

THE IMPACT OF AMENDMENT ON THE REMEDIATION OF HYDROCARBON CONTAMINATED SOILS: AN EXPERIMENTAL APPROACH

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Abstract

This study investigates the effectiveness of organic amendments and microbial inoculants in the remediation of hydrocarbon-contaminated soils. Hydrocarbon pollution, resulting from industrial spills and improper waste management, poses significant risks to soil ecosystems, human health, and water quality.

The research focuses on the application of organic materials such as compost, stabilized sludge, zeolite, and clay, which enhance microbial activity and improve soil structure. These amendments, combined with specific bacterial and fungal species capable of metabolizing hydrocarbons, accelerate the degradation process. The study evaluates key physical and chemical properties, including moisture content, organic matter, pH, and porosity, under controlled experimental conditions. The Hydrocarbon + Inoculants + Amendment treatment achieved a 19.35% increase in organic matter and reduced apparent density to 0.69 g/ cm³.

The findings demonstrate that the synergistic effects of organic amendments and microbial inoculants offer a cost-effective and sustainable method for rehabilitating hydrocarbon-contaminated soils, contributing to the development of eco-friendly remediation strategies.

Keywords

Hydrocarbon contamination, soil remediation, organic amendments, microbial inoculants, zeolite, clay.

Introduction

Hydrocarbon pollution is a consequence of industrial spills and improper waste management; it is a persistent environmental concern. This kind of contamination not only disrupts soil ecosystems but also poses significant risk to human health and water quality. Remediation of hydrocarbon contaminated soils is particularly challenging in eroded soils, where poor fertility and structural deficiencies

exacerbate environmental degradation (Truskewycz, y otros, 2019)

One promising approach for hydrocarbon remediation is the use of organic amendments combined with microbial inoculants. Organic materials, such as compost and stabilized sludge, provide essential nutrients and enhance microbial activity, fostering the breakdown of complex hydrocarbons into less harmful compounds (Kuppan, Padman, Mahadeva, Srinivasan, & Devarajan, 2024). These amendments not only improve soil structure but also contribute

to the re-establishment of microbial populations, which play a crucial role in natural attenuation processes (Ji, 2025).

Microbial interventions further enhance the biodegradation of hydrocarbons. Specific bacterial and fungal species can metabolize hydrocarbons as a source of carbon and energy, leading to the detoxification of contaminated soils (Anno, y otros, 2021). The addition of inoculants containing hydrocarbon-degrading microorganisms accelerates the degradation process, making it a viable alternative to traditional remediation techniques such as chemical oxidation or soil excavation (Mena, 2014).

Recent advances in soil remediation techniques have emphasized the use of amendments such as Zeolite and clay to enhance soil recovery. Zeolite, a microporous aluminosilicate, is known for its high cation exchange capacity and ability to retain nutrients and water, creating favorable conditions for microbial degradation of hydrocarbons (Kukowska & Szewczuk-Karpisz, 2024). Similarly, clay plays a crucial role in the remediation of hydrocarbon-contaminated soils due to its high surface area, cation exchange capacity (CEC), and adsorption properties (Yu, 2025). These characteristics make it an effective material for capturing and immobilizing hydrocarbon molecules, reducing their bioavailability and potential leaching (Bhardwaj, Kumar, & Singh, 2018).

This study investigates the application of these amendments in the remediation of hydrocarbon contaminated soils. The research focuses on evaluating their effects on key physical chemical properties, including moisture, organic matter, pH and porosity, under controlled

experimental conditions. By addressing these parameters this work aims to contribute to the development of sustainable remediation strategies for degraded and contaminated soils.

This research contributes to the growing body of literature supporting the use of eco-friendly remediation approaches. By leveraging the synergistic effects of organic amendments and microbial inoculants, this study aims to demonstrate a cost-effective and sustainable method for rehabilitating hydrocarbon-contaminated soils. The findings are expected to inform future applications in environmental management and remediation projects worldwide.

Methods

The following steps were conducted to remediate hydrocarbon contaminated soils used in organic amendments and inoculated microorganisms. The procedures include the preparation of microbial inoculants, application of amendments, and monitoring of key soil parameters.

A microbial inoculant was prepared by culturing microorganisms from previously stabilized residues. The inoculum was cultivated on agar plates using serial dilutions ranging from 10^0 to 10^5 . Plates were incubated for five days to promote microbial growth. After incubation, microbial colonies from the 10^5 dilution plate were suspended in 10 mL of distilled water for use in subsequent treatments.

One tray containing 1.8 kg of previously studied soil, was prepared. One tray was contaminated with 1.8 mL of hydrocarbons following environmental safety protocols. Initial physical and

chemical parameters, such as pH, turbidity, and chemical oxygen demand (COD), were measured to establish baseline conditions.

To initiate the remediation process, 500 g of stabilized sludge from prior experiments was used as an organic amendment. The contaminated soil was treated with 100 mL of microbial inoculant, 100 mL of Degradex, and 100 mL of SaferSoil, with the final volume adjusted to 250 mL using distilled water. The soil and amendments were thoroughly mixed to ensure homogeneity.

During the remediation process, key parameters were monitored, including bulk density and real density, measured using a 20 mL graduated cylinder. Moisture content was determined through gravimetric analysis by drying soil samples at 105°C. Organic matter was measured by placing samples in a muffle furnace at 550°C for 2.5 hours. pH and electrical conductivity were analyzed using a pH meter and conductivity probe after suspending 20 g of soil in 50 mL of distilled water. Carbon and nitrogen content were calculated based on the percentage value obtained from initial and treated samples. Finally, porosity was derived from bulk and real density measurements.

Mass balances were performed to assess the efficiency of evolution of several parameters and hydrocarbon degradation. Inputs included initial water porcentajes and hydrocarbon concentrations and amendment mass, while outputs considered residual contaminant levels and changes in organic matter content.

All experimental activities adhered to laboratory safety protocols to minimize

exposure to hazardous materials. Waste disposal complied with environmental regulations to prevent secondary contamination.

This methodology ensured a comprehensive evaluation of the effectiveness of organic amendments and microbial inoculants in the remediation of hydrocarbon-contaminated soils.

Mass balance of stabilization

Tray 1:

$$C1=1\ 000\ g$$

$$T1=61.90\ g$$

We want to eliminate 2% of water in the mixture

$$C2=T1*2\%$$

$$C2=1.23\ g$$

$$C3=C1-T1$$

$$C3=938.1\ g$$

We calculated the excesses of water present in the mixture

$$a*C1=a*C2+a*C3$$

$$(0.6190) * (1\ 000) = (1) * (1.23) + (a) * (938.1)$$

$$aa=0.65\ g$$

To calculate the weight of the dry slug we need to: C3-a

$$L= 938.1-0.65$$

$$L= 937.45\ g$$

Tray 2:

$$C1=700 \text{ g } T1=61 \text{ g}$$

From this treatment, it is desired to eliminate 2% of water present in the mixture.

$$C2=T1*2\%$$

$$C2=1.22 \text{ g}$$

$$C3=C1-T1$$

$$C3=639 \text{ g}$$

With this information, the excess water present in the mixture will be calculated.

$$a*C1=a*C2+a*C3$$

$$(0.61) *(700) =(1)*(1.22)+(a)*(639)$$

$$a=0.66 \text{ g de excedente}$$

To calculate the amount of dry sludge by weight, C3 and a must be subtracted.

$$L=639-0.66$$

$$L=638.34 \text{ g g}$$

Tray 3:

$$C1=800 \text{ g } T1=61 \text{ g}$$

From this treatment, it is desired to eliminate 17% of water present in the mixture.

$$C2=T1*17\%$$

$$C2=12.94 \text{ g}$$

$$C3=C1-T1$$

$$C3=723.84 \text{ g}$$

With this information, the excess water present in the mixture will be calculated.

$$a*C1=a*C2+a*C3$$

$$(0.7616) * (800) = (1) * (12.94) + (a) * (723.84)$$

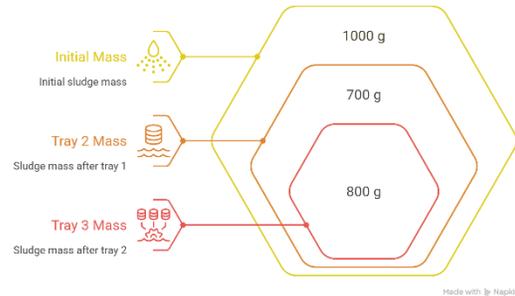
$$a=0.82 \text{ g}$$

To calculate the amount of dry sludge by weight, C3 and a must be subtracted.

$$L=723.84-0.82$$

$$L=723.02 \text{ g}$$

Graph 1. Summary of sludge mass balance



Note. Elaborated by the author, 2025.

RESULTS

The experimental results highlight the effectiveness of the T1 Hydrocarbon + Inoculants + Amendment treatment. This treatment exhibited the highest moisture content at 34.83%, indicating improved water retention capabilities. Additionally, the organic matter content was significantly elevated to 19.35%, suggesting enhanced microbial activity

and overall soil health. The carbon and nitrogen contents were also notably higher, at 11.03% and 0.97% respectively, which are crucial for soil fertility and plant growth.

Furthermore, the T1 Hydrocarbon + Inoculants + Amendment treatment demonstrated the lowest apparent density (0.69 g/cm³) and the highest porosity (9.10%). These parameters are indicative

of improved soil structure, better aeration, and enhanced water infiltration, all of which are essential for sustainable soil management. The combination of these factors underscores the potential of organic amendments and microbial inoculants to effectively remediate hydrocarbon-contaminated soils.

Table 1. Summary of stabilization materials

PHASE	PROCEDURE	
	STABILIZATION	TRAY 1
MATERIALS		WEIGHT (GRAMS)
SLUG		400
FORM		300
PIG MANURE SLURRY		300
AMENDMANT		701.3
NITROGEN SLUDGE		200
TRAY 2		
MATERIALS		WEIGHT (GRAMS)
SLUG		300
FORM		200
PIG MANURE SLURRY		300
AMENDMANT		400.6
NITROGEN SLUDGE		100
TRAY 3		
MATERIALS		WEIGHT (GRAMS)
SLUG		200
FORM		300
PIG MANURE SLURRY	300	
AMENDMANT	400.2	
NITROGEN SLUDGE	100	

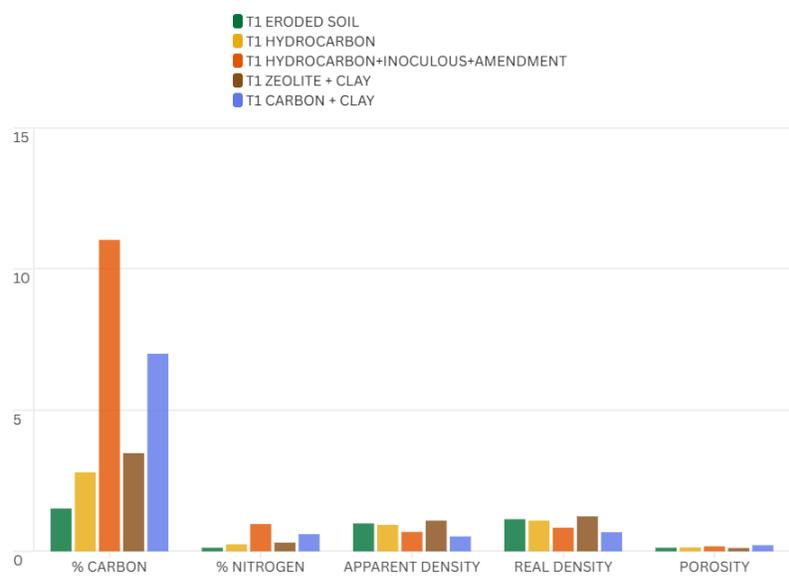
Note. Elaborated by the author, 2025.

Table 2. Summary of parameters

PARAMETERS	T1 ERODED SOIL	T1 HYDROCARBON	T1 HYDROCARBON+INOCULOUS+AMENDMENT	T1 ZEOLITE + CLAY	T1 CARBON + CLAY
Crucible weight (g)	48.00	47.99	48.01	35.50	50.20
Wet sample (g)	64.66	59.92	78.73	51.00	40.80
Wet sample + crucible (g)	112.66	107.91	126.74	86.50	91.00
Dry sample (g)	102.34	99.32	99.32	76.80	67.70
Calcined sample (g)	100.89	96.80	89.39	74.28	65.55
MOISTURE	15.96	14.34	34.83	19.02	57.11
MO	2.67	4.91	19.35	6.10	12.29
% CARBON	1.52	2.80	11.03	3.48	7.00
% NITROGEN	0.13	0.25	0.97	0.31	0.61
APPARENT DENSITY	0.99	0.94	0.69	1.09	0.53
REAL DENSITY	1.14	1.09	0.84	1.24	0.68
POROSITY	0.13	0.14	0.18	0.12	0.22
pH	7.80	9.10	9.10	7.50	7.00
°C	23.90	19.80	19.80	21.00	21.00
CONDUCTIVITY	239.50	135.90	135.90	580.00	290.00
% ASH	97.33	95.09	80.65	93.90	87.71
% DRY MATTER	84.04	85.66	65.17	80.98	42.89
C/N RATIO	11.40	11.40	11.40	11.40	11.40

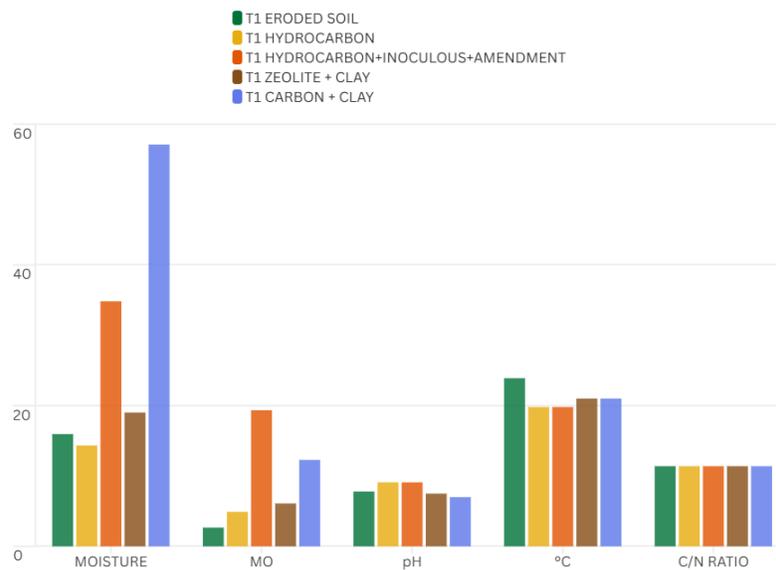
Note. Elaborated by the author, 2025.

Graph 2. Summary of bioremediation parameters (% carbon, % nitrogen, density and porosity)



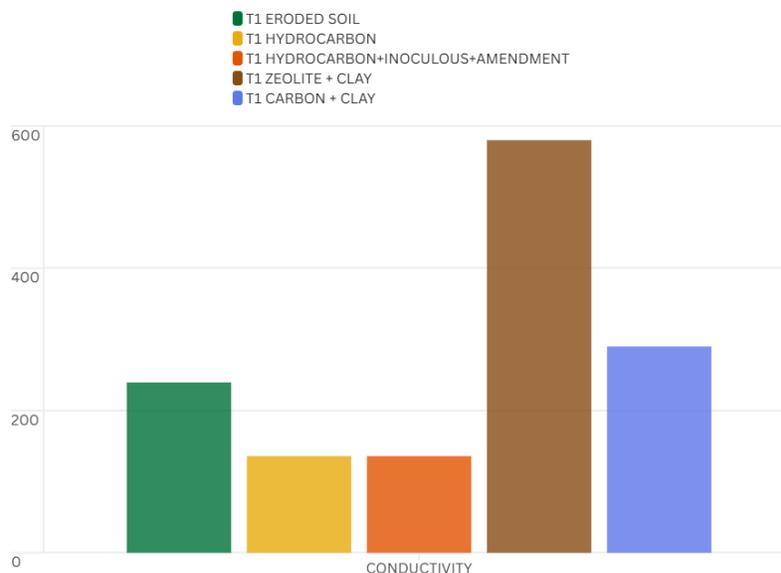
Note. Elaborated by the author, 2025.

Graph 3. Summary of bioremediation parameters (moisture, organic matter, pH, °C and carbon/nitrogen ratio)



Note. Elaborated by the author, 2025.

Graph 4. Summary of bioremediation parameters (conductivity)



Note. Elaborated by the author, 2025.

DISCUSSION

The results of this experimental study demonstrate the marked efficacy of combining organic amendments with microbial inoculants for the bioremediation of hydrocarbon-contaminated soils, yielding notable improvements in soil physicochemical properties and contaminant degradation (Mekonnen, 2024) (Alidoosti, 2024).

In particular, the Hydrocarbon + Inoculants + Amendment treatment produced a pronounced increase in organic matter (OM) to 19.35%, which is consistent with enhanced microbial proliferation and activity since organic amendments supply essential nutrients that facilitate the transformation of complex hydrocarbons into simpler, less harmful compounds (Leal, 2018) (Anno, y otros, 2021).

This observation agrees with studies reporting that locally available organic materials used in biostimulation can substantially accelerate hydrocarbon degradation, often yielding removal rates above 70% under optimized conditions (MDPI, 2023) (Xu, 2010), and in some cases biodegradation efficiencies approach those reported for agricultural wastes and sewage sludge (Obuekwe, 2009) (Ferraro, 2021).

Moisture in the primary treatment rose to 34.83%, suggesting improved water retention that supports microbial viability and the enzymatic processes central to hydrocarbon metabolism; moisture directly affects the solubility and bioavailability of petroleum hydrocarbons (Scherr, 2007) (Koshlaf, Soil bioremediation approaches for petroleum hydrocarbon polluted environments, 2017).

While optimal moisture for aerobic degradation is commonly cited in the 60–80% range, drought-tolerant taxa persist at lower moisture but with reduced degradation rates (Mekonnen, 2024) (Truskewycz, y otros, 2019). Thus, the integration of biostimulation and bioaugmentation appears to create a more favorable environment for microbial consortia, expediting natural attenuation pathways that mineralize hydrocarbons to CO₂ and H₂O (Curiel-Alegre, 2024). Recent studies further show shifts toward hydrocarbon clastic taxa and enrichment of alkane/aromatic degradation pathways following such combined treatments (Alidoosti, 2024) (Kakde, 2024).

Comparative analysis across amendment types reveals trade-offs. The T1 Zeolite + Clay treatment achieved moderate moisture (19.02%) and OM (6.10%) but produced notable enhancements in cation exchange capacity (CEC), which can immobilize residual hydrocarbons and reduce leaching risk (Wang J. , Prediction of optimal bioremediation conditions for petroleum hydrocarbon contaminated soil by automated machine learning-based analysis, 2024) (Tsai, A field-scale assessment of the efficacy of bioremediation of petroleum hydrocarbon-contaminated soils using two biostimulants, 2025). Zeolite's microporosity retains nutrients and water and can create microhabitats that support immobilized bacterial consortia, studies report zeolite-based systems removing substantially more crude oil in sandy soils than unamended controls (Yan, 2024) (Ou, Differential microbial mechanisms of TPH degradation and detoxification during stepwise bioremediation of petroleum-contaminated soil, 2025) (Zheng, 2020).

Clay amendments, owing to high surface area and adsorption capacity, also reduce hydrocarbon bioavailability and can facilitate microbial access under certain conditions (Biswas, 2017) (Dike, 2021) (Kukowska & Szewczuk-Karpisz, 2024). However, the lower OM associated with mineral amendments highlights a key trade-off: physical immobilization can limit biodegradation in nutrient-poor, eroded soils where organic carbon is the primary driver of microbial activity (Larney, 2012) (Neina, 2019).

The T1 Carbon + Clay treatment—applied to a bactericide-contaminated comparison soil—showed the highest moisture retention (57.11%), consistent with biochar/carbon's porous architecture that improves water-holding capacity and microbial colonization (Wei, Wei , Lui, Niu, & Xu, 2024) (Qin, 2013) (Dike, 2021). Biochar often acts as a carrier for hydrocarbon-degrading microbes, enhances aeration during composting, and reduces volatilization losses (Zhang, Effects of biochar immobilization of *Serratia* sp. F4 OR414381 on bioremediation of petroleum contamination and bacterial community composition in loess soil, 2024) (Han, 2016) (Xiao, 2017). Nevertheless, its OM (12.29%) remained below that of the sludge-amendment treatment, indicating that carbon amendments may emphasize adsorption and toxicity mitigation over direct biostimulation, especially when not co-applied with nutrient amendments or biosurfactants (Zhang, Comprehensive effects of biochar-assisted nitrogen and phosphorus bioremediation on hydrocarbon removal and microecological improvement in petroleum-contaminated soil, 2025) (Kookana, 2011). This differential response reinforces the need

for contamination and site-specific tailoring of amendment strategies (Bolan, 2014).

Mechanistically, increases in soil carbon (11.03%) and nitrogen (0.97%) under the primary treatment reflect improved C/N balance that supports microbial growth and efficient hydrocarbon catabolism (Ou, Nitrogen utilization efficiency assessment during bioremediation of petroleum-contaminated loess soils: insights from metagenomic analysis, 2024) (Curiel-Alegre, 2024). The literature documents that organic waste can prime microbial respiration and community shifts toward hydrocarbon clastic species, enabling high degradation rates under favorable conditions (Pacwa-Płociniczak, Monitoring the changes in a bacterial community in petroleum-polluted soil bioaugmented with hydrocarbon-degrading strains, 2016).

Bioaugmentation with specialized degraders introduces metabolic capabilities for alkane and aromatic transformation via mono- and dioxygenase pathways, facilitating ring cleavage and mineralization (Yousefi, 2021) (Rathankumar, 2020). In practice, repeated inoculation or inoculant consortia prepared from stabilized residues (applied with commercial products such as Degradex and SaferSoil) have been reported to overcome native competition and yield substantial TPH removals (Jørgensen, 2000) (Pacwa-Płociniczak, Monitoring the changes in a bacterial community in petroleum-polluted soil bioaugmented with hydrocarbon-degrading strains, 2016), with some studies reporting very high removal percentages over extended periods.

Soil structural improvements lower apparent density (0.69 g/cm^3) and increased porosity (0.18) likely enhanced oxygen diffusion and root penetration, important factors for aerobic biodegradation and potential phytoremediation synergies (Jørgensen, 2000).

Observed pH shifts toward alkalinity (~ 9.10) may stem from microbial mineralization processes and amendment buffering; while alkalinity can favor degradation of some PAHs, optimal enzymatic activity typically occurs in the pH 6.5–8 range and should be monitored.

Conductivity increases most pronounced in zeolite treatments reflect ion release and enhanced nutrient availability but raise concerns about salinity stress at higher levels (Vafa, 2025). Mass balance and composting-style calculations corroborate that observed hydrocarbon losses were primarily biotic rather than purely abiotic (Jørgensen, 2000).

Nonetheless, challenges remain. Co-contaminants such as heavy metals in amendments can inhibit microbial activity unless mitigated zeolites can help immobilize such metals but require monitoring (Helmy, 2024). Emerging approaches have potential to increase degradation rates via combined physicochemical and biological effects yet cost and scale-up are limiting factors. Phytoremediation with species such as *Typha latifolia* or *Phragmites australis* may boost TPH removal through rhizodegradation but faces limitations in bioavailability and kinetics (Wojtowicz, 2025) (Wang S. , 2025). Future research should evaluate nano-enhanced amendments, plant microbe consortia, and long-term field studies to address

scalability and stability. Overall, the results support integrated, amendment-based remediation strategies as promising, sustainable options for addressing global hydrocarbon contamination challenges.

Graph 1. Summary of bioremediation of hydrocarbon contaminated soil



Note. Elaborated by the author, 2025.

CONCLUSION

This study provides robust evidence of the effectiveness of integrated bioremediation strategies for the rehabilitation of hydrocarbon-contaminated soils. Among the evaluated treatments, the T1 Hydrocarbon + Inoculants + Amendment approach demonstrated superior performance, achieving significant improvements in key soil parameters, including organic matter (19.35%), carbon (11.03%), nitrogen (0.97%), and porosity (0.18%), alongside a reduction in apparent density (0.69 g/cm³). These results confirm that the synergistic application of organic amendments, such as stabilized sludge, together with microbial inoculants enhances microbial activity, accelerates hydrocarbon degradation, and promotes the recovery of soil structure and fertility in degraded or eroded environments.

Comparative analyses highlight the differential effects of mineral and organic

amendments. The Zeolite + Clay treatment exhibited moderate gains in moisture (19.02%) and organic matter (6.10%), primarily enhancing nutrient retention and hydrocarbon immobilization through cation exchange processes, whereas the Carbon + Clay treatment achieved higher moisture retention (57.11%) and porosity (0.22%), indicating its suitability for water-stressed or bactericide-affected soils. These findings underscore the necessity of tailoring remediation protocols to site-specific conditions, particularly contaminant type, soil characteristics, and climatic variables, to maximize both biostimulation and contaminant stabilization efficiency.

On a broader scale, these results contribute to the global advancement of sustainable, low-cost, and environmentally responsible remediation technologies. The combined use of microbial inoculants and organic amendments represents a viable alternative to conventional methods such as chemical oxidation or soil excavation, minimizing secondary contamination risks, reducing greenhouse gas emissions, and supporting biodiversity restoration. The mass balance and stabilization analyses confirm minimal resource loss and efficient hydrocarbon degradation, reinforcing the potential for practical implementation, particularly in regions facing severe soil degradation due to petroleum and mining activities.

Nevertheless, limitations associated with small-scale experimental conditions must be acknowledged, as factors such as spatial heterogeneity, microbial succession, and long-term stability cannot be fully represented under controlled environments. Future research should

therefore focus on field-scale applications, quantitative hydrocarbon analyses using chromatographic techniques, and the integration of these strategies with phytoremediation and nano-enhanced amendments. Such approaches will enable a deeper understanding of long-term efficiency, scalability, and economic feasibility. Ultimately, this study provides a foundation for the design of integrated, biologically driven remediation systems capable of restoring ecological functionality and resilience in hydrocarbon-impacted soils.

REFERENCES

- Alidoosti, F. (2024, Julio 25). *Unlocking the potential of soil microbial communities for bioremediation of emerging organic contaminants: omics-based approaches*. Retrieved from BMC: <https://microbialcellfactories.biomedcentral.com/articles/10.1186/s12934-024-02485-z>
- Anno, F. D., Rastelli, E., Sansone, C., Brunet, C., Ianora, A., & Anno, A. D. (2021). *Bacteria, Fungi and Microalgae for the Bioremediation of Marine Sediments Contaminated by Petroleum Hydrocarbons in the Omics Era*. National Library of Medicine.
- Bhardwaj, A., Kumar, R., & Singh, S. (2018). *Role of clay minerals in hydrocarbon adsorption and environmental cleanup*. Environmental Cleanup Journal.
- Biswas, B. (2017). *Mild acid and alkali treated clay minerals enhance bioremediation of polycyclic aromatic hydrocarbons in long-term contaminated soil: A 14C-tracer study*. Retrieved from ScienceDirect: <https://www.sciencedirect.com/science/article/abs/pii/S0269749116312787>
- Bolan, N. (2014). Remediation of heavy metal(loid)s contaminated soils – To mobilize or to immobilize? *Science Direct*, 141-166.
- Curiel-Alegre, S. (2024). Bioaugmentation and vermicompost facilitated the hydrocarbon bioremediation: scaling up from lab to field for petroleum-contaminated soils. *Springer Nature*.
- Dike, C. C. (2021). Can biochar be an effective and reliable biostimulating agent for the remediation of hydrocarbon-contaminated soils? *Science Direct*.
- Ferraro, A. (2021). Bioaugmentation strategy to enhance polycyclic aromatic hydrocarbons anaerobic biodegradation in contaminated soils. *Science Direct*.
- Han, T. (2016). Combination of biochar amendment and phytoremediation for hydrocarbon removal in petroleum-contaminated soil. *National Library of Medicine*.
- Helmy, Q. (2024). Enhancing field-scale bioremediation of weathered petroleum oil-contaminated soil with biocompost as a bulking agent. *Science Direct*.

- Ji, X. (2025). Synthetic bacterial community based on microbial interactions for bioremediation of petroleum contaminated sites. *Science Direct*.
- Jørgensen, K. (2000). Bioremediation of petroleum hydrocarbon-contaminated soil by composting in biopiles. *Science Direct*, 245-254.
- Kakde, P. (2024). Microbial Bioremediation of Petroleum Contaminated Soil: Structural Complexity, Degradation Dynamics and Advanced Remediation Techniques. *JPAM*.
- Kookana, R. (2011). Chapter three - Biochar Application to Soil: Agronomic and Environmental Benefits and Unintended Consequences. *Science Direct*, 103-143.
- Koshlaf, E. (2017). *Soil bioremediation approaches for petroleum hydrocarbon polluted environments*. National Library of Medicine.
- Koshlaf, E. (2017). Soil bioremediation approaches for petroleum hydrocarbon polluted environments. *NIH*.
- Kukowska, S., & Szewczuk-Karpisz, K. (2024). Biochar and Zeolite Uses in Improving Immobilization of Nutrients and Pollutants in Soils. *Taylor & Francis*, 1-24.
- Kuppan, N., Padman, M., Mahadeva, M., Srinivasan, S., & Devarajan, R. (2024). A comprehensive review of sustainable bioremediation techniques: Eco friendly solutions for waste and pollution management. *ScienceDirect*, 154-171.
- Larney, F. J. (2012). The role of organic amendments in soil reclamation: A review. *Canadian Science Publishing*, 19-38.
- Leal, A. J. (2018, Abril 8). *Microbial Inoculants development for bioremediation of gasoline and diesel contaminated soil*. Retrieved from SCIRP: <https://www.scirp.org/journal/paperinformation?paperid=83596>
- MDPI. (2023, Enero 17). *Biostimulation of Petroleum-Contaminated Soil Using Organic and Inorganic Amendments*. Retrieved from MDPI: <https://www.mdpi.com/2223-7747/12/3/431>
- Mekonnen, B. A. (2024, Febrero 21). *Bioremediation of petroleum hydrocarbon contaminated soil: a review on principles, degradation mechanisms, and advancements*. Retrieved from Frontiers: <https://www.frontiersin.org/journal/s/environmental-science/articles/10.3389/fenvs.2024.1354422/full>
- Mena, E. (2014). Effect of a direct electric current on the activity of a hydrocarbon-degrading microorganism culture used as the flushing liquid in soil remediation processes. *Science Direct*, 217-223.
- Neina, D. (2019, Noviembre 3). *The Role of Soil pH in Plant Nutrition and*

- Soil Remediation*. Retrieved from Wiley Online Library: <https://onlinelibrary.wiley.com/doi/10.1155/2019/5794869>
- NIH. (2017, Enero 19). *Eman Koshlaf*. Retrieved from NIH: <https://pubmed.ncbi.nlm.nih.gov/articles/PMC6604977/>
- Obuekwe, C. O. (2009). Hydrocarbon degradation in relation to cell-surface hydrophobicity among bacterial hydrocarbon degraders from petroleum-contaminated Kuwait desert environment. *Science Direct*, 273-279.
- Ou, Y. (2024). Nitrogen utilization efficiency assessment during bioremediation of petroleum-contaminated loess soils: insights from metagenomic analysis. *Science Direct*.
- Ou, Y. (2025). Differential microbial mechanisms of TPH degradation and detoxification during stepwise bioremediation of petroleum-contaminated soil. *Science Direct*.
- Pacwa-Płociniczak, M. (2016). Monitoring the changes in a bacterial community in petroleum-polluted soil bioaugmented with hydrocarbon-degrading strains. *Science Direct*, 76-85.
- Pacwa-Płociniczak, M. (2016). Monitoring the changes in a bacterial community in petroleum-polluted soil bioaugmented with hydrocarbon-degrading strains. *Science Direct*, 76-85.
- Qin, G. (2013). Bioremediation of petroleum-contaminated soil by biostimulation amended with biochar. *Science Direct*, 150-155.
- Rathankumar, A. K. (2020). Effect of soil organic matter (SOM) on the degradation of polycyclic aromatic hydrocarbons using *Pleurotus dryinus* IBB 903-A microcosm study. *Science Direct*.
- Scherr, K. (2007). Influence of soil fractions on microbial degradation behavior of mineral hydrocarbons. *Science Direct*, 341-350.
- Szerement, J. (2023, Agosto 30). *Restoration of soils contaminated with PAHs by the mixture of zeolite composites mixed with exogenous organic matter and mineral salts*. Retrieved from Nature: <https://www.nature.com/articles/s41598-023-41429-2>
- Szewczuk-Karpisz, S. K. (2024). Management of the soil environment using biochar and zeolite in various combinations: impact on soil condition and economical aspects. *SPRINGER NATURE*, 77-102.
- Truskewycz, A., Gundry, T., Khundur, L., Kolobaric, A., Taha, M., Aburto-Medina, A., . . . Shahsavari, E. (2019, September 19). *Petroleum Hydrocarbon Contamination in Terrestrial Ecosystems—Fate and Microbial Responses*. Retrieved from National Library of Medicine: https://pubmed.ncbi.nlm.nih.gov/articles/PMC6767264/?utm_source=chatgpt.com
- Tsai, W.-H. (2025). A field-scale assessment of the efficacy of bioremediation of petroleum

- hydrocarbon-contaminated soils using two biostimulants. *Science Direct*.
- Tsai, W.-H. (2025). A field-scale assessment of the efficacy of bioremediation of petroleum hydrocarbon-contaminated soils using two biostimulants. *Science Direct*.
- Vafa, H. J. (2025). A comparative life cycle analysis of bioremediation approaches for old-aged petroleum pollution in hypersaline soil. *Science Direct*.
- Wang, J. (2024). Prediction of optimal bioremediation conditions for petroleum hydrocarbon contaminated soil by automated machine learning-based analysis. *Science Direct*.
- Wang, J. (2024). Prediction of optimal bioremediation conditions for petroleum hydrocarbon contaminated soil by automated machine learning-based analysis. *Science Direct*.
- Wang, S. (2025). Insight into the effect of electric fields on bioremediation of petroleum-contaminated soil: A micro-ecological response. *Science Direct*.
- Wei, Z., Wei, Y., Lui, Y., Niu, S., & Xu, Y. (2024). *Biochar-based materials as remediation strategy in petroleum hydrocarbon-contaminated soil and water: Performances, hydrocarbon-contaminated soil and water: Performances, mechanisms, and environmental impact mechanisms, and environmental impact*.
- impact*. Louisiana: LSU Scholarly Repository LSU Scholarly Repository.
- Wojtowicz, K. (2025). Phytoremediation of soil contaminated with petroleum hydrocarbons using the wild plants *Scirpus sylvaticus* and *Cirsium oleraceum*, supported by bioaugmentation. *Science Direct*.
- Xiao, R. (2017). Recent developments in biochar utilization as an additive in organic solid waste composting: A review. *Science Direct*, 203-2013.
- Xu, Y. (2010). *Bioremediation of crude oil-contaminated soil: Comparison of different biostimulation and bioaugmentation treatments*. Retrieved from Science Direct: <https://www.sciencedirect.com/science/article/abs/pii/S0304389410009234>
- Yan, Z.-F. (2024). Synergistic bioremediation of petroleum-contaminated soil using immobilized consortium of *Rhodococcus rhodochrous* and *Bacillus subtilis* laccase. *Science Direct*.
- Yousefi, K. (2021). *Biodegradation of Weathered Petroleum Hydrocarbons Using Organic Waste Amendments*. Retrieved from Wiley Online Library: <https://onlinelibrary.wiley.com/doi/10.1155/2021/6620294>
- Yu, X. (2025). Effect of biochar-immobilized *Bacillus licheniformis* Y on the remediation of soils contaminated with petroleum hydrocarbons. *Science Direct*.

- Zhang, X. (2024). Effects of biochar immobilization of *Serratia* sp. F4 OR414381 on bioremediation of petroleum contamination and bacterial community composition in loess soil. *Science Direct*.
- Zhang, X. (2025). Comprehensive effects of biochar-assisted nitrogen and phosphorus bioremediation on hydrocarbon removal and microecological improvement in petroleum-contaminated soil. *Science Direct*.
- Zheng, X.-J. (2020). Assessment of Zeolite, Biochar, and Their Combination for Stabilization of Multimetal-Contaminated Soil. *ACS Publications*.