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REVIEW

Bioremediation of hydrocarbon-contaminated soils: review and perspective for Ecuador in the Latin American context

Biorremediación de suelos contaminados con hidrocarburos: revisión y perspectiva para Ecuador en el contexto latinoamericano

Solange del Rocío Lituma Carriel[1]

[1]Universidad Estatal de Milagro. Ecuador.

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Corresponding author: Solange del Rocío Lituma Carriel

ABSTRACT

Introduction: soil contamination by hydrocarbons is a critical problem in megadiverse countries like Ecuador, where oil activity generates severe environmental impacts, especially in sensitive ecosystems such as the Amazon.
Objective: to examine the state-of-the-art bioremediation techniques for hydrocarbon-contaminated soils in Latin America, with a special emphasis on Ecuador.
Development: bioremediation is addressed as a sustainable alternative for restoring contaminated soils, highlighting techniques such as phytoremediation, mycoremediation, biostimulation, bioaugmentation, and the use of biochar and biosurfactants. The role of indigenous microorganisms (bacteria and fungi) and microbial consortia in the degradation of contaminants such as total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAHs) is emphasized. Although there has been significant international progress, the applicability of these techniques in tropical and megadiverse contexts—such as those in Latin America—remains limited. Ecuador, despite its environmental vulnerability and economic dependence on oil, has limited scientific output in this field.
Conclusions: there is a need to adapt bioremediation strategies to local conditions, considering soil and climate factors, native biodiversity, and socio-environmental dynamics.

Keywords: Bioremediation; Hydrocarbons; Contaminated Soils; Ecuador.

RESUMEN

Introducción: la contaminación de suelos por hidrocarburos es un problema crítico en países megadiversos como Ecuador, donde la actividad petrolera genera impactos ambientales severos, especialmente en ecosistemas sensibles como la Amazonía.
Objetivo: examinar el estado del arte de las técnicas de biorremediación de suelos contaminados con hidrocarburos en América Latina, con especial énfasis en Ecuador.
Desarrollo: se aborda la biorremediación como una alternativa sostenible para restaurar suelos contaminados, destacando técnicas como la fitorremediación, micorremediación, bioestimulación, bioaumentación y el uso de biocarbón (biochar) y biosurfactantes. Se enfatiza el papel de microorganismos autóctonos (bacterias y hongos) y consorcios microbianos en la degradación de contaminantes como hidrocarburos totales de petróleo (TPH) e hidrocarburos aromáticos policíclicos (PAHs). Aunque existen avances significativos a nivel internacional, la aplicabilidad de estas técnicas en contextos tropicales y megadiversos —como los de América Latina— sigue siendo limitada. Ecuador, a pesar de su vulnerabilidad ambiental y dependencia económica del petróleo, presenta una producción científica escasa en este campo.

Conclusiones: se identifica la necesidad de adaptar las estrategias de biorremediación a las condiciones locales, considerando factores edafoclimáticos, biodiversidad nativa y dinámicas socioambientales.

Palabras claves: Biorremediación; Hidrocarburos; Suelos Contaminados; Ecuador.

INTRODUCTION

Soil is considered a non-renewable resource and plays a fundamental role in the functioning of all ecosystems and human well-being. It serves as a habitat for various organisms, a source of genetic diversity, a carbon sink, a natural storage and filtration system for substances, and the basis for the production of food, biomass, and raw materials necessary for various economic activities.[1]

However, the extraction and transportation of hydrocarbons, which occur daily around the world, pose a considerable environmental risk, with accidental spills being one of the leading causes of severe soil degradation.[2] In megadiverse countries, where the economy is heavily dependent on the oil industry, these incidents cause critical ecological impacts, especially in vulnerable areas such as the Amazon.[3]

In addition to the ecological effects, soil contamination with hydrocarbons poses a danger to public health, as crude oil contains organic and inorganic compounds that are toxic. These include polycyclic aromatic hydrocarbons (PAHs), which are known for their genotoxic and carcinogenic properties and can affect liver and kidney function in both humans and animals.[4]

In response to this situation, biotechnology has developed methods such as bioremediation, which aims to restore contaminated soils using microorganisms, plants, or organic amendments, thereby reducing the concentration of contaminants without generating toxic secondary waste.[5]

Bioremediation has emerged as one of the most sustainable alternatives in the face of growing concern about soil contamination caused by hydrocarbons, especially in contexts where physicochemical methods are costly, limited, or environmentally invasive. This growing interest is reflected in a significant number of international studies that prioritize the use of biological techniques in various contaminated ecosystems.[6]

The relationship between oil activity and the environment has generated constant controversy in Latin America. In this region, the consequences of extractive activities affect both the natural environment and the health of populations.[3]

This review was therefore conducted to examine the state of the art of bioremediation techniques for hydrocarbon-contaminated soils in Latin America, with a special emphasis on Ecuador.

DEVELOPMENT

Bioremediation Techniques

Phytoremediation

Phytoremediation is a biological remediation technique that uses plants to reduce, extract, contain, or transform contaminants present in soil, sediment, or water. This process is based on the ability of certain plant species to stimulate, through their root exudates, microbial activity in the soil, which increases microbial diversity and promotes the degradation of toxic compounds such as polycyclic aromatic hydrocarbons.[7]

Mycoremediation

This is a bioremediation technique that uses fungi that have the ability to colonize organic waste and soil, accelerating the degradation or transforming recalcitrant compounds of total petroleum hydrocarbons or other contaminants into less toxic substances, improving the quality of contaminated soil.[8]

Microcosms

These are small-scale experimental systems that replicate real environmental conditions in a controlled manner, allowing the study of ecological and remediation processes. In the context of contaminated soils, microcosms allow the simulation of interactions between contaminants, soils, organisms, and abiotic factors, facilitating the evaluation of techniques such as mycoremediation without the need to directly intervene in the natural environment. These tests provide valuable information on the efficiency of treatments, the dynamics of contaminants, and the effects on soil biota.[9]

Biostimulation

This is also a bioremediation technique that consists of adding nutrients, mainly sources of nitrogen, phosphorus, and oxygen, or other compounds that promote the growth and metabolic activity of native microorganisms capable of degrading contaminants such as petroleum hydrocarbons. This strategy seeks to optimize soil environmental conditions, such as the nutrient ratio, in order to enhance natural biodegradation.[10]

Biochar

Biochar is a carbonaceous material produced by the pyrolysis of residual biomass, characterized by its high chemical stability and remarkable adsorption capacity. Its porous structure and functional surface allow it to retain various organic pollutants, including pesticides, antibiotics, estrogenic hormones, perfluorooctanoic acids, and hydrocarbon compounds such as polycyclic aromatic hydrocarbons (PAHs).[4]

Biosurfactant

A biosurfactant is a compound of microbial origin that has surface-active properties, i.e., it can reduce the surface and interfacial tension between two immiscible phases, such as water and oil. These compounds are produced naturally by bacteria, yeasts, or fungi during their growth in the presence of hydrophobic carbon sources, such as oils or hydrocarbons.[11]

Bioaugmentation

This consists of introducing specific microorganisms, either pure strains or consortia, that have the ability to degrade particular contaminants in the receiving environment. This strategy seeks to improve the efficiency of bioremediation when native microorganisms are not sufficient or effective to carry out the process.[12]

Bioreactor

Table 1. Techniques used in bioremediation studies of hydrocarbon-contaminated soils in Latin America

Techniques	Subtechniques	Activity
Phytoremediation / Rhizoremediation	Phytoremediation (plants: Medicago sativa, Zea mays, Sorghum vulgare, Chrysopogon zizanioides, Eleocharis sp.) Mycoremediation associated with roots (A. bisporus, rhizosphere fungi of Rhizophora mangle)	Removing contaminants from soil or water through absorption or transformation by roots or symbiosis with mycorrhizal fungi.
Biostimulation	Biostimulants (nutrients, *B*-glucans, biochar) Biosurfactants/bioemulsifiers (anionic, rhamnolipids)	Stimulate the activity of native degrading microorganisms by improving the environment or bioavailability
Bioaugmentation	Inoculation of strains/consortia (Pseudomonas, Bosea, Sphingobium, Acinetobacter spp., Bacillus spp., BCons)	Introduce microorganisms with high degrading capacity to reinforce ecosystem activity at the contaminated site.
Ex situ processes	Biopiles, windrows, landfarming, composting.	Treatment of contaminated soil away from the original site using aerated or composted techniques.
Physicochemical-biological processes Combined	Soil washing, in situ bioaeration, multiphase extraction (MPE), pumping, packed bed bioreactor	Combining physical and chemical processes with biological degradation to maximize the removal of complex contaminants.
Bioreactors and sequential systems	SS-SBR (Soil-Slurry SBR) UAF-3SS (Up-flow Anaerobic Filter 3 phases) COD removed 80–99 % soil, 60–99 % water	Removal of contaminants in soil and water through treatment in controlled biological reactors.
Passive or hybrid strategies	Semi-passive bioremediation Monitored natural attenuation	Allow natural remediation with technical monitoring or minimal intervention.

This is a closed device or system that provides a controlled environment for carrying out biological processes, including the degradation of contaminant compounds through microbial metabolism.[13]

Table 1 summarizes the techniques and sub-techniques of bioremediation of hydrocarbon-contaminated soils in Latin America.

Bioremediation organisms in soils contaminated with hydrocarbons

Bioremediation depends on the use of organisms capable of transforming or degrading contaminating compounds (table 2) into less toxic products. These organisms are mainly classified into three groups: bacteria, fungi, and plants, which can act individually or in synergistic consortia.[14]

Bacteria

Bacteria are the most widely used group due to their metabolic capacity to degrade aliphatic and aromatic hydrocarbons and complex compounds such as PAHs.[15] Table 3 lists some examples of bacteria used for bioremediation.

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Table 2. Most common hydrocarbons in contaminated soils in Latin America

Category	Examples	Nature
Total petroleum hydrocarbons (TPH)	Mixture of C10–C28 hydrocarbons	Aliphatic and aromatic
Polycyclic aromatics (PAHs)	Phenanthrene, anthracene, naphthalene	Persistent, carcinogenic
Light and medium fractions	Diesel, gasoline, gas oil, lubricating oil	Volatile, flammable
Complex waste	Oily sludge, used oil, bioemulsified	Variable mixtures
Specific compounds	TBHP, natfalate, biodiesel	Occasional and less common

Table 3. Bacterial microorganisms used in bioremediation studies in Latin America

Microbial family	Genera/species	Most frequent applications
Pseudomonadaceae	*Pseudomonas aeruginosa*, *P. putida*, *P. sp.*	Bioaugmentation, production of biosurfactants
Bacillaceae	*Bacillus subtilis*, *B. cereus*, *Priestia flexa*	Bacterial consortia, metal resistance
Actinobacteria	*Rhodococcus sp.*, *Microbacterium sp.*	Degradation of complex PAHs
Moraxellaceae	*Acinetobacter sp.*	Production of biosurfactants and degradation of TPH
Brucellaceae	*Ochrobactrum intermedium*, *Brucella sp.*	Degradation of recalcitrant compounds
Staphylococcaceae	*Staphylococcus sp.*	Secondary participation in consortia

Fungi

Fungi, particularly filamentous fungi, possess powerful extracellular enzymes such as laccases and peroxidases that have been applied in mycoremediation (table 4), especially in soils with high levels of persistent aromatic compounds.[9]

Table 4. Fungi used in bioremediation studies in Latin America

Family	Genus/Species	Application in bioremediation
Trichocomaceae	*Aspergillus oryzae* (strain MF13) *A. flavipes* (strain QCS12) A. niger A. flavus A. egyptiacus Fusarium oxysporum	Phenanthrene degradation (PHE); mycoremediation associated with mangrove roots (*Rhizophora mangle*).
Agaricaceae	*Agaricus bisporus*	Use of residual crop substrate as a biostimulant for native bacteria

Plants

Used for phytoremediation due to their ability to absorb or transform contaminants.[16] Many species also act as hosts for rhizospheric microorganisms that enhance bioremediation.[17] Table 5 lists some examples of plants used for bioremediation.

Table 5. Plants used in bioremediation studies in Latin America

Family	Genus/species	Application in bioremediation
Fabaceae	Medicago sativa (alfalfa)	Phytoremediation of soils contaminated with hydrocarbons
Cucurbitaceae	Cucurbita pepo + rhizosphere microbiota	Phytoremediation and stimulation of rhizosphere bacteria
Cyperaceae	Bulbostylis nesiotis, Cyperus atlanticus	Phytoremediation in wetlands contaminated with hydrocarbons
Araceae	Lemna minor	Phytoremediation in potted crops.
Poaceae	Zea mays (corn) + native Sorghum vulgare, Chrysopogon zizanioides	Phytoremediation in combination with native rhizosphere bacteria Phytoremediation in potted crops.

Microbial consortia

They are natural or engineered mixtures of various microorganisms that act synergistically, improving the rate of degradation and adaptability to diverse environmental conditions. *BCons-type* consortia (hydrocarbonoclastic bacteria) have been used successfully in Ecuadorian soils contaminated with crude oil.[18]

Background information

Bioremediation has emerged as a sustainable strategy that has evolved through the use of advanced biotechnological approaches, generating growing interest around the world. However, this research has been conducted mainly in non-tropical contexts, creating a geographical imbalance in its applicability to regions such as Latin America. Despite this, intercontinental studies have highlighted the potential of bioremediation in tropical areas, emphasizing the importance of factors such as the appropriate selection of plants and microorganisms, as well as the bioaccessibility of contaminants.[6]

In Canada, a synthetic bacterial consortium capable of producing active enzymes at low temperatures was developed, demonstrating scientific progress in extreme environmental conditions. Their test, implemented in simulated soil columns, achieved a significant reduction in polycyclic aromatic hydrocarbons, highlighting the potential of these technologies in cold climate regions. However, the authors do not consider scenarios with greater environmental vulnerability, such as tropical environments and developing countries. This omission represents a significant limitation in the global applicability of the results and reinforces the need for studies that highlight these gaps through systematic bibliometric analyses. In this regard, this paper is intended as a contribution aimed at identifying research dynamics surrounding the bioremediation of hydrocarbon-contaminated soils, with a special emphasis on Ecuador. In this megadiverse region, these approaches are rarely addressed from a scientific evidence perspective.[19]

In contrast, a study conducted in China evaluated changes in soil microbial diversity following contamination with crude oil, diesel, and gasoline, revealing a notable decrease in the diversity of bacterial and fungal communities, as well as a selective enrichment of strains capable of degrading these substances. Among the most relevant findings is the isolation of two bacterial strains, *Serratia marcescens* PL and *Raoultella ornithinolytica* PS, capable of degrading more than 75 % of hydrocarbons under controlled conditions. When combined, these strains achieved a biodegradation efficiency of 96,83 %, eliminating even highly recalcitrant compounds such as phytan and pristane. These results demonstrate the potential of microbial consortia adapted for the bioremediation of hydrocarbon-contaminated soils. However, most of these studies have been conducted in non-tropical urban or industrial contexts, underscoring the need to generate localized knowledge in regions such as Latin America and, particularly, in tropical ecosystems where soil and climate conditions and microbial biodiversity differ considerably.[20]

In research in Australia [21], biocarbon has emerged as a promising alternative for the remediation of hydrocarbon-contaminated soils due to its low cost, environmental sustainability, and ability to improve the physicochemical properties of the soil. This strategy has focused particularly on its role as a biostimulant, promoting microbial growth and, therefore, the biodegradation of toxic compounds such as polycyclic aromatic hydrocarbons (PAHs) and petroleum fractions. According to Dike et al.[21], biochar promotes enzymatic activity, improves nutrient and water retention, and increases soil porosity, creating a favorable environment for the action of degrading bacteria. Although experimental studies report removal efficiencies of over 70 % under controlled conditions, significant variability in results has also been identified, attributable to factors such as biomass type, pyrolysis temperature, and interaction with added nutrients. This highlights the need for further research into its real applicability in tropical soils and highly environmentally vulnerable contexts, such as those found in developing countries.[21]

Significant advances have been demonstrated in the use of indigenous microorganisms and agro-industrial waste as key tools for bioremediation.[22] In Brazil, for example, a sustainable biosurfactant was developed from *Serratia marcescens* UCP 1549, using wastewater from cassava processing. This compound demonstrated high stability against variations in pH, temperature, and salinity, effectively removing up to 94 % of burnt oil from contaminated sand, which validates its applicability in agricultural and environmental remediation processes.

In Peru, Quiñones-Cerna et al.[23] evaluated the degradative capacity of indigenous bacteria isolated from agricultural soils in Huamachuco. The study identified strains such as *Pseudomonas protegens, Pseudomonas citri*, and *Acinetobacter guillouiae,* with degradation efficiencies greater than 90 % under controlled conditions. These results highlight the potential of microorganisms not originating from previously contaminated areas, opening up new possibilities for practical and sustainable bioremediation in Andean agricultural soils.

In Colombia, the article by Benítez et al.[16] evaluates the effectiveness of phytoremediation in removing contaminants from soils, leachates, and water. *Sorghum vulgare* was used for diesel-contaminated soils, *Chrysopogon zizanioides* for landfill leachates, and *Lemna minor* for nickel-contaminated water, achieving removals of up to 98 %. The study, conducted in Cartagena, Colombia, demonstrates that phytoremediation is a sustainable and efficient alternative for Latin American contexts.

In Venezuela, bioremediation of soil and groundwater contaminated with hydrocarbons was carried out in a tropical aquifer. An ex situ treatment was chosen, using a sequential sludge reactor (SS-SBR) and an upflow anaerobic filter (UAF-3SS), achieving up to 99 % COD removal. The study highlights the effectiveness of coupled systems in overcoming environmental limitations and improving the biodegradation of hydrocarbons in tropical contexts.[24]

In Ecuador, over the past few decades, a severe environmental problem has arisen from soil contamination resulting from hydrocarbon activities, primarily in the Amazon region. Given the strategic importance of oil for the national economy, which accounts for more than 30 % of exports and 11 % of GDP, multiple research projects have been developed to mitigate the environmental impact through bioremediation techniques.[25]

One of the most relevant studies in the Ecuadorian context was conducted by Hidalgo-Lasso et al.[1], who proposed updating soil remediation criteria based not only on total extractable hydrocarbons (TEPH), but also on bioavailable hydrocarbons (TBPH). The authors demonstrated that there is a stronger correlation between TBPH and toxicity assessed with the Microtox bioassay, which calls into question current regulatory approaches that do not consider bioavailability.

Also noteworthy is the article by Pozo-Rivera et al.[2] on the application of bioindicators using various species of dung beetles in remediated sites in the Ecuadorian Amazon. The study revealed that, although soil washing and revegetation techniques have been applied, biological diversity in degraded ecosystems remains significantly lower than in natural forests, highlighting the need to consider biological indicators in post-remediation assessments. Likewise, research such as that of Hidalgo-Lasso et al.[1] analyzed the benefits of remediation considering ecosystem variables such as eutrophication and aquatic toxicity, showing a 43 % reduction in negative impacts. These practices include the use of biodegradable surfactants, composting, windrows, and landfarming, the latter being more efficient in terms of degradation.

In Ecuador, soil is a fundamental resource for environmental balance and human development, especially in regions such as the Amazon, where the country's oil activity has been concentrated since the 1970s. Although strategic for the economy, accounting for more than 30 % of exports and contributing 11 % to the national GDP in 2022, this activity has generated significant environmental impacts, including soil, water, and air pollution. In response, since 2005, the Ecuadorian government has implemented remediation policies that have made it possible to clean up more than 1 300 contaminated sites and treat around 1,6 million tons of soil in the Amazonian provinces of Orellana and Sucumbíos. These interventions have been governed by regulatory frameworks, such as the Environmental Regulations for Hydrocarbon Operations and Ministerial Agreement 097, which establish permissible limits for pollutants, including total extractable hydrocarbons, heavy metals, and polycyclic aromatic compounds. Depending on land use, ecological risk assessments were applied to contaminated sites in eastern Ecuador, proposing adaptive remediation criteria that take into account land use, sensitive ecosystems, agriculture, or industry, which represents an advance in regulatory contextualization.

Complementarily, the work of Ojeda-Morales et al.[26] explored the effectiveness of composting combined with native microorganisms to reduce hydrocarbon concentration. It was shown that the use of native bacterial consortia and biostimulants significantly increased the removal rate in soils in the province of Sucumbíos.

On the other hand, international studies with Ecuadorian collaboration, such as that of González-Toril et al., applied metagenomic analyses in oil shale mining areas to evaluate microbial communities with bioremediation potential, opening the door to the use of omics approaches in local contexts.

Finally, a notable example of international collaboration in the field of bioremediation is the study conducted by González-Toril et al.[27] in which a natural microbial consortium isolated from the Riutort oil shale deposit in Spain, was analyzed metagenomically and then experimentally applied to Ecuadorian soils contaminated by hydrocarbons at the La Libertad Refinery and in the Ancón Field, Ecuador, achieving a 50,8 % degradation of total hydrocarbons in 60 days. This precedent not only demonstrates the potential of natural bioproducts but also the importance of transnational scientific collaboration in addressing environmental issues shared between Europe and Latin America.

In Latin America, bibliometric analyses applied to bioremediation have been developed. For example, a systematic and bibliometric review of research on bioremediation and phytoremediation in the region was conducted using the Scopus and Web of Science databases. The analysis showed that Brazil, Mexico, Argentina, and Colombia account for the most significant number of publications, with public universities being the main centers of scientific production. Degrading bacteria, fungi, native plants, and biosurfactants were also identified as the main bioremediation agents reported. One of the key findings was the low production in countries with great ecological diversity, such as Ecuador and Bolivia, suggesting the existence of significant knowledge gaps and opportunities for future research.[14]

The study by Valdiviezo Gonzales et al.[28] offers a comprehensive bibliometric review of research using techniques such as bioremediation, advanced oxidation, and washing, among others, for the remediation of soils contaminated with hydrocarbons. The analysis, based on data from the Web of Science and processed with CiteSpace, reveals that the countries with the highest scientific output are China, the United States, and Iran. Additionally, international collaborations are increasing, although a concentration of knowledge remains in countries in the Northern Hemisphere. The main keywords include "oil pollution," "bioremediation," "removal efficiency," and "phytotoxicity." The authors emphasize the need to apply this research to more ecologically and geographically diverse contexts, underscoring the importance of developing targeted studies for different regions.

In a study[29] focused specifically on Latin American scientific production, they conducted a bibliometric analysis of research related to environmental remediation in Mexico. The review, based on the Scopus database, focused on publications between 2000 and 2020, with an emphasis on topics such as bioremediation, environmental toxicology, and restoration of contaminated ecosystems. The results showed sustained growth in scientific output in the area, particularly at institutions such as the National Autonomous University of Mexico (UNAM) and the National Polytechnic Institute (IPN), which are leaders in knowledge generation. In addition, the growing contribution of inter-institutional research was highlighted, as well as the need to strengthen the link between environmental research and public policy in highly biodiverse contexts such as Mexico, where environmental liabilities associated with industrial activity still represent a significant challenge for environmental sustainability.

Overall, the studies reviewed (table 6) reflect a growing focus in Latin America on bioremediation, with scientific output led by countries such as Brazil and Mexico. However, this review also reveals an alarming shortage of research in megadiverse countries such as Ecuador, despite their high environmental vulnerability and the pressure exerted by extractive activities. Although various studies have used tools such as CiteSpace and databases such as Scopus and Web of Science to map the evolution of this field, most of them present a regional or global approach with little contextualization.

Table 6. Articles on bioremediation in the context of Ecuador

Author	Location	Bioremediation technique
Camacho et al.[3], 2024	Esmeraldas	Biocarbon with rice husks and biostimulation
Pozo-Rivera et al.[2], 2023	Orellana and Sucumbíos	Bioindicators with beetles
V. J. García et al.[30], 2019	Esmeraldas	Bioaugmentation and spectroscopy
Orejuela-Romero et al.[31], 2025	Francisco Orellana	Biostimulation through organic amendments
González-Toril et al.[27], 2023	Spain and Ecuador Freedom	Bioaugmentation with bacteria
Andrade et al.[5], 2024	Santay Island	Isolation and microbial tolerance plus biosurfactant production
Páliz et al.[15], 2021	Orellana	Bioaugmentation with native bacteria

Theoretical framework: soil contamination by hydrocarbons: environmental consequences

Petroleum hydrocarbon contamination is one of the most persistent and complex environmental problems due to the low bioavailability and high toxicity of compounds such as polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons. These contaminants directly affect the edaphic microbiota, inhibit soil enzyme activity, and alter parameters such as plant germination and growth.[32]

From a more applied perspective, the study by Ruseva et al.[33] on Chernozem soils in the Rostov region of Russia showed that oil contamination, even at low levels (0,1 %), drastically reduces catalase and dehydrogenase activity and total bacterial density and causes measurable phytotoxic effects on *Raphanus sativus* roots. This finding validates the use of biological indicators as key monitoring tools and is in line with similar studies in Asia and Europe.[34]

However, the authors also point out a methodological limitation: most of these studies are contextualized in temperate or arid soils, which do not reflect the ecological complexity of tropical soils such as those in Ecuador, characterized by their high microbial diversity.

According to Cambarieri et al.[10], biostimulation is especially effective when there are native microbial populations with degradative potential but that are limited by adverse soil conditions.

Biochar, obtained by pyrolysis of organic waste, has gained prominence as an environmental amendment due to its ability to adsorb contaminants, improve soil structure, and promote degrading microbial communities.[6]

In particular, Minnikova et al.[35] demonstrated that the combination of biochar with native bacterial strains of *Bacillus* and *Paenibacillus* resulted in a 67 % reduction in hydrocarbons within 30 days, while also recovering enzymatic and plant parameters. In comparison, the study by Ruseva et al.[33], which used biochar alone, showed only partial improvements, suggesting that synergistic bioaugmentation represents a more effective approach under conditions of high toxicity.

This evidence supports this researcher's critical stance that biochar should be conceived not as a single solution, but as part of an integrated bioremediation system that considers the local microbiota and tropical soil dynamics.

In the context of bioremediation, biochar has been extensively studied for its potential as an adsorbent for petroleum derivatives. However, most existing reviews have focused on its adsorption capacity rather than its participation in degradation processes.[4] Its effectiveness can be increased through physicochemical modifications, which optimize its properties for specific applications, especially in soils contaminated with hydrocarbons.

The use of biosurfactants produced by bacteria such as *Pseudomonas aeruginosa* or *Halomonas pacifica* has been shown to increase the bioavailability of hydrocarbons, facilitating their degradation.[36,37] This technique, in addition to being environmentally friendly, reduces the need for expensive and potentially toxic synthetic surfactants.

From an advanced biotechnological approach, Davoodi et al.[19] developed interspecies bacterial consortia adapted to low temperatures, which were applied in soil columns. Their results showed efficient reduction of PAHs through active enzyme production, marking a global trend toward bioremediation based on microbial engineering, which is still absent in Latin America.

At the Latin American level, Castillo-Campos et al.[38] and Orellana et al.[39] show incipient advances, focused on bacterial biosurfactants and compost treatments, but still with little technology transfer. The identified gap allows for a critical position that Ecuador must move towards bio-environmental innovation models based on its own edaphic biodiversity.

The document points out that biosurfactants can be classified into several types, such as glycolipids, lipopeptides, phospholipids, and tensioactive polymers, with rhamnolipids (produced by *Pseudomonas aeruginosa*) and sophorolipids (produced by *Starmerella bombicola*) being the most studied. Their environmental relevance lies in their ability to emulsify organic pollutants, thereby increasing their bioavailability and promoting microbial degradation. Unlike synthetic surfactants, biosurfactants are biodegradable, non-toxic, and active under extreme pH, temperature, and salinity conditions.[11]

In particular, it has been observed that the use of *Medicago sativa* (alfalfa) can significantly reduce the concentration of phenanthrene in contaminated soils, activating rhizodegradation processes and facilitating the development of bacterial communities specialized in the biodegradation of contaminants.[7]

In tropical environments, for example, *Eleocharis mutata*, a halotolerant plant, has been shown to grow in soils with salinities of up to 125 dS/m, contributing significantly to the recovery of areas affected by saline spills from the oil industry. Its action reduces soil salinity, increases organic matter content, and facilitates plant succession with species such as *Typha sp.*, demonstrating the potential of phytoremediation in humid tropical regions.[40]

Although the action of ligninolytic Basidiomycota has traditionally been researched, recent studies have shown that species of the phylum Ascomycota, such as *Aspergillus oryzae* and *Aspergillus flavipes*, also have a high potential to degrade phenanthrene, even at concentrations of up to 5000 mg/L, without the need for additional carbon sources. These species not only tolerate high levels of the contaminant but also degrade it effectively, making them promising organisms for the mycoremediation of hydrocarbon-contaminated soils.[8]

Monitoring and evaluation: towards functional and adaptive indicators

Beyond the removal of contaminants, ecological restoration requires functional soil assessment systems. Vergnano et al.[41] propose the use of TDR (Time Domain Reflectometry) sensors to monitor soil properties, such as conductivity and electrical permittivity, in real-time, revealing microbial activity without the need for destructive methods.

This approach is complemented by biological indicators such as those used by Ruseva et al.[33]: dehydrogenase activity, number of bacteria, and phytotoxicity bioassays. However, most studies do not adapt these indicators to tropical contexts, where microbial variability can alter their sensitivity and response. Therefore, it is necessary to develop baselines for local bioindicators in Ecuador, which would allow for the standardization of monitoring protocols with an ecosystem approach.

Conceptual synthesis and identified gaps

The literature consulted suggests that the effectiveness of bioremediation depends less on the type of amendment used and more on the soil, climate, biological, and socio-environmental context in which it is applied. Although strategies such as biocarbon and rhizoremediation have broad experimental support, their application in tropical, biodiverse, and socially sensitive soils, such as those in Ecuador, remains limited and poorly documented.

This research takes a critical view based on the reality in Ecuador. It recognizes the great potential of bioremediation technologies to address hydrocarbon contamination in soils, but also warns that it is not enough to apply international models directly.

It is necessary to adapt them to the specific environment of the country, taking into account not only ecological conditions, but also the social and cultural dynamics of each region. Although there have been significant advances and numerous successful experiences at the international level, in Ecuador, there is still much to be done. Knowledge still needs to be generated on key aspects, such as the appropriate doses, frequency of application, and compatibility between different biological amendments, especially in tropical contexts or in Andean areas where soil conditions, climate, and biodiversity have unique characteristics.

This means that isolated trials or solutions without local experimental validation are often used, which reduces their long-term effectiveness and sustainability. On the other hand, despite growing interest in bioremediation, Ecuador has limited scientific visibility in this field; the number of publications remains low, and few studies apply these techniques in Amazonian or urban contexts within the country. However, the participation of Ecuadorian researchers in international journal publications demonstrates that there are capacities and knowledge that could be strengthened through more active scientific cooperation.

CONCLUSIONS

Bioremediation is an effective and sustainable strategy for recovering hydrocarbon-contaminated soils, although its success depends on the environmental context and the appropriate selection of techniques and organisms. There is a significant gap between international research and its applicability in tropical ecosystems such as those in Ecuador, where microbial biodiversity and soil conditions are unique.

It is crucial to develop protocols adapted to local realities, integrating bioindicators, real-time monitoring, and the participation of native microbial communities. International scientific collaboration and the strengthening of local research are key to advancing soil remediation in countries with high environmental vulnerability and economic dependence on extractive industries.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Research: Solange del Rocío Lituma Carriel.
Methodology: Solange del Rocío Lituma Carriel.
Writing – original draft: Solange del Rocío Lituma Carriel.
Writing – review and editing: Solange del Rocío Lituma Carriel.