

CHEMICAL APPROACHES TO MONITORING AND EVALUATING THE BIOREMEDIATION OF OIL CONTAMINATED DESERT SOILS: A REVIEW OF MODERN METHODS

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Abstract. Oil spills in deserts and other arid regions, including Kuwait, the Arava Valley in Israel, and Western Kazakhstan, have created extensive areas of chronically contaminated soil whose remediation is constrained by low moisture, nutrient deficiency, salinity, temperature fluctuations, and the ageing of petroleum residues. The purpose of this review is to systematise modern chemical and physicochemical approaches to monitoring and evaluating the bioremediation of oil-contaminated desert soils and to identify indicators suitable for an integrated, risk-based assessment. The review considers the composition of crude oil as a multicomponent contaminant, including total petroleum hydrocarbons, polycyclic aromatic hydrocarbons, BTEX compounds, resins, and asphaltenes, as well as the soil properties that control their mobility, bioavailability, persistence, and toxicity. Natural attenuation, biostimulation, bioaugmentation, biopiling, and phytoremediation are compared with chemically enhanced treatments based on Fenton and persulfate oxidation, nanomaterials, electrokinetic processes, microwave heating, and bioelectrochemical systems. Particular attention is paid to combining chromatographic and spectroscopic determination of petroleum fractions with soil respiration, microbial and functional-gene indicators, ecotoxicological tests, and remote-sensing observations. Hyperspectral data and artificial-intelligence methods are discussed as tools for mapping contamination and tracking spatial changes during remediation. Sorbent materials, including shungite-based compositions relevant to Kazakhstan, are considered for the preliminary containment and removal of oil. The analysis shows that a decrease in total petroleum hydrocarbons alone is insufficient to demonstrate environmental recovery because persistent aromatic fractions and residual toxicity may remain.

Keywords: oil-contaminated desert soils; bioremediation; total petroleum hydrocarbons; polycyclic aromatic hydrocarbons; chemical oxidation; sorbents; environmental monitoring; remote sensing

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1. Introduction

Oil spills in deserts and other arid regions (for example, Kuwait, the Arava Valley in Israel, Western Kazakhstan) have led to extensive areas of chronically contaminated soil [1, 2]. Extreme environmental conditions act as a natural barrier to the microbial degradation of hydrocarbons, thereby limiting the potential applications of bioremediation. At the same time, many desert soils are inhabited by communities of microorganisms that are adapted not only to significant seasonal changes in temperature and salinity, but also to daily cycles of wetting and drying. These soils provide a habitat for indigenous microorganisms that degrade hydrocarbons. In addition, there are native plants which, when properly managed, possess the ability to oxidise oil.

From a chemical standpoint, petroleum contamination is not a single parameter but a complex multicomponent mixture of aliphatic, aromatic, resin-asphaltene fractions and heteroatomic compounds, each with its own resistance to degradation, toxicity, and mobility in the soil profile [3, 4]. This is precisely why a reliable assessment of remediation effectiveness cannot rely solely on the integral indicator of total petroleum hydrocarbons (TPH) - it requires a combination of:

- chemical indicators (total petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), BTEX, as well as functional groups recorded by IR and chromatography-mass spectrometry methods);
- biological indicators (abundance and composition of microorganisms, enzymatic activity, plant response);
- physical and remote-sensing methods (spectral indices, satellite mapping) [1, 5, 6];
- strategies for the bioremediation of desert oil spills (microbial remediation, phytoremediation, biopiling, as well as chemically enhanced and combined methods).

The purpose of this review is to systematise current knowledge on the chemical nature of petroleum contamination of desert soils, strategies for its biological and chemically enhanced remediation, and analytical approaches to environmental monitoring and assessment of remediation effectiveness - with an emphasis on the chemical component of each of the areas listed.

2. Chemical nature of petroleum contamination and physicochemical features of desert soils

2.1. *Composition of crude oil as a contaminant*

Crude oil is a mixture of saturated and unsaturated aliphatic hydrocarbons, mono- and polycyclic aromatic compounds (PAHs), as well as resins and asphaltenes containing oxygen, sulphur, and nitrogen. The ratio of these fractions determines the behaviour of the contaminant in the soil: light aliphatic and monoaromatic compounds (including BTEX - benzene, toluene, ethylbenzene, xylenes) evaporate and biodegrade relatively quickly, whereas high-molecular-weight PAHs and resin-asphaltene components have high sorption capacity, low

bioavailability, and can persist in soil for decades even after a substantial reduction in total hydrocarbon content [4, 6]. Petroleum contamination can alter not only the structure of the soil microbial community but also its metallome - the assemblage of mobile metal forms - which underscores the multifaceted nature of the chemical consequences of oil contamination and the need for a comprehensive rather than narrowly analytical assessment [7]. From an analytical perspective, the degradation kinetics of individual hydrocarbon fractions (including diesel fractions) are well described by models of bacterial growth and degradation, which allows the quantitative comparison of the effectiveness of different biopreparations and degrader strains [8].

2.2. Physicochemical characteristics of oil-contaminated desert soils

Desert and hyperarid soils are typically sandy or sandy-loam soils with low clay content, low water-holding capacity, and very low organic carbon content. In Kuwait, desert soils saturated with light crude oil can hold about 17.3% oil by mass [2, 9]. In such soils, hydrocarbons are retained in the upper layer, forming tar mats, oil lakes, or heavily contaminated horizons. Biodegradation is limited by the lack of nitrogen and phosphorus, moisture, and shade; however, indigenous hydrocarbon-degrading bacteria multiply rapidly once oil and moisture become available [2, 10–12]. Microbial diversity initially decreases and then shifts towards oil-degrading taxa such as Proteobacteria and certain Actinobacteria, accompanied by a strong long-term restructuring of the soil microbiome in contaminated arid soils [13]. Understanding these constraints and microbial dynamics is important for designing bioremediation measures and selecting appropriate monitoring indicators [2, 14, 15].

3. Bioremediation strategies for petroleum-contaminated desert soils: chemical and biological mechanisms

3.1. Microbial bioremediation and natural attenuation

A growing body of research from Kuwait and other arid regions demonstrates that indigenous microbial communities are able to remove substantial fractions of oil even from heavily contaminated soils. In desert soil saturated with 17.3% crude oil, natural bioremediation under open conditions (aeration and periodic moistening) removed 73-79% of the oil in about six months in model windrows (mini-piles); oil removal during the first month exceeded 50%. The number of indigenous degrader bacteria increased from $\sim 10^6$ CFU·g⁻¹ to $\sim 4.9 \times 10^8$ CFU·g⁻¹ during peak activity [2]. A subsequent study showed that self-cleaning proceeds effectively even at 20-30% oil contamination (super-saturated soils), with $\sim 70\%$ removal at 1-10% contamination and $\sim 50\%$ removal at 20-30% contamination over six months [10].

However, bioaugmentation with consortia of oil-degrading strains often fails to produce a significant improvement compared with indigenous communities. In the same microcosms of oil-contaminated desert soil (1.5% oil), a consortium of five strong hydrocarbon degraders did not significantly increase oil removal compared with untreated soil: $\sim 68.5\%$ removal versus 74.6%, respectively, after

six months, with no statistically significant difference [10]. Community analysis showed that indigenous species dominated in both treatment variants [10], i.e., well-adapted native bacteria are generally more effective than introduced consortia in desert soils [11, 12]. Thus, biostimulation (addition of nutrients and moisture) is generally more effective than bioaugmentation [11, 12, 15, 16].

3.2. Biopiling and biostimulation

Biopiling systems provide a controlled approach to treating excavated desert soil. A study of biopiles containing crude-oil-contaminated desert soil from Abu Dhabi compared four treatment variants: control, biostimulation (nutrients), bioaugmentation (commercial inoculant), and bioaugmentation + surfactant (Tween 80) [17]. After approximately 156 days, hydrocarbon removal reached 77% for the bioaugmentation + nutrients variant, ~55-56% for biopiles treated with surfactants, 23% for biostimulation without additives, and 4% in the control. Monitoring of CO₂ respiration showed increased activity in all treated biopiles, with faster peaks and earlier declines in the piles treated with surfactants owing to nitrogen depletion [17, 18]. Residual PAHs persisted in all treatment variants, indicating the presence of recalcitrant fractions and the need for long-term risk assessment [17].

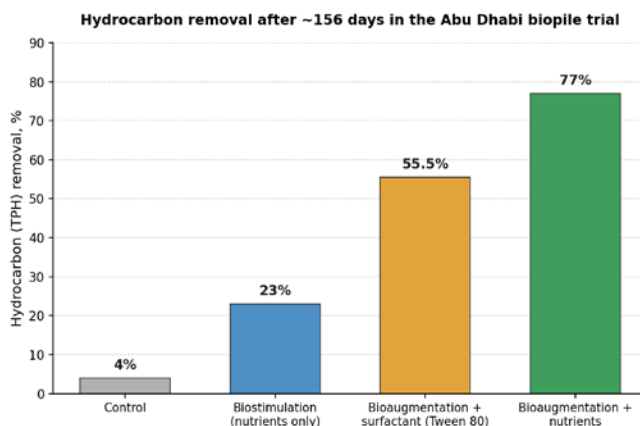


Figure 1 – Hydrocarbon (TPH) removal from crude-oil-contaminated desert soil in biopiles after approximately 156 days under four treatment regimens (Abu Dhabi biopile study) [17].

The chemical composition of the amendments applied significantly affects the outcome of biostimulation: the combined addition of nitrogen and phosphorus affects the biodegradation of different oil fractions differently, as confirmed by metatranscriptomic analysis of soil microbial communities [19]. The use of biochar as both a nutrient carrier and a sorbent simultaneously improves moisture retention and nitrogen/phosphorus bioavailability, enhancing hydrocarbon degradation and restoring soil microecological functions [19], and in some cases increases the resilience of plants growing in petrol-contaminated soils [20].

Large-scale studies at Middle Eastern desert sites show that soil excavation and biopiling (often combined with nutrient addition and irrigation) can remediate tens of thousands of cubic metres of soil to regulatory TPH thresholds within one to a few seasons [1, 14].

3.3. *Phytoremediation and plant-microbe interactions*

Desert and steppe environments are also favourable for phytoremediation using native or introduced plants. Resilient native desert plant species have been identified (for example, *Haloxylon salicornicum*, *Cyperus conglomeratus*, *Rhanterium epapposum*) that can establish on oil-contaminated sites, supporting the long-term restoration of natural vegetation. In Kuwait, the native shrub *Haloxylon salicornicum* survived and grew even in soils with 100% weathered-oil content in greenhouse experiments and showed comparable growth rates on contaminated and clean soils in field trials [21].

A field study in the Russian steppe (a low-precipitation region) compared natural and engineered phytoremediation at sites contaminated with oil (4.2-27.4 g TPH·kg⁻¹) [22]. Natural phytoremediation (spontaneous vegetation) reduced TPH content from ~13.0 g·kg⁻¹ to ~1.8 g·kg⁻¹ over five years, with decontamination exceeding 90% at some sites. Engineered phytoremediation (soil tillage, fertiliser application, and sowing of alfalfa and ryegrass) achieved a 72-90% reduction in total hydrocarbon content per year. Analysis of the root zone microflora reveals the presence of a diverse range of bacterial and fungal communities, including oil-degrading microorganisms (*Rhodococcus*, *Nocardia*, *Gordonia*, *Penicillium*), which highlights their key role in the plant root zone [12, 21].

3.4. *Chemically enhanced and combined remediation methods*

In addition to biological methods, in recent years methods have been developed that combine chemical treatment of the contaminant with subsequent or parallel microbiological degradation. Such methods are particularly relevant for persistent, weathered fractions of oil, including PAHs, which are difficult to treat using traditional biostimulation.

Pre-treatment of the soil with the Fenton reagent (Fe²⁺/H₂O₂) allows for the partial oxidation of the most stable components of weathered petroleum products, reducing their toxicity and increasing the bioavailability of the remaining fractions to the local microbiota. The effect of such combined treatment is manifested in an improvement in the soil's physico-chemical properties and a shift in the microbial community towards active degraders [23]. Following a similar principle, the use of sodium persulphate and other persulphate-based systems is demonstrated; these are capable of breaking down aromatic compounds and, when used in controlled doses, do not suppress but rather alter the functional activity of the soil microbiota. This enables further biological treatment to be carried out [24, 25].

Approaches based on the use of nanomaterials constitute a distinct field. Zinc oxide nanoparticles (nano-ZnO), applied together with plant-microbe systems (for example, involving soybean), can intensify rhizosphere metabolic processes and

accelerate the degradation of total petroleum hydrocarbons [26]. Quantum-chemical modelling (combining xTB, molecular dynamics, and density functional theory, DFT) of functionalised oxide surfaces (TiO₂, ZnO, CeO₂) makes it possible to predict, at the molecular level, their affinity for hydrocarbon molecules and their potential compatibility with microbial processes at low temperatures, opening the way to the rational selection of mineral amendments for cold desert winters [27].

Physical methods such as electrokinetic and microwave thermal treatment are also considered chemically significant tools for remediation intensification. Electrokinetic treatment combined with freeze-thaw cycles can redistribute and mobilise residual hydrocarbons in fine-grained soils, increasing the efficiency of their subsequent extraction or biodegradation [4]. Microwave thermal treatment allows selective heating of polar and conductive components of the contaminated matrix, accelerating desorption and subsequent hydrocarbon decomposition; a review of the factors and mechanisms involved highlights its promise for hard-to-reach or heavily contaminated sites [28]. Finally, bioelectrochemical systems (sediment microbial fuel cells) can simultaneously stimulate anaerobic hydrocarbon degradation and generate electrical energy, which is regarded as a low-carbon alternative to traditional means of intensifying biopiling [29]. The chemical nature of the biological intensifiers themselves is also important: novel biosurfactants (for example, trehalose tetraesters produced by *Rhodococcus erythropolis*) increase PAH bioavailability by reducing interfacial tension and emulsifying the oil phase, making them a promising addition to both biological and chemically enhanced clean-up schemes [30].

It is important to emphasise that the chemically enhanced methods listed above are generally applied not as a standalone replacement for bioremediation but as its complement - to "unlock" recalcitrant contaminant fractions and create conditions under which subsequent microbial or plant-based degradation becomes more effective.

Chemically enhanced removal also requires post-treatment verification. Fenton and persulfate oxidation may generate partially oxidised intermediates, including oxygenated aromatic compounds, aldehydes, ketones, and carboxylic acids, whose toxicity and biodegradability may differ from those of the parent hydrocarbons. Reagent addition can shift soil pH, increase electrical conductivity and sulfate or sodium loading, and alter nutrient availability; residual nanomaterials may likewise affect non-target soil organisms. Consequently, intermediate profiling, pH and salinity measurements, residual-oxidant checks, and plant or microbial toxicity assays should precede biological polishing and final acceptance of the treated soil [23–27].

4. Microbial community and molecular monitoring of bioremediation

Environmental assessment of bioremediation in desert soils increasingly relies on molecular and microbiological methods alongside chemical measurements of total hydrocarbon content.

In the hyperarid Evrona Nature Reserve (Arava Valley, Israel), high-throughput 16S rRNA sequencing [13] of soils from oil-spill sites (1975 and 2014) and nearby control plots revealed: (1) a significant long-term decrease in alpha diversity in contaminated soils compared with controls, with a stronger effect at the older (1975) spill site; (2) dominance of phyla associated with hydrocarbon degradation (Proteobacteria, Patescibacteria), and a reduction in the abundance of Actinobacteria, Chloroflexi, Gemmatimonadetes, and Planctomycetes; (3) strong shifts at the genus level, including enrichment of *Mycobacterium*, *Alkanindiges*, *Pseudoxanthomonas*, *Nocardioides*, and *Streptomyces*. These patterns suggest that long-term bioremediation monitoring in desert soils should include diversity metrics (Shannon index, OTU richness), indicator taxa of active degradation, and correlation of community changes with physicochemical soil parameters (moisture, electrical conductivity, nutrient availability) [2, 11, 13].

Studies from Kuwait show that indigenous microbial communities rapidly adapt to oil contamination and often outcompete introduced consortia: hydrocarbonoclastic communities converged over time towards highly tolerant taxa (*Dietzia papillomatosis*, *Nocardioides*, *Microbacterium*, *Alkanindiges*) regardless of dilution with other soils [2]. Bioaugmentation using microbial consortia caused a temporary change in the composition of the microbial community, but, compared with the natural microbiota, did not lead to a significant acceleration in oil degradation [10, 12]. Molecular monitoring (16S rRNA sequencing) played a key role in establishing that the introduced strains were not dominant, whilst the enrichment of rare native species contributed to bioremediation [10, 14]. These results highlight the importance of metagenomic analysis of the microbial community in environmental assessment processes: it helps to determine the stability of the introduced strains; the potential for enriching the population of native microorganisms capable of degrading substances; and the need to add nutrients [2, 11].

5. Chemical and ecotoxicological monitoring

5.1. Total petroleum hydrocarbons (TPH) and analysis of individual compounds

The main chemical parameter for assessing the effectiveness of bioremediation is the monitoring of total petroleum hydrocarbons (TPH). TPH content is measured using the gravimetric method or by IR-GC spectroscopy [12, 17, 18, 22]. In the Abu Dhabi biopile study, a 4-77% reduction in hydrocarbon content across the different treatment variants made it possible to assess the relative effectiveness of biostimulation, surfactant addition, and bioaugmentation [17]. Kinetic analysis of the degradation of individual diesel fuel fractions by indigenous strains shows that the rate and completeness of degradation depend substantially on the initial substrate concentration and strain adaptation, which allows the timing of achieving regulatory TPH values under given conditions to be predicted [8].

The comparability of TPH, PAH, and BTEX data depends strongly on sample preparation and on the analytical window of the method. Gravimetric or infrared TPH measurements provide an operationally defined bulk value, but co-extracted natural organic matter and the selected extraction solvent can reduce selectivity. Soxhlet extraction with acetone/hexane or methylene chloride/acetone is suitable for non-volatile and semivolatile hydrocarbons, whereas GC-FID resolves hydrocarbon ranges and GC-MS provides greater compound-level selectivity for PAHs. BTEX requires sealed sampling and purge-and-trap or headspace GC-MS to minimise volatile losses. Detection and reporting limits are matrix- and laboratory-dependent; therefore, studies should report the dry-mass basis, particle-size preparation, solvent composition and extraction time, cleanup procedure, surrogate and matrix-spike recoveries, calibration range, and method-specific LOD/LOQ. Results obtained with different extraction efficiencies, carbon-number windows, or detector responses should not be treated as directly interchangeable [18, 31–33].

A decrease in extractable soil concentration should not automatically be interpreted as biodegradation. Apparent removal may result from volatilization, vertical or lateral redistribution, leaching, sorption, or progressive formation of non-extractable residues. Where feasible, remediation studies should use dry-mass-normalized contaminant inventories, spatially representative replicate sampling, abiotic or untreated controls, extraction-recovery checks, and monitoring of deeper soil layers and leachate. Measurements of CO₂ evolution or other mineralization products can provide complementary evidence of biodegradation. Reporting both concentration changes and a documented mass balance prevents physical losses or reduced solvent extractability from being misclassified as biological destruction [2, 8, 17, 31–33].

Field tests under desert conditions typically use TPH threshold values (for example, 1 g·kg⁻¹) as clean-up targets in accordance with national or corporate guidelines [1, 14, 22]. However, total content alone is insufficient: residual PAHs [17] and weathered heavy fractions can persist for decades after the original spills even after a substantial reduction in TPH [13, 34]. Accordingly, monitoring of specific compounds (PAHs, BTEX, etc.) is recommended in cases where there is a risk to human health or sensitive ecosystems [1, 2, 6]; for example, in coastal sediments affected by petroleum product depots, the content of individual PAHs and the associated risks to humans and aquatic biota have been quantitatively assessed [6]. A comprehensive analysis of soil and groundwater quality in the oil-producing regions of Western Kazakhstan likewise demonstrates the need to combine chemical contaminant analysis with consideration of climatic factors when designing monitoring programmes [35]. A generalized approach to monitoring oil-contaminated soils involves a shift from the TPH method to a multi-parameter analysis of chemical and biological indicators. [36].

5.2. Soil respiration and biological activity

CO₂ release and associated parameters are widely used as criteria for evaluating bioremediation. In desert bio-piles, continuous monitoring of CO₂

revealed kinetic patterns of microbial activity: the addition of surfactants resulted in faster initial peaks; systems incorporating bio-enrichment demonstrated slower but more stable activity. [17, 18]. During the phytoremediation process, the abundance of the total number of heterotrophs and hydrocarbon-oxidising microorganisms increased as the plant cover grew, whilst the total hydrocarbon content decreased. A strong correlation was observed between plant cover, nitrogen availability and microbial abundance [12, 22]. The operational criteria that enable the optimisation of aeration, irrigation and nutrient dosing [17, 18] are respiratory rate and microbial biomass; these indicators show how effective the measures taken (such as the application of fertilisers) are [2, 11].

5.3. Ecotoxicological tests and bioassays

Bioremediation of desert soils contaminated with petroleum products not only reduces hydrocarbon levels but also restores their biological functions. For example, the germination rate of field bean (*Vicia faba*) seeds in oil-contaminated soil after six months of natural remediation was up to 96 per cent [2], and the seedlings reached maturity. Therefore, the inclusion of ecotoxicological tests (plant growth, earthworm survival) in monitoring systems [1, 14], combined with the analysis of petroleum products, is crucial for assessing the recovery of vegetation cover [2, 15].

5.4. Molecular and metabolomic markers of chemical transformation

In addition to classical chemical and microbiological indicators, molecular and metabolomic markers that directly link changes in contaminant chemical composition to ecosystem response are becoming increasingly important. It has been shown that petroleum contamination alters not only the structure of the microbial community but also its metallome - the assemblage of mobile soil metal forms - making metallome analysis an informative addition to conventional TPH and PAH monitoring [7]. Integrated mathematical and metabolomic approaches to assessing the spatial distribution of contamination make it possible to link chemical analysis data from samples to the nature and degree of toxicological impact at a specific site, improving the accuracy of identifying zones that require priority intervention [3].

6. Remote sensing, spectral analysis, and AI-assisted chemical indicators

6.1. Mapping of oil-contaminated soils and remediation progress

Given the vast spatial scale of desert oil contamination (for example, Kuwait's "oil lakes"), remote sensing has become a central element of environmental monitoring and assessment [1, 6, 34, 37]. In the Kuwait study, Landsat-5 images with a spatial resolution of 30 m and less than 5% cloud cover were used to represent extreme (1991), high (1992), and moderate (2002) contamination. Models based on Random Tree, support vector machine, and Random Forest algorithms were trained on 70% of 600 samples and tested on 180 independent points. Most model-data combinations yielded 97-100% correctly classified instances, whereas the indices-only SVM model for moderately contaminated soil achieved 78%; consequently, the highest accuracy values are

study-specific validation results rather than universal operational performance [34]. Such models allow retrospective mapping of historical contamination, evaluation of remediation outcomes (areas where spectral values approach pre-spill conditions), and prioritisation of remaining problem zones [1, 9, 34]. These approaches can be integrated with ground-based sampling for designing and monitoring bioremediation projects across large desert areas [1, 6].

6.2. Long-term spectral monitoring of vegetation response

Remote sensing is also useful for tracking vegetation stress and recovery in oil-affected desert landscapes. In Evrona (Israel), hyperspectral measurements in the 350-2500 nm range for four dominant shrub species at contaminated and control sites revealed changes in leaf reflectance and pigment composition years after the 2014 oil spill. Traditional vegetation indices were less sensitive to long-term contamination, but a new normalised blue-green stress index (NBGSI) effectively distinguished shrubs at contaminated versus clean sites (a significant correlation between contamination and pheophytin a content - a stress indicator) [37]. Machine-learning classifiers using full-spectrum reflectance data achieved high accuracy in separating shrubs at contaminated and control sites, demonstrating the potential of non-destructive spectral tools for ongoing bioremediation monitoring [1, 37].

6.3. Datasets for AI-based detection of onshore oil spills

A satellite-based database called ROSID was recently developed in Western Kazakhstan for the detection of onshore oil spills using Landsat imagery, aerial photography, and modern deep-learning models. Mask2Former and DeepLabV3+ produced the best results, with F-scores exceeding 80% and Intersection-over-Union values of approximately 67-73% for the oil class [38]. This high accuracy in identifying small spills and complex boundaries demonstrates that AI-based remote sensing can support operational monitoring of onshore oil contamination and remediation efforts. A similar principle applies to monitoring residual PAHs: combining remote sensors (including underwater drones) with knowledge-distillation methods makes it possible to predict the concentrations of individual PAH ring classes from indirect signals, substantially expanding the possibilities for operational chemical monitoring in hard-to-access environments [39]. For desert regions with developed oil infrastructure, such tools can be integrated into routine environmental monitoring and early-warning systems and can help verify the spatial effectiveness of bioremediation [1, 34, 38].

7. Sorbent materials and sustainability assessment of clean-up technologies

A separate area of chemical support for bioremediation involves the development and selection of sorbent materials for containing and partially removing oil before the biological clean-up stage begins. For Kazakhstan and neighbouring regions, natural carbonaceous minerals are of particular practical interest: carbonised shungite-based mixtures have been shown to have pronounced sorption capacity for oil, and artificial neural networks allow this capacity to be predicted with high accuracy depending on sorbent composition

and the carbonisation method, opening the way to the rational selection of low-cost local sorbents for the initial containment of spills prior to subsequent bioremediation [40].

In addition to the effectiveness of soil remediation, considerable attention is paid to the environmental and energy ‘costs’ associated with the technology itself. A life-cycle assessment (LCA) of various soil remediation schemes shows that, when choosing between biological, physico-chemical and combined methods, one should take into account not only the rate and completeness of decomposition, but also the associated greenhouse gas emissions, energy consumption and use of reagents [41]. This ‘green remediation’ approach is particularly relevant when selecting methods: for example, when choosing between intensive methods involving chemical enhancement (oxidation, electrokinetics, microwave heating) and less resource-intensive biological strategies.

The evidence base is not environmentally uniform. The electrokinetic study in [4] concerns cold-region soil, the field phytoremediation study in [22] was conducted in a temperate steppe, the PAH risk example in [6] concerns aquatic sediments, the microwave review [28] covers multiple soil and climate settings, [36] focuses on Arctic and sub-Arctic soils, and the underwater-drone example in [39] is an aquatic proof of concept. These studies support mechanisms or monitoring principles, but they do not directly validate performance in hyper-arid saline desert soils. Transfer therefore requires local testing under representative moisture, temperature, salinity, carbonate content, soil texture, contaminant ageing, and microbial-community conditions, together with desert-specific controls and endpoints.

8. An integrated framework for assessing the bioremediation of desert oil contamination

Based on the evidence presented above, an effective system for environmental monitoring and assessment of the bioremediation of oil-contaminated desert soils should include:

- baseline data and problem definition: initial mapping and classification of contamination (remote sensing, spectral indices) combined with ground-truthing (soil sampling and chemical analysis, micro- and molecular-biological analysis, soil toxicity bioassays);

- an informed choice of bioremediation strategy: for very high TPH content (>10-20% w/w), soil excavation followed by biopiling with biostimulation (nutrients, moisture, aeration) is applicable, if necessary with prior chemical treatment of recalcitrant fractions (oxidation, sorbents); for moderate or aged contamination and large areas, priority should be given to in-situ field work, monitored natural attenuation, and phytoremediation (natural or engineered) using tolerant native species; bioaugmentation should be applied only in specific situations and its effectiveness verified through microbiological and chemical monitoring;

– monitoring during remediation and after reclamation is completed: regular tracking of TPH, target compounds (PAHs, BTEX), soil respiration, microbial diversity, ecotoxicity, and, where applicable, remote spectral indicators, with comparison of results across stages and sites to ensure data comparability.

9. Conclusion

Research data from a Kuwait desert-soil windrow study show that, at an initial crude-oil content of 17.3% (w/w), open aeration and periodic moistening produced 73-79% removal over approximately six months, with more than 50% removed during the first month [2]. A separate six-month microcosm study reported approximately 70% removal at 1-10% oil contamination and approximately 50% removal at 20-30%, demonstrating the strong dependence of the reported efficiency on initial loading and treatment conditions [10].

Biostimulation and engineered systems (biopiles, landfarming) accelerate remediation and provide better control, whereas bioaugmentation often offers only limited additional benefit in removing recalcitrant compounds from soil. Chemically enhanced methods - oxidation with Fenton's reagent and persulfate, nanomaterial-based and electrokinetic approaches, microwave thermal treatment, and bioelectrochemical systems - represent a promising but as yet non-standardised toolkit for "unlocking" resistant, weathered contaminant fractions ahead of subsequent biological polishing.

Phytoremediation, whether natural or engineered, can achieve high rates of decontamination and vegetation restoration, particularly under moderate contamination, with native desert shrubs and grasses playing a key role. Environmental monitoring and assessment should integrate chemical, biological, and remote-sensing methods: measurements of total hydrocarbon and PAH content should be complemented by profiling of the microbial community and its metallome, soil respiration, plant-based indicators, toxicity tests, spectral monitoring, and, where economically justified, life-cycle assessment of the technology applied.

Key directions for further research and the implementation of arid-soil clean-up technologies should include:

1. stricter standardisation of chemical and biological monitoring protocols (combining TPH, PAHs, ecotoxicity, and microbial/metallomic indicators) adapted to desert conditions;
2. wider use of remote-sensing and artificial-intelligence tools for the operational monitoring of remediation, supported by open datasets such as ROSID;
3. systematic investigation of chemically enhanced and combined methods (oxidation, nanomaterials, electrokinetics, bioelectrochemistry) as means of increasing the bioavailability of recalcitrant oil fractions, including assessment of their compatibility with subsequent bioremediation and their associated environmental footprint (LCA);

4. long-term studies linking changes in microbial and plant diversity to ecosystem functioning and the resilience of reclaimed desert soils;

5. a shift from final endpoints based solely on total TPH content towards risk-based criteria that account for residual PAHs and their environmental significance.

Combining reliable, multifaceted chemical and biological monitoring of soil condition with bioremediation strategies tailored to the specific contamination can achieve effective clean-up and environmental restoration of oil-contaminated desert soils, while optimising costs and minimising the further impact of residual contaminants on fragile desert ecosystems.

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МҰНАЙМЕН ЛАСТАНҒАН ШӨЛ ТОПЫРАҚТАРЫН БИОРЕМЕДИАЦИЯЛАУДЫ ХИМИЯЛЫҚ ТҰРҒЫДАН БАҚЫЛАУ МЕН БАҒАЛАУ: ҚАЗІРГІ ЗАМАНҒЫ ӘДІСТЕРГЕ ШӨЛУ

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Түйіндеме. Шөлдер мен басқа да құрғақ аймақтарда, соның ішінде Кувейтте, Израильдегі Арава аңғарында және Батыс Қазақстанда болған мұнай төгінділері созылмалы түрде ластанған ауқымды топырақ аумақтарының қалыптасуына әкелді. Мұндай жерлерді қалпына келтіру ылғал мен қоректік элементтердің тапшылығына, тұздануға, температураның күрт ауытқуына және мұнай қалдықтарының ескіруіне байланысты қиындайды. Осы шөлудың мақсаты мұнаймен ластанған шөл топырақтарының биоремиациясын бақылау мен бағалаудың қазіргі химиялық және физика-химиялық тәсілдерін жүйелеу, сондай-ақ кешенді тәуекелге негізделген бағалауға жарамды көрсеткіштерді анықтау болып табылады. Мұнайдың жалпы мұнай көмірсутектерін, полициклді ароматты көмірсутектерді, БТЭК қосылыстарын, шайырлар мен асфальтендерді қамтитын көпкомпонентті ластағыш ретіндегі құрамы және олардың қозғалғыштығын, биожетімділігін, тұрақтылығы мен уыттылығын айқындайтын топырақ қасиеттері қарастырылды. Табиғи ыдырау, биостимуляция, биоаугментация, биопайлинг және фиторемиация Фентон реактиві мен персульфат арқылы тотығуға, наноматериалдарды қолдануға, электрокинетикалық үдерістерге, микротолқынды қыздыруға және биоэлектрохимиялық жүйелерге негізделген химиялық күшейтілген әдістермен салыстырылды. Мұнай фракцияларын хроматографиялық және спектроскопиялық анықтауды топырақ тынысымен, микробтық және функционалдық-гендік көрсеткіштермен, экотоксикологиялық сынақтармен және қашықтан зондаумен біріктіруге ерекше назар аударылды. Гиперспектрлік деректер мен жасанды интеллект әдістері ластануды картаға түсіру және биоремиация кезіндегі кеңістіктік өзгерістерді бақылау құралдары ретінде талданды. Қазақстан үшін өзекті шунгит негізіндегі композицияларды қоса алғанда, сорбциялық материалдарды мұнайды бастапқы окшаулау және ішінара жою сатысында қолдану қарастырылды. Жалпы мұнай көмірсутектері мөлшерінің төмендеуі экологиялық қалпына келуді толық дәлелдемейтіні көрсетілді, өйткені тұрақты ароматты фракциялар мен қалдық уыттылық сақталуы мүмкін.

Түйінді сөздер: Мұнаймен ластанған шөл топырақтары; биоремедиация; мұнай көмірсутектерінің жалпы мөлшері; полициклді ароматты көмірсутектер; химиялық тотығу; сорбенттер; экологиялық мониторинг; қашықтықтан зондау

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ХИМИЧЕСКИЕ ПОДХОДЫ К МОНИТОРИНГУ И ОЦЕНКЕ БИОРЕМЕДИАЦИИ НЕФТЕЗАГРЯЗНЁННЫХ ПУСТЫННЫХ ПОЧВ: ОБЗОР СОВРЕМЕННЫХ МЕТОДОВ

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Резюме. Разливы нефти в пустынях и других засушливых регионах, включая Кувейт, долину Арава в Израиле и Западный Казахстан, привели к формированию обширных территорий с хронически загрязнёнными почвами, восстановление которых осложняется недостатком влаги и питательных элементов, засолением, резкими температурными колебаниями и старением нефтяных остатков. Цель обзора состоит в систематизации современных химических и физико-химических подходов к мониторингу и оценке биоремедиации нефтезагрязнённых пустынных почв, а также в определении показателей, пригодных для комплексной риск-ориентированной оценки. Рассмотрен состав нефти как многокомпонентного загрязнителя, включающего общее содержание нефтяных углеводородов, полициклические ароматические углеводороды, соединения БТЭК, смолы и асфальтены, а также свойства почв, определяющие их подвижность, биодоступность, устойчивость и токсичность. Естественное разложение, биостимуляция, биоаугментация, биоайлинг и фиторемедиация сопоставлены с химически усиленными методами на основе окисления реактивом Фентона и персульфатом, применения наноматериалов, электрокинетических процессов, микроволнового нагрева и биоэлектрохимических систем. Особое внимание уделено сочетанию хроматографического и спектроскопического определения нефтяных фракций с оценкой дыхания почвы, микробными и функционально-генными показателями, экотоксикологическими тестами и дистанционным зондированием. Гиперспектральные данные и методы искусственного интеллекта рассмотрены как инструменты картирования загрязнения и наблюдения за его пространственной динамикой. Проанализировано применение сорбционных материалов, включая шунгитовые композиции, актуальные для Казахстана, на стадии локализации и первичного удаления нефти. Показано, что снижение общего содержания нефтяных углеводородов само по себе не подтверждает экологическое восстановление, поскольку могут сохраняться устойчивые ароматические фракции и остаточная токсичность.

Ключевые слова: нефтезагрязнённые пустынные почвы; биоремедиация; общее содержание углеводородов нефти; полициклические ароматические углеводороды; химическое окисление; сорбенты; экологический мониторинг; дистанционное зондирование

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