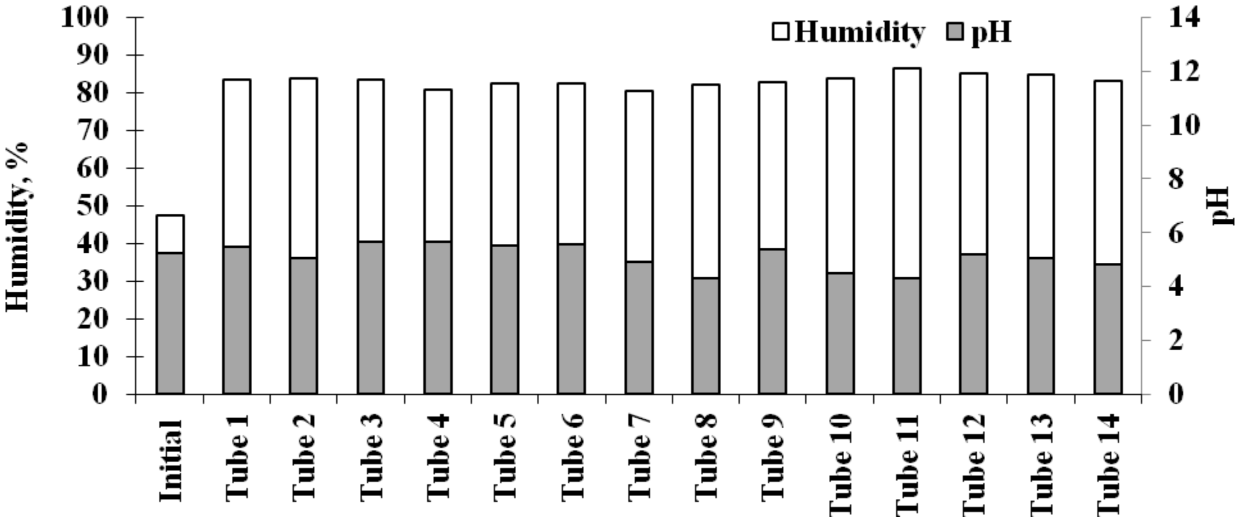

Fig. 5. Changes in pH and humidity of soil samples in geotubes compared to the initial bottom sediments.

The amount of ammonium nitrogen found in geotube samples (19.5–62.7 mg/kg of soil) was ~2-fold higher compared to the initial oil polluted sediments (Fig. 6). The content of soluble phosphates varied in the range of 110.6–308.1 mg/kg for geotube soils, i.e., ~1.5-fold higher than the phosphate content in the initial bottom sediments (Fig. 6). Thus, the agrochemical analysis of the remediated soil samples showed occurrence of active biological processes in the geotubes compared to the initial polluted bottom sediments.

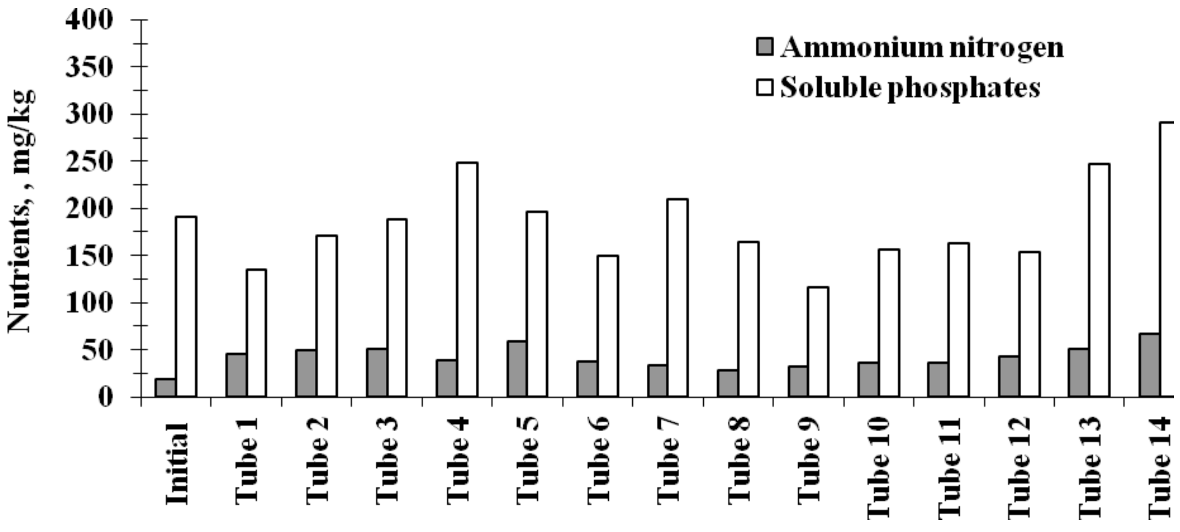

Fig. 6. Changes in nutrients in soil samples in geotubes compared to the initial bottom sediments.

Microbiological assays of the initial bottom sediments and geotube soils revealed that almost all the samples (with very few exceptions) contained several species of *Micromycetes* (*Penicillum*, *Aspergillum*, and *Mucorales*) along with *Actinomycetes* (stellate colonies, often growing in agar), including *Rhodococcus*. Other bacterial species, e.g., *Pseudomonas*, were also found.

With regard to the type of nutrition, there were found heterotrophic microorganisms utilizing nearly all organic substances including HCs; specific hydrocarbon-oxidizing bacteria utilizing HCs as the sole carbon source; and oligonitrophilic bacteria growing in a nitrogen-free medium and using nitrogen from the atmosphere.

The MPN values of heterotrophic microorganisms in the soil samples from geotubes varied from $4.5 \cdot 10^4$ to $5.7 \cdot 10^8$ CFU/g of soil. The number of HC-oxidizing cells (HCO) varied from $6.1 \cdot 10^2$ cells/g to $5.4 \cdot 10^6$ cells/g in geotubes' soils, which was higher by 2–3 orders of magnitude than HCO level of the bacteria in the initial sediments polluted with oil. However, we observed no regularity in the distribution of different kinds of microorganisms in the samples taken from the top and the bottom parts of the geotubes.

The biological activity testing revealed low activity only in the initial bottom sediments polluted with oil (Table 1). The dehydrogenase and peroxidase activities in the geotube remediated soil samples were 1.6–6.0-fold and 3.4-fold higher compared to the initial bottom sediments, respectively. The maximum dehydrogenase activity was observed in the soil sample from geotube no. 1, where the bacterial oil-degrading MD-dry biopreparation was introduced together with the sediments. However, the similarly high activity was detected in the soils from geotubes nos. 7, 9 and 10, where the biopreparation had not been added.

Table 1. Peroxidase, dehydrogenase, urease and cellulase activities in soil samples from geotubes compared to the initial bottom sediments

Tubes	Peroxidase activity, mg Quinone/1 g soil/30 min	Dexydrogenase activity, mg TPF/10 g soil/24 h	Urease activity, mg NH4/10 g soil/24 h	Cellulase activity, mg Glucose/10 g soil/46 h
Initial pollution	26.1 ± 1.5	0.6 ± 0.1	5.5 ± 0.4	2.0 ± 0.3
Tube 1	82.7 ± 3.2	3.7 ± 0.4	9.4 ± 0.8	6.0 ± 0.5
Tube 2	75.6 ± 2.3	1.9 ± 0.1	9.2 ± 0.4	7.2 ± 0.4
Tube 3	75.8 ± 3.3	2.4 ± 0.2	14.0 ± 0.5	6.7 ± 0.3
Tube 4	77.6 ± 2.1	1.7 ± 0.1	11.5 ± 0.6	7.4 ± 0.5
Tube 5	73.5 ± 2.3	1.8 ± 0.2	9.9 ± 0.4	9.9 ± 0.6
Tube 6	80.5 ± 3.4	1.6 ± 0.1	8.7 ± 0.3	7.5 ± 0.5
Tube 7	96.1 ± 4.5	3.0 ± 0.3	10.4 ± 0.6	7.7 ± 0.6
Tube 8	76.7 ± 3.2	1.3 ± 0.1	10.7 ± 0.6	7.7 ± 0.7
Tube 9	106.7 ± 5.6	3.0 ± 0.2	12.9 ± 0.7	6.6 ± 0.5
Tube 10	90.4 ± 5.2	2.6 ± 0.2	10.9 ± 0.7	7.3 ± 0.4
Tube 11	77.0 ± 3.6	1.8 ± 0.1	10.1 ± 0.6	7.6 ± 0.3
Tube 12	86.6 ± 4.2	1.2 ± 0.1	7.8 ± 0.4	7.9 ± 0.5
Tube 13	92.7 ± 5.1	1.4 ± 0.1	7.2 ± 0.3	8.2 ± 0.6

The activities of urease and cellulase were 3–4-fold higher in geotube soil samples compared to the same activities in the initial polluted sediments. These results confirmed the fact that biochemical processes occurred due to the development of microorganisms in soils of geotubes.

The phytotoxicity of the initial polluted sediments and the soils from 14 geotubes was tested using two-step seed germination procedure. The seeds of garden radish of Rubin grade were used as a test object. The soil used as a control for germination capacity of the seeds was taken from the lawn near the Faculty of Biology, Lomonosov Moscow State University. After 2 weeks, sprouted and hatching seeds were counted. All soil samples from the examined geotubes showed no detectable phytotoxicity with 53–100% of the seeds sprouted. The soils taken from the top layers of geotubes usually showed the higher percentage of the seed germination compared to the soils from the bottom layers.

Thus, our study has shown that the technology for dewatering bottom sediments from lakes polluted with oil using geotube technology is quite applicable for remediation of oil pollution and reduction of phytotoxicity of the bottom sediments. The dewatered soils can be used for reinforcing riverbanks, making hummocks, as diluents for remediation of polluted lands, as a restored soil for mechanically disturbed lands, for landscape gardening in urban settlements, and for slope protection in road construction [25].

The geotube technology can compete at cost with the remediation of bottom sediments from HC pollution with the technologies using compressors or aerators for long-term mixing of thick water layers and enrichment of water bodies with atmospheric oxygen or/and with using biological booms and preparations of oil-oxidizing microorganisms. With regard to the efficiency, the duration and probably the cost, the geotube technology is no more expensive than the application of turbicides technology for purification of bottom sediments from oil. The results also demonstrate that it is not recommended to use oil-oxidizing biopreparations together with the flocculant Praestol simultaneously with the pumping of bottom sediments into geotubes, since the addition of biopreparation (geotube no. 1) was advantageous neither for the HC degradation, nor for the enhancement of biological activity in the geotubes soils in (except for the dehydrogenase activity), nor for the MPN of different species microorganisms, nor for the content of biogenic elements. Indigenous microorganisms getting into the geotubes from bottom sediments and air while geotubes were filled with the pulp, successfully cope with remediation of bottom sediments from oil pollution. Thus, the decontaminated bottom deposits from geotubes can be used for environmental enhancement practices (wetland habitat creation).

CONCLUSION

In summary, the conducted research showed that dewatering geotube technology for remediation of oil-polluted bottom sediments of water bodies resulted in the decease of the concentrations of TPHs by 81–98% after two years of applying geotube-assisted procedure. The remediated soils from geotubes were enriched with various species of microorganisms, including those capable of using nitrogen from atmosphere. The soil samples from geotubes exhibited peroxidase, dehydrogenase, urease and cellulase activities and had no acute phytotoxicity.

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