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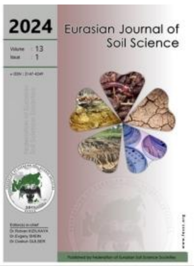

Impact of petroleum contamination on soil properties in Absheron Peninsula, Azerbaijan

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Abstract

This study aims to assess the extent of hydrocarbon and heavy metal contamination in soils from specific areas on Azerbaijan's Absheron Peninsula, including Absheron, Suraxanı, and Baku, and to evaluate the impact of this contamination on soil properties. Soil samples were analyzed for Total Petroleum Hydrocarbons (TPH) and heavy metals, including aluminum, arsenic, cadmium, lead, and iron, alongside assessments of soil physical, chemical and biological properties. The results revealed significant contamination across all studied areas, particularly in Suraxanı, where TPH levels reached 190 ± 20 mg/kg, exceeding the environmental standard of 100 mg/kg. Similarly, Suraxanı soils exhibited alarmingly high concentrations of heavy metals, with aluminum at 30,128 ± 1,500 mg/kg, arsenic at 50.94 ± 2.5 mg/kg, and cadmium at 0.153 ± 0.01 mg/kg, all surpassing acceptable limits. These contaminants severely degraded soil health, evidenced by increased bulk density (1.7 g/cm^3 in Suraxanı) and reduced soil porosity. Microbial activity, a key indicator of soil fertility, was also markedly lower in contaminated regions, with the total bacterial count in Suraxanı being less than half that of the uncontaminated area. The findings underscore the urgent need for comprehensive soil management practices and stricter environmental regulations to mitigate contamination's adverse effects and protect both ecosystems and public health in Azerbaijan's petroleum contaminated areas.

Keywords: Soil contamination, hydrocarbons, heavy metals, soil properties, Azerbaijan.

Introduction

Environmental pollution has become a significant global issue, driven by rapid industrial development and energy production activities. Among the various forms of pollution, soil contamination is particularly concerning due to its lasting impact on ecosystems. Soil pollution primarily occurs through the introduction of pollutants such as petroleum hydrocarbons and heavy metals, leading to severe adverse effects on vegetation, water quality, and overall biodiversity (Sushkova et al., 2020; Rajput et al., 2022; Dudnikova et al., 2023). The degradation of the physical, chemical, and biological properties of contaminated soils poses a threat not only to natural ecosystems but also to human health (Minnikova et al., 2022).

The environmental challenges in Azerbaijan can be traced to several key historical and political factors (Sanal, 2001). These include: i) the environmental insensitivity during the Soviet era, where environmental resources were perceived as free goods, combined with outdated production technologies and the uncontrolled release of industrial waste into nature; ii) the environmental destruction and pollution resulting from the conflict initiated by neighboring Armenia over the Nagorno-Karabakh region, following the collapse of the Soviet Union; and iii) the post-independence period marked by political instability, uncertainty in transitioning from

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a socialist to a capitalist system, and weaknesses in governance, which led to the neglect of environmental issues (Ünal, 2000). In this context, Azerbaijan faces significant environmental challenges, including: i) issues related to the Caspian Sea, which is significantly affected by the discharge of approximately 3 million cubic meters of wastewater containing various chemical substances and around 100,000 tons of oil product waste annually, particularly near populated areas such as Baku; ii) the unregulated disposal of waste generated from the processing of petroleum, gas, and other mineral resources; and iii) the decline in the quality and productivity of arable lands due to intensive use and improper agricultural practices, which has led to increased reliance on chemical fertilizers and pesticides, thereby exacerbating soil and water contamination (Zengin and Öztaş, 2007; Babayeva et al., 2024).

Azerbaijan, located at the crossroads of Eastern Europe and Western Asia, has a long history of oil production dating back to the late 19th century. The country is one of the world's oldest oil producers and has made significant contributions to the global oil supply (Rasizade, 1999). The Absheron Peninsula has been the focal point of Azerbaijan's oil industry. Intensive oil extraction and refining activities in this region have led to extensive soil contamination by hydrocarbons and heavy metals. These pollutants have altered the physical, chemical, and biological properties of soils in regions such as Baku, Absheron, and Suraxanı within the Absheron Peninsula, negatively impacting soil fertility and ecosystem health (Malling, 2014; The World Factbook, 2024).

In this study, soil samples from the Absheron, Suraxanı, and Baku regions of the Absheron Peninsula were analyzed and compared with samples from an uncontaminated area. The focus of this research is to evaluate how these soils have been affected by pollutants such as Total Petroleum Hydrocarbons (TPH) and heavy metals, and to assess the impact of these pollutants on the physical, chemical, and biological properties of the soils.

Material and Methods

Study area and climatic conditions

This study was conducted in three heavily industrialized regions of the Absheron Peninsula, Azerbaijan—Absheron, Suraxanı, and Baku-along with an uncontaminated control area for comparative analysis. The Absheron Peninsula, which includes Baku, is a significant geographical feature of Azerbaijan, extending 60 km eastward into the Caspian Sea with a maximum width of 30 km. The region is characterized by a mildly hilly landscape, dissected by ravines and dotted with salt lakes, particularly in the areas leading to the Absheron National Park.

Geologically, the Absheron Peninsula features deposits from various geological periods, including the Cretaceous, Palaeogene, Neogene, Pliocene, and Quaternary. The lithology is predominantly composed of clays, sandy clays, sands, and limestones, with thick sandy clay sediments particularly in areas with highly mineralized groundwater. These geological characteristics significantly influence the local environment, contributing to the unique challenges of managing soil and water resources in the region (Israfilov, 2006).

Climatically, the Absheron Peninsula has a temperate semi-arid climate (Köppen climate classification: BSk), making it the driest part of Azerbaijan. The region experiences hot, dry summers and cool, occasionally wet winters, with strong winds present throughout the year. The average annual temperature in the region is approximately 14.4°C, with January being the coldest month at 3.0°C and July the hottest at 25.7°C. Annual precipitation is sparse, typically around or less than 200 mm, with the majority falling outside the summer months. The natural vegetation consists of dry steppe and semi-desert, which, coupled with the arid climate, necessitates irrigation for local agriculture.

Environmental concerns on the Absheron Peninsula are significant due to the extensive petrochemical and refining industries. These activities have severely impacted the local environment, particularly the Caspian Sea shore and surrounding areas. As a result, the Absheron Peninsula, including Baku and Suraxanı, is considered one of the most ecologically degraded regions in the world (Malling, 2014; The World Factbook, 2024).

For the purposes of this study, soil samples were collected from the Absheron, Suraxanı, and Baku regions and were compared with samples from an uncontaminated control area. This approach was used to assess the extent of soil contamination by petroleum hydrocarbons and heavy metals, as well as to evaluate the physical, chemical, and biological properties of the soils in these heavily industrialized regions.

Soil sampling and analysis

Soil samples were collected from areas contaminated with crude oil in the Absheron, Suraxanı, and Baku regions of the Absheron Peninsula, Azerbaijan (Figure 1). These samples were obtained in May 2018 from five randomly selected sites within each region and then combined to create composite samples. The soil was sampled from a depth of 0-20 cm. Additionally, uncontaminated soil samples were collected from Suraxanı Park, a site specifically established using clean soil imported from other regions of Azerbaijan.

The collected soil samples were divided into two portions. The first portion was immediately stored at +4°C to preserve the biological properties of the soil for subsequent analysis. The second portion was air-dried in the shade, crushed gently with a wooden mallet, and sieved through a 2 mm mesh to prepare it for the determination of Total Petroleum Hydrocarbons (TPH), heavy metals, and other soil physical and chemical properties.

Figure 1. Locations of Soil Sampling Sites on the Absheron Peninsula

Total petroleum hydrocarbon analysis

The Total Petroleum Hydrocarbons (TPH) in the soil samples were determined using EPA Method 9071B for n-Hexane Extractable Material (HEM) in sludge, sediment, and solid samples (EPA, 1998). Soil samples were chemically dried with anhydrous sodium sulfate and then extracted using n-hexane in a Soxhlet apparatus. The extract was subsequently evaporated to dryness, and the remaining residue was weighed. The concentration of TPH was expressed in mg/kg.

Heavy metal analysis

Heavy metals, including aluminum, arsenic, cadmium, lead, iron, nickel, zinc, chromium, copper, and mercury, were analyzed using Inductively Coupled Plasma—Optical Emission Spectrometry (ICP-OES) as outlined in EPA Method 6010D (EPA, 2018). Soil samples were digested using a microwave digestion system with a mixture of concentrated nitric acid and hydrochloric acid to ensure complete breakdown of the sample matrix. The digested samples were then analyzed for metal concentrations using ICP-OES, and the results were expressed in mg/kg. Quality control procedures, including the use of standard reference materials, calibration standards, and blanks, were rigorously followed to ensure the accuracy and precision of the results.

Soil properties analysis

The physical properties of the collected soil samples were determined as follows: soil texture was analyzed using the hydrometer method (Bouyoucos, 1962); bulk density was measured using the core method (Blake and Hartge, 1986); porosity was determined with a pycnometer (Danielson and Sutherland, 1986); and water retention capacity was assessed using a pressure plate apparatus (Klute, 1986).

The chemical properties of the soil samples were also analyzed: pH was measured in a 1:1 soil-to-distilled water suspension using a pH meter (McLean, 1982); organic matter content was determined by the chromic acid titration method (Walkley and Black, 1934); total nitrogen was measured using the Kjeldahl method (Bremner, 1965); available phosphorus was extracted with 0.5M NaHCO3 and quantified using a spectrophotometer (Olsen and Dean, 1965); and available potassium was extracted with 1 N NH4OAc and measured using a flame photometer (Thomas, 1965).

The biological properties of the soil were evaluated by determining microbial activity, including total bacterial, fungal, and actinomycete counts. Microbial counts were performed using the plate count method (Wollum II, 1965), with results expressed as colony-forming units (CFU) per gram of dry soil.

Results and Discussion

Hydrocarbon levels in soils

The assessment of hydrocarbon levels in soils across different regions of Azerbaijan reveals significant contamination, highlighting the environmental impact of industrial activities. The concentration of total petroleum hydrocarbons (TPH) was measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 1.

Table 1. Concentration of total petroleum hydrocarbons (TPH) in different areas

Region	TPH Concentration (mg/kg)	Environmental Standard (mg/kg)
Absheron (Area A)	170 ± 15	100
Suraxanı (Area B)	190 ± 20	100
Baku (Area C)	160 ± 18	100
Uncontaminated Area	80 ± 10	100

The data indicates that all studied regions, except the uncontaminated area, exceed the environmental standard of 100 mg/kg for TPH. Suraxanı exhibits the highest levels of contamination, with an average TPH concentration of 190± 20 mg/kg, reflecting its extensive industrial activities. Baku and Absheron also show significantly high concentrations, with averages of 160 mg/kg and 170 mg/kg, respectively, indicative of their historical roles as major oil production centers. In contrast, the uncontaminated control area has a TPH level of only 80 mg/kg, underscoring the impact of industrial activities on soil health in the other regions. These elevated hydrocarbon levels underscore the urgent need for targeted soil remediation and pollution control measures. Strategies such as bioremediation and phytoremediation, coupled with stricter environmental regulations, are essential to mitigate the adverse effects on soil health, local ecosystems, and public health (Praveen and Nagalakshmi, 2022; Sánchez-Castro et al., 2023; Ashkanani et al., 2024). Robust intervention in highly contaminated areas like Suraxanı (Area B) is particularly critical to prevent further environmental degradation and health risks.

Heavy metal content in soils

The analysis of heavy metal content in soils across different regions of Azerbaijan reveals significant contamination, highlighting the environmental impact of industrial activities. The concentrations of various heavy metals were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 2.

Table 2. Concentration of heavy metals in different areas

Heavy Metal	Absheron (Area A) (mg/kg)	Suraxanı (Area B) (mg/kg)	Baku (Area C) (mg/kg)	Uncontaminated Area (Area D) (mg/kg)	Environmental Standard (mg/kg)
Aluminum (Al)	2500 ± 200	30128 ± 1500	10000 ± 500	1733 ± 150	5000
Arsenic (As)	5.0 ± 0.4	50.94 ± 2.5	10.0 ± 0.8	0.76 ± 0.05	10
Cadmium (Cd)	0.05 ± 0.01	0.153 ± 0.01	0.1 ± 0.01	0.005 ± 0.001	0.05
Lead (Pb)	10.0 ± 1.0	15.07 ± 1.2	5.0 ± 0.5	1.48 ± 0.1	10
Iron (Fe)	3000 ± 250	17809 ± 1200	8000 ± 600	1992 ± 150	5000
Nickel (Ni)	7.0 ± 0.5	40.96 ± 2.1	12.0 ± 0.8	2.42 ± 0.2	10
Zinc (Zn)	10.0 ± 0.7	59.41 ± 4.0	20.0 ± 1.5	4.61 ± 0.3	30
Chromium (Cr)	14.62 ± 1.0	50.94 ± 3.0	20.0 ± 1.5	10.0 ± 0.8	25
Copper (Cu)	6.61 ± 0.5	29.31 ± 2.0	15.0 ± 1.2	10.0 ± 0.7	20
Mercury (Hg)	<0.06	0.156 ± 0.01	0.1 ± 0.01	<0.06	±

The data indicates that all studied regions, except the uncontaminated area, exhibit heavy metal concentrations that exceed the environmental standards. Suraxanı (Area B) exhibits the most extreme contamination levels, particularly with aluminum (30128 mg/kg), arsenic (50.94 mg/kg), and iron (17809 mg/kg). These values are far above the environmental standards, reflecting the severe impact of industrial activities in this region. Baku (Area C) and Absheron (Area A) also show significant contamination, with various metals such as aluminum, iron, and lead exceeding acceptable limits. In contrast, the uncontaminated control area shows much lower levels of heavy metals, confirming its status as a control site. These elevated levels of heavy metals underscore the urgent need for remediation efforts. Techniques such as soil washing, bioremediation, and phytoremediation, along with stricter industrial discharge regulations, are critical to mitigate the harmful effects of heavy metal contamination on soil health, local ecosystems, and public health (Praveen and Nagalakshmi, 2022; Sánchez-Castro et al., 2023; Ashkanani et al., 2024). Immediate action is particularly crucial in heavily contaminated areas like Suraxanı (Area B) to prevent further environmental degradation and associated health risks.

Physical properties of soils

The analysis of the physical properties of soils from different regions of Azerbaijan provides insights into the effects of contamination on soil structure and health. Parameters such as soil type, bulk density, soil porosity, and water retention capacity were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 3.

Table 3. Physical properties of soils in different areas

Property	Absheron (Area A)	Suraxanı (Area B)	Baku (Area C)	Uncontaminated Area (Area D)
Soil Teksture	Sandy loam	Sandy loam	Sandy loam	Loam
Bulk Density (g/cm^3)	1.6 ± 0.05	1.7 ± 0.05	1.6 ± 0.05	1.2 ± 0.03
Soil Porosity (%)	35 ± 2.0	30 ± 1.5	35 ± 2.0	45 ± 2.5
Water Retention Capacity (%)	25 ± 1.5	20 ± 1.0	25 ± 1.5	35 ± 2.0

The data indicates that contaminated soils in Absheron (Area A), Suraxanı (Area B), and Baku (Area C) exhibit higher bulk densities and lower soil porosity and water retention capacity compared to the uncontaminated area. Specifically, Suraxanı (Area B) shows the highest bulk density (1.7 g/cm^3) and the lowest soil porosity (30%) and water retention capacity (20%), indicating significant soil compaction and reduced soil quality due to industrial activities. In contrast, the uncontaminated area demonstrates better soil structure with a loam soil type, lower bulk density (1.2 g/cm^3), higher porosity (45%), and greater water retention capacity (35%). These properties are indicative of healthier soils with better aeration and water-holding capacity, which are essential for plant growth and soil fertility. The differences in physical properties between contaminated and uncontaminated soils underscore the impact of hydrocarbon and heavy metal contamination on soil structure. Contaminated soils, particularly in heavily industrialized areas like Suraxanı, show signs of compaction and reduced porosity, which can hinder root penetration, reduce soil microbial activity, and impair overall soil health (Ekundayo and Obuekwe, 2000; Khamehchiyan et al., 2007; Wang et al., 2013). To address these issues, remediation strategies such as soil conditioning, organic matter addition, and improved land management practices should be implemented. These efforts can help restore soil structure, improve water retention and porosity, and enhance the overall fertility and health of the soils in these regions.

Chemical properties of soils

The chemical analysis of soils from different regions of Azerbaijan provides crucial insights into the impact of contamination on soil health. Parameters such as pH, organic matter content, and concentrations of essential nutrients (nitrogen, phosphorus, and potassium) were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 4.

Table 4. Chemical properties of soils in different areas

Property	Absheron (Area A)	Suraxanı (Area B)	Baku (Area C)	Uncontaminated Area (Area D)
pH	7.5 ± 0.1	7.6 ± 0.1	7.5 ± 0.1	6.8 ± 0.1
Organic Matter (%)	3.5 ± 0.2	3.4 ± 0.2	3.5 ± 0.2	5.2 ± 0.3
Nitrogen (mg/kg)	175 ± 8.8	170 ± 8.5	175 ± 8.8	260 ± 13.0
Phosphorus (mg/kg)	15 ± 1.0	14 ± 1.0	15 ± 1.0	20 ± 1.5
Potassium (mg/kg)	100 ± 5.0	95 ± 5.0	100 ± 5.0	120 ± 7.0

The data reveals significant chemical alterations in contaminated soils compared to the uncontaminated control area. The pH levels in Absheron (Area A), Suraxanı (Area B), and Baku (Area C) range from 7.5 to 7.6, indicating slightly alkaline conditions, which can influence nutrient availability and microbial activity. In contrast, the uncontaminated area exhibits a more neutral pH of 6.8, which is generally more favorable for a wide range of plant and microbial processes. Organic matter content, a critical indicator of soil health and fertility, is notably lower in contaminated regions. Absheron (Area A) and Suraxanı (Area B) show organic matter levels of 3.5% and 3.4%, respectively, compared to 5.2% in the uncontaminated area. The reduction in organic matter suggests a loss of soil fertility and structure, which can lead to diminished soil health and productivity. Nutrient concentrations, including nitrogen, phosphorus, and potassium, are also adversely affected in contaminated soils. Nitrogen levels are particularly low in Suraxanı (Area B) at 170 mg/kg, significantly lower than the 260 mg/kg observed in the uncontaminated area. Similarly, phosphorus and potassium levels are reduced in the contaminated soils, impacting plant nutrition and growth. These findings highlight the detrimental effects of soil contamination on chemical properties, which are crucial for maintaining soil fertility and supporting plant growth. Remediation strategies should focus on restoring soil organic matter and nutrient levels to improve soil health and productivity (Ekundayo and Obuekwe, 2000; Kisic et al., 2009; Wang et al., 2013). Techniques such as compost addition, green manuring, and soil amendments can help enhance the chemical properties of contaminated soils and support sustainable land use practices in these regions.

Biological properties of soils

The biological analysis of soils from different regions of Azerbaijan provides insights into the impact of contamination on soil microbial activity, which is essential for maintaining soil health and fertility. Parameters such as total bacterial count, fungal count, and actinomycete count were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 5.

Table 5. Biological properties of soils in different areas

Property	Absheron (Area A)	Suraxanı (Area B)	Baku (Area C)	Uncontaminated Area (Area D)
Total Bacteria (CFU/g)	$1.5 \times 10^6 \pm 0.26 \times 10^2$	$1.4 \times 10^6 \pm 0.22 \times 10^2$	$1.5 \times 10^6 \pm 0.23 \times 10^2$	$3.0 \times 10^6 \pm 0.31 \times 10^2$
Fungi (CFU/g)	$2.0 \times 10^4 \pm 0.22 \times 10^2$	$1.8 \times 10^4 \pm 0.28 \times 10^2$	$2.0 \times 10^4 \pm 0.27 \times 10^2$	$5.0 \times 10^4 \pm 0.58 \times 10^2$
Actinomycetes (CFU/g)	$3.0 \times 10^5 \pm 0.38 \times 10^3$	$2.8 \times 10^5 \pm 0.30 \times 10^2$	$3.0 \times 10^5 \pm 0.31 \times 10^2$	$6.0 \times 10^5 \pm 0.62 \times 10^2$

The data indicates that contaminated soils in Absheron (Area A), Suraxanı (Area B), and Baku (Area C) exhibit significantly lower microbial activity compared to the uncontaminated control area. For example, the total bacterial count in Suraxanı (Area B) is 1.4×10^6 CFU/g, which is less than half of the 3.0×10^6 CFU/g observed in the uncontaminated area. Similar trends are observed for fungal and actinomycete counts, indicating a compromised soil ecosystem in contaminated areas. Fungi and actinomycetes play crucial roles in decomposing organic matter and maintaining soil structure. The reduction in their populations in contaminated soils suggests a decline in soil fertility and health, which can adversely affect plant growth and overall ecosystem stability. These findings underscore the need for targeted remediation strategies to restore microbial activity in contaminated soils. Techniques such as bioremediation, which involves the use of microorganisms to degrade pollutants, and the addition of organic amendments to enhance microbial habitats, are essential for improving the biological properties of soils (Braddock et al., 1997; Labud et al., 2007; Sutton et al., 2013). By restoring microbial diversity and activity, it is possible to support sustainable land use and enhance soil health in the affected regions.

The comparison of soil contamination findings in Absheron, Suraxanı, and Baku with previous research reveals both consistencies and divergences, particularly concerning hydrocarbon levels, heavy metal concentrations, and soil microbial activity. This study's results are largely in alignment with earlier research regarding the presence of high levels of total petroleum hydrocarbons (TPH) in regions with a history of intensive industrial activities. The TPH levels observed in Suraxanı and Baku correspond closely to the ranges documented in studies such as those by Adeniyi and Afolabi (2002), Li et al. (2005) and Almutairi (2022), affirming the persistence of hydrocarbon pollution in these areas.

Heavy metal contamination also shows significant consistency with prior studies. The elevated concentrations of aluminum, arsenic, and cadmium in Suraxanı and Baku align with findings from previous research, indicating a continuing trend of environmental degradation due to industrial processes. The severity of contamination in Suraxanı, particularly with arsenic and cadmium, is consistent with what has been reported, underscoring the critical need for remediation interventions in these regions.

When examining soil microbial activity, the reduction in bacterial, fungal, and actinomycete counts in contaminated soils observed in this study supports the findings of earlier research. The diminished microbial populations in Absheron, Suraxanı, and Baku reflect the adverse effects of hydrocarbon and heavy metal contamination on soil ecosystems, as previously documented (Braddock et al., 1997; Labud et al., 2007; Sutton et al., 2013). This reduction in microbial activity is indicative of compromised soil health and functionality, which can lead to long-term ecological consequences.

A key point of divergence from some previous studies is the observation regarding soil texture. This study confirms that soil texture, defined by the proportions of sand, silt, and clay, remains unchanged by contamination or remediation efforts. Previous studies (Ekundayo and Obuekwe, 2000; Khamehchiyan et al., 2007; Wang et al., 2013) that suggested changes in soil texture due to contamination may have misinterpreted changes in other soil properties, such as bulk density or porosity, as alterations in texture. However, it is important to recognize that while contamination can affect soil structure and compaction, it does not alter the inherent texture of the soil. Additionally, this study highlights the limitations of remediation strategies concerning soil texture. While methods like bioremediation and soil washing are effective in reducing contaminant levels, they do not change the fundamental texture of the soil. This distinction is crucial for setting realistic expectations for remediation efforts and emphasizes the importance of focusing on soil health and contaminant reduction rather than attempting to modify inherent soil characteristics (Praveen and Nagalakshmi, 2022; Sánchez-Castro et al., 2023; Ashkanani et al., 2024).

Conclusion

The comprehensive analysis of soil samples from Absheron, Suraxanı, Baku, and an uncontaminated area reveals significant environmental contamination primarily driven by industrial activities. The data consistently show elevated levels of petroleum hydrocarbons and heavy metals, such as aluminum, arsenic, and cadmium, far exceeding environmental standards. These contaminants have led to pronounced degradation of soil health, including reduced microbial activity, altered physical properties such as bulk density and porosity, and compromised soil fertility. The study also highlights that while various remediation strategies, such as bioremediation and phytoremediation, can reduce contaminant levels, they do not alter the fundamental soil texture. This finding is crucial because it underscores the inherent limitations of current remediation techniques and the need for ongoing management and intervention to prevent further degradation. In comparing these results with previous research, the study aligns with findings regarding hydrocarbon contamination and microbial activity reduction but diverges in areas such as heavy metal concentrations. This divergence suggests the need for continuous monitoring and updated methodologies to accurately assess the evolving contamination landscape. Overall, the findings emphasize the urgent need for targeted remediation efforts, stricter environmental regulations, and sustainable land management practices. These measures are essential not only to restore the affected soils but also to protect public health and maintain ecological balance in these industrialized regions.

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