environments

Review

From TPH to Multi-Endpoint Monitoring: Rethinking Remediation of Petroleum-Contaminated Soils in Arctic and Sub-Arctic Regions

Ruslan Ya. Bajbulatov [1] and Oleg S. Sutormin [1,2,*]

[1] Scientific and Educational Center, Institute of Nature and Technical Sciences, Surgut State University, 628412 Surgut, Russia; bajbulatov_rya@surgu.ru
[2] Department of Biophysics, School of Fundamental Biology and Biotechnology, Siberian Federal University, 660041 Krasnoyarsk, Russia
* Correspondence: sutormin_os@surgu.ru; Tel.: +7-(3462)-76-29-05

Abstract

Petroleum hydrocarbon contamination of soils remains a persistent environmental problem in Arctic and sub-Arctic regions, where oil extraction, pipeline transportation, fuel storage, industrial legacy sites, and diesel-dependent infrastructure coexist with fragile cold-climate ecosystems. Remediation in these regions is constrained by low temperatures, short thaw seasons, permafrost, waterlogged active layers, slow vegetation recovery, limited infrastructure, and high mobilization costs, which limit the direct transferability of conventional temperate-zone technologies. This study presents a structured narrative review of international and Russian evidence on petroleum-contaminated soil management in cold regions, focusing on monitoring as a basis for remediation decision-making. Peer-reviewed studies, technical guidance documents, regulatory frameworks, and regional case studies were analyzed across key domains, including environmental constraints, hydrocarbon behavior, monitoring methodologies, and remediation technologies. Particular attention is given to chemical analysis, hydrocarbon fractionation, bioavailability-oriented methods, ecotoxicological bioassays, and microbial indicators as tools linking contamination assessment with remediation strategy selection. Reliance on total petroleum hydrocarbon (TPH) concentration as a primary endpoint is shown to be insufficient, especially in cold-region soils where strong sorption and limited mass transfer decouple concentration from biological exposure. Multi-endpoint monitoring systems provide a more reliable basis for assessing contaminant risk, treatment effectiveness, and soil recovery. For the Russian Arctic, the integration of national recultivation frameworks with risk-based assessment and ecotoxicological monitoring is identified as a key pathway for improving remediation outcomes. A decision-oriented framework is proposed that links environmental conditions, contaminant properties, and monitoring data to support the selection and optimization of remediation strategies. This study supports a transition from concentration-based cleanup toward risk-informed and ecosystem-oriented management of petroleum-contaminated soils in Arctic and sub-Arctic environments.

Keywords: petroleum hydrocarbons; oil-contaminated soils; Arctic; sub-Arctic; permafrost; bioremediation; landfarming; biopiles; phytoremediation; soil washing; sorbents; biochar; sustainable remediation; Russian Arctic; Western Siberia

Check for updates

Academic Editors: Carmine Massarelli and Ilaria Savino

Received: 2 May 2026
Revised: 23 May 2026
Accepted: 27 May 2026
Published: 29 May 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Petroleum hydrocarbon contamination is among the most widespread forms of anthropogenic soil pollution. It originates from oil extraction, refining, transportation, pipeline failures, storage tank leaks, fuel spills, industrial accidents, military infrastructure, and legacy contamination at abandoned or poorly managed sites [1–4]. Although petroleum-contaminated soils occur globally, remediation becomes especially complex in Arctic and sub-Arctic environments. In these regions, climatic and cryogenic factors directly affect contaminant behavior, microbial degradation, technology performance, field accessibility, and ecological recovery [1–6].

Arctic and sub-Arctic landscapes differ fundamentally from temperate remediation settings. Low annual temperatures reduce biodegradation rates; the active biological season is short; freeze–thaw cycles alter contaminant migration pathways; permafrost restricts excavation and infrastructure installation; surface hydrology is strongly seasonal; and vegetation recovery may take years or decades [1,2,5,7]. At the same time, remote locations often lack roads, grid electricity, laboratories, local disposal facilities, and year-round access. Consequently, technologies that are effective under temperate conditions may become uneconomic, environmentally disproportionate, or technically unreliable in northern territories [3,8–11].

Petroleum hydrocarbons are not a single contaminant class in practical remediation terms. Gasoline-range organics, diesel-range organics, lubricants, crude oil, heavy fuel oil, resins, asphaltenes, and polycyclic aromatic hydrocarbons differ in volatility, toxicity, solubility, sorption, biodegradability, and persistence [12–16]. Fresh contamination often contains more volatile and bioavailable fractions, whereas weathered contamination is enriched in heavier, sorbed, and recalcitrant fractions [17–19]. This distinction is critical in cold regions because low temperature, high soil moisture, limited aeration, and strong sorption to organic-rich or fine-textured soils can substantially reduce hydrocarbon bioavailability even when hydrocarbon-degrading microorganisms are present [20–23].

A critical limitation in petroleum-contaminated soil management is the widespread reliance on total petroleum hydrocarbon (TPH) concentration as the primary assessment metric. While TPH is widely used for regulatory and operational purposes, it does not adequately reflect contaminant bioavailability, toxicity, or ecological risk. In Arctic and sub-Arctic soils, strong sorption, low temperature, and limited mass transfer further decouple bulk concentration from biological exposure. As a result, monitoring approaches that integrate chemical analysis, hydrocarbon fractionation, bioavailability-oriented methods, ecotoxicological bioassays, and microbial indicators become essential not only for post-remediation evaluation but also for selecting and optimizing remediation strategies [24–27].

International experience demonstrates that Arctic remediation should be understood as a site-specific environmental engineering and ecological restoration problem rather than as a simple choice among standard technologies [1,3,8,9]. Biological approaches such as monitored natural attenuation, biostimulation, bioaugmentation, landfarming, biopiles, composting, and phytoremediation can be effective when limiting factors are properly managed [2,5,6,10,11,28–32]. Physicochemical approaches such as soil washing, surfactant-assisted treatment, sorbent amendments, chemical oxidation, and stabilization can reduce contaminant mass, mobility, or toxicity under selected conditions [33–39]. Thermal treatment and excavation can provide rapid source removal, but their environmental and logistical burdens may be high in remote Arctic sites [40–42].

The Russian Arctic and adjacent sub-Arctic regions constitute a particularly important case for international comparison. These territories include major oil and gas production regions, extensive pipeline networks, wetlands, permafrost and seasonally frozen soils, sparse infrastructure, and ecosystems with low resilience to mechanical and

chemical disturbance [43–48]. Russian remediation practice is strongly connected to land recultivation, environmental legislation, national standards, and best available technology principles [49–52]. However, contemporary remediation increasingly requires not only formal reclamation completion but also robust monitoring frameworks capable of linking contamination assessment with decision-making. This includes the integration of chemical analysis, bioavailability-oriented approaches, ecotoxicological testing, and soil-function indicators [24–27].

This study aims to synthesize international and Russian knowledge on petroleum hydrocarbon-contaminated soil remediation in Arctic and sub-Arctic regions, with a particular emphasis on monitoring approaches as a basis for remediation decision-making. The study is guided by the following research questions:

1. What remediation technologies are most commonly applied or recommended for petroleum hydrocarbon-contaminated soils in Arctic and sub-Arctic regions?
2. Which environmental, technological, logistical, and regulatory factors control their applicability?
3. What lessons can be drawn from Canada, Alaska, Greenland, Nordic countries, the European Union policy context, and Russia?
4. How can Russian Arctic remediation practice be strengthened through risk-based, ecotoxicological, and soil-function-oriented approaches?
5. What decision framework can support technology selection for cold-region petroleum-contaminated soils?
6. How can multi-endpoint monitoring approaches improve the assessment, design, and evaluation of remediation strategies in cold-region soils?

The review proposes an integrated monitoring-driven remediation framework for Arctic and sub-Arctic petroleum-contaminated soils. The framework links five elements: (i) source control and contaminant fractionation; (ii) site characterization, including soil, permafrost, hydrology, and ecological receptors; (iii) screening of biological, physicochemical, physical, and thermal remediation options; (iv) multi-endpoint monitoring based on chemical, bioavailability, ecotoxicological, microbiological, and vegetation indicators; and (v) adaptive treatment-train management. For the Russian Arctic, this framework is used to translate international evidence into a national context by connecting recultivation requirements and best available technology principles with risk-based and monitoring-based endpoints.

Recent reviews on persistent soil contaminants have emphasized the importance of linking contaminant assessment, monitoring approaches, and remediation strategies; however, Arctic and sub-Arctic petroleum-contaminated soils require a more specific framework that accounts for cold-region constraints, hydrocarbon weathering, and monitoring-informed decision-making [53].

Compared with previous reviews that have focused primarily on Arctic bioremediation, microbial degradation, individual remediation technologies, or bioavailability concepts, this review positions monitoring as the central link between contamination assessment and remediation decision-making. It integrates chemical, bioavailability- oriented, ecotoxicological, microbiological, and soil-function endpoints into a unified decision- support framework and bridges international experience with Russian Arctic and Western Siberian practice.

2. Materials and Methods

2.1. Research Design

The study was designed as a structured narrative review. This format was selected because evidence on Arctic and sub-Arctic petroleum-contaminated soil remediation and

monitoring is distributed across heterogeneous sources, including peer-reviewed laboratory studies, field-scale case studies, technical guidance documents, national standards, regulatory acts, contaminated-site management frameworks, and regional studies published in English and Russian [1–4,43–52].

Unlike a systematic review or meta-analysis, the objective was not to calculate pooled treatment efficiencies. Reported remediation performance varies widely because studies differ in soil type, contaminant fraction, petroleum concentration, contamination age, treatment duration, climate regime, analytical endpoints, microbial community, and field logistics [1,2,8,10,17,18]. Therefore, a structured narrative approach was used to integrate technological, ecological, regulatory, and practical evidence, with a particular emphasis on monitoring approaches and their role in remediation decision-making.

To improve transparency, structured elements were incorporated, including search concepts, eligibility criteria, thematic grouping, evidence categorization, and comparative synthesis.

2.2. Literature Search Strategy

A literature search was conducted using Scopus, Web of Science Core Collection, PubMed, Google Scholar, ScienceDirect, SpringerLink, MDPI, governmental databases, standards repositories, and official contaminated-site guidance sources.

The search covered publications from 1990 to 2026, with emphasis on studies published after 2000 and recent developments in monitoring approaches. This time frame was selected to capture both foundational studies on petroleum hydrocarbon behavior and biodegradation, as well as contemporary advances in monitoring and remediation strategies.

Sources were screened in both English and Russian. Russian-language sources were included to capture region-specific evidence relevant to Arctic and sub-Arctic conditions, which are often underrepresented in international databases.

The main search concepts included petroleum hydrocarbons, oil-contaminated soils, Arctic and sub-Arctic environments, remediation technologies, and monitoring approaches, including bioavailability, ecotoxicology, and microbial indicators.

Search queries were constructed using combinations of these concepts (e.g., “petroleum hydrocarbon” AND soil AND remediation AND Arctic).

Reference lists of key reviews, technical guidance documents, and regulatory sources were manually screened to identify additional relevant materials.

2.3. Eligibility Guidelines and Study Selection

Sources were considered eligible if they met at least one of the following criteria:

- addressed petroleum hydrocarbon contamination in soils, tundra, boreal, permafrost, or cold-region environments;
- evaluated remediation technologies applicable to petroleum hydrocarbon-contaminated soils;
- described laboratory-, pilot-, or field-scale remediation under Arctic, sub-Arctic, or cold-climate conditions;
- provided guidance on contaminated-site management, monitoring, landfarming, risk-based cleanup, or recultivation;
- addressed monitoring endpoints, including bioavailability, toxicity, microbial activity, or soil-function recovery.

Sources were excluded if they focused exclusively on marine oil spills without soil relevance, wastewater treatment without terrestrial relevance, non-petroleum contaminants without transferable insight, or purely commercial claims without scientific or technical support.

The retained evidence base was divided into core evidence (field studies, experimental studies, and official guidance) and contextual evidence (broader reviews, regulatory frameworks, and regional studies).

A total of 412 records were initially identified through database searches. After removal of duplicates, 326 records remained for screening. Titles and abstracts were screened, resulting in 142 records selected for full-text assessment. Of these, 78 sources were included in the core evidence base, while an additional 64 sources were used as contextual references (e.g., reviews, regulatory documents, and methodological studies). The selection process therefore followed four steps: identification, duplicate removal, title/abstract screening, full-text eligibility assessment, and final inclusion of core and contextual evidence.

2.4. Data Extraction and Organization

The following information was extracted from each source:

- geographical and climatic context;
- soil type and key properties;
- contaminant type and hydrocarbon fraction;
- contamination age and concentration (where available);
- remediation technology;
- treatment scale (laboratory, pilot, field, or guidance);
- reported treatment outcomes and limitations;
- monitoring endpoints (chemical, biological, ecotoxicological);
- ecological and logistical constraints;
- relevance to Arctic, sub-Arctic, or Russian Arctic conditions.

The evidence was organized into thematic domains (Table 1).

Table 1. Search concepts, evidence domains, and analytical use in the review.

Evidence Domain	Main Search Concepts	Main Sources Used	Analytical Role
Cold-region constraints	Arctic soils, permafrost, active layer, freeze–thaw, cold regions	Polar soil reviews, field studies, technical reports	Defines environmental limitations on remediation
Hydrocarbon behavior	TPH, diesel, crude oil, PAHs, weathering, bioavailability	Reviews and mechanistic studies	Explains why contaminant fraction and age affect treatment
Biological remediation	Biostimulation, bioaugmentation, landfarming, biopiles, composting	Cold-region field studies, microbial studies, guidance	Evaluates low-energy on-site treatment options
Physicochemical remediation	Soil washing, surfactants, sorbents, biochar, chemical oxidation	Reviews, laboratory studies, selected cold-region studies	Evaluates technologies for mass transfer, toxicity reduction, and hotspots
Thermal and excavation methods	Thermal desorption, incineration, excavation, disposal	Engineering reviews and contaminated-site guidance	Evaluates rapid source removal and its trade-offs
Monitoring and endpoints	Bioavailability, toxicity, bioassays, microbial activity, vegetation, soil functions	Ecotoxicological studies, sustainable remediation frameworks	Expands endpoints beyond TPH concentration
International governance	Canada, Alaska, EU, ISO, SuRF-UK	Official guidance and standards	Provides comparative policy and practice context
Russian Arctic synthesis	Russian standards, recultivation rules, BAT, Western Siberia studies	Russian legal/regulatory sources and regional research	Links international evidence to Russian practice

2.5. Approach to Evidence Synthesis

Thematic narrative synthesis was applied. Studies were grouped according to technology type and decision relevance, with explicit integration of monitoring approaches into the evaluation framework.

Each technology was assessed using the following criteria:

- target contaminant fraction;

- field applicability in cold regions;
- compatibility with permafrost and active-layer conditions;
- infrastructure and energy requirements;
- treatment duration;
- secondary waste generation;
- soil-function preservation;
- monitoring requirements;
- sustainability and long-term ecological implications.

The synthesis distinguishes between treatment efficiency under controlled conditions and practical applicability under Arctic field conditions, where temperature, hydrology, soil heterogeneity, and logistics strongly constrain remediation outcomes [1,2,8,10,11].

2.6. Methodological Limitations

Several limitations should be noted. The review is not a systematic review and does not provide exhaustive coverage of all studies. No quantitative meta-analysis was performed due to the heterogeneity of treatment conditions and monitoring endpoints. Some relevant regional and Russian-language sources are not indexed in international databases. Regulatory and technical documents differ across jurisdictions and cannot be directly compared as experimental studies. In addition, many studies report total petroleum hydrocarbon reduction without sufficient characterization of bioavailability, toxicity, or ecological recovery [17,18,24–27].

Despite these limitations, the chosen approach is appropriate for Arctic remediation, which requires integration of scientific, technical, regulatory, and monitoring-based evidence.

2.7. Study Area: Arctic, Sub-Arctic, and Russian Arctic Context

The study area includes Arctic and sub-Arctic regions affected by petroleum hydrocarbon contamination, including Canada, Alaska, Greenland, Nordic countries, and the Russian Arctic and adjacent sub-Arctic oil-producing regions. These environments share low temperatures, seasonal thaw, permafrost influence, fragile ecosystems, and logistical constraints [1–3,8–11].

The Russian Arctic and northern Western Siberia are treated as a focused synthesis area due to the combination of extensive oil and gas infrastructure and sensitive natural systems [43–48,54–58]. These regions are particularly relevant for evaluating monitoring approaches and remediation strategies under boreal and sub-Arctic conditions.

Figure 1 illustrates the conceptual framework used in this review.

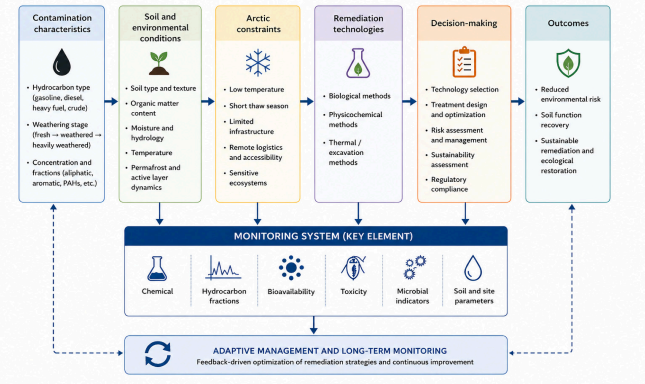


Figure 1. Conceptual framework for petroleum hydrocarbon-contaminated soil remediation in Arctic and sub-Arctic regions. The framework is based on the synthesis of recurring patterns identified across the reviewed literature, including environmental constraints, contaminant behavior, monitoring approaches, and remediation strategies.

3. Results

3.1. Environmental and Cryogenic Constraints Controlling Remediation

Remediation in Arctic and sub-Arctic soils is controlled by environmental constraints that affect contaminant mobility, microbial activity, engineering feasibility, and ecological recovery. Low temperature reduces microbial metabolism, slows enzymatic reactions, increases hydrocarbon viscosity, and limits volatilization and mass transfer [1,2,4,5]. Short thaw seasons constrain biological treatment to a limited annual window, meaning that even successful bioremediation may require several years [8–11].

Permafrost and seasonally frozen ground complicate remediation. Frozen layers may temporarily restrict vertical migration, but they also create perched water, lateral flow, and seasonal redistribution of contaminants within the active layer [1,3,5]. As the active layer deepens during summer, petroleum hydrocarbons may migrate through thawed soil or along preferential flow paths. In warming Arctic landscapes, changes in permafrost stability, thermokarst, erosion, and hydrology may alter contaminant fate over the lifetime of a remediation project [5,6].

Soil moisture has a dual role. Moderate moisture supports microbial activity, whereas waterlogging restricts oxygen diffusion and slows aerobic petroleum hydrocarbon degradation [1,2,20]. Many Arctic and sub-Arctic soils are organic-rich, peaty, or gleyed, which can increase hydrocarbon retention but reduce bioavailability. Coarse sandy soils may permit better aeration but can allow faster contaminant migration and nutrient leaching [17,18,54].

Vegetation recovery is also slow. Tundra, wetland, and northern taiga communities are sensitive to mechanical disturbance, and excavation or repeated tillage may damage root mats, moss–lichen cover, peat layers, and surface hydrology [1,3,11]. Consequently, remediation planning must balance contaminant reduction against ecosystem disturbance. In some cases, aggressive excavation may reduce chemical concentrations but worsen long-term ecological function.

These environmental constraints also directly influence monitoring design, including sampling strategy, temporal resolution, and indicator selection. The key environmental constraints and their implications for remediation design and monitoring strategies are summarized in Table 2.

Table 2. Arctic and sub-Arctic environmental constraints and implications for remediation technology selection.

Constraint	Mechanism	Remediation Implication
Low temperature	Slows microbial metabolism and hydrocarbon mass transfer	Biological treatment requires longer duration, cold-adapted microbes, nutrient/oxygen optimization
Short thaw season	Limits annual treatment window	Multi-season treatment and monitoring should be expected
Permafrost	Restricts excavation, well installation, and vertical drainage	Avoid unnecessary heat/water inputs; protect ground stability
Active-layer dynamics	Seasonal lateral and vertical contaminant migration	Sampling and monitoring must be seasonally designed
Waterlogging	Reduces oxygen diffusion	Aeration, drainage control, or ex situ treatment may be needed
Organic-rich soils	Strong hydrocarbon sorption and reduced bioavailability	Bioavailability and toxicity endpoints should complement TPH
Sandy/coarse soils	High permeability and nutrient leaching	Migration control and nutrient management are essential
Fragile vegetation	Slow recovery after disturbance	Prefer low-disturbance and restoration-oriented treatment where risk allows
Remote logistics	Limited access, high cost, short field season	Favor on-site treatment and low-energy systems when feasible
Climate change	Alters hydrology, permafrost, erosion, and access	Remediation plans should include adaptive monitoring

Note: Representative sources supporting the listed environmental constraints and monitoring implications include [1–6,8–11,17,18,20,54].

3.2. Petroleum Hydrocarbon Composition, Weathering, Toxicity, and Bioavailability

Technology selection depends strongly on petroleum hydrocarbon composition. Gasoline-range hydrocarbons are generally more volatile and mobile, while diesel-range hydrocarbons are less volatile but often biodegradable under aerobic conditions [12–16]. Heavy oils, lubricants, resins, asphaltenes, and high-molecular-weight PAHs are more persistent because they sorb strongly to soil organic matter and mineral surfaces [17–19,23].

Weathering changes contaminant behavior over time. Volatile and water-soluble compounds are lost or transformed first, leaving residual contamination enriched in heavier fractions [17,18]. This residual material may be less mobile and less acutely toxic but can be difficult to degrade. In cold regions, weathering may proceed slowly, but once hydrocarbons are incorporated into organic-rich or fine-textured matrices, bioavailability can become a primary limiting factor [17–19,23–25].

The concept of bioavailability is central. Total petroleum hydrocarbon concentration does not necessarily indicate the fraction accessible to microorganisms, plants, soil invertebrates, or groundwater pathways [24,25]. For this reason, remediation endpoints based only on bulk TPH can be misleading. A soil may show high residual TPH but low bioavailable toxicity, or conversely, moderate TPH with high ecological risk if mobile or toxic fractions remain [24–27].

This limitation is especially important in Arctic soils because strong sorption, low temperature, limited diffusion, and seasonal water movement decouple chemical concentration from biological exposure. Modern remediation strategies therefore include hydrocarbon fractionation, bioavailability assessment, toxicity testing, microbial indicators, and vegetation-based metrics [24–27,56,59]. The role of monitoring systems in remediation assessment is outlined in Table 3.

Table 3. Recommended monitoring endpoints for petroleum hydrocarbon-contaminated Arctic and sub-Arctic soils.

Endpoint Category	Recommended Indicators	Purpose
Chemical	TPH fractions, BTEX, PAHs, residual oil composition	Quantifies contaminant mass and hazardous fractions
Bioavailability	Mild extraction methods, DMSO/FTIR-based approaches, passive sampling	Estimates biologically accessible contamination
Toxicity	Microbial luminescence assays, plant germination tests, aquatic bioassays	Detects residual biological hazard
Microbiological	Respiration, enzymatic activity, hydrocarbon-degrading taxa/genes	Evaluates biodegradation potential and biological recovery
Soil properties	pH, CEC, organic matter, moisture, bulk density, hydrophobicity	Tracks soil-function restoration
Vegetation	Germination, cover, biomass, root development, native species survival	Assesses ecological restoration
Hydrological	Leachate, runoff, groundwater and surface-water monitoring	Controls off-site contaminant migration
Permafrost/active layer	Active-layer depth, ground temperature, thaw settlement	Prevents remediation-induced ground instability
Sustainability	Energy use, transport, secondary waste, emissions, cost, social acceptability	Supports sustainable remediation decisions

Note: Endpoint categories are based on bioavailability, sustainable remediation, and regional monitoring evidence [24–27,56,59–61].

3.3. Biological Remediation Strategies

Biological strategies are grouped here because they share common limiting factors in cold regions: temperature, oxygen availability, moisture, nutrient balance, and hydrocarbon bioavailability. Their applicability is therefore evaluated not only by nominal removal efficiency, but also by monitoring requirements and field controllability.

Monitored natural attenuation (MNA) relies on natural processes such as volatilization, dilution, sorption, biodegradation, and chemical transformation to reduce contaminant mass, concentration, toxicity, or exposure [12,41]. In Arctic and sub-Arctic regions, MNA is attractive because it minimizes mechanical disturbance and avoids transporting contaminated soil over long distances.

However, the approach is appropriate only under restrictive conditions. The source must be controlled, free product must be absent or recovered, contaminant migration must be limited, receptors must be protected, and monitoring must be feasible over a long period [41,42]. In cold soils, natural attenuation can be slow because microbial activity is limited by temperature, oxygen, moisture, nutrients, and hydrocarbon bioavailability [1,2,4,20].

MNA should therefore not be treated as a default low-cost option. It is defensible only when monitoring data demonstrate stable or declining contamination trends, low receptor risk, and sufficient evidence of natural degradation or containment [41,42]. In this context, monitoring is not a passive verification tool but a central component of decision-making.

- Biostimulation and nutrient-assisted bioremediation

Biostimulation enhances indigenous hydrocarbon-degrading microorganisms by adding nutrients, oxygen, or moisture control [20,28,29]. Nitrogen and phosphorus are often limiting in petroleum-contaminated soils because hydrocarbons provide carbon but insufficient nutrients for microbial biomass formation [20,28,62].

In Arctic and sub-Arctic regions, indigenous microbial communities capable of hydrocarbon degradation are typically present, but their activity is constrained by environmental factors [1,2,4,5,20]. Nutrient-assisted bioremediation has demonstrated effectiveness in various studies, including Arctic soils where nutrient addition induces shifts in microbial composition and degradation potential [6,7].

However, nutrient addition must be carefully controlled. Excess nitrogen or phosphorus may leach, alter soil chemistry, or create secondary environmental impacts [20,62]. Therefore, monitoring of nutrient dynamics, microbial activity, and hydrocarbon transformation is essential to optimize treatment performance.

Recent studies from Western Siberia further demonstrate that treatment outcomes depend on temperature regime, nitrogen form, and contamination level [56], emphasizing the need for site-specific optimization supported by experimental testing and monitoring.

- Bioaugmentation and indigenous cold-adapted microbial consortia

Bioaugmentation involves the introduction of hydrocarbon-degrading microorganisms into contaminated soils [20,29]. Although conceptually attractive for cold environments, field performance is often inconsistent due to ecological competition, environmental stress, and limited accessibility of sorbed hydrocarbons.

Indigenous or site-adapted microbial consortia are generally more effective than externally introduced strains [1,2,20]. Amendments such as peat, compost, or biochar may enhance microbial survival and activity but can also alter sorption processes and hydrocarbon bioavailability [37–39,60,61,63,64].

Bioaugmentation is most effective when integrated with biostimulation and supported by monitoring of microbial dynamics, degradation pathways, and toxicity reduction, rather

than relying solely on bulk concentration changes. This highlights the importance of combining biological and analytical indicators in Arctic remediation systems.

- Landfarming

Landfarming is one of the most practical remediation technologies for petroleum-contaminated soils in cold and remote regions. It involves excavation, spreading, and periodic tilling of contaminated soil to enhance aeration and microbial degradation [8,43,45].

Field studies in Arctic environments demonstrate that landfarming can achieve significant hydrocarbon reduction during limited thaw seasons, although residual weathered fractions may persist over multiple years [8–10]. Its advantages include simplicity, scalability, relatively low energy demand, and compatibility with remote-site logistics.

However, landfarming requires careful engineering design, including containment, drainage, runoff control, and long-term monitoring [8,43,45]. It may be unsuitable for volatile contamination or heavily weathered hydrocarbons.

Landfarming performance should be evaluated using hydrocarbon fractions, toxicity indicators, and ecological recovery metrics, rather than relying solely on total petroleum hydrocarbon reduction. Its comparative applicability relative to other technologies is discussed in Table 4. Field studies have reported TPH reductions of approximately 30–70% over one to three treatment seasons, depending on soil conditions and management practices [8–10].

- Biopiles and engineered biocells

Biopiles and engineered biocells are ex situ treatment systems in which contaminated soil is placed in piles or contained cells with controlled aeration, drainage, nutrient addition, and, in some cases, temperature regulation [11,40]. Compared with landfarming, these systems require more design and infrastructure but offer improved process control and containment.

Biopiles can be covered, lined, aerated, insulated, or heated to enhance treatment under cold conditions [11]. Aeration systems improve oxygen transfer, while covers reduce precipitation, heat loss, and volatilization. Passive or active heating may extend the treatment season, although this increases energy demand [11,40]. In cold climates, heated and humidified biopile systems have been successfully tested for diesel-contaminated soils, demonstrating that engineering controls can partially compensate for climatic limitations [11].

The main disadvantages include higher construction costs, operational complexity, the need for liners and leachate management, and energy requirements for forced aeration or heating. For remote Arctic sites, feasibility depends on access, power supply, material availability, and treatment scale.

From a monitoring perspective, biopiles provide advantages over less controlled systems because they allow systematic measurement of oxygen levels, temperature, moisture, microbial activity, and contaminant transformation. This enables more reliable assessment of treatment dynamics compared with open systems such as landfarming. The comparative applicability of biopiles relative to other technologies is summarized in Table 4. Engineered biopile systems can achieve comparable or higher removal efficiencies within shorter time frames due to improved aeration and process control.

- Composting and organic amendment-assisted bioremediation

Composting and organic amendment-assisted bioremediation involve mixing contaminated soil with organic materials such as compost, manure, wood chips, sawdust, straw, or peat [28,29,63,64]. These amendments improve porosity, moisture retention, nutrient availability, microbial biomass, and soil structure. Composting may also generate heat, which is beneficial under cold-climate conditions.

Table 4. Comparative applicability of remediation technologies for petroleum hydrocarbon-contaminated soils in Arctic, sub-Arctic, and cold-region contexts.

Technology	Main Target	Arctic Applicability	Main Strengths	Main Limitations	Best Use Case
Monitored natural attenuation	Low-risk residual contamination	Moderate	Minimal disturbance, low energy	Slow, requires strong monitoring	Stable sites with controlled sources
Biostimulation	Diesel-range and biodegradable fractions	High	Uses indigenous microbes, scalable	Nutrient runoff, oxygen limitation, seasonality	Aerated soils with nutrient limitation
Bioaugmentation	Selected biodegradable fractions	Moderate	Adds specialized degraders	Survival uncertain, not stand-alone	Combined with nutrients and carriers
Landfarming	Diesel and light-to-medium petroleum fractions	High	Simple, low energy, suitable for remote sites	Land demand, runoff, volatilization, multi-year treatment	Excavated soil at remote sites
Biopiles/biocells	Diesel and weathered hydrocarbons	High	Better control and containment	Higher design and energy demand	Sites needing containment and aeration
Composting	Weathered petroleum hydrocarbons	Moderate-High	Improves soil structure and microbial activity	Amendment quality, leachate, and dilution artifacts	Restoration-oriented ex situ treatment
Phytoremediation/ rhizoremediation	Residual contamination	Moderate	Supports stabilization and revegetation	Slow, short growing season	Polishing and ecological restoration
Soil washing	Particle-bound hydrocarbons	Moderate	Can remove contaminant mass from excavated soils	Wastewater, freezing, infrastructure	Centralized or semi-centralized treatment
Surfactant-assisted treatment	Sorbed hydrophobic fractions	Moderate	Improves mobilization/bioavailability	Toxicity, mobilization, variable response	Pilot-tested combined treatment
Sorbents/biochar/ amendments	Mobile or toxic fractions	Moderate-High	Reduces toxicity and leaching	Immobilization may reduce biodegradation	Emergency stabilization or restoration support
Chemical oxidation	Localized hotspots	Low–Moderate	Rapid mass reduction	Delivery difficulty, soil disturbance	Small high-risk source zones
Thermal treatment	Heavy and persistent hydrocarbons	Low-Moderate	High removal efficiency	Energy demand, emissions, soil-function loss	Small volumes of highly contaminated soil
Excavation/disposal	Hotspots and free product	Moderate	Immediate source removal	Transport, disturbance, liability transfer	Emergency response and accessible hotspots
Combined treatment trains	Mixed contamination	High	Matches technologies to remediation stages	Requires planning and monitoring	Most complex Arctic sites

Note: Technology categories and applicability assessments synthesize evidence from cold-region field studies, remediation reviews, guidance documents, and regional studies [1–3,8–11,20–23,28–45,54–57,59,61–63].

Organic amendments can support both contaminant degradation and ecological restoration by stimulating microbial communities and enhancing soil biological activity. In weathered petroleum-contaminated soils, amendments may promote co-metabolism of persistent hydrocarbons [28,29]. However, they may also dilute contaminants, introduce excess nutrients or salts, alter pH, increase dissolved organic carbon, or modify hydrocarbon sorption behavior [37–39,60–64].

As a result, composting outcomes cannot be interpreted solely through reductions in total petroleum hydrocarbons. A decrease in extractable TPH may reflect degradation, dilution, sorption, or analytical artifacts. Therefore, multi-endpoint monitoring is essential, including hydrocarbon fractionation, toxicity assessment, microbial activity, respiration, leaching, and vegetation response [24–27,56].

Composting is most suitable for excavated soils treated in controlled systems where runoff and leachate can be managed. Its effectiveness and sustainability should be evaluated within a broader monitoring framework, as summarized in Table 3.

- Phytoremediation and rhizoremediation

Phytoremediation uses plants to stabilize, extract, transform, or support the degradation of contaminants. For petroleum hydrocarbons, the dominant mechanism is typically rhizoremediation, where plant roots stimulate microbial degradation in the rhizosphere through root exudates, oxygen transfer, and habitat formation [30–32].

In Arctic and sub-Arctic environments, phytoremediation is constrained by short growing seasons, low biomass production, shallow rooting depth, nutrient limitation, and sensitivity of native vegetation [1,3,30]. It is generally unsuitable as a primary treatment for heavily contaminated soils but can be effective as a polishing and restoration stage following source reduction by landfarming, biopiles, composting, or excavation [30–32].

Species selection is critical. Native or locally adapted species are preferred to support ecological restoration and avoid introducing invasive vegetation. Monitoring should include plant survival, vegetation cover, root development, microbial activity, and toxicity reduction, as well as long-term ecosystem stability.

In Arctic remediation, phytoremediation should be viewed primarily as a soil-function recovery and stabilization approach, rather than a rapid contaminant removal technology. Its performance should be evaluated using ecological and biological indicators within a multi-endpoint monitoring framework (Table 3).

3.4. Physicochemical Remediation Strategies

Physicochemical strategies are grouped because they primarily modify contaminant mobility, availability, or chemical form. Their performance in Arctic soils depends strongly on delivery efficiency, secondary waste generation, toxicity, and the ability to monitor unintended contaminant mobilization.

Soil washing removes contaminants from excavated soils using water, surfactants, or other chemical and physical separation processes [33–36]. For petroleum hydrocarbons, this approach can transfer contaminants into a liquid phase or concentrate them in fine soil fractions. Surfactants increase apparent solubility and enhance the mobilization of hydrophobic compounds [33–35].

Surfactant-assisted remediation is particularly relevant where hydrocarbons are strongly sorbed and exhibit low bioavailability. However, it involves significant risks. Surfactants may mobilize contaminants into groundwater, inhibit microbial activity, alter soil structure, generate wastewater, or reduce biodegradation if hydrocarbons become sequestered in micellar phases rather than remaining bioavailable [33–36].

In Arctic regions, additional constraints include limited water availability, challenges in wastewater treatment, freezing conditions, and transport logistics.

Site-specific evidence from Western Siberia highlights the variability of surfactant performance. Sutormin et al. reported that Modified Syntherol did not enhance oil degradation in several soil types under experimental conditions, with minimal natural decomposition observed after 35 days [54]. In contrast, Petrova et al. demonstrated that Tween 80 could improve diesel-contaminated Albic Podzolic soil remediation under boreal conditions, with low or sub-critical micelle concentration (CMC) dosing achieving measurable TPH reduction and pH stabilization without acute toxicity [55].

These findings show that surfactant-assisted remediation is strongly dependent on soil properties, contaminant characteristics, and dosing conditions. Therefore, pilot-scale testing combined with toxicity, bioavailability, and hydrocarbon-fraction monitoring is essential before full-scale application.

- Sorbents, biochar, peat, mineral carriers, and other amendments

Sorbents and amendments are widely used to immobilize hydrocarbons, reduce toxicity, improve soil properties, and support microbial colonization [37–39,60–64]. Materials

include peat, compost, biochar, hydrochar, activated carbon, zeolites, clay minerals, and industrial by-products. In Arctic regions, locally available materials are particularly valuable due to logistical constraints.

Biochar and activated carbon are especially effective in sorbing hydrophobic organic contaminants and reducing bioavailability to receptors [60–64]. Recent studies also demonstrate that amendment performance depends strongly on feedstock composition, surface structure, contaminant interactions, and leaching behavior, emphasizing the need for amendment-specific monitoring rather than generalized assumptions regarding sorption efficiency and environmental safety [65]. However, this creates a trade-off. While sorption can reduce exposure and acute toxicity, it may also limit microbial access to hydrocarbons and slow biodegradation.

Therefore, amendment-assisted remediation must distinguish between risk reduction through immobilization and contaminant removal through degradation [24,25,60–64]. Monitoring strategies should explicitly account for this distinction by combining chemical, bioavailability, and toxicity endpoints.

The selection of amendments should be aligned with remediation objectives. Sorbents are appropriate for rapid toxicity reduction or migration control, while biologically active amendments should be used to support degradation and soil restoration. In all cases, effectiveness should be evaluated using multi-endpoint monitoring approaches, as outlined in Table 3.

- Chemical oxidation

Chemical oxidation involves the use of oxidants such as permanganate, persulfate, hydrogen peroxide, ozone, or Fenton-type reagents to degrade organic contaminants [38–40]. This approach can rapidly reduce contaminant mass in localized source zones and is particularly relevant where biological treatment is too slow or where immediate risk reduction is required.

In Arctic and sub-Arctic soils, however, chemical oxidation faces significant constraints. Delivery of oxidants is difficult in frozen, heterogeneous, waterlogged, or low-permeability soils. Oxidation reactions may alter soil pH, generate heat, mobilize metals, and disrupt microbial communities, potentially compromising soil biological function [38–40]. In addition, handling and transport of reactive chemicals present logistical and safety challenges in remote environments.

From a monitoring perspective, chemical oxidation requires careful evaluation beyond bulk contaminant removal. Apparent reductions in TPH may not correspond to reductions in toxicity or bioavailability. Therefore, monitoring should include transformation products, toxicity endpoints, and changes in soil biological activity, in addition to conventional chemical metrics.

Chemical oxidation is most appropriate for well-defined hotspots where rapid intervention is necessary and where delivery can be controlled. It is less suitable for large, diffuse contamination, organic-rich soils, or sites where restoration of soil function is the primary objective.

3.5. Thermal Treatment and Source-Removal Strategies

Thermal and source-removal strategies are grouped because they provide rapid contaminant mass reduction but can produce substantial disturbance, energy demand, and soil-function loss. In Arctic environments, their use should be justified by clear risk-reduction needs.

Thermal treatment technologies, including thermal desorption, incineration, and in situ heating, can remove or destroy petroleum hydrocarbons, including heavy and weathered fractions [40–42]. These methods provide high removal efficiency and are often

applied to highly contaminated soils or small volumes of material that cannot be effectively treated biologically.

In Arctic environments, however, thermal methods present substantial limitations. They require high energy input, specialized equipment, emission control systems, and often transport to centralized facilities [40–42]. In addition to logistical constraints, thermal treatment can destroy soil organic matter, microbial communities, structure, and seed banks. In permafrost-affected regions, heat input may destabilize ground conditions and alter hydrological regimes.

Importantly, thermal removal of contaminants does not equate to ecological recovery. From a monitoring perspective, post-treatment evaluation should include soil-function indicators such as microbial activity, structure, and vegetation potential, not only residual contaminant concentrations.

Thermal treatment is therefore best reserved for small volumes of highly contaminated material, emergency response scenarios, or sites posing acute risk. Its use for large, diffuse contamination is often environmentally and economically disproportionate.

- Excavation, off-site disposal, and source removal

Excavation remains one of the most widely applied remediation approaches because it enables rapid source removal, clear verification, and compatibility with construction or emergency response activities [40–42]. In Arctic and sub-Arctic regions, excavation is often necessary for free product recovery, localized hotspots, infrastructure corridors, or sites posing direct risk to water bodies or human receptors.

However, excavation does not inherently represent sustainable remediation. It frequently transfers contamination to another location, requires transport, generates emissions, disturbs vegetation, disrupts soil horizons, alters hydrology, and may destabilize permafrost or peat systems [1,3,40–42]. In remote regions, off-site disposal options may be limited or unavailable.

From a monitoring standpoint, excavation provides clear short-term endpoints (mass removal), but long-term evaluation must include site recovery, residual contamination, and ecological function. Without post-excavation restoration and monitoring, excavation may solve immediate contamination problems while creating long-term environmental degradation.

Therefore, excavation should be integrated into treatment trains rather than used as a standalone solution. It is most defensible when it removes active sources or prevents contaminant migration, rather than being applied indiscriminately to large areas of diffuse contamination.

3.6. Cross-Technology Analytical Synthesis

Across the reviewed technologies, a consistent pattern emerges: treatment performance is not primarily determined by the technology category itself, but by the extent to which limiting factors—temperature, oxygen availability, moisture, nutrient balance, and hydrocarbon bioavailability—are effectively managed.

For example, biological approaches such as landfarming and biopiles tend to fail under conditions of waterlogging, insufficient aeration, or nutrient imbalance, despite being theoretically suitable for diesel-range hydrocarbons. Similarly, surfactant-assisted approaches show inconsistent performance due to soil-specific sorption behavior and dose-dependent toxicity effects.

Monitoring data play a critical role in resolving these uncertainties. Studies incorporating bioavailability and toxicity endpoints demonstrate that similar TPH reductions may correspond to substantially different ecological outcomes. This indicates that the moni-

toring strategy directly influences remediation decisions, including technology selection, process adjustment, and endpoint definition.

3.7. Monitoring Endpoints: From Chemical Cleanup to Soil-Function Recovery

A central limitation in petroleum-contaminated soil remediation is the continued reliance on total petroleum hydrocarbon (TPH) concentration as the primary endpoint [24–27]. While TPH is a useful screening parameter, it does not distinguish between hydrocarbon fractions, bioavailability, toxicity, or ecological relevance.

In Arctic and sub-Arctic soils, this limitation is particularly significant. Strong sorption, low temperature, limited diffusion, and seasonal hydrology can decouple bulk concentration from biological exposure. As a result, soils with similar TPH values may differ substantially in ecological risk and recovery potential.

A modern remediation framework should therefore adopt a multi-endpoint monitoring strategy, including:

- chemical endpoints: TPH fractions, BTEX (where relevant), PAHs, residual composition;
- bioavailability indicators: mild solvent extraction, passive sampling, or surrogate methods [24,25,56];
- biological endpoints: microbial respiration, enzymatic activity, hydrocarbon-degrading genes or taxa;
- ecotoxicological endpoints: bioassays, including luminescent inhibition systems [27,59];
- ecological endpoints: plant germination, vegetation development, and soil-function recovery.

Recent methodological developments support this transition. Farrahova et al. [56] proposed an FTIR-based method using aqueous DMSO extraction to better align chemical measurements with biologically relevant exposure in sandy podzolic soils. Similarly, bioassay-based approaches provide integrated toxicity assessment that complements chemical analysis [59].

The transition from concentration-based cleanup to monitoring-informed remediation is therefore essential for Arctic environments, where success must be evaluated not only by contaminant removal, but also by restoration of soil ecological function.

Table 5 summarizes the core evidence supporting this integrated perspective.

Table 5. Grouped synthesis of core evidence supporting monitoring-driven remediation of petroleum hydrocarbon-contaminated soils in Arctic and sub-Arctic regions.

Evidence Group	Representative Sources	Evidence Type	Key Finding	Main Limitation	Implication for Framework
Cold-region constraints	[1–6,8–11,23]	Reviews; field and experimental studies	Temperature, thaw season, moisture, oxygen availability, and permafrost strongly control treatment performance	Findings are site-specific and often difficult to transfer directly across Arctic regions	Site characterization must precede technology selection and define monitoring frequency
Hydrocarbon weathering and bioavailability	[17,18,24,25,56]	Conceptual reviews; methodological studies	Bulk TPH values do not reliably represent bioavailable or toxic fractions	Bioavailability methods are not yet standardized across remediation projects	TPH should be complemented by fractionation, bioavailability proxies, and toxicity testing
Biological remediation	[6–11,20–23,28,29,57,62]	Field, pilot, and laboratory studies	Biostimulation, landfarming, biopiles, and composting can be effective when oxygen, nutrients, and moisture are controlled	Performance declines under waterlogging, nutrient imbalance, low temperature, and limited bioavailability	Monitoring should track nutrients, oxygen, microbial activity, toxicity, and residual fractions over multiple seasons

Table 5. *Cont.*

Evidence Group	Representative Sources	Evidence Type	Key Finding	Main Limitation	Implication for Framework
Phytoremediation and restoration	[30–32]	Reviews and experimental studies	Plants and rhizosphere processes support polishing, stabilization, and soil-function recovery	Short growing seasons and low biomass limit use as a primary treatment in Arctic sites	Vegetation indicators are best used in late-stage monitoring and restoration assessment
Physicochemical and amendment-based treatment	[33–39,54,55,63–65]	Reviews; regional experimental studies	Surfactants, sorbents, biochar, and amendments can alter contaminant mobility, toxicity, and bioavailability	Effects are soil- and dose-specific; mobilization or immobilization may be mistaken for degradation	Pilot testing and combined chemical–toxicity monitoring are required before field application
Thermal, excavation, and source removal	[40–42]	Engineering reviews and guidance	These methods provide rapid risk reduction for hotspots and free product	They may increase disturbance, energy demand, emissions, and soil-function loss	Use should be limited to source zones and evaluated through risk-reduction and sustainability criteria
Governance and decision support	[26,27,43–53,60,61,66,67]	Standards; guidance; policy documents; regional studies	Risk-based frameworks, recultivation standards, and sustainable remediation principles provide decision structure	Russian Arctic data remain unevenly reported and often lack multi-endpoint monitoring	The proposed framework links regulatory requirements with monitoring-driven adaptive management

A minimal core monitoring package for Arctic remediation should include: (i) TPH fractionation; (ii) at least one bioavailability proxy; (iii) one ecotoxicological assay; and (iv) one microbiological activity indicator. This combination provides a balanced assessment of contaminant presence, accessibility, biological impact, and recovery potential.

3.8. Comparative Applicability of Remediation Technologies

The selection of remediation technologies for petroleum-contaminated soils in Arctic and sub-Arctic regions is inherently a multi-criteria decision problem. No single technology is universally optimal, and performance depends on interactions among contaminant properties, soil conditions, climate constraints, logistical feasibility, and monitoring outcomes.

Table 4 provides a structured comparison of major remediation technologies in terms of target contaminants, Arctic applicability, strengths, limitations, and best-use conditions. However, such tabular comparisons should not be interpreted as prescriptive rankings. Instead, they serve as a decision-support tool that must be integrated with site-specific information.

A key insight emerging from this review is that technology selection should not be based solely on expected contaminant removal efficiency. In Arctic conditions, feasibility, controllability, ecological impact, and monitoring reliability are equally important. Technologies that demonstrate high efficiency under laboratory conditions may fail under field constraints related to temperature, hydrology, access, or infrastructure.

Furthermore, different technologies address different stages of remediation. For example:

- excavation and thermal treatment are effective for rapid source removal;
- biopiles, landfarming, and biostimulation support intermediate-stage degradation;
- phytoremediation and amendment-assisted approaches contribute to long-term stabilization and ecosystem recovery.

These differences support the concept of treatment trains, in which multiple technologies are combined sequentially or in parallel to address contamination at different scales and stages.

Monitoring plays a central role in this framework. Rather than serving as a post-treatment verification tool, monitoring should guide:

- technology selection,
- process optimization,
- transition between treatment stages,
- and final assessment of remediation success.

Figure 2 translates the comparative framework into a decision-oriented scheme based on key criteria, including contaminant fraction and age, soil properties, permafrost conditions, hydrology, ecological sensitivity, infrastructure constraints, treatment duration, and sustainability objectives.

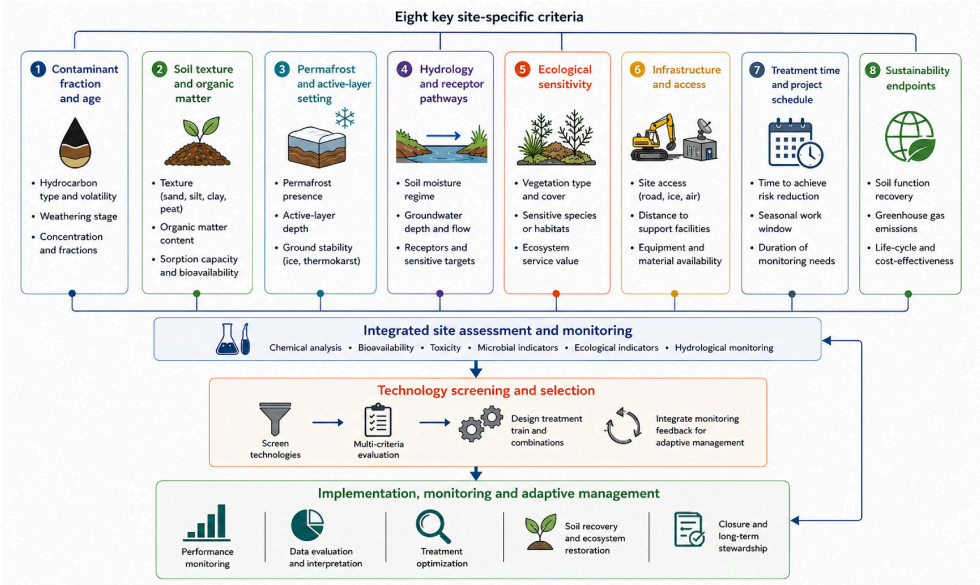


Figure 2. Criteria for selecting remediation technologies under Arctic and sub-Arctic conditions. The criteria are derived from comparative analysis of technological performance, environmental constraints, and monitoring requirements reported in the reviewed studies.

In this context, a risk-informed and ecosystem-oriented approach provides the most robust pathway for managing petroleum-contaminated soils in Arctic and sub-Arctic environments.

4. Discussion

4.1. Main Findings of the Review

The reviewed evidence supports four interrelated conclusions that are particularly relevant for Arctic and sub-Arctic remediation practice.

First, remediation performance is governed not by the nominal choice of technology, but by site-specific limiting factors, including temperature, oxygen availability, moisture regime, nutrient balance, and hydrocarbon bioavailability [1–8,20]. Technologies such as landfarming, biopiles, or surfactant-assisted treatment should therefore be interpreted as operational frameworks rather than fixed solutions. Their success depends on how effectively they address these limiting constraints under real field conditions. These recurring patterns form the basis of the conceptual frameworks proposed in this study.

Second, biological and combined on-site approaches represent the most practical and scalable options for remote cold-region environments [1–3,8–11,28,29,43,44]. Tech-

nologies such as landfarming, biopiles, composting, and biostimulation can operate with relatively low energy demand and are compatible with soil-function recovery. However, their performance must be evaluated over multi-season timeframes, as short-term assessments may underestimate their long-term effectiveness due to the persistence of weathered hydrocarbon fractions [8–11].

Third, intensive physical and chemical technologies remain necessary for specific use cases, including free product removal, localized hotspots, volatile fractions, and high-risk source zones [38–42]. However, their application in Arctic environments should be justified through risk reduction rather than concentration reduction alone. Broader impacts—including energy demand, secondary waste generation, soil disturbance, greenhouse gas emissions, and permafrost stability—must be incorporated into decision-making frameworks [26,27,40–42].

Fourth, the Russian Arctic requires a stronger integration of formal recultivation practice, risk-based contaminated-site assessment, and monitoring-driven evaluation of ecological recovery [49–52,54–59]. Existing regulatory frameworks and best available technology (BAT) principles provide a structured basis, but their effectiveness depends on implementation through site-specific, evidence-based, and monitoring-informed approaches.

4.2. Strength of Evidence and Its Practical Meaning

The strength of evidence in Arctic petroleum-contaminated soil remediation is heterogeneous and must be interpreted accordingly.

The most robust insights are derived from field-scale studies, long-term landfarming applications, and official technical guidance, particularly from Canada, Alaska, and Greenland [6–11,43–45]. These sources provide direct evidence of feasibility under real climatic and logistical constraints. However, even high-quality field studies are inherently site-specific, and their direct transferability to other Arctic regions—such as Western Siberia—is limited without adaptation to local soil properties, hydrology, and infrastructure conditions [8–10,54–57].

Laboratory and pilot-scale studies provide critical mechanistic understanding, including nutrient limitation, temperature dependence, surfactant effects, microbial dynamics, and soil-specific responses [6,7,54–57]. However, such studies often operate under controlled conditions that do not fully capture field heterogeneity, seasonal variability, and logistical constraints. As a result, laboratory evidence should be used to inform pilot testing and design optimization, rather than as a standalone basis for technology selection.

Technical guidance documents represent a distinct and highly valuable evidence category. Canadian and Alaskan guidelines translate scientific knowledge into engineering requirements, operational procedures, and monitoring protocols [43–45]. Their importance lies in addressing a common failure mode: remediation inefficiency due not to conceptual limitations, but to inadequate implementation—such as poor aeration, insufficient containment, lack of drainage control, or absence of defined monitoring endpoints.

From a monitoring perspective, a critical gap across many studies is the over-reliance on TPH as a primary endpoint, with limited integration of bioavailability, toxicity, or ecological indicators [24–27]. This gap reduces the comparability of studies and limits the ability to evaluate true remediation success, particularly in cold-region soils where concentration does not directly reflect exposure or ecological risk.

4.3. International Experience: Canada, Alaska, Greenland, Nordic Countries, and EU Policy Context

International experience provides important comparative insights into the development of Arctic and sub-Arctic remediation frameworks.

Canada represents one of the most structured approaches to petroleum-contaminated soil management in cold environments. The Canada-Wide Standard for Petroleum Hydrocarbons in Soil applies a risk-based framework linked to land use and exposure pathways [44]. Complementary federal guidance on landfarming provides detailed recommendations for design, operation, and monitoring [43]. A key transferable lesson is that landfarming must be treated as a controlled engineering process, rather than informal soil spreading.

Alaska offers a pragmatic regulatory and operational model that closely resembles many Russian Arctic conditions. The Alaska Department of Environmental Conservation explicitly distinguishes between engineered landfarming and temporary soil storage, reinforcing the importance of containment, monitoring, and defined endpoints [45]. This distinction is critical for ensuring both regulatory compliance and environmental effectiveness.

Greenland field studies provide valuable long-term performance data. Full-scale landfarming of diesel-contaminated soils demonstrated substantial initial contaminant reduction, followed by persistence of weathered fractions over multiple years [9]. This highlights the importance of multi-stage remediation strategies, where primary treatment is followed by polishing or stabilization.

Nordic countries provide an institutional perspective, emphasizing integrated contaminated-site management systems, including site investigation, risk assessment, stakeholder engagement, and transparent decision-making processes [27]. The key lesson is not the superiority of specific technologies, but the effectiveness of coordinated systems linking science, regulation, and practice.

The European Union policy framework further extends this perspective. The EU Soil Strategy for 2030 and emerging soil monitoring initiatives emphasize soil health, resilience, and ecosystem services, rather than solely contaminant concentration [60,61]. This shift aligns closely with the monitoring-driven and soil-function-oriented approach advocated in this review.

For the Russian Arctic, the main implication is that international experience should not be transferred as isolated technologies, but rather as integrated frameworks combining risk assessment, monitoring, engineering design, and long-term ecological evaluation.

4.4. Russian Arctic and Western Siberia in the International Context

The Russian Arctic and northern West Siberia share key environmental constraints with other cold-region systems, including Canada, Alaska, and Greenland. These include low temperatures, seasonal thaw dynamics, permafrost or seasonally frozen ground, remote access, extensive petroleum infrastructure, and fragile ecosystems with limited recovery capacity [43–48,54–57].

However, the institutional and regulatory context differs substantially. In Russia, remediation is strongly embedded in environmental legislation, land recultivation requirements, national standards, and best available technology (BAT) frameworks [49–52].

The Russian system has several important strengths. Land recultivation is treated as a formal environmental obligation, and regulatory documents explicitly address oil-contaminated land restoration and biodiversity recovery [49–52]. In particular, GOST R 57447-2017 defines best available techniques for remediation of oil-contaminated land [51], while Resolution of the Government of the Russian Federation of 23.12.2014 N 1458 establishes procedures for identifying and implementing BAT [50]. These instruments provide a structured regulatory basis that is comparable in scope to international frameworks.

At the same time, several limitations affect practical implementation.

First, remediation outcomes are frequently assessed using compliance-oriented indicators, rather than long-term ecological recovery metrics.

Second, aggregated national reporting does not always allow Arctic-specific interpretation, limiting its usefulness for decision-making in permafrost and cold-climate environments.

Third, TPH concentration often remains the dominant endpoint, while bioavailability, toxicity, microbial recovery, and soil-function indicators are less consistently applied.

Fourth, technology selection is not always explicitly linked to conceptual site models and exposure pathways, which limits the effectiveness of risk-based decision-making.

To address these gaps, Figure 3 proposes a stepwise, monitoring-driven framework for technology selection in Arctic petroleum-contaminated soils, integrating risk assessment, site characterization, pilot testing, and adaptive management.

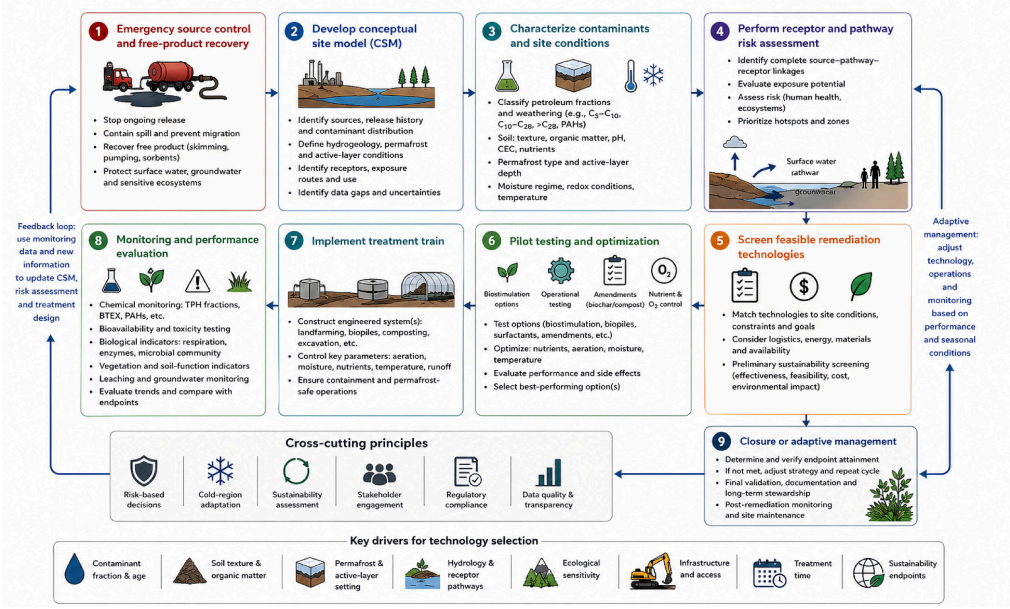


Figure 3. Stepwise decision framework for selecting remediation technologies in petroleum hydrocarbon-contaminated Arctic and sub-Arctic soils. The framework integrates key stages identified in the reviewed literature, including site characterization, risk assessment, technology screening, pilot testing, and multi-endpoint monitoring.

4.5. Applied Implications for Russian Arctic Remediation

International experience should not be transferred to the Russian Arctic as a set of predefined technologies. Instead, it should be adapted into a context-specific decision framework aligned with Russian climatic, geological, regulatory, and infrastructural conditions.

Five practical shifts can significantly improve remediation outcomes.

First, remediation should be based on a conceptual site model (CSM). This model should integrate contaminant characteristics, petroleum fractions, contamination age, soil properties (texture, organic matter, pH), permafrost conditions, hydrology, ecological receptors, land use, and logistical constraints [26,27,41,42]. The CSM should guide both technology selection and monitoring design.

Second, emergency response and long-term remediation should be clearly separated. Immediate actions should focus on spill containment, free-product recovery, and prevention of contaminant migration. Long-term remediation should address residual contamination, toxicity reduction, soil recovery, and ecosystem restoration.

Third, biological technologies should be implemented as engineered systems rather than simplified practices. Landfarming, biopiles, composting, and biostimulation require controlled design, including aeration, nutrient balance, moisture management, containment, and monitoring protocols [43,44]. Their effectiveness depends on operational quality rather than on the nominal choice of technology.

Fourth, surfactant-based and amendment-assisted treatments should be validated through site-specific pilot testing. Evidence from Western Siberia demonstrates that treatment outcomes depend strongly on soil type, contaminant composition, surfactant properties, dosage, and temperature [54,55]. Therefore, generalized product-based recommendations are insufficient for reliable application.

Fifth, monitoring should be expanded to include ecotoxicological and biological endpoints, in addition to chemical metrics. Approaches such as FTIR-based extraction methods and bioassay-based toxicity assessment provide a more realistic evaluation of environmental risk and recovery [56,59]. This is particularly important in Arctic systems, where bulk contaminant concentration may not reflect ecological exposure.

Together, these shifts support a transition from compliance-driven remediation toward monitoring-driven, risk-informed, and ecosystem-oriented management.

4.6. National Statistics and the Need for Arctic-Specific Reporting

National statistics on contaminated and recultivated lands provide important context for understanding the scale of petroleum-related environmental impacts in Russia. Available data indicate that petroleum-product-related land disturbance and recultivation remain significant nationwide. However, these datasets are typically aggregated at the national level and do not allow Arctic-specific interpretation. This highlights the need for regionally disaggregated monitoring data to support evidence-based remediation planning in northern territories.

However, these data should be interpreted with caution. They represent aggregated national indicators and do not directly reflect Arctic-specific conditions. Without regional disaggregation, it is not possible to distinguish between temperate and cold-region remediation practices, or to assess performance under permafrost and sub-Arctic constraints.

The absence of transparent, regionally resolved datasets for the Russian Arctic represents a critical gap in both research and environmental management and restricts the development of evidence-based remediation strategies.

Improved data systems should include region-specific information for key oil- and gas-producing territories, including the Khanty-Mansi Autonomous Okrug–Yugra, Yamalo-Nenets Autonomous Okrug, northern Krasnoyarsk Krai, Komi Republic, and Nenets Autonomous Okrug.

Such datasets should integrate:

- contamination source and history;
- petroleum fraction composition;
- soil type and environmental conditions;
- applied remediation technologies;
- treatment duration and operational parameters;
- chemical, biological, and ecotoxicological monitoring endpoints;
- post-recultivation land condition and ecosystem recovery.

The development of Arctic-specific monitoring and reporting systems would significantly enhance technology selection, performance evaluation, and long-term environmental management.

4.7. Treatment-Train Approach

The evidence reviewed here supports the application of treatment trains rather than isolated remediation technologies. Arctic and sub-Arctic sites typically exhibit heterogeneous contamination patterns, including fresh spills, weathered residues, free-phase hydrocarbons, diesel-range fractions, heavy components, sorbed contaminants, and soils with varying ecological sensitivity. No single remediation technology is capable of addressing all these conditions simultaneously.

A treatment-train approach allows the sequential or combined application of technologies matched to contaminant properties, site conditions, and remediation objectives. This approach is consistent with sustainable remediation principles and contaminated-site management frameworks [26,27,41,42]. Typical treatment-train configurations include:

Emergency spill response: containment → free-product recovery → sorbent stabilization → excavation of hotspots → on-site biopile or landfarming treatment → revegetation → monitoring.

Remote diesel-contaminated soil: excavation → landfarming or biopile treatment → nutrient optimization → phytoremediation polishing → toxicity and vegetation monitoring.

Weathered petroleum residues: composting or amendment-assisted bioremediation → bioavailability and toxicity assessment → revegetation → long-term monitoring.

Small high-risk hotspots: excavation or chemical oxidation → treatment of excavated soil → backfilling → ecological restoration.

Low-risk residual contamination: monitored natural attenuation → periodic fractionated TPH and toxicity assessment → adaptive management if conditions change.

The treatment-train concept reinforces the need to link monitoring data with decision-making. Technology selection should not be static but should evolve as monitoring data indicate changes in contaminant behavior, bioavailability, toxicity, and ecological recovery.

Table 3 summarizes the recommended multi-endpoint monitoring framework that supports treatment-train implementation and decision-making across remediation stages.

4.8. Limitations and Research Gaps

Several limitations and research gaps constrain current remediation practice in Arctic and sub-Arctic regions.

First, field-scale evidence remains limited. A substantial portion of the literature is based on laboratory or pilot-scale studies, while full-scale field applications are relatively few and highly site-specific. Additional multi-year field studies across tundra, taiga, peat, podzolic, gleyed, alluvial, and sandy soils are required to improve the transferability of results.

Second, remediation endpoints remain overly concentration-centered. Total petroleum hydrocarbon reduction alone does not adequately reflect risk reduction, toxicity decrease, or soil-function recovery [24–27]. Future studies should systematically integrate chemical, bioavailability, ecotoxicological, microbiological, and vegetation-based endpoints.

Third, surfactant-assisted remediation remains uncertain under cold-region conditions. While surfactants can enhance hydrocarbon mobilization or bioavailability, they may also increase contaminant migration or introduce toxicity. Evidence from Western Siberia demonstrates strong soil- and dose-dependent variability in surfactant performance [54,55].

Fourth, amendment-assisted remediation requires improved mechanistic understanding. Materials such as biochar, peat, compost, and mineral sorbents can reduce toxicity and improve soil properties but may immobilize hydrocarbons without promoting degradation [60–64]. Distinguishing between immobilization and true contaminant removal remains a critical research need.

Fifth, climate change is insufficiently integrated into remediation design. Permafrost degradation, active-layer deepening, altered hydrological regimes, erosion, and infrastructure instability may significantly influence contaminant behavior and remediation performance over time [5,6,60,61]. Adaptive, long-term monitoring strategies are therefore required.

Recent literature on petroleum-contaminated soil management and cold-region remediation likewise emphasizes the need to connect contaminant reduction with soil reuse, microbiological recovery, and region-specific management practice [53,65–67].

4.9. Future Research Directions

Future research should focus on the following priorities:

1. Field-scale comparative studies of landfarming, biopiles, composting, and biostimulation under comparable Arctic and sub-Arctic conditions;
2. Multi-season monitoring of residual and weathered petroleum hydrocarbons, including slow-degrading fractions;
3. Optimization of nutrient regimes, including type, dose, timing, and delivery methods for cold-region soils;
4. Mandatory pilot testing of surfactants and amendments prior to full-scale implementation;
5. Development of bioavailability-oriented analytical methods for petroleum-contaminated soils;
6. Integration of multi-endpoint monitoring systems, combining FTIR/DMSO-type methods, bioassays, microbial indicators, and conventional chemical analysis;
7. Evaluation of native plant species for rhizoremediation and post-remediation stabilization;
8. Life-cycle and sustainability assessment of remediation technologies under Arctic logistical constraints;
9. Climate-informed remediation design, accounting for permafrost dynamics and long-term environmental change;
10. Development of regional databases for contaminated sites and remediation outcomes in the Russian Arctic.

5. Conclusions

Petroleum hydrocarbon-contaminated soils in Arctic and sub-Arctic regions require remediation strategies adapted to low temperatures, permafrost, short thaw seasons, remote logistics, and fragile ecosystems. The reviewed evidence confirms that no single technology is universally optimal; technology selection must be site-specific and based on contaminant properties, soil and permafrost conditions, ecological sensitivity, infrastructure constraints, and monitoring capacity.

Biological and combined on-site approaches, including landfarming, biopiles, composting, and nutrient-assisted bioremediation, are generally the most feasible options for remote Arctic sites. Their effectiveness depends on engineering control, multi-season implementation, and monitoring of oxygen, nutrients, moisture, toxicity, and residual hydrocarbon fractions. Physical, chemical, thermal, and excavation-based approaches remain important for hotspots and high-risk source zones, but their use should be justified by risk reduction and sustainability criteria rather than by bulk contaminant removal alone.

The main contribution of this review is the proposed monitoring-informed decision framework. Remediation success should not be evaluated solely by TPH reduction. Instead, chemical fractionation, bioavailability-oriented methods, ecotoxicological tests, microbial indicators, and vegetation-based endpoints should guide technology selection, optimization, and adaptive management.

For the Russian Arctic, the most promising pathway is to integrate national recultivation standards, GOST requirements, and best available technology principles with risk-based assessment and multi-endpoint monitoring. Evidence from Western Siberia demonstrates that soil type, contaminant characteristics, surfactant behavior, nutrient regime, and temperature strongly influence remediation outcomes.

Overall, the effective management of petroleum-contaminated Arctic soils requires a shift from technology-centered cleanup toward adaptive, monitoring-driven, and ecosystem-oriented remediation. A robust strategy should combine source control, concep-

tual site modeling, treatment-train design, pilot testing, multi-endpoint monitoring, and long-term ecological restoration.

Author Contributions: Conceptualization, O.S.S.; methodology, O.S.S.; validation, R.Y.B. and O.S.S.; formal analysis, R.Y.B. and O.S.S.; investigation, R.Y.B. and O.S.S.; resources, O.S.S.; data curation, R.Y.B.; writing—original draft preparation, O.S.S.; writing—review and editing, R.Y.B.; visualization, R.Y.B.; supervision, O.S.S.; project administration, O.S.S.; funding acquisition, O.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Russian Science Foundation, grant number 24-14-20030, https://rscf.ru/en/project/24-14-20030/ (accessed on 1 May 2026).

Data Availability Statement: The data contained in the review article is cited and its source is included in the manuscript references. You can contact the authors with any more questions.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BAT	best available techniques
BTEX	benzene, toluene, ethylbenzene, and xylenes
CEC	cation exchange capacity
CMC	critical micelle concentration
CSM	conceptual site model
DMSO	dimethyl sulfoxide
EU	European Union
FTIR	Fourier transform infrared spectroscopy
GC-FID	gas chromatography with flame ionization detection
GC-MS	gas chromatography–mass spectrometry
ISO	International Organization for Standardization
MNA	monitored natural attenuation
PAHs	polycyclic aromatic hydrocarbons
PHCs	petroleum hydrocarbons
SOM	soil organic matter
SuRF-UK	Sustainable Remediation Forum, United Kingdom
TPH	total petroleum hydrocarbons

References

1. Aislabie, J.; Saul, D.J.; Foght, J.M. Bioremediation of Hydrocarbon-Contaminated Polar Soils. *Extremophiles* **2006**, *10*, 171–179. [CrossRef]
2. Naseri, M.; Barabadi, A.; Barabady, J. Bioremediation Treatment of Hydrocarbon-Contaminated Arctic Soils: Influencing Parameters. *Environ. Sci. Pollut. Res.* **2014**, *21*, 11250–11265. [CrossRef] [PubMed]
3. Filler, D.M.; Snape, I.; Barnes, D.L. (Eds.) *Bioremediation of Petroleum Hydrocarbons in Cold Regions*; Cambridge University Press: Cambridge, UK, 2008; ISBN 9780521869706.
4. Margesin, R.; Schinner, F. Biodegradation and Bioremediation of Hydrocarbons in Extreme Environments. *Appl. Microbiol. Biotechnol.* **2001**, *56*, 650–663. [CrossRef]
5. Whyte, L.G.; Bourbonniére, L.; Greer, C.W. Biodegradation of Petroleum Hydrocarbons by Psychrotrophic Pseudomonas Strains Possessing Both Alkane (Alk) and Naphthalene (Nah) Catabolic Pathways. *Appl. Environ. Microbiol.* **1997**, *63*, 3719–3723. [CrossRef]
6. Yergeau, E.; Sanschagrin, S.; Beaumier, D.; Greer, C.W. Metagenomic Analysis of the Bioremediation of Diesel-Contaminated Canadian High Arctic Soils. *PLoS ONE* **2012**, *7*, e30058. [CrossRef]
7. Bell, T.H.; Yergeau, E.; Maynard, C.; Juck, D.; Whyte, L.G.; Greer, C.W. Predictable Bacterial Composition and Hydrocarbon Degradation in Arctic Soils Following Diesel and Nutrient Disturbance. *ISME J.* **2013**, *7*, 1200–1210. [CrossRef]

8. Kundu, A.; Harrisson, O.; Ghoshal, S. Impacts of Arctic Diesel Contamination on Microbial Community Composition and Degradative Gene Abundance during Hydrocarbon Biodegradation with and without Nutrients: A Case Study of Seven Sub-Arctic Soils. *Sci. Total Environ.* **2023**, *871*, 161777. [CrossRef] [PubMed]
9. Johnsen, A.R.; Boe, U.S.; Henriksen, P.; Malmquist, L.M.V.; Christensen, J.H. Full-Scale Bioremediation of Diesel-Polluted Soil in an Arctic Landfarm. *Environ. Pollut.* **2021**, *280*, 116946. [CrossRef]
10. McCarthy, K.; Walker, L.; Vigoren, L.; Bartel, J. Remediation of Spilled Petroleum Hydrocarbons by in Situ Landfarming at an Arctic Site. *Cold Reg. Sci. Technol.* **2004**, *40*, 31–39. [CrossRef]
11. Sanscartier, D.; Zeeb, B.; Koch, I.; Reimer, K. Bioremediation of Diesel-Contaminated Soil by Heated and Humidified Biopile System in Cold Climates. *Cold Reg. Sci. Technol.* **2009**, *55*, 167–173. [CrossRef]
12. Atlas, R.M. Microbial Degradation of Petroleum Hydrocarbons: An Environmental Perspective. *Microbiol. Rev.* **1981**, *45*, 180–209. [CrossRef]
13. Head, I.M.; Jones, D.M.; Röling, W.F.M. Marine Microorganisms Make a Meal of Oil. *Nat. Rev. Microbiol.* **2006**, *4*, 173–182. [CrossRef] [PubMed]
14. Varjani, S.J. Microbial Degradation of Petroleum Hydrocarbons. *Bioresour. Technol.* **2017**, *223*, 277–286. [CrossRef]
15. Das, N.; Chandran, P. Microbial Degradation of Petroleum Hydrocarbon Contaminants: An Overview. *Biotechnol. Res. Int.* **2011**, *2011*, 941810. [CrossRef]
16. Haritash, A.K.; Kaushik, C.P. Biodegradation Aspects of Polycyclic Aromatic Hydrocarbons (PAHs): A Review. *J. Hazard. Mater.* **2009**, *169*, 1–15. [CrossRef]
17. Khan, M.A.I.; Biswas, B.; Smith, E.; Naidu, R.; Megharaj, M. Toxicity Assessment of Fresh and Weathered Petroleum Hydrocarbons in Contaminated Soil—A Review. *Chemosphere* **2018**, *212*, 755–767. [CrossRef]
18. Ramadass, K.; Megharaj, M.; Venkateswarlu, K.; Naidu, R. Bioavailability of Weathered Hydrocarbons in Engine Oil-Contaminated Soil: Impact of Bioaugmentation Mediated by Pseudomonas Spp. on Bioremediation. *Sci. Total Environ.* **2018**, *636*, 968–974. [CrossRef]
19. Prince, R.C. Bioremediation of Marine Oil Spills. *Trends Biotechnol.* **1997**, *15*, 158–160. [CrossRef]
20. Tyagi, M.; da Fonseca, M.M.R.; de Carvalho, C.C.C.R. Bioaugmentation and Biostimulation Strategies to Improve the Effectiveness of Bioremediation Processes. *Biodegradation* **2011**, *22*, 231–241. [CrossRef] [PubMed]
21. Bento, F.M.; Camargo, F.A.O.; Okeke, B.C.; Frankenberger, W.T. Comparative Bioremediation of Soils Contaminated with Diesel Oil by Natural Attenuation, Biostimulation and Bioaugmentation. *Bioresour. Technol.* **2005**, *96*, 1049–1055. [CrossRef]
22. Maila, M.P.; Cloete, T.E. Bioremediation of Petroleum Hydrocarbons through Landfarming: Are Simplicity and Cost-Effectiveness the Only Advantages? *Rev. Environ. Sci. Biotechnol.* **2004**, *3*, 349–360. [CrossRef]
23. Mohn, W.W.; Stewart, G.R. Limiting Factors for Hydrocarbon Biodegradation at Low Temperature in Arctic Soils. *Soil. Biol. Biochem.* **2000**, *32*, 1161–1172. [CrossRef]
24. Semple, K.T.; Doick, K.J.; Jones, K.C.; Burauel, P.; Craven, A.; Harms, H. Peer Reviewed: Defining Bioavailability and Bioaccessibility of Contaminated Soil and Sediment Is Complicated. *Environ. Sci. Technol.* **2004**, *38*, 228A–231A. [CrossRef]
25. Ortega-Calvo, J.-J.; Harmsen, J.; Parsons, J.R.; Semple, K.T.; Aitken, M.D.; Ajao, C.; Eadsforth, C.; Galay-Burgos, M.; Naidu, R.; Oliver, R.; et al. From Bioavailability Science to Regulation of Organic Chemicals. *Environ. Sci. Technol.* **2015**, *49*, 10255–10264. [CrossRef] [PubMed]
26. *ISO 18504:2017*; Soil Quality—Sustainable Remediation. ISO: Geneva, Switzerland, 2017. Available online: https://www.iso.org/obp/ui/en/#iso:std:iso:18504:ed-1:v1:en (accessed on 1 May 2026). (In English)
27. SuRF-UK. A Framework for Assessing the Sustainability of Soil and Groundwater Remediation. Available online: https://staging.claire.co.uk/surf-international-notes/category/16-surf-uk-bulletins (accessed on 1 May 2026).
28. Koshlaf, E.; Ball, A.S.; Koshlaf, E.; Ball, A.S. Soil Bioremediation Approaches for Petroleum Hydrocarbon Polluted Environments. *AIMS Microbiol.* **2017**, *3*, 25–49. [CrossRef]
29. Omokhagbor Adams, G.; Tawari Fufeyin, P.; Eruke Okoro, S.; Ehinomen, I. Bioremediation, Biostimulation and Bioaugmention: A Review. *Int. J. Environ. Bioremediation Biodegrad.* **2020**, *3*, 28–39. [CrossRef]
30. Gerhardt, K.E.; Huang, X.-D.; Glick, B.R.; Greenberg, B.M. Phytoremediation and Rhizoremediation of Organic Soil Contaminants: Potential and Challenges. *Plant Sci.* **2009**, *176*, 20–30. [CrossRef]
31. Liste, H.-H.; Alexander, M. Plant-Promoted Pyrene Degradation in Soil. *Chemosphere* **2000**, *40*, 7–10. [CrossRef] [PubMed]
32. Siciliano, S.D.; Germida, J.J. Enhanced Phytoremediation of Chlorobenzoates in Rhizosphere Soil. *Soil. Biol. Biochem.* **1999**, *31*, 299–305. [CrossRef]
33. Paria, S. Surfactant-Enhanced Remediation of Organic Contaminated Soil and Water. *Adv. Colloid. Interface Sci.* **2008**, *138*, 24–58. [CrossRef]
34. Mao, X.; Jiang, R.; Xiao, W.; Yu, J. Use of Surfactants for the Remediation of Contaminated Soils: A Review. *J. Hazard. Mater.* **2015**, *285*, 419–435. [CrossRef]
35. Ron, E.Z.; Rosenberg, E. Biosurfactants and Oil Bioremediation. *Curr. Opin. Biotechnol.* **2002**, *13*, 249–252. [CrossRef]

36. Mulligan, C.N. Environmental Applications for Biosurfactants. *Environ. Pollut.* **2005**, *133*, 183–198. [CrossRef] [PubMed]
37. Beesley, L.; Moreno-Jiménez, E.; Gomez-Eyles, J.L. Effects of Biochar and Greenwaste Compost Amendments on Mobility, Bioavailability and Toxicity of Inorganic and Organic Contaminants in a Multi-Element Polluted Soil. *Environ. Pollut.* **2010**, *158*, 2282–2287. [CrossRef]
38. Kuppusamy, S.; Thavamani, P.; Venkateswarlu, K.; Lee, Y.B.; Naidu, R.; Megharaj, M. Remediation Approaches for Polycyclic Aromatic Hydrocarbons (PAHs) Contaminated Soils: Technological Constraints, Emerging Trends and Future Directions. *Chemosphere* **2017**, *168*, 944–968. [CrossRef] [PubMed]
39. Riser-Roberts, E. *Remediation of Petroleum Contaminated Soils: Biological, Physical, and Chemical Processes*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2020; ISBN 9780367802547.
40. Khan, F.I.; Husain, T.; Hejazi, R. An Overview and Analysis of Site Remediation Technologies. *J. Environ. Manag.* **2004**, *71*, 95–122. [CrossRef] [PubMed]
41. Suthersan, S.S.; Payne, F.C. *In Situ Remediation Engineering*; CRC Press: Boca Raton, FL, USA, 2004; ISBN 9781135461959.
42. US EPA. *Treatment Technologies for Site Cleanup: Annual Status Report*, 12th ed.; US EPA: Washington, DC, USA, 2007. Available online: https://www.epa.gov/sites/default/files/2015-09/documents/asr12_full_document.pdf (accessed on 1 May 2026).
43. Environmental Technology Centre, Environment Canada. Federal Guidelines for Landfarming Petroleum Hydrocarbon Contaminated Soils: Final Report/Presented to: Contaminated Sites Division and Emergencies Engineering Technologies Office (EETO). Available online: https://publications.gc.ca/site/eng/9.899068/publication.html (accessed on 1 May 2026).
44. *PN 1398*; Canada-Wide Standard for Petroleum Hydrocarbons (phc) in Soil. User Guidance. Canadian Council of Ministers of the Environment: Winnipeg, MB, Canada, 2008. Available online: https://ccme.ca/en/res/cws_phc_user_guide_1.1_e.pdf (accessed on 1 May 2026).
45. Alaska Department of Environmental Conservation. *Landfarming at Sites in Alaska: Technical Memorandum*; Division of Spill Prevention and Response, Contaminated Sites Program: Juneau, AK, USA, 2020. Available online: https://dec.alaska.gov/media/2058/landfarm_tech_memo.pdf (accessed on 18 May 2026).
46. Petroleum Vapor Intrusion. Fundamentals of Screening, Investigation, and Management. Available online: https://projects.itrcweb.org/PetroleumVI-Guidance/Content/Resources/PVIPDF.pdf (accessed on 1 May 2026).
47. Remediation Management of Complex Sites—ITRC. Available online: https://rmcs-1.itrcweb.org/RMCS-Full-PDF.pdf (accessed on 1 May 2026).
48. Treatment of Petroleum-Contaminated Soil in Cold, Wet, Remote Regions. Available online: https://permanent.fdlp.gov/gpo246008/pdf02712801_300dpi.pdf (accessed on 1 May 2026).
49. Russian Federation. Federal Law No. 7-FZ on Environmental Protection. Available online: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC052751 (accessed on 1 May 2026).
50. Resolution of the Government of the Russian Federation of 23.12.2014 N 1458 (As Amended on 17.11.2022) "On the Procedure for Determining a Technology as the Best Available Technology, as Well as the Development, Updating and Publication of Information and Technical Reference Books on the Best Available Technologies" (Together with the "Rules for Determining a Technology as the Best Available Technology, as Well as the Development, Updating and Publication of Information and Technical Reference Books on the Best Available Technologies"). Available online: https://www.consultant.ru/document/cons_doc_LAW_172796/ (accessed on 1 May 2026). (In Russian)
51. *GOST R 57447-2017*; Best Available Techniques. Reclamation of Lands Contaminated with Oil and Oil Products. Basis Principles. Federal Agency for Technical Regulation and Metrology: Moscow, Russia, 2017. Available online: https://www.russiangost.com/p-288410-gost-r-57447-2017.aspx (accessed on 1 May 2026).
52. *GOST R 57446-2017*; Best Available Techniques. Disturbed Lands Reclamation. Restoration of Biological Diversity. Federal Agency for Technical Regulation and Metrology; Moscow, Russia, 2017. Available online: https://www.russiangost.com/p-288409-gost-r-57446-2017.aspx (accessed on 1 May 2026).
53. Correia, A.; Rasteiro, M. A Review of Persistent Soil Contaminants: Assessment and Remediation Strategies. *Environments* **2025**, *12*, 229. [CrossRef]
54. Sutormin, O.S.; Goncharov, A.S.; Kratasyuk, V.A.; Petrova, Y.Y.; Bajbulatov, R.Y.; Yartsov, A.E.; Shpedt, A.A. Effects of Oil Contamination on Range of Soil Types in Middle Taiga of Western Siberia. *Sustainability* **2024**, *16*, 11204. [CrossRef]
55. Petrova, A.M.; Farrahova, G.R.; Duryagin, A.V.; Bajbulatov, R.Y.; Sutormin, O.S. Application of Tween 80 in the Remediation of Diesel-Contaminated Podzolic Soils Under Boreal Conditions. *Processes* **2025**, *13*, 2651. [CrossRef]
56. Farrahova, G.R.; Tanykova, N.G.; Kolosova, E.M.; Petrova, Y.Y.; Bajbulatov, R.Y.; Sutormin, O.S. Reducing the Gap Between Chemical and Biological Assessment of Petroleum-Contaminated Soils: An FTIR-Based Method Using Aqueous Dimethyl Sulfoxide Extraction. *Environments* **2026**, *13*, 140. [CrossRef]
57. Duryagin, A.V.; Bajbulatov, R.Y.; Sutormin, O.S. Nitrogen Biostimulation of Petroleum-Contaminated Sandy Podzolic Soil Under Boreal Conditions: Effects of Temperature, Nitrogen Form, and Contamination Level. *Appl. Sci.* **2026**, *16*, 4190. [CrossRef]

58. Kolosova, E.M.; Sutormin, O.S.; Esimbekova, E.N.; Lonshakova-Mukina, V.I.; Kratasyuk, V.A. Set of Enzymatic Bioassays for Assessment of Soil Contamination. *Dokl. Biol. Sci.* **2019**, *489*, 165–168. [CrossRef]
59. Kolosova, E.M.; Sutormin, O.S.; Shpedt, A.A.; Stepanova, L.V.; Kratasyuk, V.A. Bioluminescent-Inhibition-Based Biosensor for Full-Profile Soil Contamination Assessment. *Biosensors* **2022**, *12*, 353. [CrossRef] [PubMed]
60. EU Soil Strategy for 2030. Reaping the Benefits of Healthy Soils for People, Food, Nature and Climate. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699 (accessed on 2 May 2026).
61. Directive (EU) 2025/2360 of the European Parliament and of the Council of 12 November 2025 on Soil Monitoring and Resilience (Soil Monitoring Law). Available online: https://eur-lex.europa.eu/eli/dir/2025/2360/oj/eng (accessed on 2 May 2026).
62. Li, Y.; Yang, J.; Song, Y.; Wei, M. Progress in Biostimulation-Based Remediation of TPH-Contaminated Soils: A Comprehensive Review. *PeerJ* **2025**, *13*, e19991. [CrossRef] [PubMed]
63. O'Connor, D.; Peng, T.; Zhang, J.; Tsang, D.C.W.; Alessi, D.S.; Shen, Z.; Bolan, N.S.; Hou, D. Biochar Application for the Remediation of Heavy Metal Polluted Land: A Review of in Situ Field Trials. *Sci. Total Environ.* **2018**, *619–620*, 815–826. [CrossRef] [PubMed]
64. Hale, S.E.; Elmquist, M.; Brändli, R.; Hartnik, T.; Jakob, L.; Henriksen, T.; Werner, D.; Cornelissen, G. Activated Carbon Amendment to Sequester PAHs in Contaminated Soil: A Lysimeter Field Trial. *Chemosphere* **2012**, *87*, 177–184. [CrossRef]
65. Losacco, D.; Campanale, C.; Triozzi, M.; Massarelli, C.; Uricchio, V.F. Application of Wood and Vegetable Waste-Based Biochars in Sustainable Agriculture: Evaluation on Nitrate Leaching, Pesticide Fate, Soil Properties, and Brassica Oleracea Growth. *Environments* **2024**, *11*, 13. [CrossRef]
66. Ambaye, T.G.; Chebbi, A.; Formicola, F.; Prasad, S.; Gomez, F.H.; Franzetti, A.; Vaccari, M. Remediation of Soil Polluted with Petroleum Hydrocarbons and Its Reuse for Agriculture: Recent Progress, Challenges, and Perspectives. *Chemosphere* **2022**, *293*, 133572. [CrossRef]
67. Sozina, I.D.; Danilov, A.S. Microbiological remediation of oil-contaminated soils. *J. Min. Inst.* **2023**, *260*, 297–312. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.