Nature-based solutions for contaminated site remediation: Key principles and a practical case

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Abstract. The article considers opportunities applying nature-based solutions to remediate oil-contaminated sites. It is suggested using such industrial wastes as brewer's spent grain, beet pulp, and lignin as structurers. It is demonstrated that structurers bearing such genes as Bacillus, Arthrobacter, etc. perform as active petroleum degraders. It was found out that the hydrocarbon removal rate ranged from 90 to 99% for all structurers studied. It is recommended using 1% of the lignin-based degrader to reduce hydrocarbon content in soils preparing them to the future phytoremediation.

1 Introduction

Over the past decade, numerous scientific and popular science publications have explored nature-like technologies and nature-based solutions. While these concepts are closely related, we believe they are not identical. Nature-like technologies involve developing artificial materials and devices in such a way that the mechanism of their operation is similar to processes in nature. These technologies include, but are not limited to, nano- and biotechnologies (e.g. biological wastewater treatment processes), and even artificial intelligence. Nature-based solutions focus on preserving, restoring, or improving natural ecosystems while providing benefits to humans. Such benefits include halting biodiversity loss, mitigating the negative effects of flooding, reducing soil erosion, and improving water and soil quality, all while providing food, fuel, medicine, and other resources.

This article analyses approaches to developing and implementing nature-based solutions and assesses potential applications of such solutions to improve soils contaminated with petroleum products, addressing a critical issue in the current environmental and climate agenda.

2 Materials and methods

In this study, interdisciplinary research approaches were employed, including an analysis of the experience in using nature-based solutions for restoring man-modified natural systems, limiting greenhouse gas emissions, and adapting to climate change.

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For the experimental part of the study, soils contaminated with petroleum products were collected from three mud pits at a hydrocarbon field located in the Orenburg region. During the experiment, a hydrocarbon degrader containing strains of microorganisms was used.

3 Results and Discussion

3.1 Developing and implementing nature-based solutions: Key principles

In current discussions on nature-based solutions, experts worldwide mainly focus on the potential and practical examples of using these tools for adapting to climate change. Island countries, coastal regions, and areas experiencing major fluctuations in river, lake, and reservoir levels strive to use nature-based solutions in combating floods [1-2].

Regarding mitigation, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) estimated in 2019 that by the year 2023, using nature-based solutions might help to achieve over 35% of the greenhouse gas emissions reductions needed to meet the Paris Agreement goals [3].

Regardless of regional or industrial characteristics, nature-based solutions always involve: (1) improving the condition of man-modified natural systems while reducing the negative environmental impact, and (2) enhancing the resilience of these systems while producing socio-economic benefits or at least preventing or reducing damage, such as environmental pollution [4-6]. Resilience, in this context, refers to a system’s ability to withstand impacts and return to its original or near-original state after major disturbances. Most publications discuss climate resilience, defined as the ability to “anticipate, prepare for, and respond to hazardous events, trends, or disturbances related to climate. Improving climate resilience involves assessing how climate change will form new, or alter current, climate-related risks, and taking steps to better cope with these risks.” [7-9] One of the well-known known examples of nature-based solutions providing for both (1) restoration of man-modified systems and (2) improving climate resilience, is rewatering of drained peatlands. Though not ideal, this solution helps preventing fires, reducing greenhouse gases emissions, and gradually restore biodiversity of peatland sites [10-11] (Figure 1).

Fig. 1. Peat fire (2010) (a) and a restored (rewatered) peat site (2024) (b) in the Meshchera Lowlands (Russia).

In the context of contaminated site remediation, a significant portion of research focuses on remediating brownfields – urban areas previously occupied by industrial facilities, cargo ports, or landfills [12]. According to [13], "remediation is the improvement of a contaminated site to prevent, minimize, or mitigate damage to the environment and human health". City and regional leaders, with public participation, make decisions on turning contaminated areas into residential zones, recreation areas, parks, stadiums, etc. This process involves determining the extent of necessary soil cleanup (or removal) and designing a new landscape, often using green remediation materials, bio- and phytoremediation approaches, etc. [14-15].

Considerable attention is given to restoring areas contaminated with petroleum products [16-19]; they include oil-producing areas [20], oil spill sites [21] (including agricultural areas [22]), and urban (primarily industrial) areas.

Quantitative data on petroleum-contaminated land in Russia is quite fragmented. At the end of 2022, oil and gas companies reported the total area of disturbed lands (637, 620 ha) and reclaimed lands (41,680 ha) [23]. However, the proportion of reclaimed lands that included petroleum-contaminated lands and the total area of petroleum-contaminated lands needing remediation remain unknown. A more rigorous approach is demonstrated by Canada, a country playing a major role in developing standards and guidelines for contaminated site management [24-25]. Canada provides detailed statistical data on contaminated areas (including those affected by petroleum): the Federal Contaminated Sites Inventory includes 6.444 sites contaminated with hydrocarbons, each with coordinates, approximate sizes, population within a 50 km radius, and estimated remediation costs. However, the total area is not specified. Both Russian and Canadian experts note that hundreds of thousands of hectares of land in oil-producing areas and industrial zones contaminated with hydrocarbons and other substances require remediation to varying degrees.

In all cases, the authors of studies and practical guidelines emphasize that at the initial (preparatory) stages it is necessary to: (1) study the condition of contaminated areas, (2) select (and develop new) methods for reducing pollutant content (focusing on hydrocarbons in this work) effective under specific conditions (including climate), and (3) field-test the selected methods [24-25].

3.2 Microbial degradation of petroleum hydrocarbon contaminants: A practical case

The most effective methods for remediating petroleum-contaminated soils are biological ones. These methods typically involve the simultaneous introduction of (1) microorganisms that act as hydrocarbon degraders and (2) structurers, which also serve as high-quality sorbents for hydrocarbons [26-28].

Ex situ bioremediation involves removing a layer of contaminated soil and subsequently cleaning and treating it outside the contaminated area. *In situ* bioremediation, on the other hand, involves cleaning soils without removing them from the contaminated area. This is done by stimulating native microflora or introducing necessary strains of microorganisms, along with organic additives, followed by soil treatment processes such as plowing. The key principles include (1) biostimulation and (2) bioaugmentation. The former involves stimulating indigenous microorganisms already present in the soil, which are unable to process pollutants due to unfavorable conditions or a lack of nutrients. The latter involves the introduction of microorganisms acting as petroleum degraders. These microorganisms are isolated from natural sources and modified under laboratory conditions.

To enhance the ability of microorganisms to degrade hydrocarbons, auxiliary measures are employed. These include loosening and plowing to prevent the formation of a hydrophobic film and improve aeration, introducing organic or mineral fertilizers or enzymes to stimulate microbial activity, adding sorbents, liming or adding gypsum to neutralize soil alkalinity or acidity, etc.

Structurers enhance soil stability, improve drainage and water retention, and reduce erosion and degradation. They also increase soil water capacity, porosity, and the hydrophilicity of soil-forming rocks. Structurers can be of natural origin (such as peat, sawdust, and sphagnum moss) or artificial (such as various polymer sorbents).

Additionally, products such as food processing waste, brewery waste, and waste activated sludge can be used as structurers. This study focuses on brewer's spent grain (BSG), beet pulp, and lignin.

BSG is the main waste category in the brewing industry, accounting for about 85% of its solid waste. The dry matter contains proteins (19-28%), fats (8.2-12%), cellulose (17.5-20%), non-nitrogenous extractives (41-55%), and minerals (4-5.5%). BSG is chemically inert and has a surface suitable as a matrix for immobilizing various types of microorganisms.

A by-product of sugar beet processing, beet pulp is a valuable carbohydrate source with high fiber and pectin content, which is used as fodder. However, it is recommended to use it only in small doses, and sugar producers still need to find ways to utilize or dispose beet pulp.

A complex polymer found in wood and plants, lignin is produced in large quantities as waste by pulp and paper mills and other industries implementing hydrolysis processes. Hydrolyzed lignin waste accounts for 30-40% of the original raw wood.

According to statistical data, waste generation in 2022 reached approximately 6 million tons for beet pulp and 1 million tons for BSG. However, the scale of their utilization is much smaller, leading to waste accumulation and the need for landfill disposal [23].

The Federal Project titled "Circular Economy" aims to increase the use of secondary raw materials in agriculture from 25% in 2024 to 50% by 2030.

The goal of our bioremediation experiment was to assess the potential of using large-scale organic wastes (lignin, BSG, and beet pulp) as structurers in combination with microorganisms for remediating petroleum-contaminates soils.

For the experiment, petroleum-contaminated soils were collected from three areas in the Orenburg region. A qualitative analysis of the samples confirmed the similarity in soil composition across these areas. Chromatograms of the samples (shown in Figure 2) indicate that the composition is almost identical, with the quantitative content of petroleum hydrocarbons ranging from 12-21% (mass).

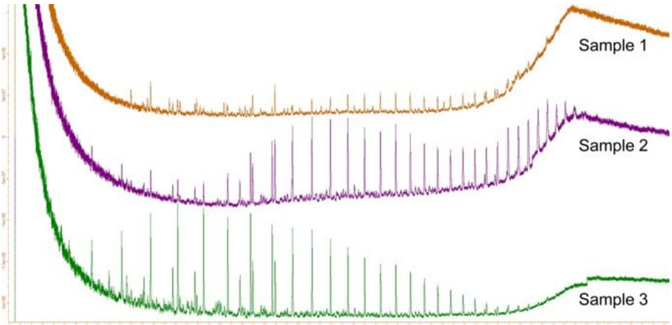

Fig. 2. Chromatograms of petroleum-contaminated soil samples.

During the experiment, a petroleum degrader was used containing the following microorganisms: *Bacillus atrophaeus*, *Pseudomonas spp.*; *Pseudomonas putida*; *Arthrobacter sp.*; *Microbacterium flavescens*; *Bacillus megaterium*.

The experiment lasted for three months, with humidity maintained at 60-70% through periodic watering. At the end of the experiment, the residual content of petroleum products was measured. The results are shown in Table 1.

In the experiment, the hydrocarbon removal rate ranged from 95 to 99% for lignin, from 89 to 97% for BSG, and from 90 to 97% for beet pulp depending on the structurer share. The highest removal rate was achieved by adding structurers in small quantities (~1%), indicating that adding structurers in high concentrations (5-10%) is impractical.

Table 1. The efficiency of using structurers in petroleum-contaminated soil bioremediation.

Structurer share in contaminated samples, % mass	Hydrocarbon removal rate, %		
	Lignin	BSG	Beet pulp
1	99.4	97.6	93.5
2	96.6	95.2	97.1
5	95.3	89.1	90.8
10	96.2	94.5	93.9

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Based on these results, pilot industrial tests were organized for the bioremediation of petroleum-contaminated soils using lignin. These tests shall prove if bioremediation of significant petroleum contaminated sites can be run *in situ* without removing soils them from the contaminated areas. The oil field operator is expected to decide on scaling up the application of the developed technique within the next one to two years.

4 Conclusion

The research conducted demonstrates that nature-based solutions are consistently aimed at (1) improving the condition of man-modified natural systems while reducing negative environmental impacts, and (2) enhancing the resilience of these systems while preventing or mitigating damage from environmental pollution.

The experiment on petroleum-contaminated soil bioremediation using small quantities (1-2%) of large-scale waste from the food industry (lignin, BSG, and beet pulp) exemplifies a nature-based solution. This solution also promotes a circular economy by repurposing waste to achieve environmental goals.

In the context of international approaches to designing and implementing nature-based solutions, a number of conclusions can be drawn. (1) Bioremediation of petroleum-contaminated soils using lignin improves the condition of areas disturbed by upstream and downstream sites of petroleum industries, reducing the hydrocarbon content in soils by more than 95%. These areas begin actively participating in nutrient cycles, limiting greenhouse gas emissions (primarily methane) [29]. (2) Bioremediation using structurers and microorganisms forms favorable conditions for subsequent phytoremediation, leading to the transformation of anthropogenic deserts into restored landscapes with enhanced resilience. (3) In terms of socio-economic benefits, this approach facilitates a gradual reduction in the amount of waste (in particular lignin) accumulated in landfills and decreases the area of disturbed land. Using industrial waste (lignin) to remediate contaminated industrial sites is a sign of the circular economy approaches, which is important from the economic, environmental and social points of view.

A promising area of future research involves selecting species for subsequent phytoremediation, with careful consideration of climatic factors.

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