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Application of Tween 80 in the Remediation of Diesel-Contaminated Podzolic Soils Under Boreal Conditions

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Abstract

Surfactant-enhanced remediation is a promising approach for treating petroleum-contaminated soils, particularly in areas where conventional methods are limited by environmental constraints. This study investigates the application of Tween 80, a non-ionic surfactant, for remediating diesel-contaminated Albic Podzolic soils typical of boreal regions. Laboratory experiments were conducted over 90 days, using two surfactant concentrations (3.0×10^{-4} and 1.5×10^{-4} mol L⁻¹) and two temperature regimes (22–24 °C and 2–3 °C), simulating seasonal variability in cold-climate contaminated sites. The lower Tween 80 concentration—below the critical micelle concentration—proved more effective, achieving up to 21% total petroleum hydrocarbon (TPH) reduction at ambient temperature and 17% under refrigerated conditions. Treated soils also exhibited pH neutralization, indicating improved chemical stability. Acute toxicity bioassays (*Vibrio fischeri* and *Ceriodaphnia affinis*) confirmed the environmental safety of the applied concentrations (≤ 0.3 mol L⁻¹). These results support the practical use of Tween 80 in the remediation of petroleum-contaminated soils under boreal constraints, providing transferable data for designing safe and efficient field-scale treatment strategies. This work also offers insights that are relevant to remediation policies in cold climates and to the adaptation of surfactant-assisted technologies for diverse field conditions.

Keywords: surfactant-enhanced remediation; diesel-contaminated soil; Tween 80; boreal soils; total petroleum hydrocarbons (TPH); pH stabilization; acute ecotoxicity; cold-region site remediation



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1. Introduction

Petroleum hydrocarbon contamination of soil remains a major environmental and practical challenge, particularly in oil-producing regions where accidental releases are common and remediation efforts are complicated by site-specific constraints. Diesel fuel, a complex mixture of aliphatic and aromatic hydrocarbons, is among the most persistent petroleum pollutants. It adversely affects the soil structure, groundwater integrity, and ecosystem function, while resisting natural degradation [1–6].

In contaminated soils, diesel disrupts key physicochemical parameters, such as porosity, acidity, and ionic composition. These disruptions are especially pronounced in cold

regions, where low temperatures suppress microbial activity and delay natural attenuation processes [7–9]. As a result, boreal and subarctic zones—often home to acidic, poorly buffered soils—require remediation approaches tailored to both local climate and soil characteristics.

A representative example is the Khanty-Mansi Autonomous Okrug–Yugra in Western Siberia, a major oil-producing territory where Albic Podzolic soils dominate. This region was selected not only as a representative cold-climate oil-producing territory, but also due to its long history of petroleum extraction, frequent accidental spills, and prior documentation of diesel contamination in Albic Podzolic soils [10]. Moreover, previous research has highlighted the particular vulnerability of soils in this area to physicochemical disturbances and poor self-recovery potential, making it a relevant target for testing improved remediation strategies [11,12]. These soils are leached, acidic, and low in organic matter, rendering them highly vulnerable to hydrocarbon accumulation and difficult to remediate using conventional methods [10–13]. Their limited buffering capacity and low biological resilience in cold seasons further hinder natural recovery [8,11].

Traditional remediation approaches—such as excavation or chemical oxidation—are often cost-prohibitive and technically challenging in remote, cold-climate environments. Surfactant-enhanced remediation (SER) offers a field-adaptable alternative by improving the mobilization of hydrophobic contaminants through reduced interfacial tension and increased solubility [14,15]. Among the available surfactants, non-ionic types like Tween 80 (polysorbate 80) are valued for their low acute toxicity and chemical compatibility with soil systems [16,17]. Comparative studies indicate that Tween 80 performs more effectively in acidic or low-buffered soils than other non-ionic surfactants, such as Triton X-100 and Brij 35, especially under low-temperature conditions [17,18]. Its high hydrophilic–lipophilic balance and relatively low toxicity further support its selection for remediation in boreal ecosystems. Tween 80 has been frequently used in oil spill dispersal and soil-washing applications due to its strong solubilization capacity and non-ionic nature, which minimizes interactions with charged soil particles. It is also biodegradable and compatible with microbial consortia involved in hydrocarbon degradation [14,16,17]. These characteristics make it a promising candidate for cold-region applications, especially in acidic soils with low buffering capacity, where ionic surfactants might disrupt soil structure or pH balance. However, their practical performance in acidic soils under boreal temperature regimes remains poorly understood.

One critical factor in SER effectiveness is the surfactant concentration relative to its critical micelle concentration (CMC). While concentrations above the CMC may trap hydrocarbons within micelles and limit biodegradation, sub-CMC levels have been shown to enhance desorption and maintain bioavailability [18]. Optimizing Tween 80 concentration for cold-region, low-buffering soils remains an important but underexplored area.

Although Tween 80 is generally regarded as safe at low concentrations, its application in open soil systems still warrants ecotoxicological evaluation. Acute bioassays using *Ceriodaphnia affinis* and *Vibrio fischeri* are widely accepted for assessing multi-trophic impacts and detecting potential side effects during and after remediation [19].

The novelty of this work lies in evaluating Tween 80 performance in highly acidic, low-buffered Albic Podzolic soils under boreal temperature constraints, which are conditions rarely addressed in previous research [15–17]. While many studies have examined surfactant-enhanced remediation in temperate or neutral soils [14,15], few have combined sub-CMC dosing, dual temperature regimes, and integrated ecotoxicological assessment [16,17]. This approach delivers both mechanistic insights into surfactant–soil–contaminant interactions and practical guidance for remediation planning in oil-producing northern territories. The present study investigates Tween 80 application for the remedia-

tion of diesel-contaminated Albic Podzolic soils under simulated boreal conditions, using two surfactant concentrations (including a sub-CMC dose) and two temperature regimes representative of seasonal variability. Unlike prior work focused mainly on temperate soils or microbial biodegradation enhancement, this study addresses the underexplored combination of acidic soil chemistry and low temperatures. It aims to (a) quantify total petroleum hydrocarbon (TPH) reduction, (b) assess soil pH changes as an indicator of chemical stabilization, and (c) evaluate acute toxicity through standardized bioassays, providing data that is directly applicable to remediation strategies in vulnerable boreal regions.

2. Materials and Methods

2.1. Soil Sampling and Characterization

Soil samples were collected near the settlement of Nizhnesortymsky ($62^{\circ}45'38''$ N, $71^{\circ}78'86''$ E), Surgut District, Khanty-Mansi Autonomous Okrug–Yugra, Western Siberia. A composite sample was prepared using the five-point method, combining five subsamples (1 kg each) taken from a depth of 0–40 cm. The bulk sample (5 kg) was classified as Albic Podzolic soil, based on the Russian national classification system [20].

The soil exhibited typical features of podzols found in boreal forest zones: sandy loam texture, acidic pH (5.2), low organic matter (0.5%), and weak buffering capacity. Samples were air-dried at room temperature for 48 h and sieved through a 1 mm mesh prior to testing.

Key physicochemical properties were determined following national standards [21–23]. Organic matter content was measured by dichromate oxidation with back-titration using 0.1 M Mohr's salt. Soil pH was determined in a 1:5 soil-to-water suspension using a calibrated glass electrode. Electrical conductivity and dense residue of aqueous extract were measured gravimetrically after evaporation at 105 °C and via conductivity meter, respectively.

Total petroleum hydrocarbons (TPH) were quantified gravimetrically after extraction with chloroform, according to Russian standard PND F 16.1:41-04 [22]. Briefly, 30–40 g of soil was shaken with 15 mL of chloroform; extraction was repeated until the solvent became colorless. The combined extracts were evaporated, and the residual hydrocarbons were weighed and expressed as mg kg^{-1} of oven-dried soil.

2.2. Diesel Contamination and Surfactant Treatment

Diesel fuel used as the pollutant was obtained from the Surgut Condensate Stabilization Plant. The fuel was diluted with n-heptane (1:4 *v/v*) to facilitate even distribution. Soil (700 g) was uniformly mixed with the solution and left for solvent evaporation under a fume hood. The final TPH content was determined to be $50.01 \pm 1.14 \text{ mg kg}^{-1}$ (Table 1).

Table 1. Experimental design for Tween 80-assisted remediation of diesel-contaminated Albic Podzolic soils.

Treatment Code	Tween 80 Concentration (mol L^{-1})	Temperature ($^{\circ}\text{C}$)	Initial TPH (mg kg^{-1})	Soil Mass (g, Dry Basis)
T ₀ (control)	–	22–24	50.01 ± 1.14	300
T ₁	3.0×10^{-4}	22–24		
T ₂	1.5×10^{-4}	22–24		
X ₀ (control)	–	2–3		
X ₁	3.0×10^{-4}	2–3		
X ₂	1.5×10^{-4}	2–3		

Note: All treatments were performed in triplicate ($n = 3$). Initial TPH and soil mass were identical across treatments.

Tween 80 (polysorbate 80) was applied at two concentrations: 3.0×10^{-4} and $1.5 \times 10^{-4} \text{ mol L}^{-1}$, corresponding to approximately 41.6 mg L^{-1} and 20.8 mg L^{-1} , respectively. The surfactant solution was sprayed onto contaminated soil at volumes approximating 30% of the water-holding capacity ($\sim 210 \text{ mL per } 700 \text{ g}$), ensuring homogeneous coverage without oversaturation. CMC of Tween 80 was not measured experimentally. Dosing was selected based on the literature values in aqueous systems at $20\text{--}25^\circ\text{C}$ (typically $\sim 10\text{--}160 \text{ }\mu\text{M}$; $\approx 15\text{--}200 \text{ mg L}^{-1}$), acknowledging that temperature, electrolyte content, and soil matrices can shift the effective CMC upward in porewater [24]. Accordingly, the lower treatment was intended to fall at or below the effective CMC in the soil–water system.

Samples were incubated for 90 days under two temperature regimes: ambient ($22\text{--}24^\circ\text{C}$)—simulating summer conditions; and cold ($2\text{--}3^\circ\text{C}$)—simulating early spring or late autumn. Ambient temperature ($22\text{--}24^\circ\text{C}$) was maintained in a climate-controlled laboratory room and monitored daily using a digital thermometer. Refrigerated conditions ($2\text{--}3^\circ\text{C}$) were sustained in a cold chamber with internal regulation ($\pm 1^\circ\text{C}$). Soil moisture content was determined gravimetrically before and after incubation to assess potential evaporation losses, using the standard oven-drying method at 105°C until constant weight [25]. All TPH concentrations were normalized to oven-dry soil mass. Moisture variations during incubation were minor ($<7\%$) and did not significantly affect the interpretation of hydrocarbon depletion trends. Soils were incubated under static conditions without periodic mixing to simulate limited disturbance typical of in situ remediation scenarios.

2.3. Ecotoxicological Assays

To evaluate potential ecological risks of the surfactant, two acute toxicity bioassays were performed: the *Vibrio fischeri* bioluminescence inhibition test (Ecolum system) and the mortality test using *Ceriodaphnia affinis*.

2.3.1. *Vibrio fischeri* Luminescence Inhibition Assay

The bacterial assay was conducted using the Ecolum test kit (Lumex Instruments, St. Petersburg, Russia) and Biotox-10M luminometer (NIKI LMT, St. Petersburg, Russia), following the manufacturer's protocol. Freeze-dried *V. fischeri* were rehydrated, calibrated, and exposed to test solutions. Toxicity index (T) was calculated as:

$$T (\%) = (I_{\text{control}} - (I_{\text{sample}}/I_{\text{control}})) \times 100, \quad (1)$$

where I_{control} is the control luminescence (distilled water), and I_{samples} is the luminescence after exposure. A T-value $\geq 20\%$ was considered indicative of acute toxicity.

2.3.2. *Ceriodaphnia affinis* Acute Toxicity Test

Cladocerans (*C. affinis*) were cultured in reconstituted water ($20 \pm 2^\circ\text{C}$) and fed *Chlorella vulgaris*. Neonates (6–24 h old) were exposed to Tween 80 at 0.05 , 0.5 , 2 , 4 , and 20 mg L^{-1} for 48 h in 50 mL glass vessels ($n = 10$ per replicate). Mortality was recorded at 24 and 48 h. Tests were considered valid if control mortality did not exceed 10%.

A schematic overview of the experimental design is presented in Figure 1. The workflow included (i) soil sampling and characterization, (ii) contamination with diesel fuel and surfactant application at two concentrations (3.0×10^{-4} and $1.5 \times 10^{-4} \text{ mol L}^{-1}$), (iii) incubation under two temperature regimes ($22\text{--}24^\circ\text{C}$ and $2\text{--}3^\circ\text{C}$) for 90 days, and (iv) subsequent analyses of (TPH, soil pH, and acute toxicity using *Ceriodaphnia affinis* and *Vibrio fischeri*). This schematic summarizes the experimental sequence and highlights the main operational parameters.

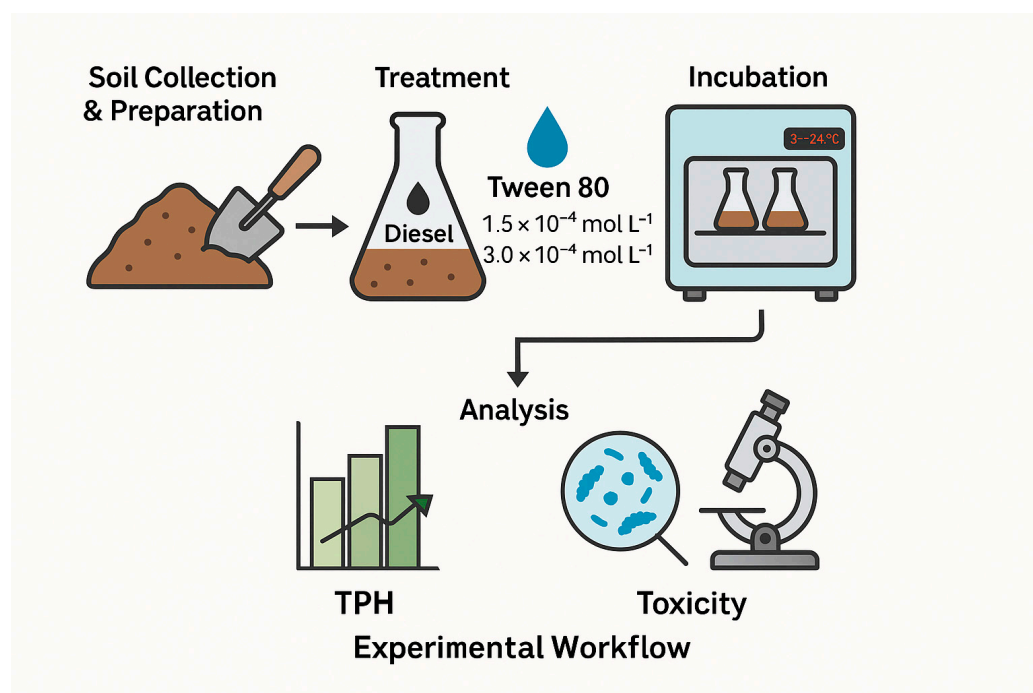


Figure 1. Schematic representation of the experimental workflow for Tween 80-assisted remediation of diesel-contaminated Albic Podzolic soils under boreal temperature conditions.

2.4. Data Processing

All experiments were performed in triplicate. Data are expressed as mean $\pm$ standard deviation (SD). Statistical significance was determined using Student's *t*-test, with $p < 0.05$ as the threshold. Analyses were conducted using Microsoft Excel 2021.

3. Results

This study evaluated the performance of Tween 80 in enhancing the remediation of diesel-contaminated Albic Podzolic soils. The effects were assessed across three key indicators: changes in total petroleum hydrocarbons (TPH), soil pH, and acute ecotoxicity. Control samples without surfactant (T_0 and X_0) were used to isolate the effects of natural attenuation from those induced by surfactant treatment.

3.1. Physicochemical Changes Following Diesel Contamination

Initial characterization revealed marked alterations in soil properties following diesel application (Table 2). Compared to the uncontaminated control, contaminated soils showed a decline in pH (from 5.50 to 5.22), a rise in electrical conductivity (from 9.82 to 10.53 mS cm^{-1}), and more than a twofold increase in total dissolved solids. These changes are consistent with acidification and ionic enrichment caused by the accumulation of low-molecular-weight by-products from partial hydrocarbon degradation.

Table 2. Physicochemical properties of soil samples before treatment.

Soil Type	Humus (%)	TPH (g kg^{-1})	$\text{pH}_{\text{H}_2\text{O}}$	Dense Residue (%)	Electrical Conductivity (mS cm^{-1})
Uncontaminated	0.40 ± 0.04	0.05 ± 0.01	5.50 ± 0.11	0.040 ± 0.004	9.82 ± 0.19
Diesel-contaminated	0.51 ± 0.06	50.01 ± 1.14	5.22 ± 0.12	0.096 ± 0.010	10.53 ± 0.31

3.2. Soil pH Response to Surfactant Application

All samples exhibited gradual pH increases during the 90 day incubation (Figure 2). In the untreated controls (T_0 , X_0), the pH rose by only 0.2–0.3 units, likely due to weak natural buffering. Tween 80-treated soils demonstrated more pronounced pH neutralization, especially under cold conditions ($p < 0.05$ for treated vs. control samples). The most notable shift occurred in the X_2 variant (1.5×10^{-4} mol L $^{-1}$ at 2–3 °C), where pH increased from 5.33 to 6.71.

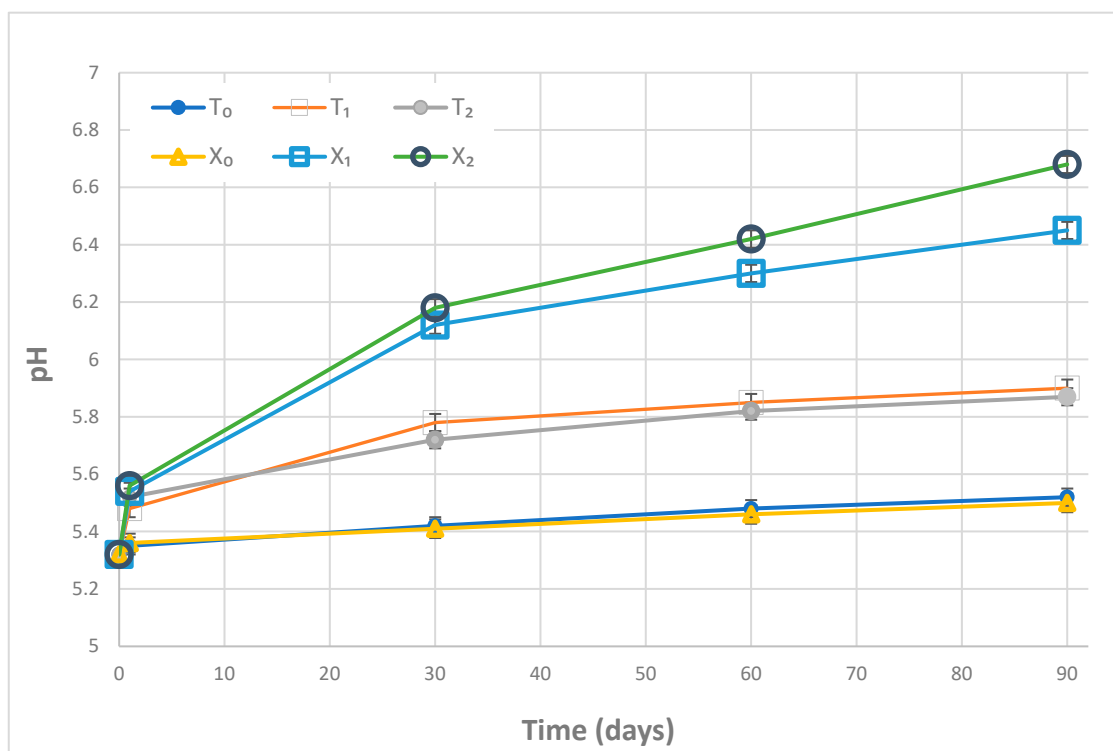


Figure 2. Soil pH over 90 days in diesel-contaminated soils treated with Tween 80 at different temperatures and concentrations. T-series: ambient temperature (22–24 °C); X-series: refrigerated (2–3 °C).

This pH adjustment may reflect partial removal or desorption of acidic intermediates and enhanced ion exchange, promoted by surfactant-assisted solubilization. Under low temperatures, Tween 80 likely improved water transport and mitigated localized acid build-up: a critical benefit in poorly buffered podzolic soils.

3.3. Reduction in Total Petroleum Hydrocarbons (TPH)

All treatment variants showed a progressive decline in TPH content. In the absence of Tween 80 (T_0 and X_0), TPH decreased by approximately 3000–4000 mg kg $^{-1}$ over 90 days (equivalent to ~6% reduction), primarily due to natural attenuation processes, such as evaporation and passive sorption. These changes were not statistically significant ($p > 0.05$), indicating negligible natural attenuation under the tested conditions.

The addition of Tween 80 significantly accelerated hydrocarbon removal ($p < 0.05$ for all treatments vs. respective controls; Figure 3). The lower concentration (1.5×10^{-4} mol L $^{-1}$) consistently outperformed the higher dose across both temperature regimes. At ambient temperature (T_2), TPH dropped by 20.8%, from 50,030 to 39,640 mg kg $^{-1}$. Under cold conditions (X_2), a 17% reduction was observed. In contrast, the higher concentration (3.0×10^{-4} mol L $^{-1}$) achieved only 14.8% and 12.2% reductions at ambient and cold temperatures, respectively.

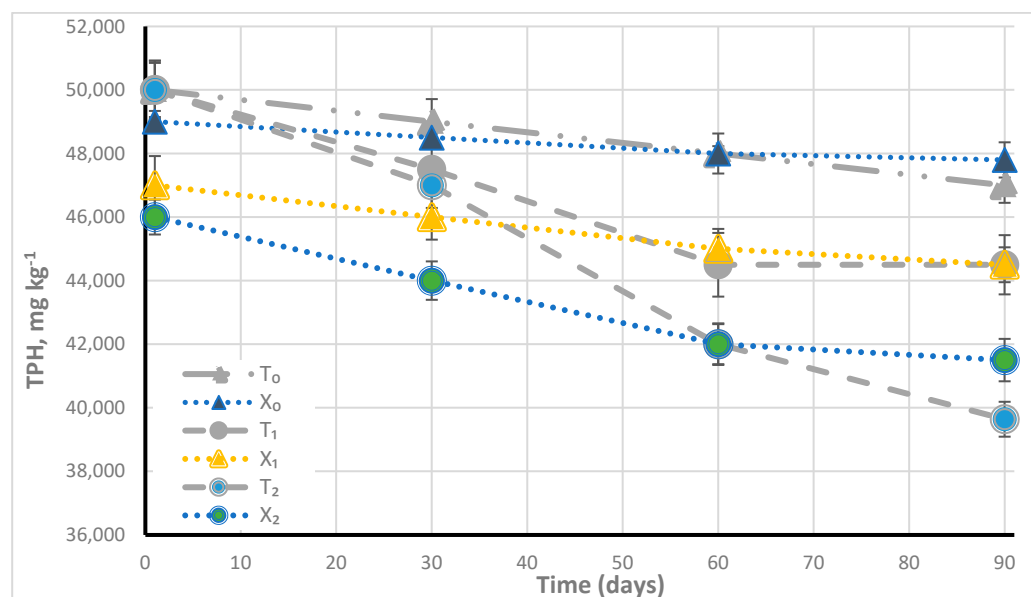


Figure 3. Temporal changes in TPH concentration in soil samples with and without Tween 80 under ambient and cold conditions.

A summary of initial and final TPH concentrations for each treatment group is provided in Table 3. The table includes calculated percentage reductions and statistical significance groupings. The highest TPH removal was observed for T₂ (20.77%) under ambient conditions, followed by X₂ (16.99%) under cold conditions, confirming the enhanced performance of sub-CMC Tween 80 dosing.

Table 3. Initial and final total petroleum hydrocarbon (TPH) concentrations in diesel-contaminated Albic Podzolic soils across all treatment groups, with percentage reduction and statistical significance annotations.

Treatment	Initial TPH (g kg ⁻¹)	Final TPH (g kg ⁻¹)	Reduction (%)	Significance *
T ₀	50.03	46.90	6.26	a
T ₁	50.03	42.60	14.85	b
T ₂	50.03	39.64	20.77	c
X ₀	50.03	47.00	6.06	a
X ₁	50.03	43.80	12.45	b
X ₂	50.03	41.53	16.99	bc

* Different letters within the same column indicate statistically significant differences between treatments ($p < 0.05$).

These results support the hypothesis that sub-CMC concentrations enhance hydrocarbon mobility without micelle entrapment. Doses above the CMC may encapsulate diesel constituents, limiting their availability for desorption or further degradation.

3.4. Acute Toxicity of Tween 80

Tween 80 displayed a clear dose-dependent toxicity in both bioassay systems (Table 4). Concentrations of 2 mg L⁻¹ and above led to significant responses: luminescence inhibition in *Vibrio fischeri* exceeded 40%, and mortality in *Ceriodaphnia affinis* approached 19%. At concentrations ≤ 0.5 mg L⁻¹—corresponding to those used in soil treatments—no adverse effects were observed.

Table 4. Acute toxicity of Tween 80 after 48 h exposure.

Concentration (mg L ^{−1})	<i>V. fischeri</i> Inhibition (%)	<i>C. affinis</i> Mortality (%)
20	74.44 ± 1.8	19 ± 2
4	54.68 ± 2.7	17 ± 3
2	41.44 ± 3.1	16 ± 2
0.5	20.62 ± 2.3	8 ± 1
0.05	5.13 ± 0.9	2 ± 1

The use of two test organisms provided complementary perspectives: *C. affinis* reflects possible impacts on aquatic invertebrates, while *V. fischeri* offers a sensitive indicator of microbial-level toxicity. Both tests confirmed that Tween 80, at operational doses, does not present acute toxicity risks.

4. Discussion

This study demonstrates the potential of Tween 80 to support the remediation of diesel-contaminated Albic Podzolic soils in cold climate conditions, addressing both hydrocarbon removal and the restoration of soil chemical balance. Diesel contamination was found to significantly lower soil pH and increase ionic load, likely due to the accumulation of low-molecular-weight degradation by-products and organic acids [6,26]. In soils with inherently low buffering capacity—such as Albic Podzols—such changes present major barriers to natural recovery. The observed pH neutralization following Tween 80 application indicates chemical stabilization, which may improve the resilience of treated soils and facilitate long-term site recovery.

A key outcome of the study was the superior performance of the lower Tween 80 concentration (1.5×10^{-4} mg L^{−1}), which remained below the compound's critical micelle concentration (CMC). Reported CMC values for Tween 80 span one order of magnitude depending on method and ionic strength; adsorption to mineral and organic phases can further elevate the apparent CMC in soils. We therefore interpret the 1.5×10^{-4} mol L^{−1} treatment as a near-/sub-CMC dose in the soil–water context [24,27]. This outcome aligns with the known behavior of surfactants below their CMC, where monomers interact more freely with hydrophobic contaminants and soil surfaces. In contrast, micelle formation at higher concentrations may isolate diesel constituents from desorption pathways, limiting their mobilization. At this level, the surfactant enhanced hydrocarbon desorption without entrapping contaminants in micellar structures, thereby maintaining their availability for removal. In contrast, higher concentrations likely promoted micelle formation, reducing bioavailability and transport.

Mechanistically, Tween 80 molecules reduce interfacial tension between soil particles and hydrocarbon droplets, improving wettability and facilitating desorption. At sub-CMC concentrations, individual surfactant monomers align at the solid–liquid interface, enhancing hydrocarbon mobility. At higher concentrations, micelles may sequester hydrophobic molecules, reducing their availability for mobilization or biodegradation. Figure 4 illustrates this conceptual mechanism.

Temperature played a decisive role in treatment efficiency. While remediation under ambient conditions (22–24 °C) yielded greater TPH reductions, the effectiveness of Tween 80 at 2–3 °C remained notable, with up to 17% reduction achieved. This supports its potential application in boreal or subarctic regions, where alternative technologies—such as excavation or thermal desorption—may be economically or logistically unviable [15,28]. While this study focused on ambient and cold temperature regimes to simulate boreal seasonal extremes, future work should investigate extended thermal gradients—including freeze–thaw dynamics or artificially elevated temperatures—to better understand temperature–

desorption relationships and their scaling potential. The ability to achieve measurable remediation at low temperatures extends the utility of surfactant-based approaches to settings where conventional remediation options are limited. These results are consistent with previous reports [17,18,24] and highlight the importance of dose selection when applying surfactants at contaminated sites, particularly where environmental safety and resource efficiency are both critical. The observed differences in both TPH reduction and pH neutralization were statistically significant ($p < 0.05$), reinforcing the robustness of these treatment effects under both ambient and cold conditions.

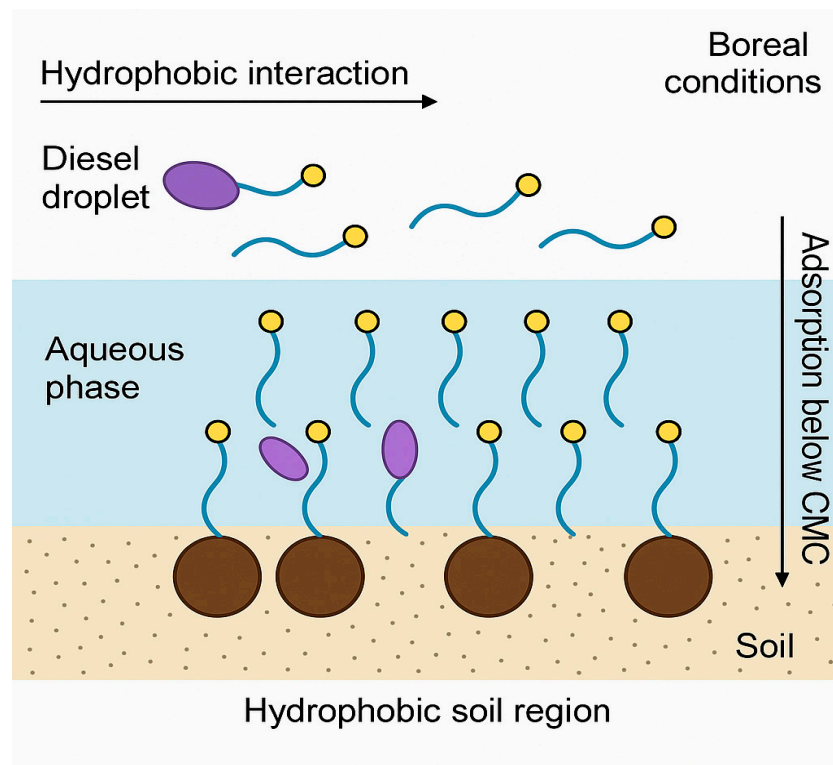


Figure 4. Conceptual diagram of Tween 80-assisted hydrocarbon mobilization in soil.

Aquatic bioassays using *Vibrio fischeri* and *Ceriodaphnia affinis* were selected due to their high sensitivity to surfactants, standardization in environmental testing, and relevance to potential groundwater exposure pathways. Both test organisms are included in internationally recognized ecotoxicological testing standards [29,30], ensuring reproducibility and comparability of the obtained data. While these organisms do not directly represent terrestrial soil fauna, they provide a conservative estimate of acute toxicity. The inclusion of soil-dwelling test species (e.g., *Eisenia fetida*) is recommended for future work to expand ecological relevance. Importantly, ecotoxicological testing confirmed the safety of Tween 80 at concentrations relevant to field application. Neither *Ceriodaphnia affinis* nor *Vibrio fischeri* exhibited adverse effects at doses $\leq 0.3 \text{ mg L}^{-1}$, supporting the use of this surfactant in environmentally sensitive contexts [19,31]. While long-term impacts remain to be fully assessed, these findings provide reassurance that short-term exposure at optimized levels is unlikely to pose ecological risks.

While acute toxicity assays confirmed the environmental safety of Tween 80 at operational concentrations, the potential chronic effects of residual surfactant and diesel degradation by-products were not evaluated in this study. Long-term ecotoxicological assessments, including chronic exposure tests on both aquatic and terrestrial organisms, are recommended to comprehensively evaluate the environmental risks associated with field-scale applications.

The concentrations used in aquatic toxicity assays ($\leq 0.3 \text{ mg L}^{-1}$) were selected to represent estimated surfactant levels in leachate or pore water following field application, assuming typical dilution and sorption processes in soil. Although the nominal application doses in soil were higher (up to $\sim 41.6 \text{ mg L}^{-1}$), strong sorption to soil organic matter and partial biodegradation are expected to substantially reduce aqueous-phase concentrations [14,32]. Therefore, the tested levels are considered environmentally realistic for potential exposure pathways to aquatic organisms. Previous studies have demonstrated that non-ionic surfactants such as Tween 80 exhibit rapid adsorption to mineral and organic soil fractions and undergo biodegradation with half-lives ranging from several days to weeks under environmental conditions, thereby limiting their persistence and mobility in aquatic systems [28,32].

Overall, the results expand current knowledge on surfactant-assisted remediation under harsh environmental conditions. Although non-ionic surfactants have been studied in temperate soils [33], their behavior in cold, acidic, and low-resilience soils remains under-documented. This study contributes site-relevant data that integrates surfactant performance, soil chemistry, and toxicity endpoints, and is thus applicable to real-world contaminated sites.

Field-scale and pilot-scale applications of Tween 80 and other non-ionic surfactants have shown comparable trends in contaminant mobilization and removal efficiency, particularly in soils with low buffering capacity. For example, Mulligan et al. [34] reported that Tween 80 enhanced hydrocarbon removal from field-contaminated soils under ambient outdoor conditions, with the performance dependent on soil texture and organic matter content. Similarly, He et al. [35] demonstrated that non-ionic surfactants such as Tween 80 could outperform anionic surfactants in surfactant-enhanced washing of aged petroleum-contaminated soils, highlighting their applicability to diverse site conditions. These findings support the consistency of our laboratory-scale results with observations from larger-scale remediation efforts. Additionally, recent studies have shown that biosurfactants such as rhamnolipids can enhance hydrocarbon biodegradation by accelerating microbial uptake and degradation reactions. For example, a recent investigation demonstrated that rhamnolipid application increased oxidoreductase activity and facilitated the degradation of polycyclic aromatic hydrocarbons (PAHs), indicating functional benefits even in challenging environmental contexts [36]. Although this study focused primarily on the physicochemical and acute ecotoxicological effects of Tween 80 application, microbial degradation processes were not directly monitored. Previous research indicates that non-ionic surfactants, including Tween 80, can enhance microbial hydrocarbon degradation by increasing contaminant bioavailability and facilitating enzymatic breakdown [9,31,32]. Future work should incorporate microbial community analysis and activity assays to quantify the contribution of biodegradation to overall hydrocarbon removal under boreal soil conditions.

Taken together, the findings support the use of sub-CMC concentrations of Tween 80 as a viable and safe remediation strategy for diesel-contaminated soils in boreal regions. The results offer practical insight for designing treatment protocols suited to challenging environments and provide a foundation for scaling up surfactant-based technologies in contaminated site management.

From a scalability perspective, the field implementation of Tween 80-assisted remediation will inevitably face challenges not fully captured in laboratory settings. Soil heterogeneity may lead to uneven surfactant distribution and variable hydrocarbon mobilization rates across a site [34]. Weather-related factors, such as seasonal temperature fluctuations, precipitation, and freeze–thaw cycles, can influence both the kinetics of contaminant desorption and the persistence of the surfactant [15–28]. Furthermore, Tween 80 is known to

undergo biodegradation in soil, with rates depending on microbial activity, moisture, and nutrient availability [32]. While biodegradability is environmentally beneficial, it may also reduce effective treatment duration, necessitating re-application or integration with complementary remediation methods [7,13]. Addressing these factors through pilot-scale studies will be essential for optimizing treatment protocols under real-world conditions [7,13,34].

The fate of Tween 80 in the soil environment was not directly measured in this study. However, previous research indicates that non-ionic surfactants, including Tween 80, are subject to biodegradation in soils, with degradation rates depending on microbial activity, temperature, and nutrient availability [9,28,32]. Such biodegradation can significantly reduce surfactant persistence in field applications, which is environmentally beneficial but may shorten the effective treatment duration. In boreal ecosystems, characterized by low temperatures and reduced microbial activity, the degradation rate of Tween 80 is likely to be slower, potentially extending its functional effectiveness compared to warmer regions. Similarly, studies on surfactant-enhanced remediation of hydrophobic contaminants highlight the dual role of Tween 80 in both mobilizing hydrocarbons and promoting their subsequent microbial degradation [9,31]. Quantifying residual surfactant and its transformation products after treatment would improve understanding of its environmental persistence and guide dosing strategies for large-scale applications.

Table 5 compares the remediation performance of Tween 80 with other commonly used surfactants under different soil and environmental conditions. While biosurfactants such as rhamnolipids may offer higher removal efficiencies under optimal laboratory conditions, their cost and availability often limit practical application. Tween 80 shows a promising performance in acidic, cold-region soils, where many other surfactants are less effective or destabilize soil chemistry. These comparisons highlight Tween 80's suitability for field-scale deployment in northern contaminated sites.

Table 5. Comparative performance of surfactants in hydrocarbon-contaminated soils.

Surfactant	Soil Type	Temperature (°C)	Max TPH Removal (%)	Reference
Tween 80	Albic Podzolic	2–24	17–21	This study
Triton X-100	General sandy loam	~20	~15–18	[35]
Rhamnolipid	General soils	Ambient (~22)	~24–26	[36]

5. Conclusions

This study confirms the applicability of Tween 80 as an effective and environmentally acceptable surfactant for the remediation of diesel-contaminated Albic Podzolic soils under boreal climate conditions. The treatment resulted in measurable reductions in TPH and promoted a shift toward pH neutralization, contributing to the chemical stabilization of vulnerable acidic soils.

The results demonstrate that surfactant performance is influenced by both application dose and temperature regime. Notably, sub-critical micelle concentrations of Tween 80 were more effective than higher doses, and appreciable remediation was achieved even at low temperatures (2–3 °C). These findings align with reports from other laboratory and pilot-scale studies on non-ionic surfactants, reinforcing the practical relevance of sub-CMC dosing strategies in cold, acidic, and low-buffered soils.

Ecotoxicological testing confirmed the absence of acute toxicity at the applied concentrations ($\leq 0.3 \text{ mg L}^{-1}$), supporting the environmental safety of this approach in sensitive settings. By providing site-relevant data and linking physicochemical performance with toxicity endpoints, this work offers insights that are directly applicable to remediation planning in boreal and subarctic environments, where conventional technologies may be limited by environmental or logistical constraints.

Beyond laboratory conditions, the results have broader implications for cold-region remediation policies and the adaptation of surfactant-assisted methods to heterogeneous field conditions. Future research should focus on validating these findings under field scenarios, assessing long-term ecological effects, and integrating surfactant-based approaches with biological or passive stabilization techniques to enhance the overall remediation efficiency in challenging environments.

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Abbreviations

The following abbreviations are used in this manuscript:

TPH	Total Petroleum Hydrocarbons
CMC	Critical Micelle Concentration
EC	Electrical Conductivity
<i>V. fischeri</i>	<i>Vibrio fischeri</i>
<i>C. affinis</i>	<i>Ceriodaphnia affinis</i>
SER	Surfactant-Enhanced Remediation
PAHs	Polycyclic aromatic hydrocarbons

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