

CRANFIELD UNIVERSITY

IKEABIAMA NDUBUISI AZUAZU

ENHANCING NATURAL ATTENUATION FOR OIL-CONTAMINATED SOILS
USING A COMBINATION OF LOW-CARBON BIOENGINEERED
APPROACHES

SCHOOL OF WATER, ENERGY AND ENVIRONMENT

PhD

Academic Year: 2022 – 2023

Supervisor: Prof. Frederic Coulon
Associate Supervisor: Dr Pablo Campo

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ABSTRACT

This thesis presents an extensive study aimed at optimising natural attenuation for oil-contaminated soils by employing a combination of low-carbon bioremediation strategies. Responding to the urgent need for sustainable remediation practices, this work systematically evaluates the efficiency of bioremediation techniques, focusing on their potential implementation in the Niger Delta, a region severely impacted by oil contamination. An initial review identified bioremediation and bioadment with compost or biochar as effective low-carbon strategies, tailored to the unique conditions of the Niger Delta. An elaborate laboratory investigation of diverse biostimulation strategies subsequently confirmed the superior efficiency of combined treatments over singular approaches. Notably, integrating oxygen-release compounds (ORC) with food waste compost significantly enhanced microbial activities, accelerating the degradation of total petroleum hydrocarbons (TPH). Further exploration revealed the benefits of bioaugmentation with biochar for managing recurring spills. The combination of wheat straw biochar and specific bacterial strains resulted in markedly higher remediation efficiency in recurrently contaminated soil, underscoring the crucial role and adaptability of microbial communities in such scenarios. To streamline decision-making processes, a decision tree framework based on the Analytical Hierarchy Process (AHP) was developed. This tool assesses the techno-economic and sustainability aspects of the proposed remediation strategies. The decision tool highlights that the use of ORC with compost, and wheat straw biochar augmented with *Pseudomonas aeruginosa* and *Bacillus sonorensis* holds substantial promise. However, it underscores the importance of comprehensive site assessments, drawing attention to potential constraints in diverse environmental contexts. This research offers novel insights into refining bioremediation techniques and paves the way for future advancements in this critical field. The findings could guide the development of more efficacious, sustainable, and cost-effective remediation strategies for oil-contaminated soils, with continued refinement and application anticipated.

Keywords: Bioremediation, biostimulation, bioaugmentation, Niger Delta, sustainability, decision tree, Analytical Hierarchy Process, biochar

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
Avg	Average
ANOVA	Analysis of Variance
AHP	Analytical Hierarchy Process
BHT	Butylhydroxytoluene
BioA	Bioaugmentation
BioS	Biostimulation
Bio2char	Biochar+Bioaugmentation
Br	Basal respiration
BS	Bacillus sonorensis
BSE	Backscattered Electron
BTEX	Benzene Toluene Ethylbenzene and Xylene
CLCB	Combined Low-Carbon Bioremediation
CNP	Carbon Nitrogen Phosphorus ratio
CO ₂	Carbon dioxide
Diff	Difference
DO	Dissolved oxygen
EC	Electrical conductivity
EC ₅₀	Half maximal effective concentration
EGASPIN	Environmental Guideline and Standard for Petroleum Industry in Nigeria
EKR	Electrokinetic remediation
FWC	Food waste compost
GC-MS	Gas chromatography-mass spectrometry
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GMO	Genetically Modified Organism
HYPREP	Hydrocarbon Pollution Remediation Project
ISCO	In Situ Chemical Oxidation
IUCN	International Union for Conservation of Nature

LCA	Life Cycle Analysis
LCB	Low-Carbon Bioremediation
MCDA	Multi-Criteria Decision Analysis
MNA	Monitored Natural Attenuation
NOSDRA	National Oil Spill Detection and Response Agency
NPK	Nitrogen phosphorus potassium ratio
OPEC	Organization of Petroleum Exporting Countries
ORC	Oxygen Release Compound
PA	Pseudomonas aeruginosa
PABS	Pseudomonas aeruginosa + Bacillus sonorensis
PAH	Polycyclic Aromatic Hydrocarbon
PCA	Principal Component Analysis
PFAS	Polyfluoroalkyl Substances
pH	Power of Hydrogen
PHC	Petroleum Hydrocarbon Compounds
PLFA	Phospholipid Fatty Acids
RABIT	Rapid Automated Bacterial Impedance
RENA	Remediation by Enhanced Natural Attenuation
R ²	Coefficient of determination
N&P	Nitrogen and Phosphorus solution
SCAT	Shoreline Clean-up and Assessment Technique
SDG	Sustainable Development Goal
SEM	Scanning Electron Microscope
SP	Sewage Pellets
SPDC	Shell Petroleum Development Company
SURF	Sustainable Remediation Forum
SVE	Soil Vapour Extraction
TPH	Total Petroleum Hydrocarbon
UK	United Kingdom
UNEP	United Nations Environmental Programme

USA	United States of America
USDA	United States Department of Agriculture
VOC	Volatile Organic Compound
WSP	Wheat Straw Pellets

1. INTRODUCTION

1.1 Background

Crude oil contamination of soils presents an ongoing and severe environmental issue, particularly in regions with extensive petroleum exploration and extraction activities. One such region is Nigeria's Niger Delta region, recognised worldwide for its vast oil reserves (Kadafa, 2012). This area has witnessed substantial environmental degradation due to frequent oil spills, often resulting from pipeline failures and other industrial accidents (Okparanma et al., 2017). Over time, these spills have had deleterious effects on the local environment, leading to loss of soil fertility, pollution of groundwater resources (Cundy et al., 2008), the decimation of local ecosystems (Bodo 2020), and deleterious impacts on the health and livelihoods of the resident communities (Sam et al., 2016; Nathanail et al., 2013; Nwilo and Badejo, 2004; UNEP, 2011). This challenge has necessitated the treatment of crude oil-contaminated soils and allowed for its reuse.

Over the past few decades, a multitude of techniques have been deployed to address the issue of crude oil contamination in soils (Davis, 2016). These range from different physical and chemical methods, such as soil washing, stabilisation and solidification and thermal desorption (Xiang et al., 2007; Zhou and Song 2004). However, these conventional remediation strategies often fall short of addressing the challenge effectively, primarily due to incomplete degradation of hydrocarbons, leaving behind residual contamination with associated environmental risks (Das and Chandran, 2011; Thavamani et al., 2015). Additionally, these methods often involve high costs and can create further environmental harm, making them less sustainable and feasible for large-scale deployment.

Various studies have attempted to address this challenge using bioremediation strategies. However, there is a clear gap in the current understanding and application of these strategies. Many of these efforts have not been thoroughly evaluated for their technical, economic, and environmental performance, particularly in the specific context of the Niger Delta region. Furthermore, many existing decision-support tools for bioremediation strategies are insufficiently holistic, failing to adequately integrate the multiple dimensions relevant to the selection and implementation of effective remediation strategies.

In light of these shortcomings encountered with physical and chemical strategies, the use of biological processes over the decades to degrade contaminated soils. This process,

broadly called bioremediation, has emerged as a promising alternative for sustainable and cost-effective remediation of oil-contaminated soils to the physical and chemical processes. Bioremediation leverages the inherent metabolic capabilities of natural microbial communities to degrade organic contaminants, including petroleum hydrocarbons (Abdulsalam et al., 2011).

In order to accomplish this, bioremediation of soils contaminated with crude oil is typically executed by biostimulation (providing nutrients and a conducive environment to boost microbial growth and activity) or by bioaugmentation (introduction of individual strains or a group of microorganisms possessing the necessary properties for contaminant degradation). Recent research has pivoted towards combining two key biological strategies—biostimulation and bioaugmentation—to enhance the natural attenuation of oil contaminants (Galdames et al., 2017; Margesin and Schinner 2001; Rasekh and Partovinia, 2018). Biostimulation involves the addition of nutrients or other amendments to stimulate the activity of indigenous oil-degrading microbes. In contrast, bioaugmentation involves introducing specially selected strains of oil-degrading bacteria into the contaminated environment (Megharaj et al., 2014; Smith et al., 2019; Wu et al., 2016; Cai et al., 2016).

Given this background, my research will critically assess the limitations and opportunities of existing bioremediation strategies, particularly in the Niger Delta region. It will explore how the region's unique climatic and environmental conditions influence the effectiveness of biostimulation and bioaugmentation approaches and will strive to develop optimized strategies for this specific context. The tropical conditions prevalent in the Niger Delta offer a unique context for the implementation of these bioremediation strategies. High temperatures and abundant rainfall typical of the region could potentially stimulate microbial activity and thus enhance the natural attenuation of oil pollutants. However, these same conditions also pose significant challenges, such as increased leaching of contaminants, which complicates remediation efforts (Ijah and Antai, 2003; Obire and Akinde, 2004; Adeniran et al., 2023). Therefore, a critical assessment and optimisation of biostimulation and bioaugmentation strategies under these specific tropical conditions are needed.

While the advancement of low-carbon bioremediation technologies presents a promising trajectory, the effective and sustainable implementation of these strategies requires a

holistic evaluation considering their technical, economic, and environmental aspects. There is a clear and urgent need for a comprehensive decision support tool that integrates these multiple dimensions. Such a tool would facilitate the selection and application of appropriate bioremediation strategies in the Niger Delta and other regions grappling with similar challenges. Therefore, this research will fill a significant gap by developing a decision-support tool that is specifically designed to holistically evaluate bioremediation strategies. The tool will incorporate a range of criteria including the extent of cost, effectiveness, social acceptance, and environmental Impact.

Moreover, as recurring spills in the Niger Delta continue to pose significant environmental risks, the need for continuous research to improve the efficiency of bioremediation strategies and tailor them to the specific conditions of the region becomes even more pertinent. It is thus vital to understand the response of local microbial communities to various biostimulation and bioaugmentation approaches and evaluate their effectiveness for recurring oil spills in the region. One significant gap that has been identified in the application of these bioremediation strategies is the lack of comprehensive and objective means to evaluate and compare their performance. Each strategy has its strengths and weaknesses, and what works best can depend on numerous site-specific factors, including the type and extent of contamination, soil properties, and local climate conditions. Moreover, the success of a bioremediation strategy is not solely based on its technical performance. Economic aspects, such as cost-effectiveness, and sustainability considerations, such as the strategy's carbon footprint, are also crucial for decision-making (Sarkar et al., 2005).

To address this gap, a key objective of this research is to develop a decision-support tool that integrates these multiple dimensions. This tool will facilitate the selection of the most appropriate and effective bioremediation strategy for a given context based on a holistic evaluation of its techno-economic performance and sustainability. The tool will consider a range of criteria, including but not limited to the extent of hydrocarbon degradation, cost, effectiveness, social acceptance, environmental Impact, cost-effectiveness, resource consumption, emissions, waste production, and potential impacts on local biodiversity and ecosystem services. The development of such a decision support tool will not only enhance our understanding and application of bioremediation strategies but also provide a valuable resource for stakeholders, such as environmental managers, policymakers, and

community leaders. This tool will aid them in making informed decisions about managing oil-contaminated sites, in the Niger Delta and beyond, in a manner that balances the needs for effective remediation, economic feasibility, and environmental sustainability.

While the journey towards a sustainable and effective solution to crude oil-contaminated soils is fraught with challenges, it also presents opportunities to innovate and improve. The key lies in combining various bioremediation strategies and developing decision-making tools that consider technical, economic, and environmental factors to ultimately enhance the effectiveness of natural attenuation for crude oil-contaminated soils. Through the objectives of this research, the technical, economic, and environmental performance of selected bioremediation strategies will be rigorously evaluated. Furthermore, the study will attempt to identify optimal combinations of these strategies, paving the way for more efficient and sustainable remediation of crude oil-contaminated soils in the Niger Delta.

1.2 Aim and Objectives

The aim of this research is to enhance the effectiveness of natural attenuation for crude oil-contaminated soils using a combination of different bioremediation approaches.

The objectives of the research are:

1. To critically review recent progress towards low-carbon bioremediation technologies for sustainable remediation approaches.
2. To assess the combination of different biostimulation strategies to enhance the natural attenuation of crude oil-contaminated soils under tropical conditions.
3. To evaluate the response of microbial communities to a selected set of bioaugmentation approaches and validate their performance for recurring spills typically encountered in the Niger Delta.
4. To develop a decision support tool to assess the techno-economic and sustainability of the enhanced bioremediation system developed.

1.3 Structure of the Thesis

This thesis is presented in paper format. Each of the following papers is self-contained research which on the whole form this PhD research:

Chapter 2: Challenges and Opportunities for low-carbon remediation in the Niger Delta towards sustainable environmental management. This chapter critically reviews the challenges encountered during remediation and the recent progress towards low-carbon bioremediation technologies and identifies opportunities for sustainable remediation approaches.

Chapter 3: Low-carbon bioremediation strategy to enhance the natural attenuation of crude oil-contaminated soils. This chapter assesses the impact of different biostimulation strategies to enhance the natural attenuation of crude oil-contaminated soils under tropical conditions. The degradation rate of PHCs, basal respiration, changes in microbial communities, and baseline information were monitored for the biostimulation approaches.

Chapter 4: Assessing the efficacy of biochar and bioaugmented biochar for the remediation of repeatedly crude oil-contaminated soils. This chapter evaluates the response of microbial communities to biochar and bioaugmented biochar and their effectiveness in remediating recurrent crude-oil spills in the Niger Delta. *Pseudomonas aeruginosa*, *Bacillus sonorensis*, wheat straw biochar, and sewage biochar were adopted for the analysis in duplicates. The degradation rate of petroleum hydrocarbons, the microbial communities' dynamics, and the basal respiration were observed for the diverse mesocosms.

Chapter 5: A decision tree approach for sustainable decision-making for enhanced crude oil bioremediation. In this chapter, a decision support tool is developed to assess the techno-economic feasibility and sustainability of the enhanced bioremediation system developed during this research, taking into consideration, the biostimulation strategy and the combined biostimulation and bioaugmented strategies (bioaugmented biochar).

Chapter 6: Discussion and Conclusion. This chapter provides the overall discussions and conclusions drawn from the research, offers recommendations for further studies, and discusses the implications and significance of the research findings for stakeholders in the Niger Delta region.

1.4 Publications

1.4.1 Journal Papers

As of the moment this thesis was written, four articles have been published in internationally recognised, peer-reviewed journals. Three papers I participated in as a co-author and one paper in which I am the primary author are listed below. As the primary author of the paper, I, Ikeabiana Azuazu, took the lead role in creating the content, conducting the analysis, discussing the findings, and drawing conclusions. For the published works, my contributions were made in collaboration with other authors, playing a significant part in the research and writing process. Prof. Frédéric Coulon and Dr Pablo Campo have been instrumental in providing their expert supervision, offering valuable editing, proofreading, and guidance throughout.

1. **Azuazu, I.**, Sam, K., Campo, P., & Coulon, F. (2023). Challenges and Opportunities for Low-Carbon Remediation in the Niger Delta: Towards Sustainable Environmental Management. Paper submitted to Science of the Total Environment. (Chapter 2)
2. Raphael B. Jumbo, Frederic Coulon, Tamazon Cowley, **Ikeabiana Azuazu**, Emmanuel Atai, Imma Bortone, & Ying Jiang (2022). Evaluating different soil amendments as bioremediation strategy for wetland soil contaminated by crude oil. Sustainability 2022, 14 (24), 1 - 22. <https://doi.org/10.3390/su14241656>.
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2 Challenges and Opportunities for Low-Carbon Remediation in the Niger Delta: Towards Sustainable Environmental Management

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Abstract

There is increasing demand for low-carbon remediation strategies for reducing greenhouse gas emissions and promoting sustainable development in the management of environmental contamination. This trend is within the broader context of sustainable remediation strategies that balance environmental, economic, and social aspects. This article critically reviewed existing literature to evaluate and compare various low-carbon remediation methods, such as bioremediation, phytoremediation, in situ chemical oxidation, soil vapour extraction, and electrokinetic remediation, to identify suitable techniques for the remediation of oil-contaminated sites in the Niger Delta region of Nigeria. We analysed the UK sustainable remediation frameworks (SuRF-UK) to glean lessons for the Nigerian context. Our findings indicate that bioremediation and phytoremediation are particularly promising low-carbon remediation technologies for the Niger Delta region due to their cost-effectiveness and adaptability to local conditions. We proposed a framework that deeply considers opportunities for achieving multiple goals including effective remediation and limited greenhouse gas emissions while returning net social and economic benefit to local communities. The proposed framework will help decision makers to implement effective remediation technologies that meet sustainability indices, integrates emissions considerations return net environmental benefit to local communities. There is a need for policymakers to establish and enforce policies and regulations that support sustainable remediation practises, build the capacity of stakeholders, invest in research and development, and promote collaboration among stakeholders to create a regulatory environment that supports sustainable remediation practises and promotes environmental sustainability in the region. This study provides insights for achieving low-carbon remediation in regions addressing land contamination by different contaminants and facilitates the adoption of remediation technologies that consider contextual socio-economic and environmental indices for sustainable development.

Keywords: cost-effective remediation, sustainability, contaminated sites, Niger Delta, legacy oil spills, sustainable remediation, low-carbon remediation

2.1 Introduction

Increased industrial and technological activities in developed and developing countries have continued to contaminate environmental media including land and water. As a result, different countries have developed strategies and policies to address environmental contamination. For example, the United Kingdom (UK), the United States of America (USA) and the Netherlands have developed and implemented contextual management strategies and policies in the last five decades to tackle contaminated land (Luo et al., 2009). Thus, management of environmental contamination has evolved over the last five decades shifting from a cost-centred approach in the 1970s, through a technology-feasibility era in the 1980s, to a risk-based approach in the 1990s (Pollard et al., 2004). In the 2000s, the management of environmental contamination moved from being socially robust to sustainability, acknowledging that the transition towards sustainability doesn't necessitate a conflict between risk-based objectives and sustainability goals (Smith, 2019). Currently, attention has shifted to low-carbon approaches that not only account for social acceptance and economic feasibility but integrate environmental considerations to reduce energy and natural resource consumption, and greenhouse gas emissions that exacerbate climate change impacts (Ossai et al., 2020). In the context of this paper, low-carbon remediation specifically refers to these environmental cleanup strategies that are designed to minimise greenhouse gas (GHG) emissions, thus mitigating climate change while addressing environmental contamination.

However, adopting and integrating low-carbon technologies in developing regions such as Nigeria would require new infrastructure, technologies, capabilities, and resources to implement. For example, the remediation of complex contaminants in soil might require the integration of different soil management technologies (Kumar et al., 2022), that are not readily available (Sam et al., 2016; 2022). The integration process or remediation treatment train might require critical skills that might be lacking in a particular region or there might be limited economic resources to develop the needed infrastructure for implementing combined technologies. Thus, existing environmental remediation practices in such regions are yet to consider prerequisites for low-carbon remediation technologies.

Nigeria operates an economy significantly dependent on hydrocarbon exploitation. The oil and gas sector stands as a pillar of the Nigerian economy, contributing a substantial portion to the country's gross domestic product (GDP) and significantly influencing the dynamics of the foreign exchange market. As of 2015, the hydrocarbon industry accounts for approximately 86% of the country's export and foreign exchange earnings and 10% of the GDP (Nweze and Edame, 2016). This economic reliance on hydrocarbon exploitation has both positive and negative impacts. While it generates substantial revenue, it also places the country at the mercy of global oil price fluctuations, potentially leading to economic instability during periods of low oil prices. Most of Nigeria's oil and gas resources are concentrated in the Niger Delta region. Over the past five decades, the Niger Delta region considered the hub of oil production in the country, has experienced significant environmental impacts due to both minor and major oil spills. As of 2018, there were over 6,000 contaminated sites reported in the region, illustrating the extensive environmental damage caused by the oil industry (Nwozor et al., 2018).

In 2011, the United Nations Environment Programme (UNEP) published a report detailing the social, economic, and environmental impacts of environmental contamination caused by hydrocarbon exploration in the Niger Delta. The report highlighted severe impacts, including widespread contamination of drinking water sources with hydrocarbons, significant degradation of ecosystems and biodiversity, disruption of livelihoods due to the pollution of farmland and fisheries, and serious health risks to local communities due to prolonged exposure to polluted air, water, and soil. In 2016, the Government inaugurated the Hydrocarbon Pollution Remediation Project (HYPREP) to implement the recommendations of the UNEP report and remediate soil and water contamination in sections of the Niger Delta region (Sam et al., 2022; Duum, 2019). However, an assessment of sites remediated by HYPREP indicated elevated levels of contaminants, exceeding the Tier 1 criteria outlined in the Environmental Guideline and Standards for the Petroleum Industry in Nigeria (EGASPIN) (Sam et al., 2022; DPR, 2018). This indicates a number of factors including 1) weakness of existing policies (Sam et al., 2017; Rim-Rukeh, 2015), 2) implementation of inappropriate remediation technologies (Sam, 2023; Sam et al., 2023), limited monitoring and enforcement (Sam et al., 2015), and lack of involvement by relevant stakeholders in the area (Zabbey et al., 2021), as a result, remediated and certified sites continue to pose an unacceptable risk to local communities.

With limited monitoring of potential petroleum hydrocarbon-releasing activities, the number of oil spills that contaminate environmental media continues to increase. For example, according to data retrieved from the National Oil Spill Detection and Response Agency (NOSDRA) website, 993 oil spill incidents were recorded between 2019 to 2021, with 2895 tonnes spilt on land and swampy regions (NOSDRA, 2022). While this data is considered conservative as many oil spills remain unreported, there is also no report of remediation undertaken.

There are two major environmental projects ongoing in Nigeria. First is the remediation work undertaken by HYPREP commissioned by the Nigerian Government as part of the response to the UNEP report. This remediation is undertaken in Ogoniland and is estimated to take between 20 to 30 years to achieve ecological restoration in the area. The second environmental remediation project is the Bodo Creek remediation project undertaken by the Shell Petroleum Development Company of Nigeria as part of an out-of-court settlement in the Bodo Vs SPDC case of 2013. Evidence exists that both projects adopt the bioremediation strategy (Gbarakoro and Bello, 2022; Sam et al., 2022). For example, it is reported that remediated and certified sites undertaken by HYPREP contain elevated concentrations of contaminants and continue to present unacceptable risks to the local population (Sam et al., 2022). Similarly, the adoption of shoreline clean-up and assessment technique (SCAT) by the Bodo Creek remediation project seems not to have enhanced sound science in remediation decision-making. For example, many completed and verified remediated sediments contained between 15,000 mg/kg to 40,000 mg/kg of Total Petroleum Hydrocarbon (TPH), which is above the 50 mg/kg regulatory threshold established by the regulatory authority (Sam et al., 2022). Thus, existing remediation strategies adopted in the region are struggling with the reduction of contaminant levels and have yet to progress to explore low-carbon strategies.

Despite the inherent potential for bioremediation in the Niger Delta region, given its warm, wet, verdant environment, the success of remediation practices, including the use of recommended approaches such as stabilisation and solidification (Opete et al., 2010) and in-situ remediation by enhanced natural attenuation (Maduekwe et al., 2016; Chikere et al., 2017; Okparanma et al., 2017), these approaches have reportedly been unsuccessful due to a range of factors including governance, limited technical capacity of stakeholders, ad-

hoc monitoring of remediation projects, weak regulations, limited sustainability considerations, lack of infrastructure and uncertainties in the risk assessment process (Sam, 2023; Roy et al., 2018; Zabbey et al., 2017; Sam et al., 2015; 2023).

Although several researches have been undertaken in the Niger Delta region exploring remediation technologies, however, there is yet to be developed a framework that deeply considers opportunities for achieving multiple goals including effective remediation and limited greenhouse gas emissions, while returning net social and economic benefit to local communities.

Despite the Niger Delta's natural suitability for bioremediation, given its warm, wet, and verdant conditions that expose microbes to crude oil naturally, efforts to optimise remediation practices face numerous challenges. These include but are not limited to, the limited technical capacity of stakeholders, ad hoc monitoring of remediation projects, weak regulations, limited sustainability considerations, a lack of infrastructure, and uncertainties in the risk assessment process (Sam, 2023; Roy et al., 2018; Zabbey et al., 2017; Sam et al., 2015; 2023). Despite several research initiatives exploring remediation technologies in the Niger Delta region, a framework that deeply considers opportunities for effective remediation, limited greenhouse gas emissions, and net social and economic benefits to local communities has yet to be fully developed. This article seeks to provide deeper insights into the challenges of implementing effective remediation technologies that meet sustainability indices, integrate emissions considerations, and return net environmental benefits to local communities in the Niger Delta of Nigeria.

2.2 Overview of remediation approaches in the Niger Delta region

2.2.1 The Niger Delta Context

The Niger Delta has a landmass of approximately 70,000 km², with a population of 45 million people, living in scattered settlements (Chris et al., 2023). This region on Nigeria's coast lies between latitudes 4 and 6 degrees north of the Equator and longitudes 5 and 7 degrees east of Greenwich. Most of the oil-producing communities in the region are located on or near fresh or salt water, making this a very wet region. The type of soil found in the Niger Delta region is a blend of sand and clay (mostly Oxisols) (USDA, 2005). The Niger Delta region has been described as a biodiversity hotspot of global significance, with

its mangroves providing carbon sequestration capacity, and sustaining a diverse range of fauna and flora (Ansah et al., 2022). The Niger Delta region is Africa's most significant wetland and the third largest in the world. The ecosystem is classified as barrier islands, freshwater swamps, estuary mangroves, lowland rainforests, and streams, according to Izah et al. (2017). However, a decline in biological diversity caused by overexploitation, urbanisation/industrialisation, deforestation/habitat destruction, bush burning, soil erosion, crude oil pollution, climate change, and local factors (e.g., bunkering and crude oil pipeline vandalism) has been reported over the years (Numbere, 2018; Ibimilua, 2013).

Among the factors contributing to the biodiversity loss in the Niger Delta, oil exploration is one of the most significant. Oil exploration in Nigeria, primarily situated in the Niger Delta, has resulted in the country becoming one of the world's largest oil producers. The initial discovery of oil seepages in Araromi, which is now part of Ondo State, set off a wave of oil exploration efforts, climaxing in the discovery of petroleum in Oloibiri, Bayelsa State, in 1956 (Udosen et al., 2009). Today, Nigeria stands as the largest oil producer in Africa and the sixth largest in the Organization of Petroleum Exporting Countries (OPEC) (Ugochukwu and Ertel, 2008). However, this economic advantage has come at an environmental cost as a result of oil spill incidences. For example, oil-related accidents such as well "blow-outs", pipeline vandalism, oil theft, bunkering activities, and subsequent spills have resulted in extensive soil and water contamination, predominantly in the Niger Delta region. These spills have led to noticeable declines in local vegetation and fauna mortality in the affected water bodies. There have been instances of fire hazards in some areas, and recurring pollution of already contaminated soils, including contamination of the water table (Bayode et al., 2011).

Further exacerbating this is the disposal of drilling mud, oil-based mud, and drill cuttings in areas of oil exploration and exploitation, adding to the severe soil and water contamination. This contamination significantly impacts the ecosystem, most notably the local communities, which rely on these resources for survival. The ensuing health hazards, agricultural damage, degradation of water sources, and destruction of mangrove forests underscore the urgent need for environmental remediation in the region. These remediation efforts are crucial not only for the restoration of the ecosystem but also to improve the quality of life and economic opportunities for the region's inhabitants.

Therefore, the extensive environmental degradation resulting from oil exploration in the Niger Delta underscores the need for comprehensive and effective remediation strategies.

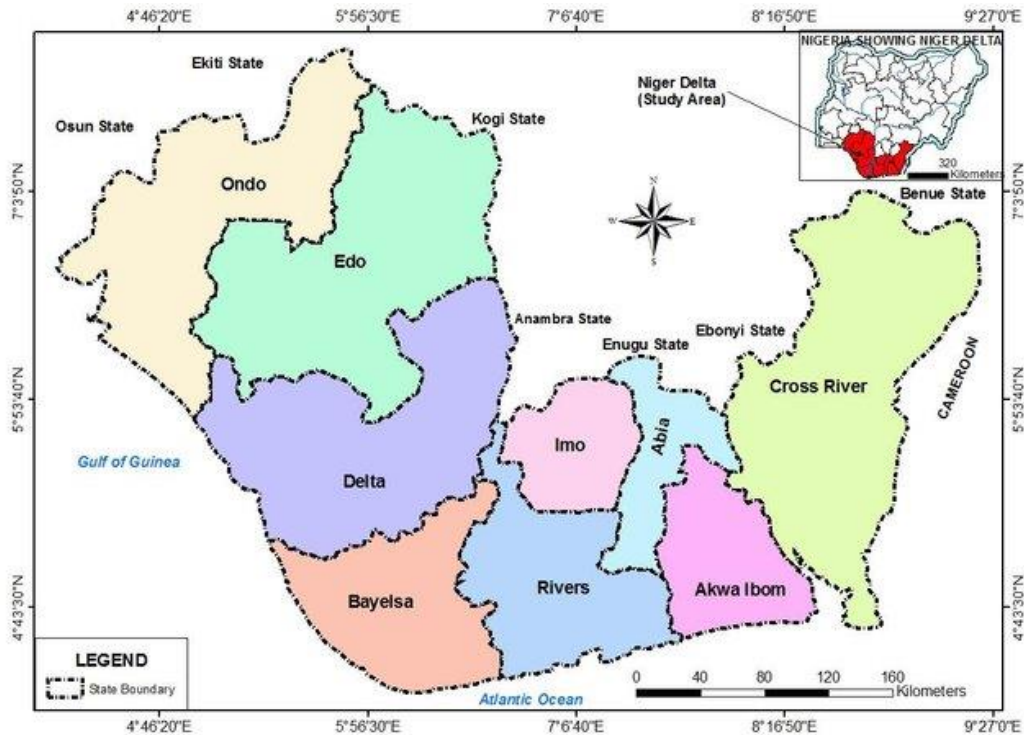


Figure 2. 1 Map of Niger Delta showing states (Oweikeye, 2017)

2.2.2 Sustainability and Resilience in Environmental Remediation

The Niger Delta, a crucial ecological region depicted in Figure 2.1, is characterised by its extensive wetlands and rich biodiversity. The map highlights the states within the Niger Delta—ranging from Ondo to Akwa Ibom and extending to the fringes of the Atlantic Ocean—outlining the areas that have been substantially affected by pollution, predominantly from oil spills. The map delineates the geographical extent of the Niger Delta, providing context for its role as a hub for Nigeria's oil and gas industries and highlighting the significant economic activities related to crude oil production in the region.

An in-depth understanding of sustainability and resilience is key to developing remediation strategies that effectively address the unique environmental challenges in the Niger Delta. These principles shape the approach to ensuring that remediation efforts not only address immediate environmental issues but also consider long-term ecological health and

community resilience against ongoing and future impacts (Fatoba et al. 2011). Sustainability, at its core, is about meeting the needs of the present without compromising the ability of future generations to meet their own need (Kuhlman and Farrington, 2010). This concept includes three fundamental pillars: economic, environmental, and social, often called the 'Triple Bottom Line.' In the context of the Niger Delta, economic sustainability implies that the region's natural resources, such as oil, should be managed and utilised in a manner that ensures long-term economic viability (Onwuka, 2005). This involves establishing sustainable livelihoods, minimising economic disparities, and ensuring the equitable sharing of benefits from resource extraction among its inhabitants. Furthermore, environmental sustainability pertains to the protection of the Delta's vast biodiversity, wetlands, and ecosystems. The emphasis here is on the remediation of polluted lands, guaranteeing clean water and air, and mitigating the adverse impacts of activities like oil spills on the environment (Ogeleka et al. 2016). On the other hand, social sustainability revolves around enhancing the quality of life for the region's inhabitants. It encompasses upholding human rights, championing social justice and equity, ensuring community engagement in decision-making processes, and forging conditions for stable, safe, and just societies (Deinne and Ajayi, 2019). In contrast, resilience refers to the capacity of a system, community, or society to withstand and recover from disturbances, such as environmental disasters or economic challenges (Donkor, 2020). In the context of the Niger Delta, resilience could involve strategies enabling communities to recover from oil spills and adapt to changing environmental and economic landscapes (Isidiho et al. 2023). The application of these concepts in the Niger Delta involves developing strategies that not only foster environmental health but also support the social and economic stability of the region, enabling it to navigate and thrive amidst various challenges, including recurrent oil spills. Having established the importance of sustainability and resilience in environmental efforts, it's essential to delve into the specific remediation techniques applied in Nigeria, a region facing significant environmental challenges.

2.2.3 Remediation of contaminated sites in Nigeria

Several sites including water and soil contamination have been reported in Nigeria (UNEP, 2011). A key factor exacerbating these issues is the prevalence of illegal refining activities in the region. These unregulated activities not only add to the severity of the contamination

but also introduce new contaminants, thereby significantly complicating the remediation processes. Many of these sites are reportedly remediated using different remediation technologies including bioremediation, and chemical and physical methods (Sam et al., 2017; Koshlaf and Ball, 2017). Bioremediation largely depends on the soil's ability to determine and sustain conditions that support a sufficiently high level of biodegradation of contaminants (Guarino et al., 2017). Various bioremediation strategies have been adopted, even on a large scale, to degrade petroleum hydrocarbon via in-situ or ex-situ methods (Rumaila, 2020). However, Rylott and Bruce (2020) propose that multi-disciplinary approaches should be implemented to overcome limitations in bioremediation, accompanied by a better understanding of how microbial communities cooperate metabolically.

Bioremediation is the primary remediation approach used in the region as it is seen as environmentally friendly (Zabbey et al., 2017). As a result, different bioremediation approaches including bioaugmentation, bio-stimulation, remediation by enhanced natural attenuation (RENA) and use of biosurfactants have been reported (Abdulsalam et al., 2011; Chikere et al., 2017; Onuoha et al., 2020). For example, RENA, a remediation method where natural processes are enhanced to work at a faster rate to clean up contamination, and sometimes it can encompass techniques like landfarming, is commonly used to reclaim lands contaminated by TPH. However, there are indications that it might be limited in remediating soils where contamination is not beyond 1 m (Maduekwe et al., 2016; UNEP, 2011; Zabbey et al., 2017), thus it is ineffective in treating contaminants at depths beyond 1 m, as found in many legacy sites in the Niger Delta region of Nigeria (UNEP, 2011; Sam et al., 2017).

Bioremediation techniques in Nigeria vary significantly, each offering distinct advantages and facing unique challenges. These differences are crucial in determining the most appropriate method for specific types of contamination and environmental conditions prevalent in the region, as detailed in Table 2.1. Also, these different approaches require different manipulations (e.g., available nutrients and oxygen) and control to achieve desired remediation outcomes (Table 2.2). The availability of nutrients and oxygen in the soil primarily determines the rate of microbial degradation of hydrocarbons, a critical aspect in bioremediation processes (Uloaku et al., 2022). Exploring further into the specific methods used in bioremediation, it's crucial to understand their distinct properties and effectiveness. For a comprehensive overview of these agents, refer to Table 2.2. To

enhance degradation, studies have demonstrated that the addition of nutrients, such as fertilisers, can decrease TPH levels in the soil (Remelli et al., 2020; Solomon et al., 2018), indicating the potential of indigenous microorganisms to break down biodegradable contaminants. Onifade and Abubakar (2007) found that nutrient addition can reduce TPH concentration in soil by enhancing the activities of indigenous microorganisms. Similarly, Okparanma et al. (2017) utilised fertilizer applications and windrows to provide nutrients and oxygen, respectively, accelerating oil spill degradation. However, the cost of acquiring large quantities of fertilizer poses a significant challenge in implementing these techniques.

Other studies have focused on the degradation abilities of different strains of bacteria and their potential for detoxifying contaminated soils (Uloaku et al., 2022). For example, Barathi and Vasudevan (2003) showed that using *Pseudomonas fluorescens* for remediation of crude oil-contaminated soil resulted in a higher rate of alkane degradation than unamended soil. In addition, Nnabuife et al. (2022) found that using different consortia of *Pseudomonas aeruginosa* strains to remediate crude oil-polluted soil could be effective. Notably, the effectiveness of hydrocarbon degradation can be improved when these consortia are developed from isolates obtained from the same polluted site. Successful degradation depends on the microbes' suitability to the compound they are trying to degrade, and a combination of different microbes may be necessary to account for the specific characteristics of the environment and the contaminants being targeted. Fungi have also been studied for their ability to degrade hydrocarbons, and their application in bioremediation indicated their ability to generate substantial biomass and quickly proliferate (Wu et al., 2011; Potin et al., 2004). Anderson et al. (2003) investigated the potential of wood-rotting fungi, *Pleurotus ostreatus* and *Antrodia vaillantii*, for the bioremediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs), and both fungi significantly accelerated the degradation rate of the PAHs. However, real-world application of fungi for bioremediation may take longer and require higher dosages than expected.

Various biowastes in the Niger Delta region have not yet been explored for their potential use in the bioremediation of land contamination. For instance, Onuoha et al. (2020) used coconut husk and pineapple peels to degrade hydrocarbon-contaminated soil. The pineapple peels supplied nutrients that stimulated microbial growth, while the coconut husk char acted as a bulking agent, improving the soil's ability to retain these nutrients, and

thereby enhancing microbial activity for the degradation of hydrocarbons. The study indicated that the biowastes streams introduced had no toxic effects on soil microbial activity and had a stabilising and microbe-stimulating property due to their nutrient content. Nwankwo (2014) found that compost from a feedstock mixture of food and green wastes could degrade crude oil-contaminated soil. This is an indication that compost made from waste streams in the Niger Delta could be used to remediate contaminated soil in the region, helping to preserve the environment and reduce the need for chemical treatment of contaminated soil with mineral fertilisers.

Bioremediation strategies should be informed by risk assessment, which may require reassessing human health and ecological soil screening levels as well as revising remedial intervention and target values. In some cases, a single remedial approach may be feasible for specific sites; however, while long-chain hydrocarbons may not be easily degraded, it's important to note that their lower solubility and volatility often reduce their associated risk (Brown et al., 2017). Nonetheless, site conditions may require a combination of methods, such as the introduction and combination of bacterial cultures with the chosen remediation strategy, to enhance the degradation of a broader range of contaminants (Bala et al., 2022; Xiang et al., 2022). Having explored the various bioremediation techniques and their applicability in Nigeria, it becomes imperative to investigate the methods of assessing the extent of contamination. A rigorous assessment is crucial not only for determining the scale of pollution but also for guiding the selection of the most appropriate remediation strategy.

2.2.4 Analytical Methods for Contaminant Assessment in Remediation

Understanding the nature and extent of contamination is the foundation of effective remediation. Over the years, various extraction methods have been developed to assess and analyse soil properties, contaminants, the environmental effects of contamination, and the detailed examination of microbial community structure. This detailed examination involves analysing the composition and interactions of different microbial species in the soil, which is crucial for understanding the biodegradation processes in contaminated sites. One key extraction method focuses on the extraction of total petroleum hydrocarbons (TPHs) from soil, shedding light on the degree and character of petroleum contamination (Risdon et al., 2008; Cipullo et al., 2019). On a parallel note, phospholipid fatty acid (PLFA) analysis stands as a trusted technique for discerning microbial

community structures in diverse environments (Frostegård et al., 1993). Since PLFAs are integral to microbial cell membranes, their profiles can vary based on the species present and their metabolic functions. From such analysis, one can assess the biodegradation capacity of a given contaminated site.

In assessing the efficacy of bioremediation, it is important to employ different methods that collectively provide evidence of microbial degradation and the reduction of hydrocarbon concentration and toxicity. One such method involves hydrocarbon extraction, a process where soil samples from the contaminated site undergo solvent extraction to isolate hydrocarbons. This is followed by characterising these hydrocarbons using gas chromatography-mass spectrometry (GC-MS), which helps in identifying specific hydrocarbons and determining their concentrations. In conjunction with hydrocarbon extraction, phospholipid fatty acid (PLFA) analysis is utilised to analyse microbial community structures. The diversity and composition of these microbial communities can indicate the level of biodegradation occurring in the soil. By integrating the results from both hydrocarbon extraction and PLFA analysis, a comprehensive understanding of both the chemical and biological aspects of the remediation process is achieved, offering insights into the extent of degradation and the reduction of toxicity.

However, determining the concentrations of hydrocarbons represents only one aspect of a broader analysis. Equally important is the assessment of their potential toxic effects. This necessitates the use of toxicity assays, which involve evaluating the adverse impacts of contaminants on various biological organisms, such as luminescent bacteria and seeds in the germination phase. Through these assays, a clearer understanding of the risks posed by these contaminants to both ecological systems and human health can be obtained. Integrating PLFA analysis, hydrocarbon extraction, and toxicity assays provides a comprehensive assessment of the level of contamination, characteristics of hydrocarbons, and associated risks. Such thorough investigations are fundamental for making informed decisions about remediation and ensuring environmental protection. Having explored the complexities of remediation, it becomes imperative to advocate for environmentally sustainable solutions to oil contamination. Given the critical need to reduce carbon emissions, there is an increasing emphasis on low-carbon remediation approaches. Nigeria, with its diverse environmental, economic, and social contexts, provides a significant case study for these efforts. Building on this foundation, this thesis will further

explore low-carbon remediation techniques, with a specific emphasis on the Nigerian landscape.

Table 2. 1 Biological remediation strategies and their respective challenges

Remediation Technique	Drawbacks	Region Applied	Ways to better manage the technique	References
Biostimulation	<ul style="list-style-type: none"> Misuse or overuse of fertiliser composition, leading to unbalanced nutrient provision for microbial activity. Limited access to large quantities of fertiliser due to cost Environmental factors (pH, temperature, emissions, etc.) control its potentiality as factors cannot easily be controlled 	<ul style="list-style-type: none"> India, South Africa, Nigeria, UK 	<ul style="list-style-type: none"> Recognise that the theoretical C:N:P ratio of 100:10:1 may not always be effective in large-scale remediation due to site-specific conditions such as soil type, pollutant composition, and existing microbial communities. Excessive or insufficient application can limit the degradation process. Nutrient limitation assessment should be carried out to supplement the specific nutrient needed in the right quantity/ratio to save time, resources, and cost. Access to large quantities of fertiliser is not readily available to remediation contractors in the Niger Delta region due to high costs. Varieties of bio-wastes (coconut husk char, pineapple peels etc., could be used as alternate nutrient sources but in combination with available and appropriate fertilisers, as they are cost-effective and readily available in the region. The soil pH levels necessary for effective degradation can be sustained by preparing environmentally friendly additives like potassium phosphate, ammonia sulphate and citric acid to overcome any pH shifts. For controlling evaporation and maintaining soil humidity and temperature, a semi-permeable cover could be considered, which can reduce moisture loss while allowing for oxygen exchange. Regular aeration or bioventing could be paired with the cover, if necessary, to maintain optimal oxygen levels. These covers can also act as a shield to prevent excess water infiltration and reduce soil erosion from rainfall in the region. 	<p>Coulon et al. (2012) Wang et al. (2012) Sarkar et al. (2016) Chikere, (2012); Orji et al. (2012); Atagana, (2008) Adesodun and Mbagwu, (2008)</p>
Bioaugmentation	<ul style="list-style-type: none"> A single strain of bacteria cannot metabolise every kind of waste. Lack of standard level of inoculation Suboptimal application of available resources due to lack of information on the most efficient inoculation requirement. Lack of soil tests to evaluate the availability of hydrocarbon-utilising microbes. 	<ul style="list-style-type: none"> China, Australia, Nigeria, Malaysia, Brazil 	<ul style="list-style-type: none"> Using a combination of different bacteria strains and fungi or a consortium of strains from the same contaminated soils can enhance degradation. These consortia, due to their co-evolution with the pollutants, are better adapted and capable of degrading a wider range of contaminants. Genetically modified organisms GMOs can be combined with bioaugmentation to boost hydrocarbon degradation. Leveraging established bio-inoculation methods from agriculture, this technique could be employed to introduce these microbial consortia into the contaminated soil matrix. No particular technical issues are anticipated in this approach Assessment of inoculum size specific to pollution size is needed as inoculum sizes applied to soils vary widely. A database specifies the optimum inoculum size for the polluted landmass area needs to be adopted. Proper multivariate techno-economic analysis to aid in the development of a process or tool for optimal inoculation strategy selection. 	<p>Bhattacharya et al. (2002) Tyagi et al. (2011) Phale et al., (2019) Wu et al. (2012) Lee et al. (2011) Firmino et al. (2015); Chen et al. (2013) Adesodun and Mbagwu, (2008); Fan et al. (2014)</p>

Bioventilation	<ul style="list-style-type: none"> A high flow rate of air may lead to the transfer of volatile organic compounds (VOCs) to the vapour phase. The challenge of maintaining optimal oxygen levels for effective bioremediation. 	<ul style="list-style-type: none"> USA, Mexico, Estonia, Nigeria, China, Taiwan 	<ul style="list-style-type: none"> An integrated method of bioventing with bio-trickling filter technologies can be adopted to manage the risk of VOC. Oxygen release compounds (ORC), though not traditionally associated with bioventing, could theoretically be employed to help maintain optimal oxygen levels for microbial activity. However, this application is innovative and would necessitate further validation through research. 	<p>Hahn, (1997) Azubuike et al. (2016) Kunukcu, (2007).); Landmeyer et al. (2001) Rojas-Avelizapa et al. (2005) Goi et al. (2011)</p>
Remediation by enhanced natural attenuation (RENA)	<ul style="list-style-type: none"> Not effective at depths below 1 m No control over infiltration and runoff from the heavy rain Requires access to large quantities of fertiliser due to cost. RENA application to improve nutrient availability achieves about 40% remediation for fresh and residual hydrocarbon pollutants as increased toxicity of metabolites hinders usable growth of oil-degradable organisms. Not efficient for recalcitrant and legacy contaminants 	<ul style="list-style-type: none"> Nigeria 	<ul style="list-style-type: none"> An ex-situ form of RENA can be adopted where leachate collection systems and high-density polyethene membranes can be introduced before clean-up starts. A variety of bio-wastes can be introduced to complement or supplement inadequate fertiliser quantities. The soil conditions preceding remediation must be known to incorporate the correct use of nutrient composition. An investigation to assess the presence of optimum microbial community is critical to the success of this approach 	<p>Orji et al. (2012) Okparanma et al. (2017)</p>
Land farming	<ul style="list-style-type: none"> The technique requires a large amount of land. Heavier components of petroleum are not efficiently degraded. Contaminant transfer from the treatment plant to a previously undisturbed site is possible, together with potential leaching. May be ineffective for high constituent concentrations (> 50,000 mg/kg) 	<ul style="list-style-type: none"> Nigeria 	<ul style="list-style-type: none"> Biotreatability studies can include special studies to evaluate out-of-range parameters. For high chemical concentrations, soil blending could be considered to mix high and low concentrations prior to treatment. If leaching becomes a concern, one may consider treating the basement soil after the treatment is complete, providing a more sustainable alternative to using a bottom liner. A possible solution may include combining the technique with other low-carbon technologies to address more significant TPH concentrations. 	<p>Brown et al. (2017)</p>

Table 2. 2 Conditions that maximise bioremediation strategies

Remediation strategy	Summary	Conditions that maximise the result	Reference
In situ	<ul style="list-style-type: none"> • This strategy takes place in the subsurface of the soil or groundwater and applies biological treatments to clean up toxic compounds in the environment. • Microbial processes with organic contaminants are typically regulated and optimised in the convergence of numerous scientific and engineering disciplines. • Examples include biosparging, bioventing, bioaugmentation, phytoremediation etc 	<ul style="list-style-type: none"> • Microorganisms' ability in the media to break down pollutants into non-toxic forms depends on their availability of nutrients, electron donors, and acceptors. • The two widely used nutrients for microbial growth are nitrogen and phosphorus, generally supplemented as ammonia and orthophosphate. • As an electron acceptor, oxygen is the most common type used, and organic pollutants are converted to CO₂, water, and microbial mass under aerobic conditions. • Some microorganisms use alternative acceptors of electrons such as manganese, nitrate, iron, carbon dioxide, sulfate, and iron in the absence of oxygen. • For phytoremediation, the choice of plant species and the types of microorganisms present significantly influence the success of the treatment process. 	Das and Dash, (2014); Megharaj et al., (2014) Tang and Angela, (2019)
Ex situ	<ul style="list-style-type: none"> • The techniques involve treating contaminated soils away from the contaminated site. • Ex-situ bioremediation can be carried out in two ways: bioremediation of the solid phase and bioremediation of the slurry phase. • These strategies are also highly economical, easy to monitor, fast, and can handle a wide range of pollutants. • Examples include land farming, windrow, composting, bioreactor, and notably biopiles, which have shown effectiveness in field-scale biodegradation of total petroleum hydrocarbons and soil restoration 	<ul style="list-style-type: none"> • Contamination breakdown and treatment are done above ground using the indigenous microbial population. • Oxygen is an integral part of this process because it is essential for the growth of petroleum-degrading bacteria, so it is also much more important to use the excavation methods. • Conditions are controlled to assist microbial degradation of contaminants by monitoring temperature, pH, mixing rate, and nutrient levels. • Recent advancements in biopiles include functionalizing biochar with hydrocarbon oxidising microorganisms, to further enhance their potential. 	Kuppusamy et al. (2016) Gomes et al. (2013) Martinwz-Cuesta et al.(2023), Alkaabi et al. (2023), Bolan et al. (2023)

2.3. Implementation of low-carbon remediation strategies: An overview with a focus on Nigeria

Low-carbon technologies are strategies that aim to reduce greenhouse gas emissions (GHG), particularly carbon dioxide, into the atmosphere and energy consumption during the remediation process (Yuan et al., 2011). Implementing low-carbon remediation strategies can clean up contaminated sites, improve the health and well-being of people living in affected areas, and promote sustainable development by utilising natural processes and environmentally friendly technologies (Pavel and Gavrilescu, 2008).

However, it is essential to clarify that not all remediation techniques can be readily adapted to a low-carbon approach. Physical remediation techniques like excavation, dredging, or soil washing often require heavy machinery and transport. These requirements can result in high fuel consumption and GHG emissions (Amponsah et al., 2018). Likewise, many chemical remediation methods involve energy-intensive processes, such as heating or the generation of reactive chemicals. These processes lead to considerable carbon emissions (Gabrielli et al., 2020). Consequently, despite their effectiveness in certain scenarios, these methods' inherent characteristics may not align with the objectives of a low-carbon remediation strategy (Campiglio, 2016).

Considering this, the low-carbon approach to bioremediation has emerged as an appealing strategy. This method capitalises on naturally occurring or introduced microorganisms to degrade or transform pollutants. At the same time, it leverages renewable energy sources to provide necessary nutrients and conditions. The approach prioritises energy-efficient processes and environmentally friendly practices to minimise the environmental impact relative to traditional remediation methods (Sharma, 2021). However, its effectiveness may be influenced by various factors. These include low temperatures, low oxygen levels, and high acidity or salinity, as well as contaminant type and concentration, nutrient and electron acceptor availability, and microbial community composition (Azubuike et al., 2016).

Despite these challenges, a range of innovative low-carbon remediation technologies have been developed. These technologies capitalise on the principles described above. They include:

1. **Bioremediation:** The use of naturally occurring microorganisms or leveraging renewable energy sources to provide necessary nutrients and enabling conditions to support the biodegradation of contaminants. Given the minimal use of natural resources, the little or no impacts on the environment and/or greenhouse gas emissions, bioremediation is considered a prominent low-carbon strategy. Recent advancements in metagenomic analysis have elucidated specific microbial metabolic pathways involved in pollutant degradation, fostering the development of targeted bioremediation strategies (Offiong et al., 2023). For instance, newly discovered microbial capabilities to remediate emerging contaminants such as microplastics and fluoroalkyl substances (PFAS) have expanded the applicability of bioremediation (Mayakaduwa et al., 2022). Innovations in bioaugmentation, i.e., the introduction of pollutant-degrading bacteria, have significantly expedited biodegradation processes, expanding their effectiveness across diverse settings such as brownfields, industrial sites, and agricultural areas (Muter, 2023). Additionally, biostimulation techniques have evolved with the incorporation of sustainable, slow-release nutrient sources like biochar, enhancing the longevity and effectiveness of bioremediation interventions (Sim et al., 2021). These cutting-edge developments have mitigated certain traditional limitations of bioremediation related to site-specific conditions and variability in microbial community composition. Nevertheless, a successful application still requires careful consideration of factors like contaminant type, concentration, and nutrient and electron acceptor availability. While the advantages of bioremediation, such as lower costs, reduced system maintenance, and minimal environmental disruption, remain pivotal, it's the infusion of these novel techniques that has reinvented the field, making it more efficient and adaptable to various contamination scenarios.
2. **Phytoremediation:** This ecologically sustainable method relies on natural plant processes and requires minimal energy inputs for remediating contaminants in

soil and water systems (Bolan et al., 2011). Innovative research has highlighted the efficacy of specific plant species and genetically engineered plants in remediating diverse contaminants through unique metabolic pathways (Fasani et al., 2018). The use of genetic engineering has notably broadened the scope of contaminants that can be treated, accelerating the remediation process (Yan et al., 2020). Recent studies also indicate that mycorrhizal fungi, which form symbiotic relationships with plants, enhance phytoremediation's effectiveness by boosting nutrient and contaminant uptake (Ma et al., 2022). Innovative techniques like combining phytoremediation with biochar application have also been explored, which help improve soil conditions and augment contaminant removal (Zhang et al., 2019). Despite a longer implementation period, phytoremediation provides long-term site improvement and contributes to habitat restoration and carbon sequestration, particularly when using native or perennial plants. Therefore, it's especially suitable for sites unfit for more invasive remediation or where residual contamination persists post other remediation methods (Vangronsveld et al., 2009).

3. In situ chemical oxidation: In situ chemical oxidation (ISCO) uses oxidants such as hydrogen peroxide, sodium persulfate, and potassium permanganate to degrade contaminants in situ, reducing the need for energy-intensive transport and excavation (Chang et al., 2022; ITRC, 2005). Although ISCO may not inherently be a low-carbon method, it can be adapted to low-carbon implementations, particularly when using hydrogen peroxide, which requires minimal energy inputs. ISCO could also be part of a remediation treatment train for effectively remediating certain contaminants. Recent advancements have included the development of novel, green oxidants derived from natural substances or produced through eco-friendly processes. These biodegradable, non-toxic oxidants are capable of efficiently degrading a wide range of pollutants (McBeath and Graham, 2021). Moreover, modern ISCO methods have explored the use of catalysts to enhance the reactivity of the oxidants, leading to more efficient remediation (Kurakalva, 2022). Another potential enhancement for ISCO is the use of biosurfactants which have shown promise in increasing the dispersion and delivery of oxidants in the treatment area. The integration of biosurfactants not only enhances the effectiveness of ISCO but also contributes to its sustainability by reducing the amount of oxidants needed for successful

remediation, making it a more efficient and sustainable method (Xu et al., 2021). However, ISCO's effectiveness may vary depending on the type of contaminant, choice of oxidant, and subsurface conditions, and it may face limitations in certain soil conditions (Derby, 2009).

4. Soil vapour extraction: Soil vapour extraction (SVE) is a remediation method commonly used for eliminating volatile organic compounds (VOCs) from the soil, with its effectiveness influenced by factors like contaminant nature, extent, and subsurface conditions (Shackelford, 2013; Sharma and Reddy, 2004). The low-carbon approach to SVE involves using renewable energy sources to power vacuums or adopting natural ventilation instead of mechanical extraction, making it a more sustainable option. However, certain conditions can limit the effectiveness of SVE, such as the presence of specific soil types like clay, which can impede airflow, if contaminants exhibit low volatility, or if extraction wells are inadequately positioned or designed. Given these challenges, there is potential for advancements in other fields to benefit SVE. For instance, development in fields such as building information modelling and artificial intelligence have led to the creation of sophisticated modelling and monitoring systems. These systems, which have improved efficiency and reduced errors in their respective applications, could potentially enhance remediation methods like SVE by guiding the optimal design and placement of extraction wells (Sacks et al., 2020)
5. Electrokinetic remediation: Electrokinetic remediation (EKR) utilises an electric field to extract contaminants from soil and groundwater, proving effective for heavy metals (Ferro et al., 2014), radioactive substances (Xiao et al., 2020), and organic pollutants (Ricart et al., 2008). The process, involving the installation of electrodes in soil and the creation of an electric field, enables the collection and removal of charged contaminants, especially in soils such as clays and silts (Wang et al., 2021). Recently, advancements in nanotechnology have led to the development of more efficient electrodes, which enhance the EKR process by generating stronger and more focused electric fields (Chen et al., 2021). Additionally, the use of chelating agents to improve the mobility of contaminants has been employed, thereby increasing the effectiveness of EKR (Ryu et al., 2017). A promising development for the future of EKR could be the integration of sensor technologies for real-time monitoring of the remediation process. Such systems could provide instant feedback on contaminant levels and the

effectiveness of the electric field, allowing for immediate adjustments and increased efficiency (Blotevogel et al., 2021). Using renewable energy sources like wind or solar power can provide a low-carbon option for powering EKR.

Low-carbon bioremediation has shown promise. It can help reduce greenhouse gas emissions, including CO₂ and methane, throughout the remediation process. Meanwhile, Qin et al. (2013) used rice straw biochar to degrade crude oil in the soil. They found that adding biochar considerably enhanced the degradation efficiency without negatively affecting soil microbial communities. Thus, low-carbon methods could enhance remediation decisions in the Niger Delta and safeguard public health and the environment. Table 2.4 provides examples of how low-carbon techniques can be integrated with bioremediation techniques for contaminant removal. However, the adoption of these strategies would require extensive research, considerable investment, robust regulatory frameworks, and harmonious implementation. Despite these difficulties, the implementation of low-carbon remediation strategies is critical to addressing environmental contaminations and fostering sustainability.

In the pursuit of addressing the impacts of oil pollution in the Niger Delta region, the role of remediation methods and their corresponding greenhouse gas (GHG) emissions cannot be overlooked. Historically, traditional remediation methods such as excavation and removal, pump-and-treat systems, or chemical treatments have been predominant in Nigeria. However, these methods often lead to high greenhouse gas emissions and can be inefficient in terms of time or overall environmental benefit. Moreover, a significant limitation of these traditional methods is their tendency to leave behind residual contamination, posing ongoing environmental and health risks. This residual contamination arises from the incomplete removal or destruction of pollutants and necessitates continued monitoring and potential further treatment. In contrast, more innovative approaches like landfarming, engineered biocells, RENA, stabilisation & solidification, phytoremediation, and bioremediation each offer unique ways to mitigate the effects of oil pollution with potentially lower environmental impacts and reduce the likelihood of residual contamination. These methods, through their utilisation of either naturally occurring processes or methodologies that are less disruptive to the environment, not only adhere to low-carbon initiatives but also contribute to enhancing the overall

effectiveness of remediation efforts, thereby addressing the limitations inherent in traditional techniques.

RENA harnesses natural processes to degrade contaminants over time, further accelerated by nutrient amendments. However, its dependency on natural processes can sometimes mean longer remediation periods, which might not be ideal for areas requiring immediate intervention (Okparanma et al., 2017; Orji et al., 2012). Landfarming involves the use of tilling to promote the biodegradation of contaminants in the soil. Its efficiency depends heavily on tilling frequency and there is a need for optimisation to minimise GHG emissions (Mmom and Deekor, 2010). Engineered biocells are specialised systems designed for ex-situ (on-site or off-site) bioremediation techniques. This technique involves the excavation of contaminated soil, typically from depths of 6m to 10m below the ground surface, and its subsequent treatment in a controlled environment. The treatment process in engineered biocells often involves systematic tilling and the application of microbial nutrient amendments to enhance the biodegradation of contaminants (Mmom and Igbuku, 2015). On the other hand, stabilisation & solidification involve mixing contaminants with a binding agent to prevent their spread, with a high potential for exploring lower carbon footprint materials and processes (Opete et al., 2010). Thermal Desorption uses heat to volatilize contaminants, thereby requiring advancements towards more energy-efficient technologies (Rim-Rukeh and Nwokoma, 2022). Phytoremediation makes use of plants to absorb, sequester, or metabolise pollutants, with ongoing research on plant species and management practices that optimise carbon sequestration (Izinyon and Seghosime, 2013; Tanee and Akonye, 2009). Lastly, bioremediation offers an innovative approach that leverages microorganisms to degrade pollutants. This method is not only more environmentally friendly, but can also be tailored to specific types of pollutants, making it more efficient (Nwankwo, 2014; Akpanke et al., 2019). In addition, it generally results in lower GHG emissions compared to traditional methods.

Table 2.3 offers a comprehensive overview of these methods, categorising them based on their GHG emission potential and identifying areas for potential improvements. This comparative analysis provides a roadmap for adopting more sustainable practices in the region, aiding in the selection and optimisation of remediation techniques. The methods range from those with lower emission

potentials, like remediation by enhanced natural attenuation (RENA) and engineered biocells, to ones with higher potentials, such as stabilisation & solidification and thermal desorption. By identifying areas for improvement, it will assist in the development of more sustainable and efficient remediation strategies that contribute to the overall goal of reducing GHG emissions.

Table 2. 3 Overview of Remediation Methods and Greenhouse Emission Potentials in Nigeria

Remediation method	Greenhouse emission potential	Potential Improvement	Implementation status	References
Remediation by enhanced natural attenuation (RENA)	Low-Moderate	Further research on the impact of nutrient amendments on GHG emissions	Implemented	Okparanma et al. (2017); Orji et al. (2012)
Landfarming	Moderate	Optimisation of tilling frequency and method to minimise GHG emissions	Implemented	Mmom and Deekor, (2010); Ausma, (2001)
Engineered biocell	Low-Moderate	Improved Biocell design to minimise GHG emissions	Implemented	Mmom and Igbuku, (2015)
Stabilisation & solidification	High	Exploration of lower carbon footprint materials and processes	Implemented	Opete et al. (2010)
Thermal Desorption	High	Development of more energy-efficient thermal desorption technologies	Implemented	Rim-Rukeh and Nwokoma, (2022)
Phytoremediation	Low	More research on plant species and management practices that can optimise carbon sequestration	Implemented	Izinyon and Seghosime, (2013); Tanee and Akonye, (2009)
Bioremediation	Low-medium	Further research to optimise bioremediation methods and minimise GHG emissions	Implemented	Nwankwo, (2014); Akpanke et al. (2019)

With advancements in bioremediation and its potential in the Niger Delta region, there are significant opportunities to improve its application. Various waste streams, such as bio-wastes/agro-wastes, compost, sewage sludge, biochar, and specific bacteria strains, fungi, or earthworms, have shown promise in enhancing biodegradation and reducing remediation time (Xiang et al., 2022). These cost-effective and highly degradable materials can help resolve pollution issues and restore soil quality (Nwankwo, 2014). When combined with slow-release oxygen compounds and crude oil-tolerant plants, these waste streams could offer promising research opportunities for improving the natural attenuation process and achieving successful remediation. These potential improvements are further elaborated in Table 3, which presents current remediation practices in Nigeria and their potential enhancements.

To provide a practical perspective to our theoretical considerations, Table 2.4 illustrates the application of various integrated low-carbon remediation technologies

through a series of case studies. These real-world examples offer insights into how different remediation methods perform under diverse conditions, underscoring the real-world implications of our research. Following this, we delve deeper into the examples of integrated low-carbon remediation technologies for contaminant removal in the subsequent table. This comprehensive analysis is pivotal as it substantiates our discussions with real-world applications and validations. The case studies not only demonstrate the effectiveness of these remediation methods in different contexts but also illuminate the factors potentially influencing their success. By analysing the performance of these techniques in practical settings, we can refine our theoretical understanding and predictions further. Such insights are essential for shaping future remediation strategies in the Niger Delta and beyond, potentially steering policy decisions, determining funding priorities, and guiding future research directions.

2.4. Development of sustainable remediation in Nigeria

Sustainable Remediation Forum (SuRF) was established to “promote sustainable practices during environmental clean-up activities to conserve natural resources, biodiversity, enhance the quality of life in surrounding communities, exchange professional knowledge and provide educational outreach” However, SuRF is viewed differently by different countries with distinct perspectives, priorities, and considerations. For instance, SuRF-Canada prioritizes the three dimensions of sustainability (social, economic, and environmental) when making decisions about contaminated site restoration and management. However, SuRF-UK advances the understanding of sustainable remediation. Thus, these aims and principles inform the development of approaches and contaminated land management strategies that engender and sustain environmental sustainability practices in these countries and distinguish the contaminated land management regimes (Table 2.5).

Nigeria can play a leading role in a sustainable remediation framework by applying the principles of SuRF and policies already in place to address soil contamination in the Niger Delta region. This could present a significant step towards achieving and mainstreaming sustainable remediation approaches in Nigeria and the African region. Achieving this would require a contextual framework developed to engender

and enhance environmental sustainability. The conceptual framework proposed in this research will facilitate the establishment of (SuRF-Nigeria) and advance the prioritisation of contextual challenges including biodiversity conservation, sustainable livelihoods, and habitat degradation caused by oil contamination. In all, sustainable remediation in Nigeria could be enhanced by elaborate stakeholder involvement, participatory decision-making (IUCN, 2013), and the adoption of treatment trains that return net benefits to the local population.

Table 2. 4 Examples of integrated low-carbon remediation technologies for contaminant removal

Contaminant	Time (days)	Treatment	Performance	Region	References
Pyrene (spiked soil)	30	Bioremediation: A mixture of compost and bulking agent	86-100%	Spain	Sayara et al. (2011)
TPH (contaminated soil)	182	Bioremediation: Mineral nutrient and gravel grass clippings mixed with sheep manure	96.7%	Canada	Mihial et al. (2006)
TPH (contaminated soil)	373	Bioremediation: Compost (kitchen waste) and a bulking agent (sand, shredded waste wood)	74% TPH removal and 97% PAH removal	Sweden	Kripalu et al. (2007)
Lubricating oil and diesel oil-contaminated soil	150	Bioremediation: Commercial fertiliser and soil/spruce bark	70% and 71% TPH removal	Finland	Jürgensen et al. (2000)
Crude oil-contaminated soil	1825	Phytoremediation: alfalfa (<i>Medicago sativa</i> L.), ryegrass (<i>Lolium perenne</i> L.)	72-90% removal	Russia	Panchenko et al. (2023)
TPH contaminated soil	180	Bioremediation: Urea, mineral nutrients, and soils/straw	94% TPH removal	Mexico	Rojas-Avelizapa et al. (2007)
TPH contaminated soil	150	Bioremediation: Mineral nutrients and soils/softwood sawdust/river sand	94% TPH removal	Serbia	Beškoski et al. (2011)
Bitumen contaminated soil	21	In situ chemical oxidation: NPK/Hydrogen peroxide/NPK and Hydrogen peroxide	60.8%, 52% and 60.4%	Nigeria	Agarry (2014)
Crude oil-contaminated soil	180	Phytoremediation: Acacia seiberiana Tausch	49-79% degradation	Sudan	Abdallah et al. (2022)
TPH, PAH and n-alkane (contaminated soil)	60	Bioremediation: Pseudomonas species, fertiliser, rice husk and ploughing	95% TPH, PAH, and n-alkenes,	China	Xu et al. (2016)
Diesel oil-contaminated soil	175	Bioremediation: Activated sludge, TPH-degrading bacteria and compost	83% TPH removal	Taiwan	Wang et al. (2016)
TPH contaminated soil	70	Bioremediation: Pseudomonas aeruginosa/Bacillus subtilis and NPK	75% TPH removal	Nigeria	Abdulsalam et al. (2011)
TPH contaminated soil	84	Bioremediation: Consortia isolated from contaminated soil/(NH ₄) SO ₂ /K ₂ HPO ₄	45% and 73% TPH removal	USA	Bento et al. (2005)
Benzene (in the presence of metal oxides, clays, and representative aquifer solids)	32	In situ chemical oxidation (persulfate with goethite, ferrihydrite, and pyrolusite)	12% (goethite), 65% (ferrihydrite), and 45% (pyrolusite) persulfate loss	USA	Liu et al. (2014)
Uranium contaminated soil	5	Electrokinetic remediation (electrolyte combined with ferric chloride)	The removal rate of uranium increased by 36-62%	China	Xiao et al. (2020)
BTEX, trichloroethylene and perchloroethylene soil	1300	Soil vapour extraction	73% VOC removal	Italy	Labianca et al. (2020)
TPH contaminated soil	60	Bioremediation: Petroleum degrading bacteria (PDB) with biochar	58% TPH removal	China	Zhang et al. (2019)

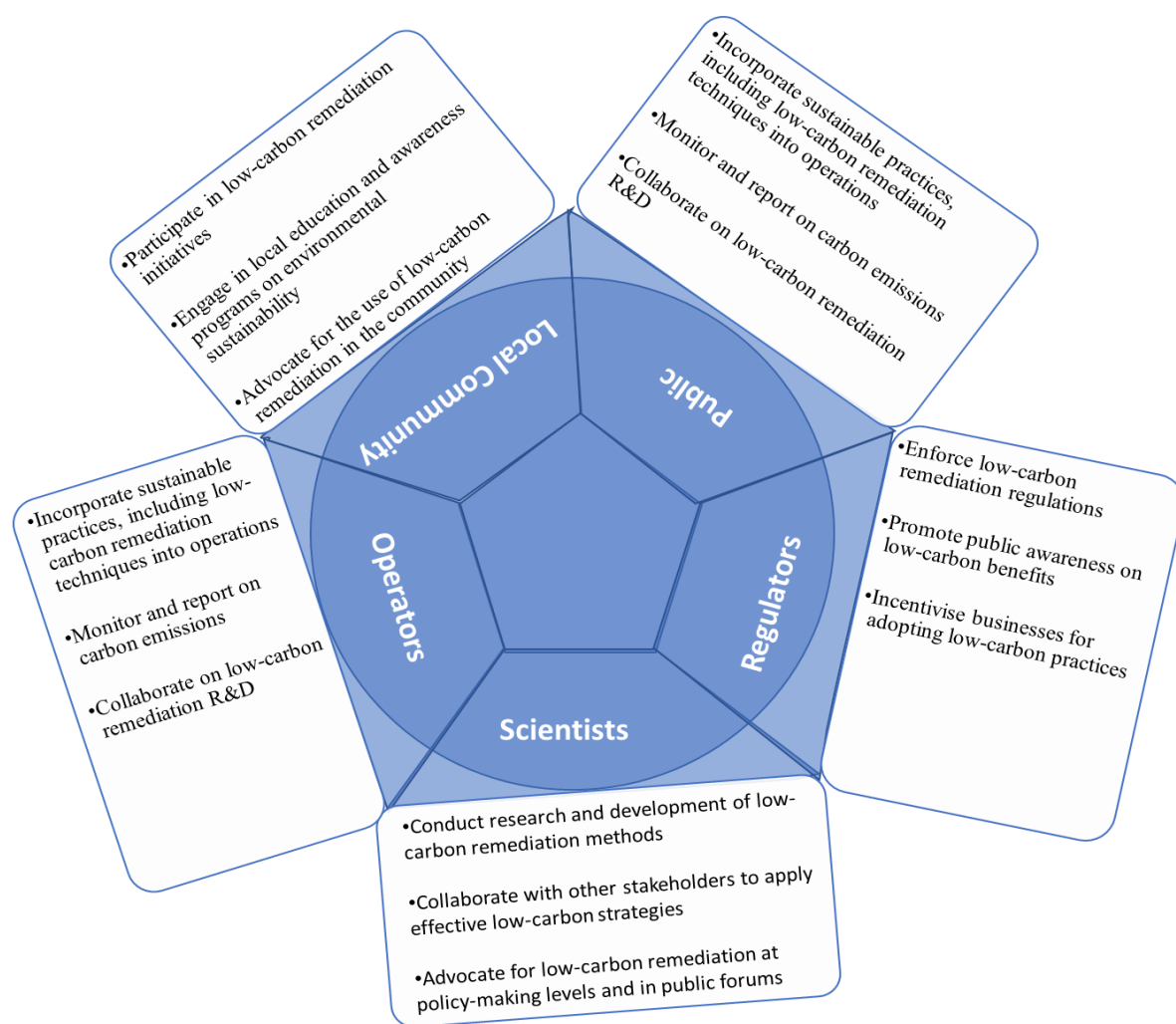


Figure 2. 2 Stakeholders' roles in promoting Low-carbon remediation practices

The journey towards sustainable remediation in the Niger Delta, as depicted in Figure 2.2, requires a multi-faceted approach involving various stakeholders. These stakeholders should focus on actions that promote low-carbon remediation in their respective roles. Regulators, entrusted with the legal and regulatory framework, must shoulder the responsibility of devising conservative criteria to manage health risks and establish feasible target values for different land uses and enforce low-carbon remediation regulations (Fergus and Ajay, 2020). The SuRF-Nigeria framework can guide this process, necessitating more accountability from the government to the citizens, particularly those impacted by oil and gas activities. Balancing environmental concerns, particularly the need for low-carbon remediation, is a challenge regulators face (Campiglio, 2016). They could use data-driven approaches and environmental impact assessments to make informed decisions about low-

carbon practices, leveraging revisions to laws regarding fines and taxes on oil and gas companies to further bolster these efforts (Meltzer et al., 2014).

Scientists play a key role in pushing the boundaries of low-carbon remediation through research and development of innovative techniques. For example, scientists have tried and tested different biowaste such as coconut husks and spent mushrooms, as bioremediation resources at the global and local levels (Onuoha et al., 2020). Scientists communicate and disseminate these innovative remediation resources and approaches, knowledge and skills through education and training, and by collaborating with other stakeholders, such as operators and regulators, on low-carbon remediation projects.

The local communities, bearing the brunt of oil and gas activities, play a pivotal role within the SuRF-Nigeria framework. They can participate more in low-carbon remediation initiatives, contributing valuable insights, and ensuring the remediation efforts align seamlessly with their needs and expectations (Olujobi et al., 2022). Their increased participation in remediation projects and stakeholder meetings can offer invaluable local insights, ensuring the remediation efforts align seamlessly with their needs and expectations.

The public, comprising citizens and organisations, has a critical role in demanding transparency and accountability from the government and advocating for sustainable remediation (Bello, 2022). Their active support for eco-friendly initiatives can bring about substantial change in the remediation landscape. Operators, on the other hand, should commit to respecting the revised laws and paying the necessary fines and taxes, thereby contributing to increased government revenue (Kennedy et al., 2021). Importantly, their adoption of low-carbon remediation techniques and active participation in capacity-building initiatives can significantly enhance the effectiveness of remediation efforts (Olujobi et al., 2022). Implementing new low-carbon practices might involve significant investments, which can be encouraged through government incentives and robust public-private partnerships (Meltzer et al., 2014).

If all stakeholders effectively play their roles, the Niger Delta could transition from an area marred by pollution to a region that balances oil and gas production with

environmental sustainability. This multi-stakeholder approach, underpinned by the principles of accountability, participation, transparency, and sustainability, is integral to achieving long-term, low-carbon, sustainable remediation in the Niger Delta region (Ellawule, 2021).

Table 2. 5 Major differences between developed and developing countries in some contexts of site management (Braun et al., 2020)

Themes	Developed Countries	Developing Countries
Management	Effective process for detecting contaminated areas.	Challenges exist in accurately identifying contaminated locations.
	Pre-remediation activities include risk assessment	Risk evaluations are only used in a limited number of remediation processes.
	Site remediation is a standard development procedure in the majority of these countries	The remediation of contaminated sites is primarily motivated by the requirements of public authority
	The "suitable for future use" principle is the standard for evaluating and remediating contaminated sites.	The absence of contaminated site database hinders not only the remediation process, but also the credibility and quality of decisions made at the conclusion of impact assessments and restoration projects.
	Remediation projects are often supported by robust data management systems that track and monitor the progress of site clean-up, providing transparency and accountability.	The traditional focus on "soil quality" restoration for contamination site remediation still prevails.
Regulation	Contaminated land is clearly defined	No clear description of contaminated land.
	Defined regulations exist for contaminated sites.	Absence of a clear policy framework that suits the developing countries' realities
	Policy framework is clear and applicable	Soil quality standards often rely on international guidelines which may not suit the specific needs of developing countries
	Soil quality standards are set based on scientific analysis.	Insufficient number of knowledgeable and experienced professionals in public positions.
	Presence of experienced professional in public positions aids in improving regulations, and inspecting contaminated sites.	In some cases, international regulations have an impact on local laws, which may not always be appropriate given the particular difficulties and circumstances of developing nations.
Competency	Contaminated site managers often undergo training	Periodic training and technical education for professionals is lacking
	There's emphasis on knowledge and information sharing. For example, regular training platforms are established for contaminated land management professionals in regions like the UK and the US	The absence of sufficient knowledge and technical capability to deploy an effective cleanup technology, given the extent of the contamination
	Public agencies are furnished with authorities' primary specialised technical authorities	There is shortage of specialised professionals accountable for polluted sites in public bodies across all tiers of government
Responsibility	In certain countries, it falls under the jurisdiction of local authorities to handle the impacts of soil contamination on public health and the management of contaminated sites	The structure of authorities responsible for contaminated sites is not clear.
	Local authorities are effectively organised and skilled with distinct and well-coordinated responsibilities. They establish quality standards that take into account regional attributes, with local authorities serving as the main regulators	The responsibility for remediation is divided among various government levels (national, regional, and local), leading to conflicts in governance

	Various legislative regimes regulates contaminated sites. In an interconnected manner	The regulatory framework is feeble, and accountability for contaminated sites is dispersed among various government departments. There's an absence of a unified national legislative system for contaminated sites, leading to differing and contradictory methods and target values employed to regulate the clean-up of contaminated land
	The remediation liability is placed on the original polluter and the current owner/occupier.	The remediation liability is often unclear, falling between the original polluter, current owner/occupier, and the government, leading to delays and disputes in remediation actions.
Financing	Government provides funding incentives for remediation of contaminated sites. For instance, the Superfund in the United States serves as a financial resource for the clean-up of contaminated sites	There is minimal government motivation in providing funds for the clean-up of contaminated sites
	There is political encouragement for private site owners to voluntarily undertake the cleanup of contaminated sites	The cleanup of contaminated sites hinges on the voluntary initiatives of property owners or societal pressure. Resource limitations hinder the distribution of incentives for the remediation of contaminated sites.
	A sustainable funding strategy is established to guarantee prompt action towards sites that pose a threat to human health and the environment	The accountability of the cleanup of contaminated sites is often ambiguous, leading to the blame frequently being placed on the polluter. Nevertheless, the government typically ends up handling the remediation of public spaces
Sustainability	In managing and making decisions regarding contaminated sites, they aim to incorporate societal benefits while trying to decrease environmental costs and harm	There is minimal regard for the cost-benefit analysis of cleanup procedures, indicating that societal benefits are often overlooked
Public consultations	Conscientisation of the public in participating in the decision-making processes of the cleanup projects.	Public awareness and engagement in the management of contaminated sites is lacking
Stakeholders	Increased stakeholder participation in decision-making regarding managing contaminated sites. For instance, in the United Kingdom, involving stakeholders has become a compulsory part of the policy-making process (Cundy et al., 2013).	There is shortfall in engagement from different stakeholder groups in deliberations about strategies to assure the remediation of contaminated sites
	Comprehensive and solid strategies that guarantee stakeholder involvement.	There are often fragmented and inconsistent mechanisms for stakeholder involvement, which can result in poor or limited participation and engagement in remediation processes.
Remediation Programs/Historical Contamination	Many nations already have programs aiming to merge national registers of contaminated sites with remediation techniques	There is an absence of national cleanup programs
	Enhanced awareness of countries' contaminated sites	Challenges arise when addressing historical contamination due to unsuitable policies or lack of pertinent information about the contaminated area, creating issues during remediation process
	Unified databases on contaminated sites that can be remediated	There is a general lack of consolidated databases for contaminated sites, and as a result, information about site history and contamination levels is often sparse and poorly documented, impeding effective remediation efforts

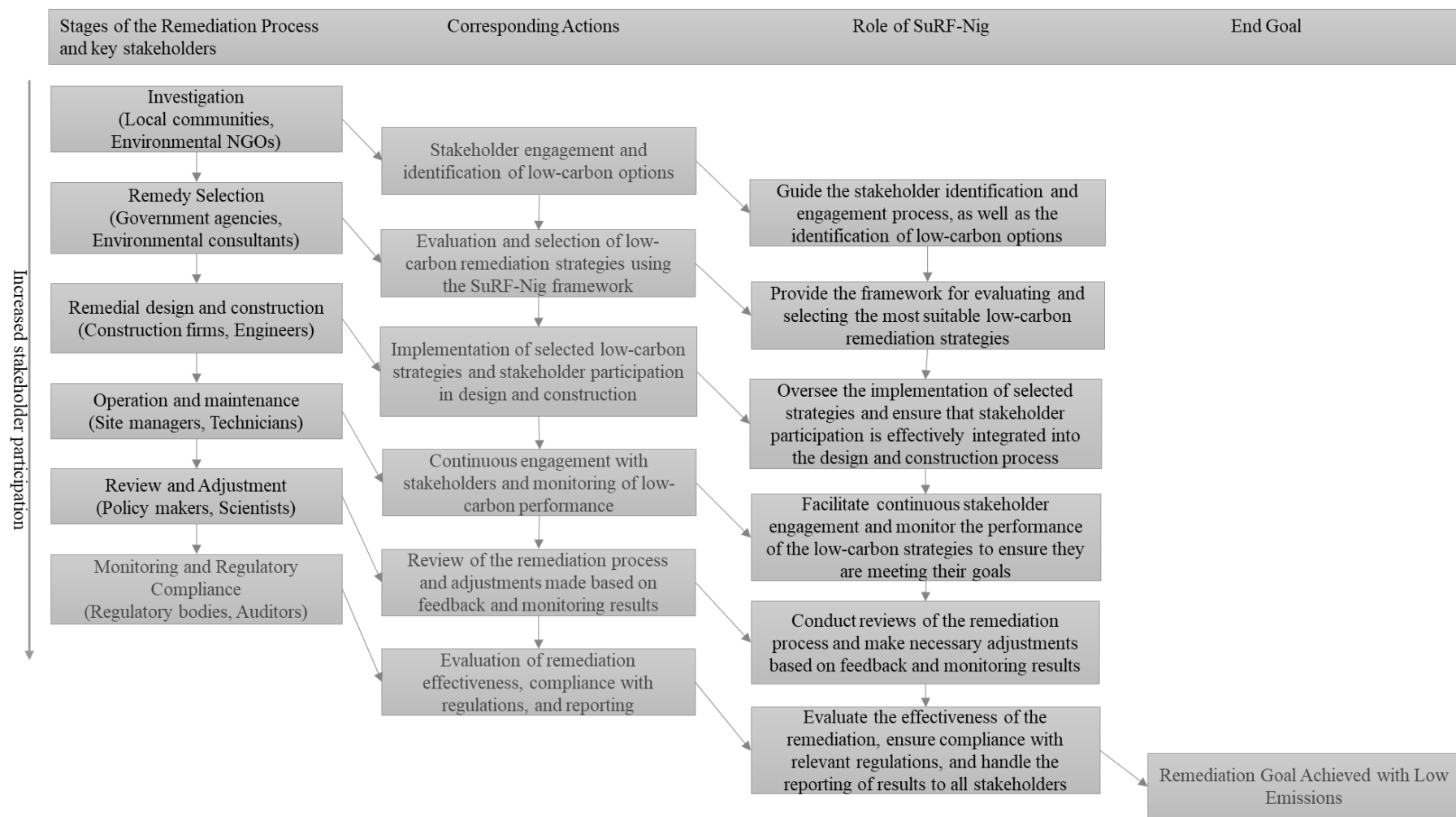


Figure 2. 3 Conceptual framework for integrating sustainable remediation approaches for achieving low carbon remediation in the Niger Delta

2.5. Future opportunities for sustainable remediation in the Niger Delta: An Integrated Framework Approach

Addressing the significant environmental challenges in the Niger Delta requires a systematic framework for sustainable remediation tailored to the region's unique circumstances. This study's developed Integrated Framework for Sustainable Low-Carbon Remediation provides a roadmap for this endeavour (Fig 2.3). The following future opportunities correspond to each stage of the framework, outlining a comprehensive path towards sustainable remediation in the region:

- 1. Investigation and Stakeholder Engagement - Remediation of Polluted Sites:** Engaging stakeholders such as local communities and environmental NGOs is crucial during the investigation of numerous contaminated sites in Nigeria, such as oil spills in the Niger Delta, abandoned mines, and industrial sites. SuRF-Nigeria can guide this process, helping to identify sustainable practices like phytoremediation, bioremediation, and chemical oxidation to restore the environment, protect human health, and reduce greenhouse gas emissions. Challenges such as limited technological capabilities and a lack of awareness among stakeholders about these low-carbon options could pose obstacles.
- 2. Remedy Selection and Evaluation - Sustainable Waste Management:** Government agencies and environmental consultants play a crucial role in managing significant amounts of waste generated in Nigeria. SuRF-Nigeria can aid this process by using a locally adapted, criteria-based assessment tool to evaluate potential strategies like composting, recycling, and waste-to-energy. However, biases in selection due to vested interests and limited data on the effectiveness of different strategies can be potential challenges.
- 3. Remediation Design and Construction - Green Infrastructure:** Construction firms and engineers are key stakeholders during this stage. SuRF-Nigeria can advocate for the implementation of green infrastructure like green roofs, rain gardens, and permeable pavements. These strategies can help reduce stormwater runoff and improve water quality, contributing to the region's overall sustainability. Still, the realisation of these strategies could be obstructed by monetary constraints and technical complexities.

4. **Operation, Maintenance, and Renewable Energy:** Site managers and technicians are key stakeholders during the operation and maintenance phases. SuRF-Nigeria can facilitate the implementation of renewable energy technologies, capitalising on Nigeria's rich solar and wind resources. This can help reduce greenhouse gas emissions and promote sustainable development. Nevertheless, obstacles such as insufficient infrastructure and a shortage of trained workforce could present difficulties.
5. **Review, Adjustment, and Commitment to Net Zero and Blue Economy:** Policymakers and scientists hold a pivotal position in the appraisal and modification process. SuRF-Nigeria can guide the Niger Delta region's commitment to achieving Net Zero and embracing the blue economy, which involves the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems. Yet, potential hurdles could arise from reluctance to adopt new strategies and time lags in obtaining feedback and results from monitoring efforts.
6. **Monitoring, Compliance and Alignment with Global Goals:** In this final stage, regulatory organisations and auditors play a pivotal role. SuRF-Nigeria can be instrumental in ensuring regulatory compliance. The effectiveness of the remediation strategies will be evaluated using key indicators such as reductions in pollutant concentrations, improvements in local health statistics, and reductions in GHG emissions. This phase aligns with the United Nations Decade for Ecosystem Restoration and Sustainable Development Goals (SDGs). However, the potential challenge lies in the scarcity of adequate monitoring tools and potential regulatory constraints. **Future Directions:** Further research is needed to explore new low-carbon remediation technologies, study the long-term impacts of these strategies, and develop new tools for stakeholder engagement. Research could also focus on refining the SuRF-Nigeria's criteria-based assessment tool and expanding its use in other regions.

By adopting this integrated framework, the Niger Delta can navigate its path towards sustainable remediation, contributing to both local environmental health and global sustainability goals. To fully realise the opportunities for sustainable remediation in

Nigeria, several actions are needed. These are summarised in Table 2.6, which provides an overview of the current state and prospects for various aspects of sustainable remediation in the Niger Delta.

Table 2. 6 Future Opportunities for sustainable remediation in the Niger Delta

Theme	Current Level	Prospects
Regulation	Inadequate	A new set of guidelines can be explored consistently with sustainable technology transition while the present one is analysed and improved. Oil spill clean-ups can be assessed considering recent advances in remediation technology compatible with the realities of implementation.
Funding	Inadequate	A long-term funding structure can be devised to ensure prompt attention to sites endangering human health and the environment.
Human health and environmental protection	Inadequate	Standardised methods for establishing human health and ecological screening levels can be established and implemented.
Sustainability	Inadequate	A coherent framework can be developed to incorporate socio-economic, cultural, and environmental context (sustainability indicators) decision-making on contaminated land.
Management	Deficient	An integrated contaminated land management centre can be built, and the "suitable for future use" principle can be adopted as the benchmark for evaluating and remediating contaminated sites.
Stakeholders	Not fully involved	All stakeholders can fully participate in decision-making for the present, and future remediation projects as such engagement engender transparency.
Database	Inadequate	Guidelines for developing a database containing information about the size and condition of contaminated land in Nigeria can be created and made available to all.

Addressing the significant environmental challenges facing the Niger Delta requires a change in mindset and increased awareness of the importance of sustainable remediation practices among all stakeholders in the region. The adoption of sustainable remediation practices is feasible and can contribute to a comprehensive approach to addressing environmental issues. By focusing on these opportunities and recommendations outlined in Table 2.6, the Niger Delta can work towards a more sustainable future, improving the quality of life for its residents and preserving the environment for future generations.

2.6. Conclusion

Low-carbon remediation strategies can have considerable benefits for countries engaged in the remediation of contaminated land, contributing to global environmental goals. In this regard, a holistic and integrated approach, which includes methods such as phytoremediation, chemical oxidation, and EKR, alongside bioremediation, was found to be a more suitable prospect for the clean-up of oil-contaminated lands in the Niger Delta region. This approach allows for more nuanced and tailored solutions depending on the specific nature of the contamination, local environmental conditions, and socio-economic factors. However, challenges persist in Nigeria, including a lack of awareness, an inadequate regulatory framework, illegal refining, and insufficient funding, which impede the adoption of sustainable remediation practices. Lessons learned from case studies in the Niger Delta region, such as the Ogoniland cleanup project, underscore the importance of community engagement, transparency, and monitoring of the remediation process. Furthermore, there is a pressing need for capacity building and technology transfer to local communities and stakeholders involved in the cleanup efforts. A framework has been developed in this research to address these challenges, aiming to promote active stakeholder participation, create sustainable livelihoods, sensitise locals, develop a database for information accessibility, and build the capacity of respective stakeholders. To promote sustainable remediation principles, stronger regulations for polluted sites should be integrated into Nigeria's legal framework, including the use of science-based decision tools like life cycle analysis (LCA), which can help evaluate the environmental impacts of remediation alternatives and provide a framework for decision-making. Overcoming the challenges associated with remediation approaches requires the development and implementation of innovative strategies and frameworks such as SuRF-Nigeria that integrates contextual sustainability indices to demonstrate above-average levels of effectiveness and efficacy for a successful contaminated land management regime. Such initiatives will push towards adopting effective low-carbon remedial approaches, offering significant net benefits from clean-up efforts, and fostering a sustainable remediation framework in Nigeria. This study provides insights for achieving low-carbon remediation in regions addressing land contamination by different contaminants. The study will also serve as an exemplar for regions with

similar experience as Nigeria, as it will prevent trial and error in the adoption of remediation technologies that consider contextual socio-economic and environmental indices for sustainable development.

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3 Low-carbon bioremediation strategy to enhance the natural attenuation of crude oil-contaminated soils

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Abstract

A 180-day laboratory study investigated the efficacy of various biostimulation strategies for enhancing the natural attenuation of crude oil in soils. We evaluated three distinct strategies: oxygen release compounds (ORC, B1), ORC combined with a nitrogen and phosphorus solution (ORC + N&P, B2), and ORC mixed with food waste compost (ORC + FWC, B3). Key parameters assessed included total petroleum hydrocarbon (TPH) degradation, basal soil respiration rate (Br), microbial community dynamics, and ecotoxicological response. The treatments had a significant impact on the total and bioavailable concentrations of TPH, resulting in remarkable reductions of 88%, 92%, and 96% for treatments B1, B2, and B3, respectively, starting from an initial concentration of 10,000 mg kg⁻¹. The decrease in medium- to long-chain aliphatic compounds (EC16–35) and medium-molecular-weight aromatic compounds (EC16–21) was most significant in treatment B3, showing reductions of approximately 95% and 93%, respectively. While reductions were also observed in B2 and B1, they were less significant than in B3. A strong correlation was found across all treatments between TPH degradation and ecotoxicological assays, indicating that toxicity decreased as TPH concentration was reduced. By the end of the treatment period, the soil under treatment B3 demonstrated the most significant ecological restoration, marked by a 91% improvement in ecotoxicological response compared to monitored natural attenuation (MNA). Although B2 and B1 also exhibited improvements, these were less significant than B3. The study underscores that a combined biostimulation approach, using ORC with either an N&P solution or FWC, optimises the natural attenuation of crude oil-contaminated soils. This combination markedly outperformed the use of ORC alone in terms of TPH degradation rate and toxicity reduction. The superior effectiveness of B3 can likely be attributed to the synergistic effect of the ORC with the nutrient-rich FWC enhancing microbial activities responsible for TPH degradation. Thus, the study advocates prioritising these combined biostimulation strategies over traditional singular approaches like soil

excavation and disposal, and stabilisation/solidification, for efficient and cost-effective bioremediation of hydrocarbon-contaminated soils.

Keywords: Petroleum hydrocarbon, bioremediation, low-carbon technologies

3.1 Introduction

Oil spills, whether accidental or deliberate during extraction, production, transportation, storage, or processing, have devastating environmental impacts and pose global health risks (Berthe-Corti and Hofner, 2005; Uloaku et al., 2022). They lead to alterations in soil characteristics, disrupting microbial populations and affecting physical, chemical, and biological properties such as structure, water-holding capacity, redox conditions, and nutrient availability (Hewelke et al., 2018). One notable example is the Ibeno spill in Akwa Ibom, Nigeria, in 2014, which caused extensive damage to soil and water in the area. These environmental disruptions, including the decline in soil fertility and overall health, present significant challenges in their remediation.

The adhesion of hydrocarbons to soil components makes them especially difficult to eliminate or degrade, posing ongoing threats to both surface and groundwater systems. This context frames a significant challenge: the necessity for the creation and implementation of ecologically sustainable and economically viable strategies for accelerating hydrocarbon decomposition and the restoration of soil fertility. Despite advances in this area, there remains a crucial need to overcome current obstacles and fill existing research gaps. Specifically, prevailing strategies frequently depend on chemical additives or energy-intensive processes, such as thermal desorption and incineration, each leading to environmental hazards or cost limitations (Cheng et al., 2019).

Traditional approaches such as excavation, landfilling, and incineration have been deemed inefficient and costly, often exacerbating the problem rather than solving it (Megharaj and Naidu, 2017). Bioremediation has emerged as a particularly promising method. It offers an ecologically sustainable and low-cost solution capable of degrading a wide range of organic contaminants with minimal residues (Lohner et al., 2009). However, the success of bioremediation relies heavily on optimal microbial growth conditions, which are influenced by several factors such as nutrient availability, temperature, and oxygen content. As Shukry et al. (2013) highlight, insufficient nutrient supply can limit the natural processes of crude oil degradation.

As alternatives to these traditional approaches, low-carbon bioremediation strategies, which prioritise the degradation of pollutants with minimal carbon emissions, have emerged as promising contenders. This is where biostimulation,

including the use of compost, comes into play. By adding organic matter and nutrients to contaminated soil, we can stimulate soil microbes, balance pH, and enhance the degradation process, leading to an increase in soil quality and water-holding capacity (Wang et al., 2017). Specifically, compost amendment has demonstrated significant effectiveness in remediating contaminated soils by not only providing a nutrient boost but also introducing diverse microbial communities with various catabolic abilities (Baldantoni et al., 2017; Davie-Martin et al., 2017). This advantage is mainly attributed to the enriched microbial populations and nutrients in compost, which enhance the degradation of hydrocarbons into less harmful compounds (Al-Daher et al., 2001; Marin et al., 2006; Cai et al., 2007; Plaza et al., 2009).

In addition to compost amendment, another remediation method employed is the use of oxygen-release compounds (ORCs). ORCs supply dissolved oxygen (DO) in oxygen-limiting conditions (Seifan et al., 2017). The released oxygen creates an environment conducive to aerobic microorganisms, leading to a faster and more comprehensive breakdown of contaminants. Furthermore, oxygen can chemically oxidise hydrocarbons as well, transforming them into forms that are easier for microbes to metabolise (Yang and Huang, 2017). To offset the adverse effects of crude oil on soil and promote microbial activity, the addition of fertilisers is another practical approach. Mineral fertilisers provide the balanced nutrient supply required for hydrocarbon-degrading microbes to thrive. Nitrogen and phosphorus, being essential nutrients for microbial growth and metabolism, can therefore enhance the activities of hydrocarbon-degrading bacteria (Agarry et al., 2010; Agarry, 2018; Chukwuma et al., 2012; Baek et al., 2007).

Despite the recognition of bioremediation as an effective environmental recovery approach, its application in areas like the Niger Delta region can be complex due to unique factors such as high humidity, soil salinity, acidity, and distinct temperature regimes. As a result, translating and applying bioremediation strategies that have been proven in temperate climates often yield mixed results in this region. This emphasises the need for customised bioremediation strategies and further research, considering the unique characteristics of the Niger Delta region. In view of achieving a faster remediation endpoint, a practical and realistic solution calls for integrating

several strategies, leveraging economically accessible, readily available resources, and addressing long-term sustainability demands. One promising strategy gaining traction in these regions is the utilisation of biowastes (Nwankwo, 2014). These are organic materials, such as kitchen food wastes and green wastes, that serve as bioamendments for impacted soils. This low-cost alternative can counter the increased fertiliser cost for contaminated soil remediation, particularly in regions like the Niger Delta where such wastes are often openly discarded and burned.

The primary objective of this research was to evaluate not just the individual effectiveness of ORC, but also its combined effect with compost (specifically food waste compost, FWC), and a nitrogen and phosphorus solution (N&P), in enhancing the natural attenuation of crude oil-contaminated soils. The study presents a comprehensive exploration of these low-carbon bioremediation strategies, contributing to the ongoing efforts in finding effective, economically viable, and sustainable solutions for oil-contaminated soil remediation.

3.2. Materials and Methods

3.2.1. Soil physicochemical properties

A total of 160 kg of soil were collected from a depth of 30 cm at an excavation site at Cranfield University. The soil was air-dried, sieved through a 2 mm mesh to remove large particles and impurities, and stored in a temperature-controlled facility at 20 °C for four days, ensuring its physical properties were stabilised. No previous history of petroleum hydrocarbon contamination is recorded for this site. The gravimetric method was used to determine the soil's water content after drying a sub-sample at 105 °C for 24 hours. Soil pH was determined by a 1:2.5 soil-to-deionized water mixture. The soil's total organic carbon, total hydrogen, and phosphorus content were measured following BS 7755 Section 3.8 (1995), while potassium content was determined according to BS 3882 (1994). Particle size distribution was analysed following BS-ISO 11277 (2009) and ISO 11277 (2009) with a Laser Analyzer Mastersizer (MS3000) from Malvern Instruments Ltd., Worcestershire, UK, fitted with a hydro adaptor. The soil's texture was classified based on clay, silt, and sand proportions after the US Department of Agriculture's (USDA) soil textural

classification scheme. The detailed physical and chemical properties of the experimental soil are presented in Table 3.1.

Table 3. 1 Physical and chemical characteristics of the experimental soil and compost

Property	Value	
	Soil	Compost
Sand	47.0%	-
Silt	46.0%	-
Clay	7.0%	-
pH	8.7	7.1
Moisture content	26.0%	-
Loss of Ignition	3.4%	-
WHC	47.0%	-
Total Organic C	3.8%	2.0%
Organic Carbon	2.9%	-
Total hydrogen	1.1%	-
Total Nitrogen	0.1%	3.4%
Total P	23.4 mg kg ⁻¹	27.0 mg kg ⁻¹
Phosphorus	5.9 mg kg ⁻¹ dry soil	
Magnesium	149.0 mg kg ⁻¹ dry soil	91.2 mg kg ⁻¹
Potassium	236.0 mg kg ⁻¹ dry soil	196.8 mg kg ⁻¹

3.2.2. Incubation experiment

Mesocosm experiments were conducted in 14-litre black buckets, each filled with 2 kg of the sieved soil previously prepared and characterised. Although the soil used in this study was from Cranfield University, it was selected as a surrogate for Niger Delta soil due to its similar texture and mineral composition. However, the pH of the soil at Cranfield University was not similar to that of the Niger Delta region, where pH values typically range between 5.7 and 5.9 (Onu et al., 2014). Hence, the soils in the mesocosms were acidified using HNO₃ to achieve a pH level of 5.9 to replicate the acidic conditions in the Niger Delta region. The soil was then spiked with Sweet

Crude Oil sourced from Shell Gas Direct Ltd., London, UK. This oil, characterised by less than 0.5% sulphur content and predominantly composed of aliphatic, alicyclic, and aromatic hydrocarbons, was added to the acidified soils to achieve an initial total petroleum hydrocarbon (TPH) concentration of 10 g kg⁻¹. This level was chosen as it matches observed values reported in the soils of the Niger Delta region (Okafor et al., 2021; Ugochukwu et al., 2018). To ensure the thorough mixing of the oil, 20 mL of sweet crude was directly spiked into each mesocosm and manually mixed. Subsequently, the mesocosms were kept at a constant 28 °C for a period of five days to acclimatise, simulating the average temperature in the Niger Delta as reported by Fubara-Manuel et al. (2017).

Three different amendments were then applied to the soils: a nutrient solution (N&P), an oxygen-release compound (ORC) product, and FW compost. The order of the addition was first the oil, then the amendments, to ensure that the soil was contaminated before the start of the remediation. The amendments were thoroughly mixed with the contaminated soil to ensure uniform distribution. The nutrient solution was a mix of NH₄NO₃ (25.7g L⁻¹), KH₂PO₄ (21.4g L⁻¹), and K₂HPO₄ (21.4g L⁻¹). The ORC product, commercially available in the United Kingdom, was composed of dipotassium phosphate, monopotassium phosphate, and a combination of calcium dihydroxide and calcium peroxide. The compost was locally sourced from a UK garden and comprised decomposed food and garden waste. The application rate of 30% for the compost was chosen based on previous studies and empirical evidence indicating that higher compost percentages can accelerate the degradation of petroleum hydrocarbons (Rumaila, 2020). The increased organic matter from the compost provides both an energy source and a matrix for microbial growth, enabling faster and more efficient biodegradation. Moreover, using a high application rate ensures that the soil receives an ample amount of beneficial microbes and nutrients that can stimulate biodegradation processes. While there are various recommended compost application rates for remediation purposes, 30% was deemed to provide a balance between enhancing biodegradation and avoiding excessive organic matter addition, which might lead to other complications such as oxygen depletion. Each of these conditions was replicated three times, as detailed in Table 3.2.

Table 3. 2 Overview of the mesocosm biostimulation treatments

Mesocosm condition	Treatment Code
Pristine soil (2 kg)	Control
Pristine soil acidified at pH 5.9, spiked at 10g kg ⁻¹ with crude oil	Monitored Natural Attenuation (MNA)
Pristine soil acidified at pH 5.9 and spiked at 10g kg ⁻¹ with crude oil + 1% Oxygen Release Compound (ORC)	Biostimulation 1 (B1)
Pristine soil acidified at pH 5.9 and spiked at 10g kg ⁻¹ with crude oil + 1% ORC + 3% N&P	Biostimulation 2 (B2)
Pristine soil acidified at pH 5.9 and spiked at 10g kg ⁻¹ with crude oil + 1% ORC + 30% Compost.	Biostimulation 3 (B3)

Over the course of six months, the mesocosms were incubated in a temperature-controlled environment set to match the conditions of the Niger Delta region, which has a tropical monsoon climate with high humidity and temperatures between 25°C and 30°C throughout the year. The mesocosms were covered to prevent waterlogging, simulating the rainy and dry seasons typical to the Niger Delta region. The mesocosms were homogenised every two weeks to ensure consistency. Throughout this period, soil samples were taken at predetermined intervals (0, 7, 30, 90, 150, and 180 days) and subsequently stored at -20 °C until needed for chemistry and toxicity analyses.

The mesocosms were incubated in a garden shed for six months, offering an environment more akin to the Niger Delta region compared to direct outdoor exposure. The shed provided a warmer setting, guarded against waterlogging, and indirectly simulated the rainy and dry seasons typical of the Niger Delta. To ensure consistency, the mesocosms were homogenised every two weeks. Throughout this period, soil samples were taken at predetermined intervals (0, 7, 30, 90, 150, and 180 days) and subsequently stored at -20 °C until needed for chemistry and toxicity analyses.

3.2.3 Soil microbial respiration rate

The CO₂ generation rate was determined through soil basal respiration, a measure of the steady rate of microbial respiration in soil, following the method proposed by He and Hu (2021). This measurement was taken using the Rapid Automated Bacterial Impedance Technique (RABIT) respirometer (Don Whitley Scientific, Bingley, UK), following the protocol described in the study conducted by Jumbo et al.

(2013). Three replicates of 1g soil samples, saturated to their water-holding capacity (Table 3.1), were placed in a glass boat. The microbial respiratory response was monitored for 48 hours at a constant temperature of 25 °C. Changes in conductivity were quantified with the RABIT software (version 2.31, 01-1999) and subsequently converted to CO₂ concentration following the method of Ritz et al. (2006). The quantification of conductivity changes was achieved by measuring the impedance shift due to CO₂ evolution, in a procedure similar to that described by Pawlett et al. (2013). Soil basal respiration was measured at the onset of the experiment and subsequently on days 7, 30, 90, 150, and 180 of the mesocosm study.

3.2.4 PLFA Analysis

The microbial community structure was examined by phospholipid fatty acid (PLFA) analysis following a modified protocol from Frostegård et al. (1993) as described in Cipullo et al. (2019). Ten grams of freeze-dried soil underwent solvent extraction using a solution of chloroform, methanol, and citrate buffer in a volume ratio of 1:2:0.8. The resulting extract was further derivatised by mild alkaline methanolysis. The resulting fatty acid methyl esters were evaluated using gas chromatography, following the procedure outlined by Pawlett et al. (2013). A total of 34 different PLFAs, used as biomarkers for specific microbial groups (i.e., Gram-positive, Gram-negative, fungi, and actinobacteria), were identified. Their relative abundance was determined following the procedures established by Pawlett et al. (2013) and the categorisation proposed by Quideau et al. (2016).

3.2.5 Hydrocarbon Extraction and Analysis.

The extraction and analysis of total petroleum hydrocarbons (TPHs) and readily available hydrocarbons in our soil samples were performed following modified procedures by Risdon et al. (2008) and Cipullo et al. (2019). Briefly, total hydrocarbons were extracted from 2.5 g of soil samples using a 1:1 dichloromethane:hexane solvent mixture, while the readily available fraction was extracted with methanol. Both extraction processes involved sonication and shaking steps, and the resulting extracts were cleaned on Florisil columns, with final volumes adjusted to 0.5 ml. Deuterated alkane and PAH standards were added prior to analysis with a Shimadzu Gas Chromatography-Mass Spectrometry (GCMS-

TQ8040) with an AOC-600 Autosampler. The analytical system allowed for a full scan mode (range m/z 50–500) for quantitative evaluation of targeted aliphatic and aromatic hydrocarbons. The total extractable hydrocarbon and readily available hydrocarbons were analysed on days 0, 7, 30, 90, 150, and 180. The alkanes were grouped into C10-C12, C12-C16, and C16-C35, while the petroleum PAHs were grouped into C12-C16, C16-C21, and C21-C35. Calibration was carried out with alkane and PAH standards, and quality control involved the regular analysis of calibration checks and blanks.

3.2.6 Toxicity assay

The toxicity of the contaminated soil was evaluated via the luminescent bacteria *Vibrio fischeri* response with the Microtox Model 500 (M500) analyser, following the standard procedures outlined by the manufacturer (Modern Water Microtox Acute Toxicity). The EC_{50} values, indicating the soil concentration that inhibits 50% of the light output, were calculated and expressed as a percentage of the pristine sample. As the EC_{50} values increase, it denotes a decrease in toxicity. Phytotoxicity was assessed through a germination assay with wheat seeds (*Triticum aestivum*), sourced from a UK local market. The choice of wheat was motivated by its widespread cultivation and its sensitivity to the presence of hydrocarbons (Risdon et al., 2018). In each experiment, five wheat seeds were sown into 50 g of air-dried soil adjusted to 65% of its water-holding capacity. The germination response was monitored at the beginning and 90 days into the experiment. The number of germinated seeds provided a measure of soil toxicity, with replicates performed to ensure statistical validity. As a positive control, germination was also monitored in uncontaminated soil.

3.2.7 Data analysis

Statistical analyses were performed with Microsoft Excel 2016 and SPSS to assess the effects of different treatments (MNA, B1, B2, and B3) on toxicity over various time points (0, 7, 30, 90, 150, and 180 days). A one-way ANOVA test was conducted to compare treatments, incubation time, and their impact on the toxicological response. Additionally, Spearman's rank-order correlation test was used to identify possible relationships between the variables (PLFA profiles, respiration rate, toxicity,

and TPH). These relationships were further visualised using Draftsman's plot. The significance of each relationship was determined at a p-value less than 0.05.

3.3 Results and Discussion

3.3.1 Microbial respiration

Figure 3.1 shows the effect of oxygen and nutrient amendments on CO₂ production for the tested amendments. Degradation rates were inferred from changes in the microbial community, CO₂ production, and biomass, which play significant roles in microbial growth, metabolism, and reproduction (Chi and Hieu, 2017). From the onset, all samples exhibited measurable CO₂ production, which may be linked to the biodegradable hydrocarbons produced by the extant soil microbes (Jumbo et al., 2022). By day 30, treatments B1, B2, and B3 had significantly increased CO₂ production by 2, 2.5, and 3-fold, respectively, compared to the MNA treatment. This increase could be attributed to the activation of hydrocarbon-degrading microbial communities utilising crude oil, ORC, and compost as sources of carbon, energy, oxygen, and nutrients, creating optimal conditions for microbial growth. Among the treatments, B3 showed the best performance, with the highest CO₂ production and the greatest reduction in TPH levels. The additional organic content provided by the compost in B3 likely stimulated further microbial respiration, as evidenced by the increased CO₂ production. The decrease in TPH levels from 4348.14 mg kg⁻¹ on day 7 to 255.95 mg kg⁻¹ by day 180 in treatment B3 suggests that the compost served as an additional source of carbon and nutrients, stimulating microbial growth and promoting efficient hydrocarbon degradation. Treatment B2 demonstrated 1.3 times higher CO₂ production than B1, while B3 was 1.4 times higher than B2. The progressive increase in CO₂ production across the treatments implies oxygen and nutrient limitations in treatments B1 and B2, with the addition of compost in B3 potentially offsetting these constraints. Comparatively, CO₂ values show a positive correlation with hydrocarbon removal. The marked increase in CO₂ production, especially in B3, mirrors the substantial decrease in TPH levels, further indicating that active microbial respiration corresponds with effective hydrocarbon degradation. Hence, the biostimulation treatments significantly enhanced CO₂ production and hydrocarbon degradation, in alignment with earlier findings that improved soil

nutrient quality fosters soil microbial community activities and stability (Sándor, 2020).

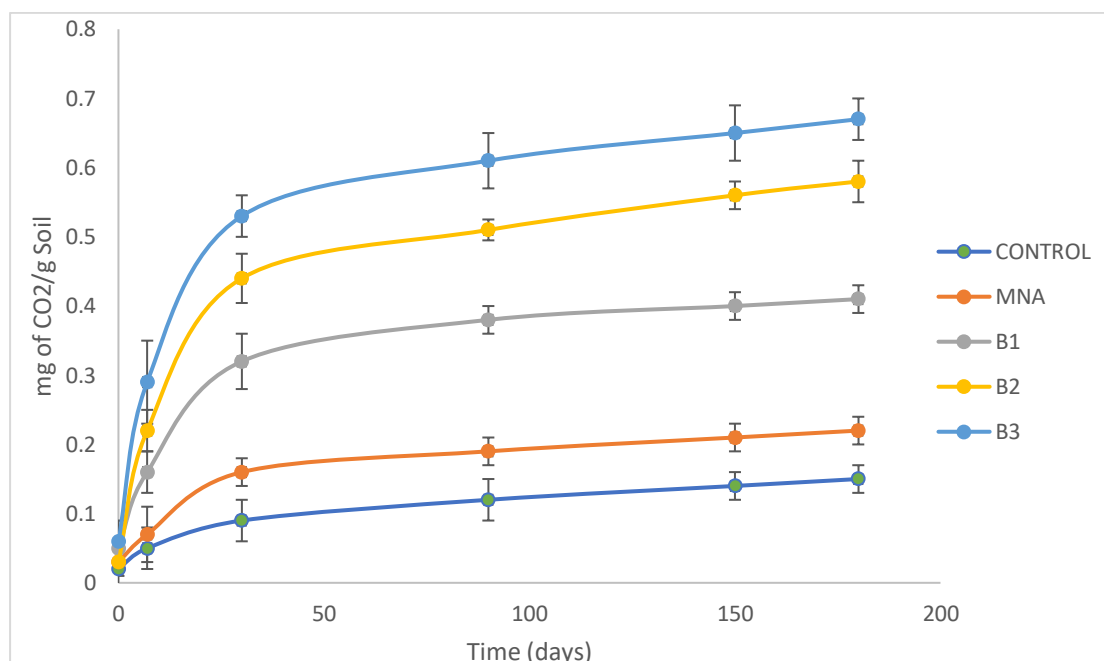


Figure 3. 1 Cumulative curve of CO₂ production expressed in mg CO₂/g soil for soil treatments with Control, MNA, B1, B2, and B3 tested at 0, 7, 30, 150, and 180 days. Error bars represent the standard deviation of three replicates.

3.3.2 Soil microbial community structure

Our study observed a notable increase in microbial community composition from day 0 to day 30, as displayed in Fig 3.2. We noted substantial increases across Gram-negative bacteria, fungi, and Gram-positive bacteria by 28–53%, 19–51%, and 5–26%, respectively. In response to these changes, the total biomass increased by 26–33% across all treatments, attesting to the efficacy of our biostimulation process. Specifically, treatment B3 notably increased the count of cultivable microorganisms, aligning with findings from numerous studies on hydrocarbon-contaminated soils (Trejo-Hernandez et al., 2007; Gandolfi et al., 2010; Cipullo et al., 2019).

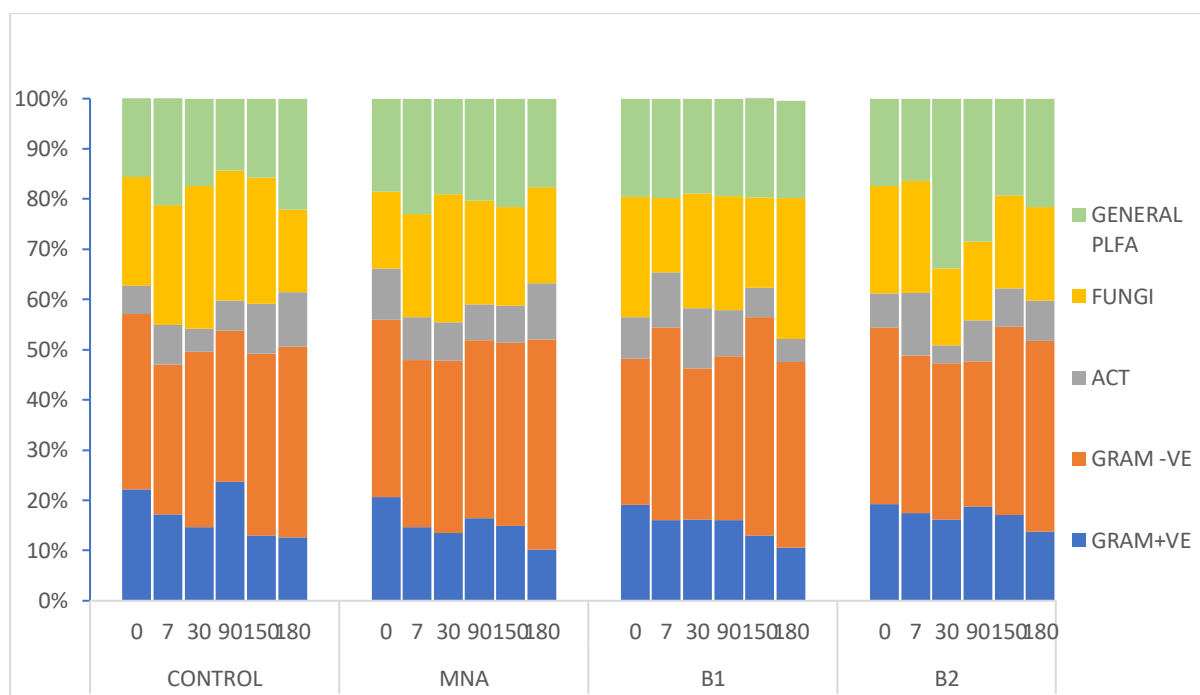


Figure 3. 2 Classification of PLFA identified for treatments MNA, B1, B2, and B3, comparing sampling days 0, 7, 30, 90, 150, and 180. The relative abundance of each individual PLFA was portrayed as a percentage of the overall target response.

However, this increase in biomass did not mirror the increase in soil respiration. The correlation analysis revealed only a weak-to-moderate relationship between respiration and PLFA biomass, with R^2 values ranging from 0.0152 to 0.2629 across treatments. This insight suggests that respiration and microbial biomass may respond to different sets of influences, and augmentation in biomass doesn't necessarily equate to increased respiration. Moreover, these findings underline that variations in microbial community composition resulting from differing treatments could significantly impact the community's overall capacity for respiration. Shedding light on these variations, the shifts in microbial community composition over time, as evinced by PLFA profiles, could be indicative of adaptive responses to hydrocarbon-induced stress. At the onset of the biostimulation treatments (B1-B3), we noted increased biomass of Gram-positive bacteria, Gram-negative bacteria, actinomycetes, and fungi. These microbial groups seemingly demonstrated a heightened resilience to initial hydrocarbon stress and could harness the added nutrients more effectively, enhancing their metabolic activity and overall soil respiration.

Yet, the eventual decrease in biomass for most microbial groups under these treatments, juxtaposed with sustained or even elevated respiration rates, could hint at a prolonged stress response to persistent hydrocarbons. This response could potentially involve alterations in community composition, metabolic activity, or a blend of both, as the microbial community navigates through a scarcity of resources and heightened hydrocarbon-induced stress over time. Interestingly, we found that the increase in microbial abundance did not significantly impact microbial diversity ($p > 0.05$). Dominant microbial groups maintained their predominance, despite a 16% reduction in total biomass, primarily driven by Gram-negative bacteria, after 180 days. This decrease may be tied to the dwindling availability of substrates and energy sources such as crude oil, echoing previous research that links petroleum hydrocarbon loss with the abundance of Gram-negative bacteria and soil fungi (Al-Hawash et al., 2018).

Overall, the results highlight a complex interplay between microbial community dynamics and hydrocarbon-induced stress within the context of biostimulation. We observed an initial increase in biomass across specific microbial groups, potential adaptive responses to hydrocarbon stress, and an intriguing decoupling of biomass and respiration rates. These findings shed light on the resilience of microbial diversity amidst fluctuations in abundance and pave the way towards more effective bioremediation strategies.

3.3.3 Extractable total and readily available hydrocarbons concentrations

Over the 180-day incubation period, we observed that each treatment yielded a significant decrease in TPH. For instance, treatment B1 recorded a reduction from 4818.2 mg kg⁻¹ on day 7 to 1058.36 mg kg⁻¹ by day 180, indicating a decrease of 78%. Similarly, treatment B2 showed a more pronounced reduction from 4990.6 mg kg⁻¹ to 475.38 mg kg⁻¹, corresponding to a 90% decrease, while treatment B3 demonstrated a reduction from 4348.14 mg kg⁻¹ to a mere 255.95 mg kg⁻¹, therefore a decrease of 94%. This notable decrease in TPH can be correlated to the increased microbial activity, potentially promoted by the introduced compost and nutrients (N&P), along with the accelerated respiration rate facilitated by the Oxygen Release Compound (ORC). As a result, the readily extractable hydrocarbon content

diminished progressively over time. Significant alterations were observed in the medium-long chain aliphatic (EC16–35) and medium molecular weight aromatic (EC16–21) fractions (Fig 3.3).

ALIPHATICS

AROMATICS



Figure 3. 3 Total (Grey + black) and readily available (black) concentrations (expressed in mg kg⁻¹) of aliphatics (EC₁₀₋₁₂, EC₁₂₋₁₆, and EC₁₆₋₃₅) and aromatics (EC₁₂₋₁₆, EC₁₆₋₂₁, and EC₂₁₋₃₅) and across the sampling time (0, 7, 30, 90, 150, and 180 days). Aliphatic EC₃₅₋₄₀ and aromatic EC₁₀₋₁₂ fractions are not displayed (below the detection limit for all soil samples). Error bars denote to the standard deviation across replicates for each grouped compound

Specifically, in the MNA treatment, these fractions decreased by 10% and 45%, respectively, while in the B1 treatment, the reductions were 49% and 28%. In treatments B2 and B3, the respective reductions were 76% and 32%, and 78% and 32%. As for the readily extractable aliphatic fractions, decreases in the B1, B2, and B3 treatments were 92%, 96%, and 98%, respectively, whereas the aromatic fractions decreased by 91%, 93%, and 96%. The significant reductions in these hydrocarbon ranges highlight the efficacy of the treatments over time. By day 30, all treatments had recorded their peak degradation rates, with B1 and B2 exhibiting rates of approximately $77 \text{ mg kg}^{-1} \text{ day}^{-1}$, approximately double that of the MNA rate. B3, however, reached a degradation rate of $84 \text{ mg kg}^{-1} \text{ day}^{-1}$, 2.5 times that of MNA. These enhanced degradation rates are indicative of increased microbial activity, potentially facilitated by the greater surface area provided by the compost for microbial interaction and attachment, which aligns with the findings of Wu et al., (2020). Our study also echoes and expands upon the findings of Jumbo et al. (2022) and Atai et al. (2023), which highlighted that hydrocarbons degrade at different rates based on their molecular weight. They reported a more effective degradation of high-molecular-weight PAHs, while Atai et al. (2023) also observed a more rapid degradation of medium-weight hydrocarbons than their heavier counterparts. Expanding upon these insights, our results suggest that following the amendment introduction, high molecular weight aromatic fractions (EC21–35) were the dominant residual hydrocarbons in the treated soils (Fig 3.3). This finding underscores the complex interactions between hydrocarbons and soil constituents, potentially influencing the biodegradation process. Notably, treatment B3 was the most effective in reducing TPH concentrations, reaching the remediation endpoint quicker than other treatments, reaffirming its suitability for crude oil-contaminated soil remediation. Our research adds to this ongoing conversation.

3.3.4 Soil Ecotoxicology

3.3.4.1 Microtox solid phase test

At the start of the experiment, the acute toxicity was high across all treatments, as indicated by low EC_{50} values, due to the high TPH concentration of the oil contaminant (Fig 3.4). As the treatments progressed, hydrocarbon degradation led to decreased toxicity levels, corresponding to increasing EC_{50} values. After 180 days,

the reduction levels were 66%, 78%, and 80% for B1, B2, and B3, respectively, with B3 demonstrating the highest reduction in toxicity. The inverse relationship between the decrease in TPH concentration and the increase in EC₅₀ values, which will be visually depicted later, suggests the effectiveness of the bioremediation treatments in reducing the toxicity of organic pollutants, consistent with earlier findings by Macken et al. (2008) and Khan et al. (2013). There was a distinct difference in toxicity reduction between MNA and the bioremediation treatments (B1, B2, and B3), supporting the conclusion that bioremediation was more effective. The three bioremediation treatments (B1, B2, and B3) were all comparably effective, yet the B3 treatment showed the highest efficacy, rendering it the most promising approach for mitigating the toxicity of oil-contaminated soils. Although MNA does allow for the natural degradation of hydrocarbons over time, the rate of degradation is slower than when using introduced amendments, as is common in bioremediation. Therefore, the EC₅₀ values remained relatively consistent for MNA throughout the study period because the slower degradation rate did not provide the same degree of toxicity reduction as observed in the bioremediation treatments. This consistent EC₅₀ value for MNA underscores the effectiveness of the bioremediation treatments in reducing soil toxicity by promoting faster hydrocarbon degradation.

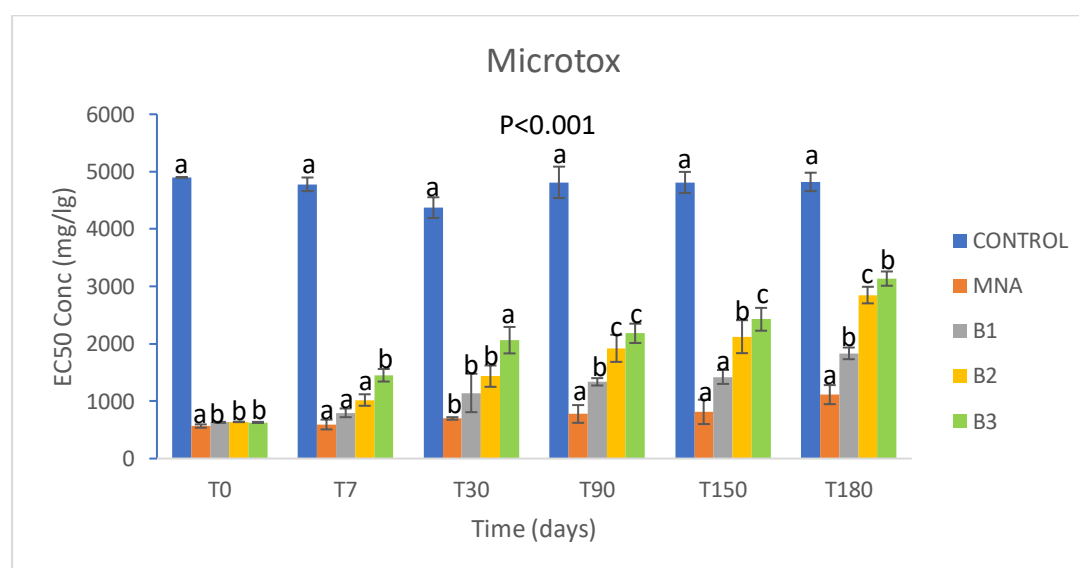


Figure 3. 4 Ecotoxicity Signal Change for MNA, B1, B2, and B3 Over Time

3.3.4.2 Seed Germination

No growth was observed in wheat planted in the oil-contaminated soil at the outset of our experiment, possibly due to the hydrocarbon toxicity and poor aeration, resulting from oil clogging the soil pores, which inhibited water absorption and growth. On the seventh day, over 60% of seeds in uncontaminated soil had already germinated, marking a stark contrast to the germination rate observed in all treated soil samples. By the end of the experiment, all seeds planted in uncontaminated soil achieved a germination rate exceeding 80%. However, after 90 days, our biostimulation strategies notably improved wheat germination in the oil-contaminated soil. The germination rate was highest for treatment B3 (over 53%), followed by B2 (over 33%), and B1 (over 27%), all surpassing the rates achieved by MNA (Fig. 3.5).

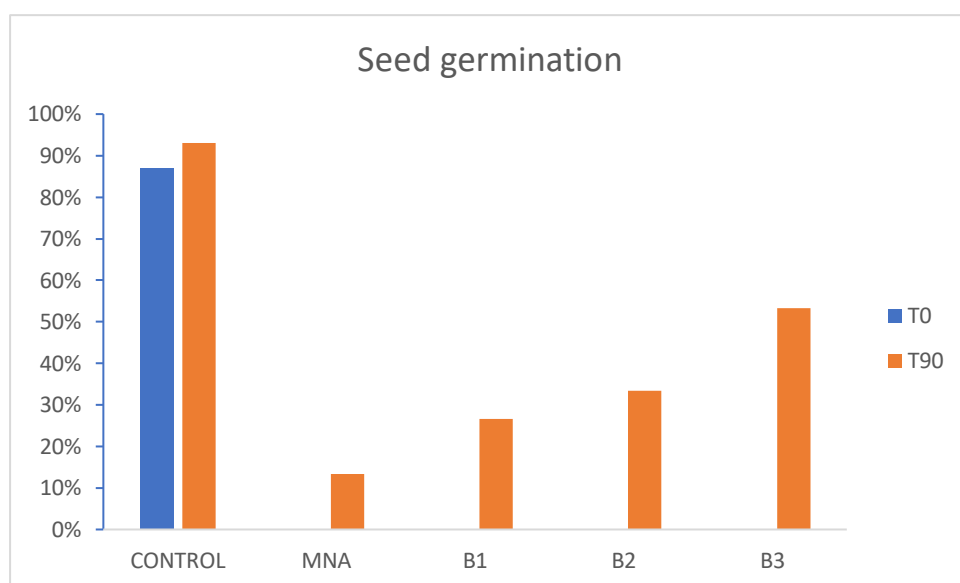


Figure 3. 5 Seed germination assay for wheat seed (*T. aestivum*). Germination rate (shown as a percentage of the total) at two sampling times (onset and 90 days) for treatments MNA, B1, B2, and B3.

The observed improvements in germination in the bioremediation treatments suggest a reduction in soil toxicity, potentially driven by the enhanced degradation of organic contaminants by an enriched microbial community, as revealed in our PLFA analysis. We observed increased microbial biomass and shifts in community composition, reflecting an adaptive response to the hydrocarbon-induced stress and indicating the community's role in contaminant degradation. Cipullo et al. (2019) reported increased seed germination in compost-amended soils, indicative of reduced toxicity

likely due to microbial degradation of contaminants. Their findings align with ours, showing similar community changes, thus supporting the notion that microbial community changes can effectively mediate soil toxicity reduction. Our data also show a time lag effect, with the greatest improvement in germination occurring after 90 days. This could potentially be ascribed to the time required for the microbial community to degrade the hydrocarbons and thereby reduce soil toxicity.

3.3.5 Correlation between treatments

In this study, both Spearman correlation and linear regression analysis were employed, as these methods complement each other. Spearman correlation identifies monotonic relationships between variables, regardless of their linearity, making it ideal for understanding complex, non-linear relationships often seen in ecological data. On the other hand, linear regression analysis models the relationship between two variables by fitting a linear equation to observed data, assisting in data predictions. We used these tools to delve into the relationships within the bioassays. The strength of these correlations, identified by Spearman's rank-order correlation test, could be a key determinant in the effectiveness of various strategies promoting hydrocarbon degradation. We used the Spearman correlation to analyze the interrelationships between basal respiration (Br), EC₅₀, and TPH degradation (Table 3.3).

Table 3. 3 Spearman correlation among basal respiration, EC₅₀, and TPH degradation

Treatment	Br- TPH (rho)	Br-TPH (p-value)	EC ₅₀ - TPH (rho)	EC ₅₀ -TPH (p-value)	Br- EC ₅₀ (rho)	Br- EC ₅₀ (p-value)
MNA	-0.821	0.088	0.914	0.030	0.941	0.017
B1	-0.956	0.011	-0.954	0.012	0.891	0.042
B2	-0.962	0.009	-0.969	0.007	0.883	0.047
B3	-0.949	0.014	-0.946	0.015	0.875	0.052

Br- Basal respiration, TPH: Total Petroleum Hydrocarbon, rho-correlation coefficient

A strong correlation ($\rho > 0.94$ and $p < 0.001$) is evident between TPH concentrations and ecotoxicity (Microtox), most distinctly in treatments B3 and B2. This correlates with a decrease in TPH concentrations, leading to a decrease in

toxicity and an increase in soil respiration and EC₅₀. These findings are consistent with the study by Jiang et al. (2016), which demonstrated that higher respiration rates are associated with more extensive hydrocarbon degradation by active microbial communities. Moreover, we further substantiated these findings through linear regression analysis, showing the interrelationships between TPH, EC₅₀, and basal respiration, as detailed in Table 3.4.

Table 3. 4 Linear Regression Analysis of the Relationship between TPH, EC₅₀, and Basal respiration

Variables	Treatment	R ²	Regression equation
TPH vs EC ₅₀	MNA	0.911	y=-20.199x+20615
	B1	0.9385	y=-3.7944x+7562.7
	B2	0.8952	y=-2.4385x+7029.5
	B3	0.8353	y=-2.5085x+7624.3
TPH vs Br	MNA	0.674	y=-36339x+11452
	B1	0.9138	y=-13976x+7273.5
	B2	0.9252	y=-11563x+7811.2
	B3	0.9006	y=-9925.1x+7434.1
Br vs EC ₅₀	MNA	0.8846	y=0.0005x-0.1867
	B1	0.794	y=0.0002x+0.0175
	B2	0.7803	y=0.0002x+0.1161
	B3	0.7657	y=0.0002x+0.0505
Biomass vs Br	MNA	0.2099	y=0.0015x+0.3174
	B1	0.0152	y=0.0006x+0.3951
	B2	0.1265	y=0.0028x+0.7837
	B3	0.2629	y=0.0004x+1.0354

Br- Basal respiration, TPH: Total Petroleum Hydrocarbon

This analysis revealed that as TPH concentrations decreased, toxicity followed suit, enabling an increase in microbial diversity, which resulted in more vigorous soil respiration and higher EC₅₀ values. Yet, TPH and biomass exhibited a different relationship, despite consistent biological responses such as soil respiration,

Microtox, and seed germination across treated samples. A relatively weaker correlation ($r^2 < 0.61$) between TPH and biomass suggested that toxicity changes might be driven by several factors.

To shed light on these complexities, we generated a Draftsman correlation plot (Fig. 3.6) based on the data in Table 3.3. This plot provides a multi-faceted view of the relationships between TPH, toxicity data, microbial relative abundance, and soil respiration, revealing the potential drivers behind the observed changes in toxicity. The Draftsman correlation plot identified that soil respiration and TPH were generally inversely related. However, the presence of outliers indicated the potential influence of additional variables, possibly relating to soil composition or the presence of specific microbial communities. Shifts in the microbial community could predominantly be attributed to alterations in soil and nutrient availability, as suggested by Zhao et al. (2016). Notably, we observed a positive correlation ($r^2 > 0.89$ and $p < 0.05$) between respiration and ecotoxicity. When CO₂ increased, toxicity decreased for treatments B1, B2, and B3. This pattern underlines the value of using multiple indicators to monitor treatment effects and ecosystem recovery. Nevertheless, the significant relationship ($p < 0.05$) observed between the biostimulation methods and hydrocarbon degradation underscores the potential of these strategies in mitigating hydrocarbon contamination.

We further analysed the actual degradation rates of individual alkanes and aromatics, observing distinct variations in their degradation kinetics in response to the presence of oxygen and nutrients. It was noteworthy that alkanes appeared to degrade faster when both oxygen and nutrients were abundant, as seen in treatments B2 and B3. In treatment B2, which had oxygen amendments, the medium molecular weight aliphatic compounds (EC16–21) showed an increased degradation rate of 69% by day 180. However, in treatment B3, where both oxygen and nutrients were added, this rate was even higher, reaching 78%. Meanwhile, the rate of degradation of medium-long chain aliphatic compounds (EC16–35) increased by 26% in B2 and 32% in B3, both significantly higher than the degradation rate of 10% observed in B1 where only nutrients were added. This suggests that while both oxygen and nutrients enhance hydrocarbon degradation, the presence of both seems to act synergistically to increase the degradation rates of alkanes. This further substantiates the significant role of both oxygen and nutrient amendments in

enhancing the degradation of different classes of hydrocarbons. Nevertheless, the relationship observed between the biostimulation methods and hydrocarbon degradation underscores the potential of these strategies in mitigating hydrocarbon contamination.

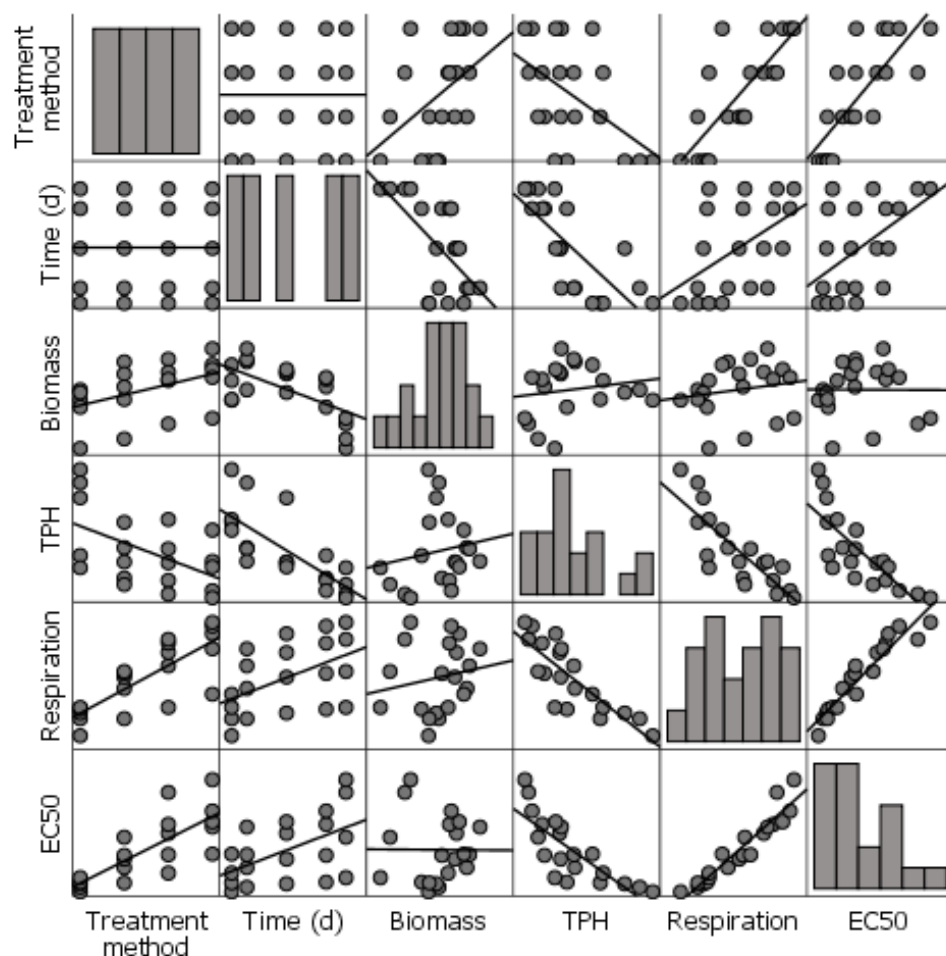


Figure 3. 6 Draftsman correlation plot between TPH, toxicity data, microbial relative abundance and soil respiration

3.4. Conclusion

Our research critically evaluated the role of oxygen and nutrients in biostimulation treatments to facilitate the degradation process in crude oil-contaminated soils. This study contributed more than just a general understanding of the effectiveness of these treatments. It unveiled the dynamics of hydrocarbon degradation, elucidating

how individual and combined treatments influence the degradation rates of different classes of hydrocarbons, including those often considered persistent or recalcitrant. The treatments showed efficacy in enhancing hydrocarbon degradation and reducing soil toxicity over the 180-day period. The introduction of oxygen alone (B1) substantially accelerated the degradation process, achieving an 88% increase in TPH degradation and a two-fold reduction in soil toxicity relative to MNA. However, the synergy of oxygen with nutrients or compost (B2 & B3) proved to be more efficient. These integrated treatments resulted in significant decreases in TPH content and toxicity levels, with reductions of 92% and 88% for B2, and 96% and 91% for B3, respectively. The degradation rates peaked on day 30 across all treatments, with B3 exhibiting the highest degradation rate of $82 \text{ mg kg}^{-1} \text{ day}^{-1}$. This rate was 1.06 times faster than B2 and 1.22 times faster than B1. In scenarios where time is a crucial factor for remediation, these minor differences in degradation rates can have meaningful impacts, potentially saving considerable time in large-scale contamination incidents or when regulatory deadlines apply. The research underscored the significant interplay between TPH degradation and ecotoxicological bioassays, demonstrating that as TPH concentration decreased, toxicity levels correspondingly diminished, as indicated by the increasing germination rate of wheat seeds. Our results showcase the effectiveness of the biostimulation treatments in mobilising microbial communities to enhance TPH degradation, particularly for treatment B3, thus emphasising their potential in remediation strategies. This study, therefore, provides compelling evidence that the strategic use of oxygen and/or nutrients effectively enhances TPH degradation and reduces soil toxicity, making these treatments valuable options for the remediation of crude oil-contaminated soils. However, we recommend further studies to explore and validate these findings in larger field trials. While this study demonstrates the potential of biostimulation treatments in degrading hydrocarbons and reducing soil toxicity, it is important to note that the assessment of heavy metals was beyond its scope. Future research should consider the implications of heavy metals in bioremediation strategies, as their presence can significantly impact both the efficacy of treatments and the environmental health post-remediation

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4 Assessing the Efficacy of Biochar and Bioaugmented Biochar for Remediating Repeatedly Crude Oil-Contaminated Soils

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Abstract

Crude oil spills, which frequently occur in areas such as the Niger Delta, pose a significant environmental challenge requiring efficient and effective remediation strategies. This study evaluated the use of wheat straw biochar (B1), sewage biochar (B2), and their augmentations with *Pseudomonas aeruginosa* (PA) and *Bacillus sonorensis* (BS) for remediation of recurrent crude oil-contaminated soil. Our findings demonstrated a notable difference in efficiency between the initial remediated contamination event and soil subjected to recurrent contamination, with the latter showing a higher remediation efficiency. The B1PABS method, combining wheat straw biochar and both bacterial strains, stood out for its superior efficiency, achieving a 96% total petroleum hydrocarbon (TPH) reduction and a 121% increase in soil respiration in 90 days, particularly in recurrently contaminated soil. This enhanced degradation rate, along with a 120% increase in total phospholipid fatty acid (PLFA), indicates the adaptability of microbial communities under recurrent oil spills and the potential benefits of biochar and bioaugmentation strategies. Furthermore, our analysis revealed the differential influence of these treatments on microbial diversity and composition. Notably, the B1PABS method stimulated microbial communities capable of TPH degradation, as indicated by an early surge in total PLFA and concurrent TPH reduction over time. Hierarchical cluster analysis further unveiled two distinct patterns of microbial adaptability to degrade petroleum hydrocarbons, regardless of the initial contamination level. These findings stress the crucial role of microbial communities in TPH degradation, paving the way for future tailored remediation strategies. Overall, this study provides important insights into the effectiveness of different remediation methods for crude oil-contaminated soil and recurrent spilled contaminated soil. The study highlights the need for tailored approaches to the management of contaminated sites, as different treatments impact the microbial communities and their relationship to key environmental variables differently. This information can be used to potentially lead to more efficient and cost-effective remediation efforts in the future.

Keywords: Petroleum hydrocarbon, bioaugmentation, biochar, repetitive oil spill

4.1. Introduction

The devastating impacts of oil spills on the environment, particularly soil ecosystems, cannot be overstated, causing significant damage to biodiversity and ecological health (Brown et al., 2017; Bamgbose and Anderson., 2020). To address such challenges, various remediation methods have been developed, with bioaugmentation and biostimulation being among the most promising. Bioaugmentation is a process that involves introducing specific hydrocarbon-degrading bacterial species, such as *Rhodococcus*, *Acinetobacter*, *Pseudomonas* sp., and *Bacillus* sp., into the contaminated environment, enhancing the degradation process (Wu et al., 2016). In tandem, biostimulation involves the addition of nutrients and carbon sources to the contaminated soil, thereby promoting the activity of indigenous microorganisms (Rizwan et al., 2016). The synergistic use of these two techniques has been shown to revitalize the microbial community and improve soil conditions (Saeed et al., 2021).

Despite the successes of bioaugmentation and biostimulation, these methods often encounter difficulties when applied to hydrocarbon-contaminated soils. These challenges arise due to the toxicity of hydrocarbons, nutrient scarcity, and microbial competition, which can collectively inhibit the efficiency of microbial degradation processes (Adesina and Adelasoye, 2014). To address the challenges encountered in bioaugmentation, the use of a protective carrier may be necessary to provide a suitable habitat for bacteria and increase their resistance to harsh soil conditions (Xue et al., 2019; Shi et al., 2018; Wang et al., 2019). Agricultural waste products such as rice straw, peanut shells, and biochar have been found to be effective carrier materials, with biochar being unique due to its positive effect on soil fertility and ability to retain water, immobilize bacteria and nutrients, and improve enzyme activity and microbial biofilm establishment (Awad et al., 2018; Babalola et al., 2019; Zhang et al., 2019). However, the interactions between biochar and microbes must be well understood to establish their effectiveness in remediation processes.

The problem of recurrent oil spills on previously remediated sites, especially in regions like the Niger Delta, further amplifies the need for more effective, sustainable remediation methods (Davis, 2016; Ikhumetse et al., 2022). The current study, therefore, proposes an innovative approach—integrating bioaugmentation with

specific bacterial strains, *Pseudomonas aeruginosa* and *Bacillus sonorensis*, and biochar derived from wheat straw and sewage pellets—to enhance the removal and degradation of hydrocarbons in recurrently contaminated soils.

Recurring oil spills on previously remediated sites pose a significant challenge, and sustainable remediation methods are needed to facilitate faster degradation and remediation endpoint. This study proposes the combination of bioaugmentation using *Pseudomonas aeruginosa* and *Bacillus sonorensis* with biochar made from wheat straw pellets and sewage pellets as a promising approach to enhance the removal and degradation of hydrocarbons in crude oil-contaminated soil. The study aims to evaluate the effectiveness of this approach and its potential as a sustainable and cost-effective remediation strategy for repetitive crude oil-contaminated soil. The findings will provide insights into the changes in the microbial community, a comparison of the bioaugmented biochar with initial biostimulation strategies, and the potential of bioaugmented biochar in remediation processes. This research will contribute to the scientific knowledge base and have significant implications for environmental land management practitioners.

4.2. Materials and methods

4.2.1. Soil and biochar samples

This study utilised soil that had previously undergone remediation for crude oil contamination. The initial crude oil spill had a concentration of 10,000 mg kg⁻¹, and after remediation for 180 days, the residual concentration ranged between 256 mg kg⁻¹ and 1058 mg kg⁻¹. From the previous experiment, it was known that the soil samples had been homogenised, air-dried, and sieved through a 2 mm sieve to remove larger particles and impurities. The water content was gravimetrically determined to be 60% (w/w) after heating a sub-sample at 105 °C for 24 hours. The soil was tested for pH and was found to be 8.72 after mixing 1 part soil with 2.5 parts deionized water. The soil had a moisture content of 26%, and the total organic carbon and total nitrogen concentrations were determined using CHN analysis. The grain size analysis of the soil revealed that it had a sandy silt loam structure with 7% clay (< 0.002 µm), 46% silt (0.002-0.063 µm), and 47% sand (0.063-2 µm).

The biochar used in this study was derived from two sources: wheat straw pellets (WSP) and sewage pellets (SP). WSP was selected due to existing research that demonstrated its capability as a biostimulator to mitigate the negative impacts of crude oil contamination on soil organic carbon mineralization and oil degradation (Alotaibi et al., 2018). Furthermore, the use of biochar derived from wheat straw has been associated with reduced greenhouse gas emissions, making it an attractive choice for sustainable agriculture practices (Duan et al., 2020). SP was chosen as another source of biochar due to its potential for improving soil fertility and reducing greenhouse gas emissions, as suggested by previous research. Sewage sludge-derived biochar has been demonstrated to provide significant improvements in soil quality and contribute to environmental sustainability (Zhao et al., 2023). Both WSP and SP biochars were derived from the UK Biochar Research Centre, produced in a pilot-scale rotary kiln pyrolysis unit, and pyrolyzed at 550°C at heating rates of 80°C min⁻¹ and 86 °C min⁻¹, respectively. The basic physicochemical properties of the soil and biochar are presented in Table 4.1.

Table 4. 1 Physicochemical properties of soil and biochar

Properties	Soil	Biochar (WSP)	Biochar (SP)
Sand (%)	47	-	-
Silt (%)	46	-	-
Clay (%)	7	-	-
pH	8.72	9.94	8.17
Electrical Conductivity (dS m ⁻¹)	1.45	1.70	280.80
Total Nitrogen (%)	0.11	1.39	3.75
Ash (%)	-	21	59
Moisture content (%)	26	2	3
Biochar C stability (%)	-	97	84
H:C _{tot}	-	0.37	0.54
Heating rate (°C min ⁻¹)	-	80	86
TPH (g kg ⁻¹)	255.95	-	-
Nominal Heating Temperature (°C)	-	550	550

4.2.2. Incubation experiment

Duplicate soil mesocosms were set up using 2 kg soil in 2.5 L transparent polytetrafluoroethylene (PFTE) containers. The selection of duplicate mesocosms, as opposed to triplicates, was due to the limited availability of certain critical materials such as biochars, specific liquid media, and solvents necessary for comprehensive PLFA and hydrocarbon analyses. These materials are not only specialized but also resource-intensive to procure and prepare. Considering these constraints, using duplicates was deemed an appropriate compromise to balance the need for experimental replication with the availability of resources. This strategic choice allowed for a controlled and thorough examination of each treatment condition, ensuring the conservation of valuable materials throughout the study. The soils were acidified using HNO_3 to achieve a pH level of 5.9, typical of most areas in the Niger Delta region (Onu et al., 2014). Following the acidification, each soil mesocosm was spiked with 20 mL of crude oil (< 0.5% sulphur) to attain a targeted hydrocarbon concentration of 10,000 mg/kg. This setup simulated a recurring oil spill incident over a three-month period, mirroring a realistic contamination scenario prevalent in the Niger Delta region and thereby facilitating the evaluation of the effectiveness of the proposed remediation strategies under such conditions.

In this experimental setup, the control treatment consisted of soil that had been previously subjected to remediation without any additional re-contamination with crude oil or further amendments. This control serves as a baseline to compare the bioaugmented biochar treatments and assess the effectiveness of the added treatments in promoting further degradation of pollutants. It represents a negative control where no further remediation activity is expected given that the soil is not subjected to additional stress or modification.

The mesocosms were then incubated for five days at 28°C, reflecting the average temperature in the Niger Delta region. Nine distinct mesocosm conditions were assessed, as outlined in Table 4.2, throughout a three-month period, with the mesocosms being homogenised on a bimonthly basis. Soil samples were collected at predetermined intervals (0, 7, 21, 42, and 90 days) and stored at -20°C until required for chemical and toxicity analysis. These analyses aimed to provide insights into the influence of the treatments on the microbial communities over the incubation

period. They served to evaluate the rate of degradation and offer a comparative study against the initial experiment's biostimulation strategies.

4.2.3 Construction and optimization of oil-degrading bacterial consortia

Two bacteria strains, *Pseudomonas aeruginosa* (DSM 288) and *Bacillus sonorensis* (DSM 13779) were selected for their robust petroleum-degrading abilities, which have been well-documented in oil-contaminated environments (Behdarvandan et al., 2020; Ali Ebadi et al., 2018). These strains were purchased from the Leibniz Institute DSMZ-German collection of microorganisms and cell cultures GmbH. These strains were selected based on their ability to thrive in a wide variety of environments, tolerate high temperatures up to 37° C, and withstand saline conditions-factors essential for effective bioremediation in the challenging Niger Delta context. The preparation of the bacterial cultures was conducted as follows: (1) the strains were introduced into LB liquid medium and cultured at 37 °C, 180 rpm to logarithmic phase ($OD_{600}=1.0$), which typically occurs between 16-24 hours; (2) Then the bacterial culture was subjected to centrifugation at 3500 rpm for 10 min; the supernatant was discarded and sterilised minimal salt medium (MSM) was added to re-suspend the strains; (3) the suspension was adjusted to the required cell density ($OD_{600}=1.0$, which was equivalent to a cell concentration of 1.4×10^7 CFU/ml) using MSM. This approach to adjusting bacterial cell density using optical density measurements was adopted in the study carried out by Beal et al. (2020). Then the suspensions of PA and BS were mixed in a 1:1 ratio to establish consortia: PABS.

4.2.4 Immobilisation of bacterial consortium onto biochar and SEM observation

The samples were prepared according to the method described by Xiong et al. (2017). Briefly, 1 g of the soil matrix sample was sifted through a 1 mm sieve before being placed in a sterilised Erlenmeyer bottle containing 10 mL of LB medium. The bacterial consortium was then immobilised using an orbital shaker set at 30°C and 80 rpm for 48 hours. We then separated the soil matrix using a 75 µm filter paper, and the immobilised bacterial consortium on the soil matrix was washed three times with 15 mL sterile water to remove any free cells.

Table 4. 2 Summary of the bioaugmented biochar treatments evaluated along with the controls

Mesocosm	Condition
A	Control
Biochar 1 (B1)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) wheat straw pellets biochar
Biochar 1 + PA (B1PA)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) wheat straw pellets biochar + <i>Pseudomonas aeruginosa</i>
Biochar 1 + BS (B1BS)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) wheat straw pellets biochar + <i>Bacillus sonorensis</i>
Biochar 1 + PA + BS (B1PABS)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) wheat straw pellets biochar + <i>Pseudomonas aeruginosa</i> + <i>Bacillus sonorensis</i>
Biochar 2 (B2)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) Sewage Pellets biochar
Biochar 2 + PA (B2PA)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) Sewage Pellets biochar + <i>Pseudomonas aeruginosa</i>
Biochar 2 + BS (B2BS)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) Sewage Pellets biochar + <i>Bacillus sonorensis</i>
Biochar 2 + PA + BS (B2PABS)	Crude oil remediated soil + spiked again with 10,000 mg kg ⁻¹ crude oil + 10% (w/w) Sewage Pellets biochar + <i>Pseudomonas aeruginosa</i> + <i>Bacillus sonorensis</i>

All conditions were done in duplicates

The samples were fixed using the procedure reported by Wang et al. (2019), where the soil matrix was submerged in 4% (w/v) glutaraldehyde in 0.2 M phosphate-buffered saline (PBS) for 3 hrs at 4°C. Following fixation, samples were transferred and stored in a PBS/ethanol solution (50:50, v/v) at -20°C in preparation for imaging. The samples were dried for 2.5 hours. The dried composite material was observed by SEM using a Quanta FEG 650 SEM. One to two-centimetre square representative areas of each filter paper were cut from the larger filters and placed on a specially constructed multi-filter sample holder, then placed within the SEM without any further preparation. The SEM was operated in low-vacuum mode (approximately 0.83 Torr), which does not require non-conductive material to be gold or carbon-coated. Samples were imaged using a backscattered electron (BSE) detector using an operating voltage of 8 or 10 kV. Multiple SEM images were captured for each sample at a range of various magnifications from 500x to 20,000x to ensure a comprehensive assessment of the immobilised bacterial consortium in the soil matrix.

4.2.5 Soil microbial respiration rate

The CO₂ generation rate was measured using soil basal respiration, which is an assessment of the consistent rate of microbial respiration in soil. The soil basal respiration was recorded at the start of the experiment and then again on days 7, 14, 21, 42, and 90 of the mesocosm study. The measurement was taken using the Rapid Automated Bacterial Impedance Technique (RABIT) respirometer from Don Whitley Scientific in Bingley, UK. Duplicates of 1 g of soil sample were saturated in a glass boat and used for the determination of soil basal respiration, following the procedure described by Pawlett et al. (2013). The microbial respiratory response was monitored for 48 hours at 25°C. The variations in conductivity were calculated and converted to CO₂, following Ritz et al. (2006). The quantification of the conductivity was done using the RABIT software (version 2.31, 01-1999).

4.2.6 PLFA Analysis

The microbial community composition was assessed using a modified version of the method described by Frostegård et al. (1993), which involved analysing phospholipid

fatty acids (PLFAs). 10 grams of freeze-dried soil were extracted using a solvent blend of chloroform, methanol, citrate buffer, and butylhydroxytoluene (BHT), as reported by Cipullo et al. (2019). The extracted phospholipids were transformed into fatty acid methyl esters and evaluated by gas chromatography with a flame ionisation detector. A total of 34 different PLFAs (biomarkers) were identified and expressed as a percentage of the total PLFA peaks, as shown by Pawlett et al. (2013). Based on the approach outlined by Quideau et al. (2016), these biomarkers were grouped into gram-positive, gram-negative, fungi, and actinobacteria.

4.2.7 Hydrocarbon Extraction and Analysis.

The extraction and analysis of total petroleum hydrocarbons (TPHs) were adapted from Risdon et al. (2008). Total hydrocarbons were extracted from 2.5g of soil samples using dichloromethane:hexane solvent mixture (1:1 ratio), followed by a cleaning process of Florisil columns and resulting extracts adjusted to a final volume of 0.5 ml. The analysis was performed with a Shimadzu TQ8040 GC–MS, employing a full scan mode (m/z 50–500) for quantitative TPH analysis. Deuterated alkane and PAH standards were added before the analysis. Measurements were made on days 0, 7, 21, 42, and 90, grouping alkanes into C10-C12, C12-C16, and C16-C35, and PAHs into C12-C16, C16-C21, and C21-C35. Calibration employed alkane (C8-C40) and PAH standards (EPA 525 PAH Mix A) with concentrations ranging from 1–5 ppm, and blank controls were assessed every 20 samples for quality control.

4.2.8 Data analysis

We applied a one-way ANOVA to assess the effect of treatments on TPH, total biomass, and respiration rates across specified intervals (0, 7, 21, 42, and 90 days). We also explored the impact of the treatments over the course of the incubation period. Principal Component Analysis (PCA) was conducted on multivariate datasets using Statistica® version 14.0.0.15 to illustrate shifts in microbial community dynamics and respiration profiles in response to various treatments and incubation durations. Further, Hierarchical Cluster Analysis (HCA) was performed in Minitab to group similar sets of data based on specific responses to treatments, such as TPH, soil respiration, and total biomass (as indicated by PLFA profiles). These clusters

help in identifying patterns and understanding the underlying structure of the data. Any p-value less than 0.05 was considered statistically significant.

4.3 Results and Discussion

4.3.1 Soil and biochar and immobilised bacteria characteristics

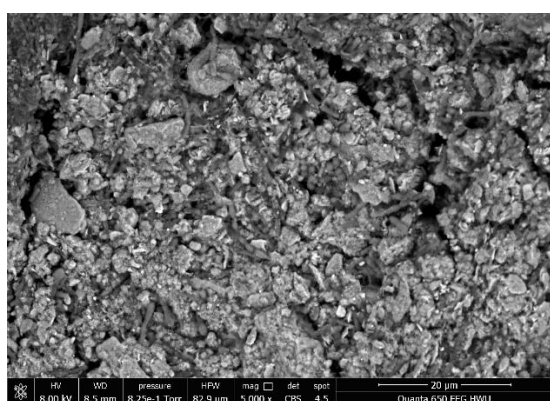
The physicochemical properties of the soil and biochar play a significant role in their potential use in the bioremediation of petroleum hydrocarbon-contaminated soil. The soil in this study is characterised by a high content of sand and silt, accounting for approximately 93% of the total soil composition, and a low clay content of about 7%. Such a composition ensures good drainage and aeration, which are critical for microbial activity and bioremediation. This observation was noted in the previous chapter and is essential for understanding the context of this study.

Building on the previous experiment, the soil originally had an alkaline pH of 8.7. However, to mimic the conditions of the Niger Delta, the soil pH was intentionally acidified to approximately 5.9 using HNO_3 . Under these new conditions, the soil was spiked with crude oil and prepared for a subsequent round of bioremediation. The biochars (WSP and SP), with high pH values of approximately 10 and 8, respectively, play a critical role in this context. The addition of biochar to the acidified soil has the potential to buffer the pH, moving it closer to neutrality: the WSP biochar amended soil pH is 7.9, the SP biochar amended soil pH is 7.3, and the WSP&SP biochar amended soil registers a pH of 8.1. This pH adjustment can be particularly beneficial for bioremediation, as many hydrocarbon-degrading microorganisms thrive in near-neutral to slightly alkaline environments.

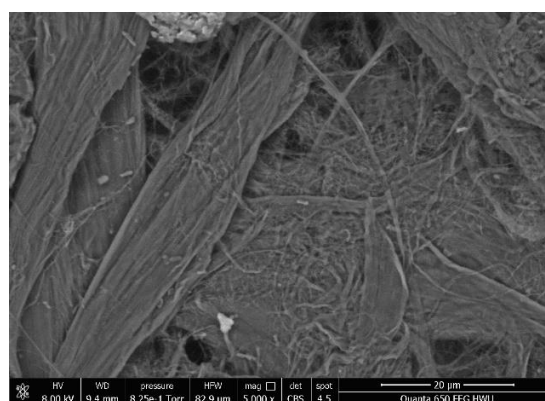
The EC of Biochar (WSP) and Biochar (SP) are 1.70 and 280.80 dS m^{-1} , respectively, indicating high levels of salt content in Biochar (SP). The total nitrogen content in Biochar (WSP) is 1.4%, which is significantly higher than that in the soil and Biochar (SP). The ash content in biochar (WSP) and biochar (SP) is 21% and 59%, respectively, which is much higher than that in the soil. The moisture content in biochar (WSP) and biochar (SP) is lower than that in the soil, indicating good stability. Biochar (WSP) and Biochar (SP) also have different carbon stability and heating rates. Biochar (WSP) has higher carbon stability at 96% compared to Biochar (SP) at 84%. The heating rate of biochar (WSP) is $80^\circ \text{C min}^{-1}$, while that of

biochar (SP) is $86^{\circ}\text{C min}^{-1}$. The total petroleum hydrocarbon (TPH) content in the soil is substantial, at approximately 256 g kg^{-1} . In contrast, TPH content is not detected in either type of biochar, signifying that the biochars themselves are free from petroleum hydrocarbons. The nominal heating temperature for both biochars was set at 550°C during pyrolysis.

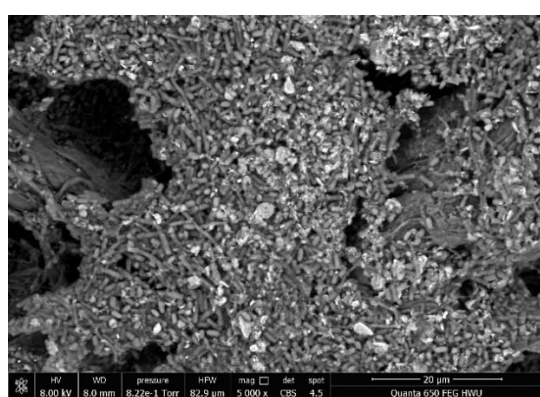
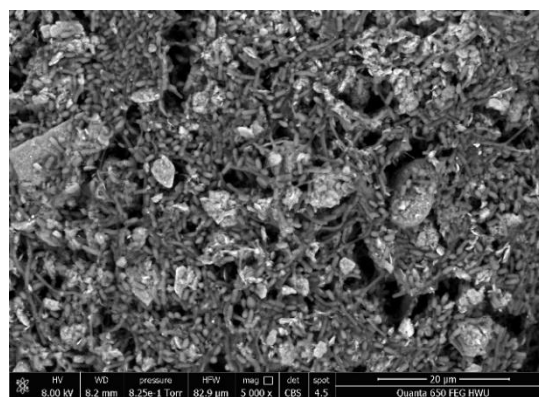
The SEM images of the materials used in the study were analysed, and the results are shown in Figure 4.1. The analysis of SEM images provided detailed insight into the surface morphology and features of the biochar used in our study. SEM image (a) displays WSP with no bacteria attached, serving as a reference point for comparing the other samples. The Sewage Pellets (SP), as shown in Figure 4.1b, displayed a contrasting structure due to their different origin and preparation process. Figures 4.1c and 4.1d show the immobilised bacteria on WSP and SP, respectively, offering valuable insights into the interaction between bacterial strains and the biochar materials.



1 (a)



1 (b)



1 (c)

1 (d)

Figure 4. 1 Scanning electron microscopy (SEM) images of (a) Wheat straw pellets (WSP); (b) Sewage pellets (SP); (c) immobilised bacteria on the surface of WSP and (d) immobilised bacteria on the surface of SP.

Notably, while some bacteria successfully attached to the biochar particles, others did not. This observation suggests that the bacteria may not have successfully colonised or attached to the biochar surface. It is possible that the physical preparation process caused the bacterial cells to detach from the biochar surface, as seen in the SEM image. This detachment may have led to a reduction in the efficiency of the immobilised bacteria, which could negatively impact the performance of the remediation method. The SEM images underscore the need for optimising the preparation and immobilisation processes to improve the attachment and colonisation of the bacteria on the biochar surface, potentially enhancing the efficiency of the remediation method.

4.3.2 Microbial respiration

The microbial respiration rates in the biochar and bioaugmented biochar mesocosms demonstrated clear changes over the course of the experiment. A gradual increase in respiration was observed after 7 days in all mesocosms, signifying enhanced microbial activity (Fig 4.2). The surge in microbial activity after seven days could potentially be attributed to the microbes adapting to their environment and beginning to utilise the nutrients present, including petroleum hydrocarbons. This inference is supported by our observation that the respiration rates in all mesocosms, including the biochar and bioaugmented biochar samples, exhibited an increase from the initial time point to day 7. In particular, the biochar and bioaugmented biochar samples demonstrated a greater increase in respiration rates compared to the control. This observation suggests that the biochar and/or introduced microorganisms may have facilitated enhanced microbial activity. Moreover, the persistent increase in respiration rates in the biochar and bioaugmented biochar mesocosms up to day 42, as opposed to a smaller increase in the control, further suggests that the microbes were continuously adapting and utilising available nutrients over time. While these observations align with our inference, a direct assessment of soil nutrient levels and microbial responses to the biochar and bioaugmentation procedures would provide more conclusive evidence. Such assessments should be the focus of future studies.

Scanning electron microscope (SEM) analysis yielded intriguing observations about the interaction between bacteria and the biochar matrix. The initial SEM results suggest that the bacteria may not have fully adhered to or colonised the biochar surface, potentially due to the physical preparation process. This observation aligns with the presence of detached bacterial cells observed in the SEM images. Despite this potential lack of complete colonisation, the biochar and bioaugmented biochar treatments still had significant impacts on microbial respiration. Yet, this lack of colonisation could imply the potential for further improvements in the bioaugmentation process and the overall efficacy of the remediation strategy. If full colonisation were to be achieved, it is plausible that the remediation effect could be even more pronounced. Future research should therefore focus on optimising the physical preparation of biochar to facilitate better microbial adherence and colonisation. In contrast to the initial oil spill data, the microbial activity in this experiment began to surge earlier, particularly in the combined bioaugmentation mesocosms (B1PABS and B2PABS). By day 42, CO₂ production had increased significantly, signifying a marked acceleration in microbial growth metabolism and TPH degradation. These observations might suggest that a second oil spill in the same environment could trigger a faster microbial response, possibly due to the enhanced adaptability and abundance of the microbes. This hypothesis, however, warrants further research for confirmation.

Quantitative comparison elucidates this more clearly. By day 42 of the initial experiment, the most effective treatment had exhibited a CO₂ production of 0.61, approximately 6.1 times the baseline value. In the current experiment, by the same day, B1PABS and B2PABS displayed CO₂ production of 1.1 and 1.05, respectively—about a 1.74-fold and 1.75-fold increase over the maximum value from the initial experiment, respectively. We hypothesise that this increased response in the current experiment could be due to the environmental stress from the first oil spill and the selection of more robust hydrocarbon-degrading microbial strains. However, this is speculative, and further dedicated research involving metagenomic and transcriptomic analyses of the microbial communities is needed. The respiration rates displayed a close negative correlation with the TPH removal rate, suggesting that higher respiration values could enhance the TPH remediation process. The biochar provided a favourable buffer system for the microorganisms, offering a

competitive advantage for the exogenous bacteria, which were able to improve their density, soil porosity, permeability, and activity stability. This could have facilitated a synergistic effect between indigenous and exogenous bacteria, leading to high-efficiency TPH degradation with no toxic effects on the soil or microorganisms. The immobilised microorganisms in the biochar had high efficiency in TPH degradation and produced no toxic effect on the soil or microorganisms, achieving a dual function of waste reuse and soil rehabilitation. These findings suggest that the use of biochar and bioaugmentation may provide a sustainable and cost-effective solution for the remediation of petroleum-contaminated soil. More research is needed to optimise these methods, enhance the bacteria-biochar interaction, and explore potential applications in other contamination scenarios and their scalability for widespread environmental use.

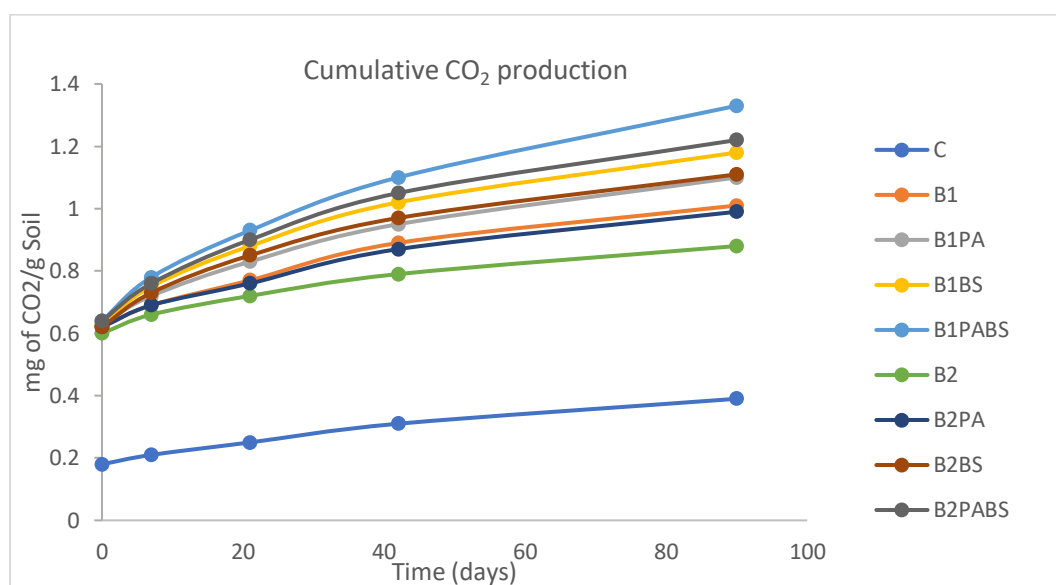


Figure 4. 2 Cumulative curve of CO₂ production expressed in mg CO₂/g soil for soil treatments with Control, B1, B1PA, B1BS, B1PABS, B2, B2PA, B2BS, and B2PABS tested at 0, 7, 21, 42, and 90 days. Error bars denote the standard deviation across duplicates.

4.3.3 Soil microbial community structure

Our study shows that the bioremediation treatments utilised had notable impacts on the structure of microbial communities. As highlighted by the principal component

analysis (PCA) plot, which accounted for 28.91% of the variance, significant shifts in microbial community structure over time were observed. This reflects the adaptability of these communities to environmental stressors such as TPHs. Initially (day 0), the microbial communities across most treatments exhibited similar compositions, clustering closely together on the PCA plot (Fig 4.3). However, on day 7, significant shifts were observed, with the majority of these treatments forming distinctive clusters, indicating a rapid microbial response to the introduction of TPH. By day 21, most of the treatments showed further shift, while B1BS and B1PA formed separate clusters, highlighting their continuous adaptation during the study period. These adaptative changes were further pronounced by day 42, when all treatments converged closer to their initial positions, implying a common TPH degradation strategy across microbial communities. Interestingly, by day 90, microbial communities across treatments had become more distinct, with B1PABS being the exception as they continue to diverge. All other treatments showed similar responses, suggesting differential microbial reactions to extended TPH exposure. These observed patterns align with previous findings, underscoring the sensitivity of microbial communities to population disturbances and their structural shifts when faced with environmental stressors like crude oil contamination (Steven and Martiny, 2008). The temporal shifts could be associated with changes in ecosystem processes or might reflect functional redundancy, where the altered community persists to perform similar functions (Shade et al., 2012). Furthermore, the unique temporal dynamics exhibited by the treatments illustrate how the combination of biochar and bacterial strains influenced the microbial community structure and its response to TPH degradation. For instance, treatments like B1PABS, which showed distinct patterns on the PCA plot, had notable PLFA profiles, suggesting successful stimulation of microbial communities capable of TPH degradation. Detailed PLFA analysis revealed that treatments B1PABS and B2PABS had the highest microbial biomass, presumably due to TPHs stimulating microbial growth. In contrast, treatments B2 and B2PA experienced the highest level of bacterial stress, as suggested by the lower level of total PLFA detected. The analysis also demonstrated significant temporal shifts in the microbial community structure in response to TPH exposure, with an early surge in total PLFA content (0–7 days) suggesting increased microbial biomass. Concomitantly, a significant reduction in TPH content over time indicated the capability of the microbial community to degrade TPHs in the soil.

These findings also illustrated variations in the microbial community structure across treatments. Treatments B1 and B1PA experienced higher bacterial stress compared to others, likely due to high TPH exposure. Interestingly, there was an increase in the relative abundance of gram-negative bacteria over time, especially in B2 and B2PA treatments, known for their higher TPH degradation capacities. This suggests that the composition of the microbial community can be influenced by the biochar type and bacterial strain used, affecting the overall TPH degradation capability of the microbial community. While we did not analyse specific microbial taxa or groups in this study, our results underscore the impact of biochar type and bacterial strain on the overall structure of the microbial community. Given the observed effects of the treatments on microbial community dynamics, it's plausible that different treatments might favour or inhibit certain microbial groups. These findings provide critical insights for tailoring bioremediation strategies. They underscore the potential of using biochar and specific bacterial strains as tools for sustainable remediation of TPH-contaminated soils, especially in oil-prone regions like the Niger Delta. However, further research is needed to identify microbial taxa that respond to different treatments and clarify their roles in TPH degradation, which would help optimize bioremediation strategies, foster beneficial microbial communities, and expedite soil recovery.

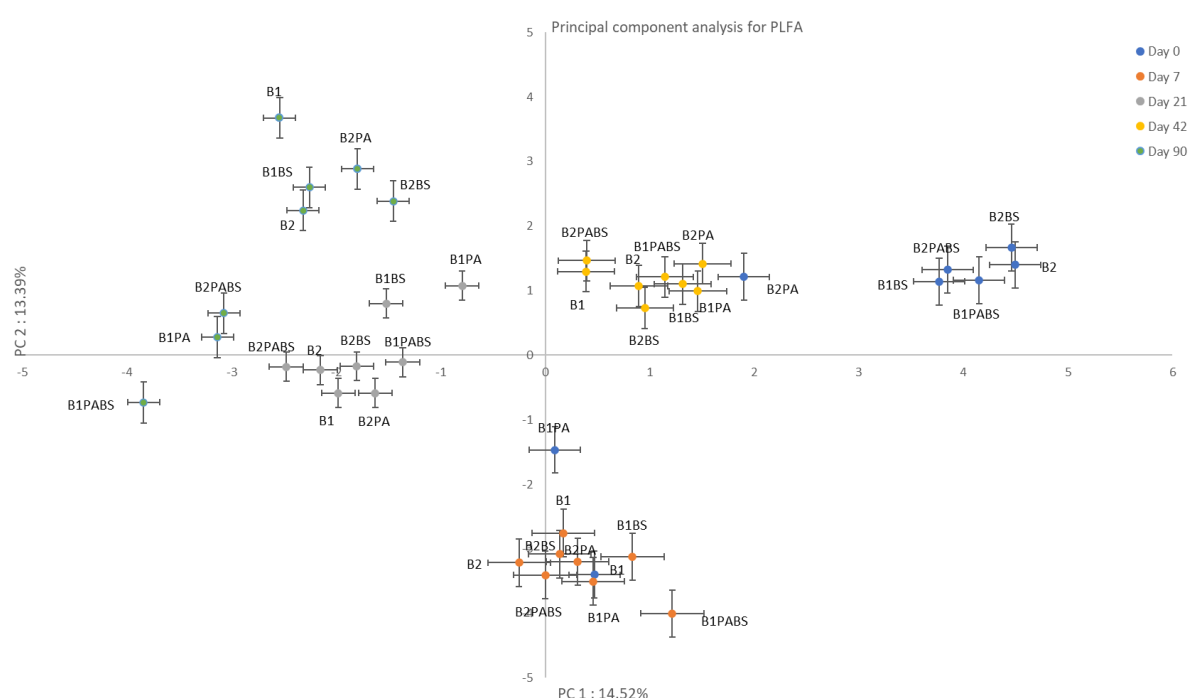


Figure 4. 3 Temporal Dynamics and Shifts in Microbial Community Composition under Various Biochar and Bacterial Strain Treatments: A PCA Analysis of PLFA Over 90-Day Incubation. The error bars denote the standard error for each set of replicates with a treatment. B1: Wheat straw pellets; B2: Sewage pellet; PA: *Pseudomonas aeruginosa*, BS: *Bacillus sonorensis*

4.3.4 Biodegradation of petroleum hydrocarbons

TPH was significantly reduced ($p < 0.05$) in biochar and bioaugmented biochar-treated soils as depicted in Table 4.3. The biochar mesocosms (B1 and B2) showed a TPH degradation rate of 85% after 90 days. The bioaugmented biochar-mesocosms had higher TPH degradation rates. Specifically, treatments B1PA, B1BS, B1PABS, B2PA, B2BS, and B2PABS had TPH degradation rates of 90%, 95%, 96%, 90%, 93%, and 95%, respectively. The application of bioaugmented biochar (B1PA, B1BS, B1PABS, B2PA, B2BS, and B2PABS) to the contaminated soil resulted in the highest TPH decrease, followed by the biochar treatment alone (B1 and B2). The reason for the better performance of the immobilised group could be attributed to the larger specific surface area and rough surface structure of biochar, which can better support the attachment of biofilms produced by microorganisms. This, in turn, leads to the formation of covalent bonds and specific adsorption between biochar and bacteria, resulting in the promotion of microbial activity in a shorter time frame and an improved rate of adsorption and degradation of hydrocarbons. Moreover, B1PABS and B2PABS showed TPH concentrations 2-fold higher than B1BS and B2BS, and 3-fold higher than B1PA, B1, B2PA, and B2 respectively. This could be due to the introduction of two strains capable of degrading a broader spectrum of contaminants than a single species as illustrated by Dombrowski et al. (2016). However, B1PABS showed better results than B2PABS, likely due to the higher biochar Carbon stability value of B1 (97%) compared to B2 (84%). A higher stability value suggests that biochar is less likely to decompose in soil over time, providing a longer-term benefit for improving soil health and reducing hydrocarbon contamination. Furthermore, wheat straw biochar may have a higher porosity and surface area, which can enhance its ability to adsorb hydrocarbons and other contaminants in soil. Biochar introduction had shown a significant increase both in the absence and presence of immobilised bacteria.

Table 4. 3 Mean concentrations and percentage degradations for alkane groups (>EC10-12, >EC12-16, >EC16-35) and PAH groups (>EC12-16, >EC16-21, >EC21-35)

Aliphatic (mg kg ⁻¹)	Initial	B1 (%)	B1PA (%)	B1BS (%)	B1PABS (%)	B2 (%)	B2PA (%)	B2BS (%)	B2PABS (%)
>EC10-12	78.7	99	97	98	99	98	99	96	98
>EC12-16	223.4	88	89	94	97	88	87	93	96
>EC16-35	812.2	85	87	93	94	84	84	92	93
Aromatic (mg kg ⁻¹)									
>EC12-16	2.7	94	95.7	99	99	93	95	95	99
>EC16-21	82.1	88	89	94	95	87	87	92	94
>EC21-35	170.9	84	86	92	93	84	85	90	92
PAH indicator									
Acenaphthylene	0.4	94	96	99	99	94	95	99	99
Fluorene	0.3	90	92	96	97	90	91	94	95
Phenanthrene	0.3	90	92	96	96	90	91	94	95
Anthracene	0.3	90	92	96	96	90	91	93	95
Pyrene	11.4	90	91	96	96	89	90	92	95
Benz(a)anthracene	8.2	90	91	95	95	89	90	92	95
Chrysene	9.7	90	90	95	95	88	89	92	95
Benzo[b]fluoranthene	10.4	89	90	94	95	88	89	92	95
Benzo[k]fluoranthene	6.6	89	90	94	95	88	89	90	95
Benzo[a]pyrene	26.6	87	88	94	95	86	87	90	95
Benzo[ghi]perylene	44.6	87	88	94	95	86	87	90	95
Dibenz[a,h]anthracene	4.7	87	88	94	95	86	87	90	94
Indeno[1,2,3-cd]pyrene	21.7	87	88	94	95	86	87	90	94

Table 4. 4 Percentage change in concentration of Different Alkane Groups across various Treatments at Day 90.

Alkane Group	Initial(mg kg ⁻¹)	B1 (%)	B1PA (%)	B1BS (%)	B1PABS (%)	B2 (%)	B2PA (%)	B2BS (%)	B2PABS (%)
Undecane	392.2	95	96	99	99	93	95	98	99
Dodecane	477.8	95	96	98	99	93	95	97	98
Tridecane	485.2	95	96	98	99	93	95	97	99
Tetradecane	390.1	95	96	98	99	93	95	97	97
Pentadecane	385.4	93	94	96	99	92	93	95	97
Hexadecane	327.4	93	94	96	99	92	93	95	97
Heptadecane	333.8	92	94	96	98	91	91	95	97
Octadecane	332.2	92	93	96	98	91	91	94	97
Phytane	292.2	92	93	96	96	91	91	94	96
Nonadecane	364.7	92	93	96	97	91	91	93	97
Eicosane	377.9	91	90	95	97	90	90	93	97
Henicosane	400.1	91	90	95	97	90	90	93	97
Dosocane	415.1	91	90	95	97	90	90	93	96
Tricosane	430.8	90	89	95	97	89	89	93	96
Tetracosane	224.4	90	89	95	97	89	89	93	96
Pentacosane	457.7	90	89	95	97	89	89	93	96
Hexacosane	414.1	90	89	95	97	89	89	93	96
Heptacosane	410.5	89	89	95	97	89	89	93	96
Octacosane	189.9	88	88	95	97	88	88	93	96
Nonacosane	362.9	88	88	95	97	88	88	93	96
Triacontane	325.9	88	88	95	97	88	88	93	96
Hentriacontane	231.5	88	88	95	97	88	88	93	96
Dotriacontane	175.2	88	88	94	97	88	88	93	96
Tetratriacontane	146.8	88	88	93	97	88	88	93	95
Tetratriacontane	294.7	88	88	91	97	88	88	91	95
Pentatriacontane	260.5	88	88	91	97	88	88	91	94
Hexatriacontane	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d

n.d: Not detected

The effective degradation of TPH is an essential benchmark in assessing the success of bioremediation strategies. However, considering the diverse composition of TPH, it was equally crucial to examine the degradation of individual hydrocarbons, especially those resistant and toxic compounds. Attention was placed on specific compounds as indicators for diverse hydrocarbon ranges. For lighter hydrocarbons (>EC12-16), acenaphthylene, fluorene, phenanthrene, and anthracene were selected due to their common presence in petroleum contaminants and their varied degradation rates, which provide a comprehensive overview of the biodegradation process under different treatments. These compounds demonstrated degradation rates ranging from 90% to 99% after 90 days across all treatments. In the case of heavier hydrocarbons (>EC21-35), compounds like benzo[a]pyrene, benzo[ghi]perylene, dibenz[a,h]anthracene, and indo[1,2,3-cd]pyrene were examined due to their complexity and persistence in the environment, showed a similar reduction over time, albeit at a slower rate. The percentage degradation on day 90 ranged from 87% to 95% across all treatments, demonstrating the potential of the consortium to break down even complex hydrocarbons.

These compounds not only represent a spectrum of petroleum hydrocarbons but also provide a gauge of how well the biochar treatments performed against a variety of challenges within a contaminated environment. If these treatments can efficiently degrade these resistant compounds, it implies their efficacy. It would suggest a broader effectiveness against the majority of hydrocarbons found in petroleum contamination. As detailed in Table 4.3, across all treatments, these indicator compounds (light-heavy) demonstrated significant degradation rates after 90 days, suggesting their potential as reliable markers for the monitoring of treatment efficacy. The high efficiency is likely attributable to the broad substrate ranges of *Pseudomonas aeruginosa* and *Bacillus sonorensis* bacteria, combined with the absorption properties of the wheat straw and sewage biochar. These findings underscore the promising potential of our biochar treatments to degrade a wide array of hydrocarbons, contributing to effective soil bioremediation.

Alongside the degradation of various hydrocarbons, the degradation rates of different alkane groups: >EC10-12, >EC12-16, and >EC16-35 were evaluated. Each of these classes showed significant percentage decreases over the 90-day period across all treatments as depicted in Table 4.4. For the lighter alkanes (>EC10-12), percentage

reductions ranged up to 99% in B1PABS and B2PABS treatments. The mid-range alkanes (>EC12-16) showed reductions up to 99% in B1PABS treatment. Heavier alkanes (>EC16-35) also demonstrated significant reductions, with a maximum reduction of approximately 98% in the B1PABS treatment. This emphasizes the versatility of our combined biochar and bioaugmented biochar treatments in degrading different alkane classes, further illustrating the efficiency of our combined treatment strategies in biodegradation processes. Taken together, our study underscores the effectiveness of biochar, and especially bioaugmented biochar, in the degradation of a wide range of petroleum hydrocarbons. Future research should continue to refine these strategies, focusing on the optimization of conditions for bacterial activity and the broad-spectrum degradation of various hydrocarbon contaminants, thereby promoting effective and efficient bioremediation processes.

4.3.5 Correlation between treatments

A hierarchical cluster analysis was performed to further explore the relationships between treatment, time, biomass, TPH, and respiration. This multivariate analysis provided a deeper understanding of the dynamics among these variables and allowed us to identify two distinct response patterns within the treatments. The analysis organised our observations of treatments over time into two groups: Cluster 1, which consisted of 24 observations (treatment conditions over time), and Cluster 2, with 8 observations (Table 4.5). Both clusters showed similar trends: as respiration increased, TPH levels decreased, indicating an efficient degradation of petroleum hydrocarbons. Furthermore, both clusters exhibited a positive correlation between respiration and biomass, consistent with the increase in microbial activity. Despite these commonalities, the clusters also displayed unique characteristics. Cluster 1 had relatively lower biomass and higher TPH concentrations at the start of treatment, while Cluster 2 started with higher biomass and lower TPH concentrations. However, by the end of treatment, both clusters exhibited increased biomass and reduced TPH, showing the efficacy of the treatments. The statistically significant differences between the clusters for all variables (biomass, TPH, and respiration) substantiate the validity of this two-cluster solution. Despite their distinct starting points, both clusters evolved to show a reduction in TPH and an increase in biomass and respiration, demonstrating the adaptability and resilience of the microbial communities to different contamination levels and their ability to degrade

petroleum hydrocarbons. These findings underscore the importance of respiration in the remediation of petroleum hydrocarbon-contaminated soils, regardless of the initial contamination level. The increase in microbial biomass, as evidenced by the rise in PLFA, highlights the crucial role of microbial communities in TPH degradation.

Table 4. 5 Summary of Hierarchical Cluster Analysis Results, Biomass, TPH, Respiration Levels, and Treatment Case Numbers Over Time

Initial and Final cluster centres				
	Initial Cluster Centre 1	Initial Cluster Centre 2	Final Cluster Centre 1	Final Cluster Centre 2
Biomass	72.29	153.04	109.17	135.71
TPH	5644.20	726.36	4781.67	1256.73
Respiration	0.66	1.33	0.84	1.10
ANOVA Results				
	Cluster	Error	F	Sig.
Biomass	4224.93	392.63	12.82	0.001
TPH	74551212.02	284188.99	262.33	<0.001
Respiration	0.43	0.02	26.55	<0.001
Number of Cases in Each Cluster				
1	24			
2	8			

Table 4. 6 Comparison of remediation methods for crude oil-contaminated soil and repetitive spilled contaminated soil

Remediation stage	Contamination level (mg kg ⁻¹)	Methods used	Timeframe (days)	Respiration (% increase)	TPH (% degradation)	Total PLFA (increase)
Initial Crude oil remediated soil	10,000	MNA	90	56	37	3
		A1		61	75	5
		A2		63	76	6
		A3		68	78	19
Initial Crude oil remediated soil	10,000	MNA	180	42	79	39
		A1		57	89	41
		A2		61	95	46
		A3		62	97	56
Remediation of repetitive spilled contaminated soil	10,000	B1	42	44	75	80
		B1PA		51	77	82
		B1BS		62	88	97
		B1PABS		72	90	102
		B2		32	73	77
		B2PA		40	75	83
		B2BS		56	78	87
		B2PABS		64	89	97
Remediation of repetitive spilled contaminated soil	10,000	B1	90	62	82	108
		B1PA		74	90	115
		B1BS		87	95	117
		B1PABS		107	96	120
		B2		47	85	86
		B2PA		60	90	87
		B2BS		82	93	103
		B2PABS		91	95	104

MNA: Monitored Natural Attenuation; A1: Oxygen Release compound (ORC); A2: ORC+ N&P (Nitrogen and Phosphorus); A3: ORC + Compost

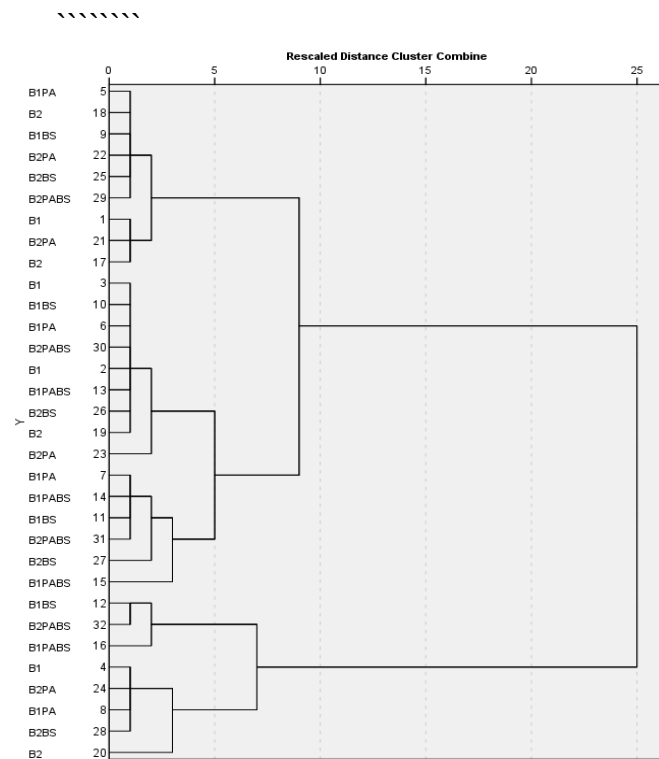
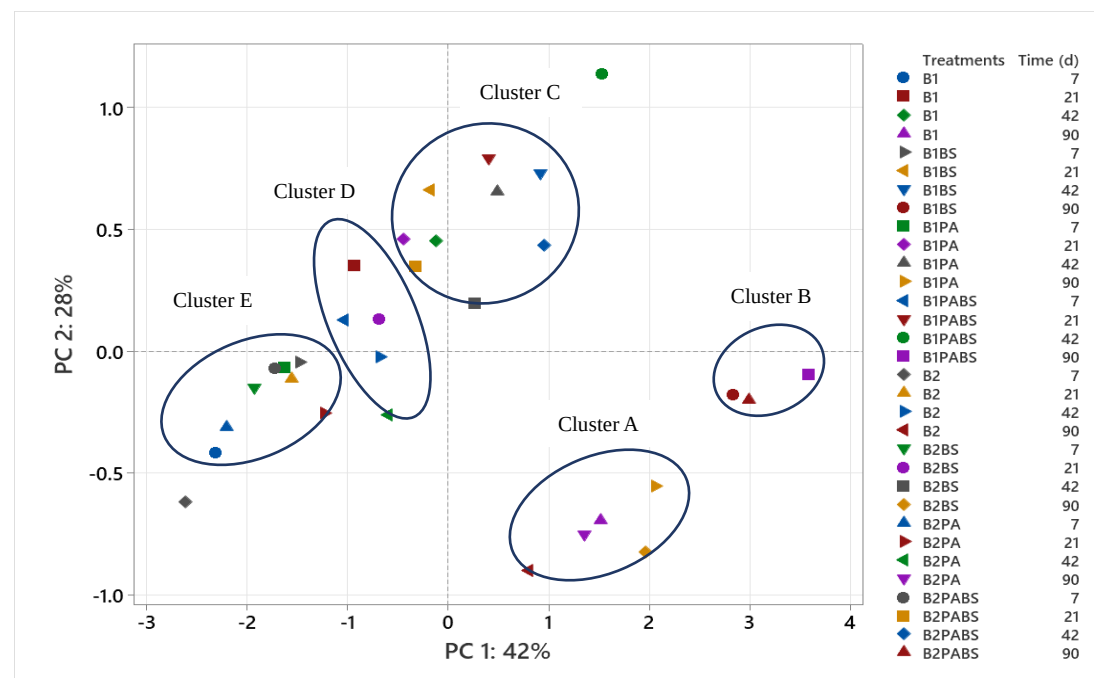


Figure 4. 4 Hierarchical clustering analysis of microbial community responses in relation to biomass, Respiration, and TPH degradation across the different treatments.

Building upon the cluster analysis, further detailed exploration was conducted to understand the specific microbial responses to distinct treatments. It was observed that different bacterial interactions with different biochar types led to noticeable variations within our clusters. The combined bioaugmented biochar treatments (B1PABS and B2PABS) notably clustered together in Cluster B (Fig 4.4). In contrast, bioaugmented biochar treatments (B2PA, B2BS, and B1PA) involving only one bacterium type were predominantly seen in Cluster A. This clustering pattern suggests the synergistic use of *Pseudomonas aeruginosa* and *Bacillus sonorensis* with either type of biochar enhances hydrocarbon degradation, with similar respiration, biomass, and TPH patterns at the 90-day mark. On the other hand, treatments with biochar and a single type of bacterium exhibited slightly different trends, implying that each bacterial type interacts uniquely with the biochar and hydrocarbons, affecting degradation rates and extents. These observations enrich the understanding of the intricate dynamics between treatments, time, biomass, TPH, and respiration. They highlight the importance of precise microbial and treatment combinations in optimising petroleum hydrocarbon degradation.

4.3.6 Comparison between initial remediation and respilled remediated soil

This research scrutinised the efficiency of various remediation techniques applied to initial crude oil contamination and repeated oil spills, both maintaining a contamination level of 10,000 mg kg⁻¹ (Table 4.6). The remediation methods for the initial contamination were labelled MNA, A1, A2, and A3, whereas repeated spill remediation incorporated the strategies B1, B1PA, B1BS, B1PABS, B2, B2PA, B2BS, and B2PABS. When comparing the 90-day outcomes from the repeated oil spill scenario with the 180-day outcomes from the initial contamination, the remediation methods used for the repeated spills proved to be significantly more efficient. The B1PABS approach showed superior effectiveness. For example, the most effective method for the initial contamination achieved a TPH degradation percentage of 82% after 180 days, whereas B1PABS accomplished a degradation of 93% in just 90 days for repeated spills. This equates to an approximately 1.1-fold increase in efficiency within half the timeframe. This increased degradation may be attributed to the biochar application in the B1PABS method, which might have increased the bioavailability of petroleum hydrocarbons for microbial metabolism. It's also possible that repeated exposure to oil spills could have selected for more robust

hydrocarbon-degrading microbial strains, thereby enhancing the overall microbial activity and promoting more efficient degradation. Respiration also increased significantly in the repeated spills scenario with B1PABS, marking a substantial 107% increase after 90 days, a 1.7-fold and 1.2-fold increase over the initial contamination scenario's most effective method at 90 and 180 days, respectively. This increased respiration could be a result of a 'priming effect', where the soil's microbial communities respond more rapidly and effectively to repeated spills due to previous exposure to oil. Even more striking was the total PLFA increase. The initial contamination's most effective method achieved a 56% increase after 180 days. However, in the repeated spill scenario, the B1PABS method achieved a remarkable 120% increase in total PLFA in just 90 days, translating to a more than six-fold (6.32 times) and two-fold (2.14 times) increase higher than the initial spill for days 90 and 180, respectively. This dramatic increase may be attributed to enhanced nutrient cycling induced by biochar application or the selection of more diverse and efficient oil-degrading microbial communities during the second spill. While these theories suggest plausible explanations for the observed results, the precise mechanisms underpinning this time-dependent efficiency remain an open question. This enhanced remediation potential for recurrently contaminated soils, observed within a shorter time span, highlights the adaptability of microbial communities under recurrent oil spill conditions. It underscores the potential role of biochar and bioaugmentation strategies, such as B1PABS, in optimising the remediation of crude oil spills in areas repeatedly affected, like the Niger Delta. Further research should focus on elucidating the precise mechanisms and exploring other possible factors contributing to the observed increased efficiency, and how this can be leveraged to optimise remediation strategies, especially for areas suffering from recurrent oil spills.

4.4 Conclusion

The current study looked at the efficacy of various remediation techniques on crude oil-contaminated soil and repetitive spilled contaminated soil. The results showed that the remediation of the repetitive spilled contaminated soil was more efficient than the initial remediation of crude oil-contaminated soil. The B1PABS method was consistently the most effective remediation method for the repetitive spilled contaminated soil in terms of TPH degradation, soil respiration increase, and total PLFA increase. The microbial community analysis revealed that the different

treatments applied had varying effects on the abundance and composition of the microbial communities. The study also looked at the relationship between total petroleum hydrocarbons (TPH), phospholipid fatty acids (PLFA), and respiration at a contaminated site that was treated in different ways. The results showed that the relationships between these variables varied depending on the treatment applied and that the microbial communities in the soil responded differently to the different treatments. In some cases, TPH was negatively correlated with PLFA, while in other cases it was positively correlated. Across all treatments, the relationship between TPH and respiration was consistently negative, whereas the relationship between respiration and PLFA was consistently positive. In summary, the study provides important insights into the effectiveness of different remediation methods for crude oil-contaminated soil and repetitively spilled contaminated soil. The findings can inform future management strategies for contaminated sites and help reduce the environmental impact of such incidents. The results also shed light on the complex relationships between TPH, PLFA, and respiration in contaminated soils, highlighting the need for tailored approaches to the management of such sites.

4.5 References

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5 A Decision Tree Approach for Sustainable Decision-Making for Enhanced Crude Oil Bioremediation

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Abstract

This study presents an innovative and systematic approach to remediating soil contaminated with crude oil by combining low-carbon bioremediation (CLCB) techniques combined with bioaugmented biochar (Bio2char). To support informed decision-making, a decision tree framework based on the Analytical Hierarchy Process (AHP) was developed. The framework consists of two main sections. The first section focuses on implementing various CLCB strategies, including the use of oxygen release compound (ORC), ORC combined with nitrogen and phosphorus (N&P), and ORC combined with compost. Monitored natural attenuation (MNA) is also considered. Laboratory-simulated site conditions and influencing factors are also considered. The AHP analysis emphasises the need to balance effectiveness, cost, environmental impact, and social acceptability when making decisions regarding the remediation strategy. The second section of the framework explores the application of different Bio2char strategies for managing recurring spills on previously remediated soil. This involves the utilization of Bio2char derived from various sources such as wheat straw pellets and sewage pellets, combined with different bacterial strains. Laboratory evaluations and site conditions are considered to assess their efficacy. The findings highlight that the combination of ORC and compost (B3) for CLCB and the utilization of wheat straw pellets combined with *Pseudomonas aeruginosa* and *Bacillus sonorensis* (B4PABS) for Bio2char show great promise in their respective applications. However, the effectiveness of the framework is depending on comprehensive site assessment, indicating potential limitations when dealing with different types of contamination or environmental contexts. Future research should explore potential synergies among various remediation strategies and expand the applicability of the framework.

Keywords: Bioremediation, Combined low-carbon bioremediation, Bio2char, Decision tree

5.1 Introduction

Soil contamination is a pressing environmental issue that poses significant risks to human health and ecosystems, negatively impacting soil quality (Aqeel et al., 2014; EEA, 2022). Over time, various remediation strategies have been developed to address this issue, including physical, chemical, and biological approaches. Among these, the biological method has been drawing more attention due to its efficacy, sustainability, and cost-effectiveness, although it can be time-consuming. Bioremediation involves the use of microorganisms to break down contaminants through oxidative or reductive procedures, leading to the complete degradation of organic contaminants into non-toxic derivatives such as carbon dioxide, water, organic acids, and methane (Bhaskar et al., 2020). However, the ideal conditions for bioremediation to occur depend on various factors such as the area, volume, and concentration of the contaminated environmental matrix (i.e., soil, groundwater, surface water).

The Niger Delta region has been experiencing oil spills for several decades, leading to severe environmental degradation and health problems for the local communities. Bioremediation has been identified as a viable option for cleaning up the oil-contaminated soil and water in the region. In particular, bioremediation can be enhanced by using compost made from biowaste as a source of nutrients for microorganisms. In the Niger Delta region, the waste stream consists of a significant amount of organic waste, roughly 30-50%, that can be composted due to its high moisture content (Nnaji, 2015; Ndukwe et al., 2019). This biowaste can serve as a valuable resource for enhancing the bioremediation of crude oil-contaminated soils by providing essential nutrients to support the growth of oil-degrading microorganisms. However, the current lack of a market or infrastructure for processing and storing compost can limit the practice. To address this, it is essential to promote the use of composted waste as a valuable resource for bioremediation.

This can be achieved by encouraging individuals and organisations to participate in developing a well-regulated, accessible, and cost-effective compost industry that focuses on the production and distribution of compost suitable for bioremediation purposes. By doing so, farmers in the Delta region can benefit from using compost to enhance their soils, while also contributing to the efficient cleanup of oil-contaminated sites. Compost can help to increase microbial activity and restore land

degraded by crude oil or other pollutants, resulting in safe and functional ecosystems for human habitation. By implementing large-scale composting practices in the Delta region, it can provide a significant opportunity to improve the current inefficient biowaste system, directly linking the biowaste stream with bioremediation efforts and benefiting both the environment and the local economy (Angaye et al., 2017).

Another potential solution is the use of biochar produced from waste biomass such as agricultural residues or food waste. This creates an additional income stream for farmers, and the use of biochar in soil remediation can also create jobs in the region. Moreover, an innovative solution lies in the use of bioaugmented biochar, which refers to the practice of enhancing biochar with specific microbial species to improve its remediation capabilities and soil health (Guirado et al., 2021). This approach aims to capitalise on the beneficial interactions between biochar and introduced microorganisms, which can contribute to processes such as contaminant degradation, nutrient cycling, and overall soil fertility (Olga, 2023). The application of bioaugmented biochar for soil remediation has been examined in several studies. For instance, research has shown that the immobilisation of petroleum-degrading bacteria on biochar was more effective in reducing total petroleum hydrocarbons (TPHs) and specific n-alkanes in soil than using free bacteria or biochar alone (Zhang et al., 2019).

To ensure the practical application of biochar in soil remediation efforts, it is critical to quantify the amount needed for effective treatment. For contaminated soils in the Niger Delta with a TPH concentration of 10,000 mg/kg, a 10% weight/weight ratio of wheat straw biochar to soil is indicated, as gleaned from field studies. Given a soil bulk density of 1.35 g/cm³ and a common remediation depth between 10-40 cm, we can calculate the necessary quantity of biochar. For example, remediating one hectare of land to a depth of 30 cm would require approximately 405 tonnes of biochar, an estimation informed by both the material's adsorption properties and its interaction with petroleum-degrading bacteria. This dosage is expected to replicate the high degradation rates of TPHs observed in controlled settings, where a 93% reduction was achieved within 90 days, adapting to field conditions that vary across different remediation sites.

Biochar and/or bioaugmented biochar with oil degraders can offer significant opportunities for remediating oil-impacted soils in the Niger Delta and can be highly

beneficial for the region for several reasons. Firstly, biochar and bioaugmented biochar can be used to remediate contaminated soil by providing an environment that supports the growth of oil-degrading microorganisms (Zahed et al., 2021; Gupta and Kua, 2017). Biochar is highly effective at adsorbing contaminants, and when combined with oil-degrading microorganisms, it can break down hydrocarbons in the soil, thereby remediating contaminated soil. Secondly, the use of biochar can sequester carbon, which is vital for mitigating the effects of climate change. Biochar is a stable form of charcoal that can remain in the soil for a long time, sequestering carbon and mitigating the impact of greenhouse gas emissions (Anae et al, 2021). Thirdly, biochar has been shown to improve soil fertility by increasing soil organic matter content, nutrient retention, and water-holding capacity. This can improve plant growth and increase crop yields in the Niger Delta, which is an important agricultural region.

However, the effectiveness of these solutions would depend on several factors such as the type and extent of soil contamination, the availability of suitable biomass feedstocks for biochar production, and the availability of oil-degrading microorganisms. Therefore, it is necessary to develop a decision tree to assist in identifying the key criteria for selecting the appropriate bioremediation approach. This would help decision-makers in the region to make informed decisions on the most suitable bioremediation approach for a specific situation. The objective of this study is therefore to develop a decision support tree that incorporates combined low-carbon bioremediation (CLCB) and bio2char strategies for the efficient remediation of soil contaminated with petroleum hydrocarbons.

5.2 Material and Methods

This study used a combination of literature reviews and experimental approaches to assess the effectiveness of low-carbon bioremediation strategies, focusing on the application of bacteria and biochar in soil remediation. Two experiments were designed and conducted to investigate these strategies, each with its own unique focus and objectives. The first experiment investigated the application of low-carbon bioremediation strategies, particularly focusing on the use of oxygen-release compounds (ORC), a blend of compost and ORC, and a combination of fertiliser and ORC. This part of the study aimed to elucidate the potential of these approaches for optimising the bioremediation process by creating a conducive environment for

microbial activity essential for contaminant degradation. In response to recurring oil spills and subsequent remediation efforts in the region, the second experiment specifically focused on evaluating how the use of bacteria and biochar could enhance and speed up the remediation process. Specifically, it examined the potential of bacteria, known for their oil-degrading properties, and biochar, acknowledged for its adsorptive properties and ability to support microbial activity, to work together to accelerate the breakdown of oil contaminants in the soil. The underlying hypothesis was that a soil environment previously exposed to oil spills and subjected to remediation could potentially host a microbial community that could accelerate the remediation of newly spilled oil. The study aimed to verify this theory by comparing the effectiveness of bioaugmented biochar remediation strategies in such an environment. A literature review accompanied the experiments to provide a broader context for existing knowledge and potential research gaps around bioremediation. This comprehensive approach allowed for a direct and informed evaluation of the various remediation methods for crude oil-contaminated soil in the Niger Delta region.

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5.2.1 Experimental design approach

In the first experimental procedure, the relationship between total petroleum hydrocarbons (TPH), phospholipid fatty acids (PLFA), and respiration at a contaminated site treated with various biostimulation strategies was investigated. The combined low-carbon bioremediation (CLCB) strategy involved spiking 2 kg of soil with Sweet Crude oil to achieve a contamination level of 10,000 mg/kg. The implemented CLCB strategies included Oxygen release compound (ORC), a combination of compost and ORC, and a combination of fertiliser and ORC. The soil was placed in 15 L cylindrical builders' buckets each measuring 36 cm in height and 37 cm in diameter. Over time, we monitored changes in soil respiration, microbial activity, ecotoxicity, and TPH degradation. Lastly, we performed statistical analysis to determine the significance of the differences observed between treatments.

In the second experimental procedure, soil mesocosms from the first experimental procedure were spiked again with sweet crude oil and amended with either biochar or bioaugmented biochar. The biochars used were wheat straw pellets (B4) and sewage sludge pellets (B5). *Bacillus sonorensis* (BS) and *Pseudomonas aeruginosa* (PA) were used for bioaugmenting the biochars, termed Bio2Char in this study. The effectiveness of the different strategies was assessed by monitoring changes in soil respiration, microbial activity, and TPH concentration over time. A statistical analysis was performed to compare the different treatments.

5.2.2 Selection Criteria for Remediation

The selection of appropriate remediation strategies was an integral part of this study. Instead of simply listing or comparing different strategies, a systematic decision-making process was followed to identify the most suitable approach for the specific experimental conditions. A Multi-criteria decision analysis (MCDA) method was used to guide this process. MCDA is a systematic process of evaluating and ranking potential remediation strategies based on multiple criteria, such as effectiveness, cost, environmental impact, and social acceptability. It has been widely applied to various environmental management problems, including the selection of remediation strategies for contaminated sites (Yang et al., 2012; Qin et al., 2008; Andrea et al., 2009).

Table 5. 1 Saaty's Scale for Relative Importance Judgement in AHP Analysis

Intensity of Importance	Definition
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Intermediate values

The Analytic Hierarchy Process (AHP), a frequently used method within the framework of MCDA, was developed by Saaty (2008). The method facilitates the decision-making process by structuring the overall problem into a hierarchy of simpler sub-problems, each of which can be independently evaluated. It assigns weights to each criterion, reflecting their respective significance in the decision-making process. This method has been successfully used to prioritise environmental projects and select remediation strategies for contaminated sites. For instance, Michael et al. (2006;2008) applied the AHP method in the context of prioritising and selecting the most appropriate environmental remediation projects. Subsequently, Mendoza and Martins (2006) also used the AHP methodology to prioritise alternatives for the remediation of contaminated sites in Portugal. The researchers identified four main criteria for the selection of remediation strategies: effectiveness, cost, environmental impact, and social acceptability. These criteria were further divided into sub-criteria, and the stakeholders participating in the decision-making process assigned weights to each criterion based on their respective significance. The final ranking of the alternatives was obtained by aggregating the weighted criteria scores, allowing the decision-makers to choose the most appropriate remediation strategy for each site.

In determining the weights for our criteria, we consulted with a panel of ten experts in the field of environmental remediation, who are either based in the Niger Delta region or have extensive experience with the region's context. The experts included both industry professionals and academics. They were chosen for their diverse backgrounds, including roles in project management, technical expertise, consulting, and academia. The questionnaire sought their professional judgement on the importance of various criteria, such as social acceptability. The questionnaire is provided in the supplementary materials for a comprehensive review. It covers key aspects such as expert demographics, stakeholder engagement, decision criteria weighting, and additional comments. One of the experts, an experienced academic in environmental engineering, rated the importance of social acceptability as 9 out of 9 (see Appendix). The expert justified this rating by emphasising the role social

acceptability plays in fostering peace, and harmony, and guaranteeing security within the communities involved. The other experts' ratings varied, reflecting their unique perspectives and experiences. For instance, a restoration scientist rated social acceptability as 6, citing the importance of stakeholder input and community acceptance, while an environmental policy consultant gave it a rating of 7, emphasising the crucial role of community support in successful strategy implementation. The supplementary materials can provide more details on each expert's ratings and justifications. The AHP method's standard scale was used, ranging from 1 (equal importance) to 9 (extreme importance), with intermediate values for in-between judgements. The experts rated the importance of each criterion relative to the others, and these ratings were then used to calculate the weights. Table 5.2 provides a summary of the decision criteria used in our AHP analysis, along with their assigned weights and justifications, as derived from expert questionnaire results.

Table 5. 2 Decision Criteria Weights and Justifications Based on Expert Questionnaire Results

Criterion	Weight	Justification
Cost	0.1	While cost is a significant consideration, it is not the only factor in determining the best strategy. Some strategies with higher costs may be more effective or socially acceptable.
Effectiveness	0.4	Effectiveness was given the highest weight, as the primary goal of any bioremediation strategy is to remediate the contamination successfully.
Environmental Impact	0.3	Environmental impact was also given significant weight, as minimising additional environmental harm is a key part of sustainable remediation practices
Social Acceptability	0.2	Social acceptability was given substantial weight to reflect the importance of public support and local community buy-in for the successful implementation of a strategy

The specific scores for each bioremediation strategy were derived through an in-depth analysis of the experimental data available in conjunction with expert opinion.

Each of the criteria was evaluated based on how each strategy performed. The assessment of the effectiveness criterion involved determining the success level of each bioremediation strategy in remediating the contamination. Similar scoring scales were used to evaluate the strategies against the cost, environmental impact, and social acceptability criteria. After obtaining the scores for each strategy in each criterion, the overall score was calculated for each strategy. This was done by multiplying the score of each strategy in a particular criterion by the weight of that criterion and then summing the products to get the total score.

Applying the MCDA and AHP methodologies to oil-contaminated soils in the Niger Delta facilitates a more systematic and transparent process for selecting appropriate remediation strategies, taking into account multiple criteria and the region's unique challenges and constraints. Unique factors relevant to the Niger Delta, such as the diverse ecosystem, the socio-economic status of its inhabitants, and the historical context of oil contamination in the area, were considered when assigning weights to different criteria. Defining a successful bioremediation approach involved not only looking at the degradation of TPH levels but also considering other factors such as the restoration of microbial activity, reduction of ecotoxicity, and the feasibility of the approach in terms of cost and social acceptability (Christopher et al., 2016).

By integrating both qualitative and quantitative information, the use of MCDA and AHP methodologies provides a comprehensive, robust, and transparent framework for decision-making. This approach ensures the chosen remediation strategies for oil-contaminated soils in the Niger Delta are not only effective and cost-efficient but also environmentally sustainable, leading to informed choices that align with the long-term goal of achieving environmental recovery.

Table 5. 3 Pairwise Comparison Matrix

Criteria	Effectiveness	Cost	Environmental Impact	Social Acceptance
Effectiveness	1.00	0.25	0.50	0.33
Cost	4.00	1.00	2.00	3.00
Environmental Impact	2.00	0.50	1.00	2.00
Social Acceptability	3.00	0.33	0.50	1.00

The relative importance of one criterion over another is shown in Table 5.3. Each entry in the matrix corresponds to the expert's consensus regarding the importance of one criterion over another. Furthermore, it was essential to verify the consistency of the pairwise comparisons made in the analysis. A consistency ratio of less than 0.10 indicates reasonably consistent judgements, and for this analysis, the consistency ratio was calculated to be 0.03. Prevailing literature strongly recommends that the Consistency Ratio (C.R.) be less than 0.1. A C.R. greater than 0.1 indicates the presence of inconsistency, thus making the decision less reliable (Okparanma et al., 2018). The low consistency ratio implies reliability in the judgements made during pairwise comparisons, thereby enhancing the robustness of the analysis. Local priorities underwent normalization to establish a consistent scale across all criteria. Such normalization facilitates the comparison and combination of scores across all criteria. Upon calculating and normalising local priorities, the overall score for each potential bioremediation strategy was determined. These scores emerged from the process of multiplying the normalised local priority of each criterion by the respective weight, followed by aggregating these weighted scores for each strategy. These final scores denote the comprehensive performance of each strategy, taking into account all the considered criteria and their respective weights. Consequently, the strategy with the highest score is deemed the most suitable based on the evaluation methodology of this study. This robust and systematic method facilitates more educated and sustainable decision-making in the remediation process, resonating with long-term environmental recovery objectives in the Niger Delta.

The relative importance of one criterion over another was determined through a consensus matrix, developed by consulting with a panel of five environmental experts with over 10 years of experience in bioremediation in the Niger Delta region. Entries in this matrix represent the agreed-upon judgements of these experts on the importance of one criterion relative to another. Consensus was achieved through multiple rounds of discussion and revision, each guided by an independent facilitator. The process was iterative, with each expert initially providing individual judgements, followed by group discussion and subsequent rounds of individual evaluation until consensus was reached. To ensure validity and reliability in the approach, it was essential to verify the consistency of the pairwise comparisons made by these experts. The Consistency Ratio (C.R.) was utilised for this purpose. A C.R. of less than 0.10 indicates reasonably consistent judgements. In the analysis, the consistency ratio was calculated to be 0.03, suggesting a high degree of consistency in the experts' judgements. This process involved the pairwise comparison of the criteria and subsequent computation of the eigenvalue method to derive the C.R., as suggested by Saaty (2000). Literature strongly recommends that the C.R. be less than 0.1, and a C.R. greater than 0.1 indicates the presence of inconsistency, thus making the decision less reliable (Okparanma et al., 2018). The low consistency ratio in this study validates the reliability of the judgements made during pairwise comparisons, enhancing the robustness of the analysis.

5.3 Results and Discussion

5.3.1 Effectiveness of different biostimulation strategies on hydrocarbon degradation

The efficacy of various biostimulation strategies for the remediation of hydrocarbon-contaminated soils over 180 days is presented in Table 5.4. The strategies assessed include Monitored Natural Attenuation (MNA), Oxygen Release Compound (ORC, B1), ORC with additional Nitrogen and Phosphorus (B2), and ORC supplemented with compost (B3).

Table 5. 4 Average values and percentage differences of biostimulation strategies for hydrocarbon degradation in contaminated soil over 180 days

Treatment	Avg Biomass (mol %)	Avg TPH (mg/kg)	Avg Respiration (mg of CO ₂ /g soil)	Avg EC50 (mg/l)	% Diff. in Biomass	% Diff. in TPH	% Diff. in Respiration	% Diff. in EC50
MNA	96	5290	0.17	759				
B1	107	2640	0.334	1306	12	50	96	72
B2	114	2435	0.462	1870	20	54	172	146
B3	120	1975	0.55	2252	26	63	224	197

MNA: Monitored natural attenuation, B1: ORC, B2: ORC+N&P, B3: ORC + Compost

Results demonstrate that MNA was less effective than all the biostimulation treatments (B1, B2, and B3) in enhancing hydrocarbon degradation. B3, which combines ORC and compost, emerged as the most effective strategy. This suggests that the additional nutrients from the compost substantially enhance microbial growth and activity, thereby improving the biostimulation process. These findings underscore the potential of biostimulation strategies, especially those incorporating ORC and other additives, for effective hydrocarbon-contaminated soil remediation. The study emphasises the importance of selecting the appropriate biostimulation strategy, considering the specific conditions of the contaminated site and the choice of additives, to optimise remediation outcomes.

5.3.2 Synergistic effects of biochar-based biostimulation and bioaugmentation on hydrocarbon degradation

Table 5.5 presents the results for the synergistic effects of biochar-based biostimulation and bioaugmentation (bioA) on hydrocarbon degradation, examining the changes in biomass, TPH, and respiration across different treatments and time points.

Table 5. 5 Measurement of biomass, TPH reduction, and respiration across different treatments and time intervals

Treatment	Avg Biomass (mol %)	Avg TPH (mg/kg)	Avg Respiration (mg of CO ₂ /g soil)	% Diff. in Biomass	% Diff. in TPH	% Diff. in Respiration
Control	52	6128	0.27			
B4	110	4181	0.84	111	31	21
B4PA	121	3889	0.90	129	36	235
B4BS	127	3777	0.96	130	38	257
B4PABS	136	3523	1.04	159	43	286
B5	100	4209	0.76	91	31	185
B5PA	102	4019	0.83	95	34	209
B5BS	111	3875	0.92	111	37	241
B5PABS	121	3731	0.98	131	39	266

B4: Wheat straw pellet (WSP), B5: Sewage pellets (SP); B4PA or B5PA: bioaugmented biochars with *Pseudomonas aeruginosa*, B4BS or B5BS: bioaugmented biochars with *Bacillus sonorensis*, B4 or B5PABS: bioaugmented biochars with PA+BS.

Overall, all treatments exhibited an increase in biomass, indicating that the treatments facilitated microbial growth. Treatment B4PABS showed the highest percentage increase in biomass at 90 days, followed by B5PABS and B4BS, suggesting that these treatments were particularly conducive to enhancing microbial growth. Reduction in TPH was observed across all treatments and time intervals, with B4PABS showing the most significant TPH reduction at 90 days. This highlights the need for optimised treatment strategies tailored to specific time frames. Additionally, an increase in respiration was observed across all treatments, with treatment B4PABS demonstrating the highest percentage increase at 90 days. These findings assert that treatments B4PABS, B4PA, B4BS, B5BS, and B5PABS have been observed to effectively enhance microbial metabolic processes involved in pollutant degradation. Treatments B4PABS, B4PA, and B4BS were effective in promoting biomass growth, while B5BS, B4PABS, and B5PABS demonstrated the most significant TPH reductions. Treatment B4PABS consistently resulted in the highest respiration increases across time points. These results provide valuable insights for the development of targeted and effective bioremediation strategies, and further research is needed to optimise treatment combinations for enhanced pollutant degradation.

5.3.3 Integrated Analysis: Comparison of MNA, Biostimulation (BioS), combined BioS and bioaugmentation (BioA)

An integrated analysis which involves comparing the effectiveness of MNA, biostimulation (bioS), and combined BioS and BioA treatments, provides a comprehensive understanding of their impacts on hydrocarbon degradation. This analysis, which uses data from Tables 3 and 4, covers percentage changes in biomass, TPH, and respiration for each treatment at different times (7, 21, 42, 90, and 180 days). The MNA approach, which involves the least intervention, showed the lowest effectiveness, with minor increases in biomass and TPH degradation over time. This underscores the need for proactive remediation strategies to speed up hydrocarbon degradation. Biostimulation strategies (B1, B2, and B3), involving ORC or combinations of N&P and compost, outperformed MNA. These strategies spurred biomass growth, improved TPH degradation, respiration, and EC50. Particularly, the B3 strategy, which included compost, stood out among biostimulation strategies, likely due to the added nutrients enhancing microbial activity. When examining combined bioaugmentation strategies (B4PA, B4BS, B4PABS, B5PA, B5BS, B5PABS) using biochar, *Pseudomonas aeruginosa*, and *Bacillus sonorensis*, distinct outcomes were seen. Enhanced biomass growth, particularly with B4PABS and B5PABS, underscores the potential of bioaugmentation to stimulate microbial activity essential for hydrocarbon degradation. A comparison between combined BioS (B2 & B3) and combined BioA (B4PA, B4BS, B4PABS, B5PA, B5BS, B5PABS) reveals insights. While BioS strategies were effective at promoting biomass growth, BioA strategies showed superior TPH reduction. Interestingly, at 90 days, the standout BioA strategies (B4PABS and B5PABS) showed 67% more TPH degradation, a 116% increase in respiration, and a 22% increment in biomass compared to combined BioS strategies. At 180 days for combined BioS vs 90 days for standout BioA, these standout BioA strategies showed a 94% increase in respiration, and a 75% increment in biomass. These observations underscore the effectiveness of the BioA strategies, even in half the duration. The combined BioS and BioA strategies were the most effective, with B4PABS and B5PABS treatments (which used biochar-based biostimulation with both PA and BS) leading in biomass growth, TPH reduction, and respiration rates. This underscores the potential of integrated strategies that exploit both biostimulation and bioaugmentation for optimal

hydrocarbon degradation. These results emphasize the need to transition from MNA towards more active remediation strategies. They highlight the promise of combined BioS and BioA approaches. Future research should aim to determine the best combination and conditions for these strategies, considering the unique requirements of each contaminated site.

5.3.4 Bioremediation Plan for oil-contaminated soil in the Niger Delta

5.3.4.1 Fresh spill

The bioremediation plan outlined in Table 5.6 provides a practical and effective approach for treating contaminated soils with varying degrees of contamination. This method involves the use of organic amendments such as oxygen-releasing compounds (ORCs) and kitchen waste compost. These amendments, when combined with contaminated soil and adequately watered, can promote the growth of indigenous microorganisms capable of degrading total petroleum hydrocarbons (TPH). To enhance microbial activity and retain moisture, a thin layer of organic mulch may be applied to the soil surface in a field application. The recommended dosages of ORCs and compost are 1% and 30% by weight, respectively. Periodic soil sampling should be carried out to monitor TPH degradation rates.

Table 5. 6 Proposed strategies for bioremediation of crude oil-contaminated soil based on laboratory results and soil characteristics

Parameter	Laboratory Application	Field application (Based on volume and weight)
Soil Quantity (kg)	5 kg	Determined by site area and depth of contamination
Contamination Level (mg kg ⁻¹ TPH)	10,000 mg kg ⁻¹ TPH	10,000 mg/kg TPH
Soil Type	Sandy silt loam	Sandy silt loam
Water Holding Capacity	60%	60%
pH Level	6-8	6-8
Temperature (°C)	20-30	20-30
Bulk Density (g/cm ³)	1.35	1.35
Area of Contaminated Site (m ²)	0.1071 m ²	Contingent on the specific conditions of individual site
Treatment Depth Required (cm)	30 cm	Variable, generally 10-40 cm
Amendment Used	ORC + Kitchen/garden waste compost	ORC + kitchen waste compost
Recommended Dosage (based on soil weight)	ORC 1% by wt., compost 30% by wt.	ORC 1% by wt., compost 30% by wt.
Mixing of Amendment with Contaminated Soil	Use appropriate equipment such as a spatula	Use appropriate equipment such as a rotary tiller or disc plough
Covering of Bioremediation Site	Kept in a garden shed	Use a thin layer of straw or other organic mulch to retain moisture and promote microbial activity
Monitoring and Sampling	Collect soil samples at intervals for analysis of TPH degradation	Collect soil samples at intervals for analysis of TPH degradation
TPH degradation	90 days: 79%; 180 days: 97%	Treatment effectiveness, assessed through periodic measurements, may vary with site conditions

Laboratory experiments have shown that TPH degradation rates of 82% and 96% were achieved within the initial 90 and 180 days, respectively, which could be replicated in a field application. However, soil type, temperature, and moisture content can have an impact on the degradation rates. The recommendation of 1% ORC by volume is based on the minimum oxygen concentration (0.5 mg L⁻¹) required for natural microbial activity. A 30% compost-soil blend was found to be an effective mixture for supplying sufficient nutrients to support oil digestion and decomposition. While most studies suggest that an optimal organic amendment level for TPH degradation is 5-10%, the recommended compost proportion of 30%

provides a balance between providing enough organic matter for microbial activity and avoiding nutrient overload.

In areas with higher levels of oil contamination, such as the Niger Delta region, a higher compost percentage may be necessary to provide additional nutrients and organic matter for effective contaminant degradation. A higher compost percentage also helps to retain more moisture, reducing soil dry-out rates. However, excessive amendment additions can lead to nutrient overload and other complications. Given the abundance of organic waste in Nigeria and the high cost of fertilisers, the recommended compost proportion of 30% presents a practical and efficient method for bioremediating contaminated soil in the country.

5.3.4.2 Recurring spill

Table 5.7 outlines a practical method for treating recurring spills of petroleum hydrocarbons in contaminated soil. The approach involves using wheat straw biochar amendments and bacterial strains, *Pseudomonas* and *Bacillus*, to facilitate the growth of indigenous and exogenous microorganisms capable of degrading total petroleum hydrocarbons (TPH).

Pseudomonas and *Bacillus* strains, chosen for their hydrocarbon-degrading abilities, resilience in saline conditions, and use of crude oil as a carbon and energy source, were added to the soil at a concentration of 10% v/w. This optimal concentration, determined through laboratory experiments, promotes microbial activity and hydrocarbon degradation. Alongside, a 10% w/w dose of wheat straw biochar was also added. Laboratory experiments demonstrated 93% TPH degradation rates after 90 days, suggesting field effectiveness of this treatment approach. However, effectiveness may vary based on soil type, temperature, and moisture content. The use of wheat straw biochar, along with *Pseudomonas* and *Bacillus* strains, presents a promising strategy for treating recurring spills. Still, further research is essential to confirm its broad applicability.

The application rate of bioremediation amendments necessary for field-scale bioremediation can be estimated using a few key parameters. The total volume of contaminated soil should be calculated, considering both the area of contamination and the required treatment depth. This volume should then be multiplied by the bulk

density of the soil to estimate the total weight of the soil to be treated. For example, a site measuring 1000 m² requiring treatment to a depth of 30 cm would have a contaminated soil volume of 300 m³. Given a soil bulk density of 1.35 g cm⁻³ (or 1350 kg m⁻³), the weight of the soil requiring treatment would be approximately 405,000 kg. Subsequently, the weight of ORC and compost required can be estimated at 1% and 30% of the total soil weight, respectively. In the case of our example, this equates to 4050 kg of ORC and 121,500 kg of compost. It should be noted, however, that these calculations serve as an initial guide. As the characteristics of each site can vary significantly, conducting a comprehensive site assessment prior to amendment application remains crucial to accurately address the specific bioremediation needs of each site.

Table 5. 7 Bioremediation plan for recurring petroleum hydrocarbon spills in contaminated soil: laboratory experiment results and field application recommendations

Parameter	Laboratory Application	Field application (Based on volume and weight)
Soil Quantity (kg)	2 kg	Determined by site area and depth of contamination
Contamination Level (mg/kg TPH)	10,000 mg kg ⁻¹ TPH	10,000 mg kg ⁻¹ TPH
Soil Type	Sandy silt loam	Sandy silt loam
Water Holding Capacity	60%	60%
pH Level	6-8	6-8
Temperature (°C)	20-30	20-30
Bulk Density (g/cm ³)	1.35	1.35
Area of Contaminated Site (m ²)	0.1071 m ²	Contingent on the specific conditions of individual site
Treatment Depth Required (cm)	30 cm	Variable, generally 10-40 cm
Amendment Used	Wheat straw + Pseudomonas + Bacillus	Wheat straw + Pseudomonas + Bacillus
Recommended Dosage (based on soil weight)	WSP 10%w/w + PABS 10% v/w	WSP 10%w/w + PABS 10% v/w
Mixing of Amendment with Contaminated Soil	Use appropriate equipment such as a spatula	Use appropriate equipment such as a rotary tiller or disc plough
Covering of Bioremediation Site	Kept in a garden shed	Use a thin layer of straw or other organic mulch to retain moisture and promote microbial activity
Monitoring and Sampling	Collect soil samples at intervals for analysis of TPH degradation	Collect soil samples at intervals for analysis of TPH degradation
TPH degradation (%)	90 days: 93%	Treatment effectiveness, assessed through periodic measurements, may vary with site conditions

Table 5.7 delineates a proposed approach for the application of a bioremediation plan based on laboratory experiments and field applications. It underscores the translation from laboratory conditions to field conditions, emphasising the requirement for site-specific assessments and adaptations. In field applications, the quantity of soil and depth of contamination can vary extensively, necessitating tailored strategies for effective bioremediation. The table encapsulates these variables, offering a guide for practitioners to estimate the required amount of bioremediation amendments based on site-specific parameters. It further emphasises the importance of consistent monitoring and sampling for tracking TPH degradation in field conditions. While laboratory results showed 93% TPH degradation within 90 days, this rate may vary under field conditions depending on soil properties, climatic factors, and the specific composition of the petroleum hydrocarbon contaminant. In summary, this paper reiterates the significance of laboratory-based bioremediation experiments. Yet, it also highlights the need for integration and adaptation of these lab-derived insights to address the complexities and challenges presented by field-scale bioremediation.

5.3.4.3 Scalability and Material Quantification

To ensure the practicality of the proposed bioremediation plans for both fresh and recurring oil spills in the field, it is crucial to discuss their scalability. Scaling up laboratory findings to field applications requires careful consideration of material availability, cost, and the environmental footprint of remediation efforts. To address these considerations, simple calculations are used to estimate the required amounts of remediation materials, grounded in data obtained from laboratory experiments and adapted to reflect real-world conditions.

For the purpose of these calculations, we assume a standard contaminated site area of $X \text{ m}^2$ with a contamination depth of $Y \text{ cm}$. The total volume of contaminated soil requiring treatment is thus calculated as $(X \text{ m}^2 \times Y \text{ cm})$, which will require a bulk density assumption of $Z \text{ g/cm}^3$ to estimate the weight of soil. Based on these estimates, the weight of the soil to be treated is calculated as follows:

Weight of Contaminated Soil = Area × Depth × Bulk Density

Subsequently, the amounts of ORCs, compost, biochar required are:

ORC Required (kg) = Weight of Contaminated Soil × 1 % ORC

Compost Required (kg) = Weight of Contaminated Soil × 30 % Compost

Biochar Required (kg) = Weight of Contaminated Soil × 10 % Biochar

These figures are initial estimates and must be refined through a comprehensive site assessment to tailor the approach to the specific conditions of each bioremediation project. Assumptions made during these calculations include: (i) The homogeneity of soil contamination across the site (ii) Constant bulk density of soil at varying depths. (iii) Availability of ORCs, compost, and biochar in sufficient quantities for large-scale application (iv) No significant economic or logistical barriers to scaling up the treatment process. By acknowledging these assumptions, we can outline a provisional framework for practitioners to estimate the scale of amendments needed for field applications, which will ultimately guide the practical execution of the bioremediation plans.

5.4. Decision Tree for combined low-carbon Bioremediation (CLCB) and Bio2char Strategies

The decision tree framework for combined low-carbon bioremediation (CLCB) and Bio2char strategies provides a step-by-step approach for addressing crude oil contamination in soil and determining the most feasible and effective remediation option (Fig 5.1). The framework is divided into two main sections: applying CLCB in crude oil-contaminated soil and implementing Bio2char in cases of recurring spills on remediated soil. This discussion aims to provide a comprehensive analysis of this decision tree framework, exploring its various stages, decision points, and potential implications.

In the first section, the decision tree framework assesses whether a site assessment has been carried out to determine the nature and extent of contamination and the feasibility of CLCB. If a site assessment has not been conducted, additional

characterisation is required. The framework then evaluates whether exposure levels are above acceptable limits and whether monitored natural attenuation (MNA) is a suitable option to meet clean-up requirements. If MNA is not feasible or factors influencing its acceptance are present, the framework assesses whether CLCB can meet closure requirements. If CLCB is the best option, the remediation process proceeds and results in remediated soil. In the second section, the decision tree framework evaluates whether exposure is above acceptable limits in cases of recurring spills on remediated soil. If it is, the Bio2char strategy is applied to achieve remediated soil. If exposure is below acceptable limits, the framework again evaluates the feasibility of MNA to meet clean-up requirements. If MNA is not feasible or factors influencing its acceptance are present, the Bio2char strategy is applied to achieve remediated soil.

The decision tree framework for CLCB and Bio2char strategies provides a comprehensive and systematic approach to addressing crude oil-contaminated soil, considering various factors and conditions that may influence the feasibility and effectiveness of these strategies. The success of this framework is anchored in its clarity and structured methodology. However, delving deeper into the practical applications of this approach reveals a more nuanced picture. While structured problem-solving offers clear guidance, the real-world scenarios, as in the Niger Delta contexts, expose the framework's reliance on accurate data and its static nature, which may not account for unexpected environmental variations or complex ecological interactions. The decision tree framework for combined low-carbon bioremediation (CLCB) and Bio2char strategies stands as a testament to structured problem-solving, offering clear, step-by-step procedures that guide practitioners through complex decision-making processes inherent in addressing crude oil contamination in soil. The adaptability of the decision tree allows for strategic modifications in response to observed outcomes, a crucial feature in the dynamic field of environmental management. However, pivoting our attention to its limitations, we understand that the structured approach is contingent upon the accuracy and completeness of site assessment data. Data inaccuracies, as seen in the Niger Delta context, can lead to inefficient strategic choices, underscoring the critical need for reliable data. Furthermore, the unpredictable nature of environmental systems, often evident in sites with a history of multiple contamination events, presents

unpredictable variables that can skew the expected outcomes. For instance, in the complex environmental context of the Niger Delta, one could anticipate how variations in microbial interactions might impact treatment efficacy.

The decision tree framework may recommend a strategy based on a set of expected conditions; however, in practice, unanticipated biological responses to bioremediation efforts could necessitate a reassessment of the chosen path. Furthermore, the inherent static design of decision trees, despite their feedback loops, may not completely capture the fluid dynamics of an environmental system. The framework, while robust, might not fully account for real-time changes such as unexpected weather events or the emergence of new sources of contamination, which could require immediate strategic adjustments beyond the scope of the initial analysis. This acknowledgement of potential uncertainties emphasizes the importance of flexibility and the willingness to adapt strategies in the face of evolving site-specific challenges. It reflects an understanding that while decision trees provide a valuable starting point, their application must be dynamic, incorporating ongoing learning and adaptation to the complexities of environmental remediation. Despite these limitations, the decision tree remains an invaluable scaffold for environmental remediation efforts, paving the way for more responsive and adaptable approaches informed by practical experience and further research. Nevertheless, certain considerations should be acknowledged during the implementation of this framework. Firstly, the accuracy and comprehensiveness of site assessments and characterisations are crucial. Secondly, the framework does not explicitly address potential synergies or interactions between CLCB and Bio2char strategies, which may be worth exploring in future research. Lastly, the framework is designed to facilitate decision-making in crude oil-contaminated soil and may not be directly applicable to other types of contamination or environmental contexts.

Overall, the decision tree framework for CLCB and Bio2char strategies is the first step towards the development of a valuable tool for practitioners and researchers to better understand the potential benefits and limitations of these strategies and make informed decisions on their implementation. Further research and development of this framework could contribute to more efficient and sustainable remediation practices for crude oil-contaminated soils.

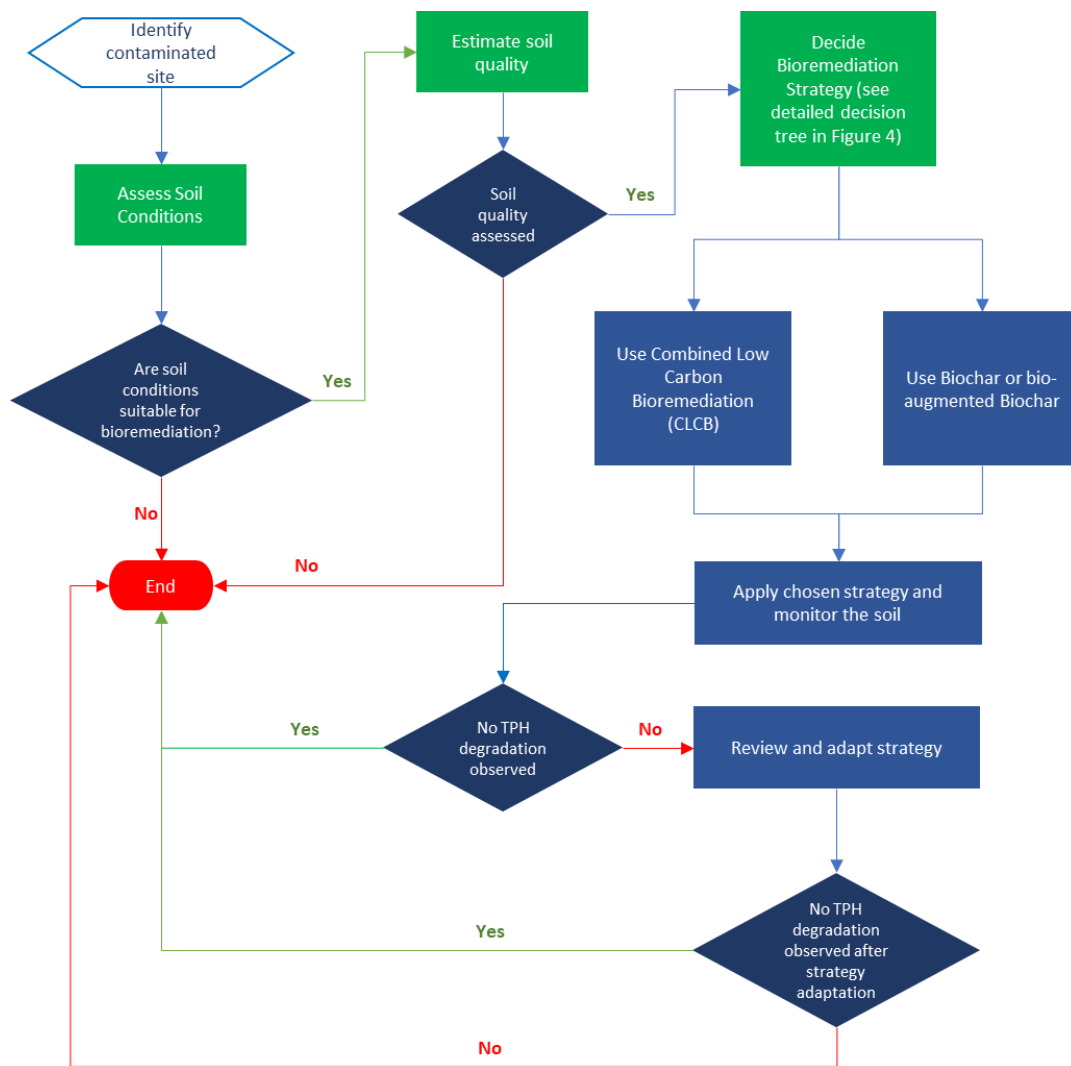


Figure 5. 1 Overview of the Decision-Making Process for Bioremediation Strategy Selection

The success of bioremediation strategies relies heavily on an efficient decision-making process. As shown in Figure 5.1, the process begins with the identification of a contaminated site. Once confirmed, a detailed assessment of soil conditions follows, evaluating factors such as pH, water holding capacity (WHC), oxygen level, TPH concentration, microbial count, and nutrient availability. Integral to this characterization is a comprehensive analysis of the soil's elemental and mineral composition. Elements such as carbon, nitrogen, and phosphorus are fundamental in fostering microbial activity that is essential for bioremediation, while the presence and ratios of minerals can exert a substantial influence on the bioavailability and degradation pathways of contaminants.

A nuanced understanding of the soil's elemental and mineralogical profile is essential, as these characteristics may dictate the suitability and efficacy of specific bioremediation amendments and techniques. For instance, soils with high clay content may inhibit bacterial mobility and nutrient distribution, thus necessitating tailored approaches to enhance permeability and microbial activity. Conversely, soils with adequate mineral composition for nutrient support may favour the application of certain bioremediation techniques over others. In instances where the conditions are deemed unsuitable, the decision-making process reaches its terminus. However, in the event of a favourable soil assessment, the process advances to the next pivotal stage: quantifying the soil. This evaluative step plays a crucial role in determining the extent of the required remediation. As the decision-making process advances to the next stage, the focus is streamlined towards choosing an appropriate bioremediation strategy. Here, the decision tree splits into two possible pathways: the use of CLCB or the employment of biochar or bioaugmented biochar. The choice between these two hinges on a combination of factors, including the intensity of the contamination, the nature of the contaminants, and the overall ecological state of the site. Following the selection of a strategy, it is then meticulously implemented and monitored for signs of TPH degradation. Successful observation of degradation signals a successful end to the process. However, if degradation remains elusive, the process retraces its path to the strategy selection stage, enabling a re-evaluation and adjustment of the strategy. This dynamic, iterative element of the decision-making process ensures that the chosen strategy remains adaptable and effective.

Figure 5.1 introduces the overarching decision-making process involved in bioremediation strategy selection. It provides a high-level roadmap that leads us into the more intricate steps detailed in Figure 5.2. Each stage of this roadmap involves consequential actions, all of which contribute to the selection and implementation of the most effective strategies.

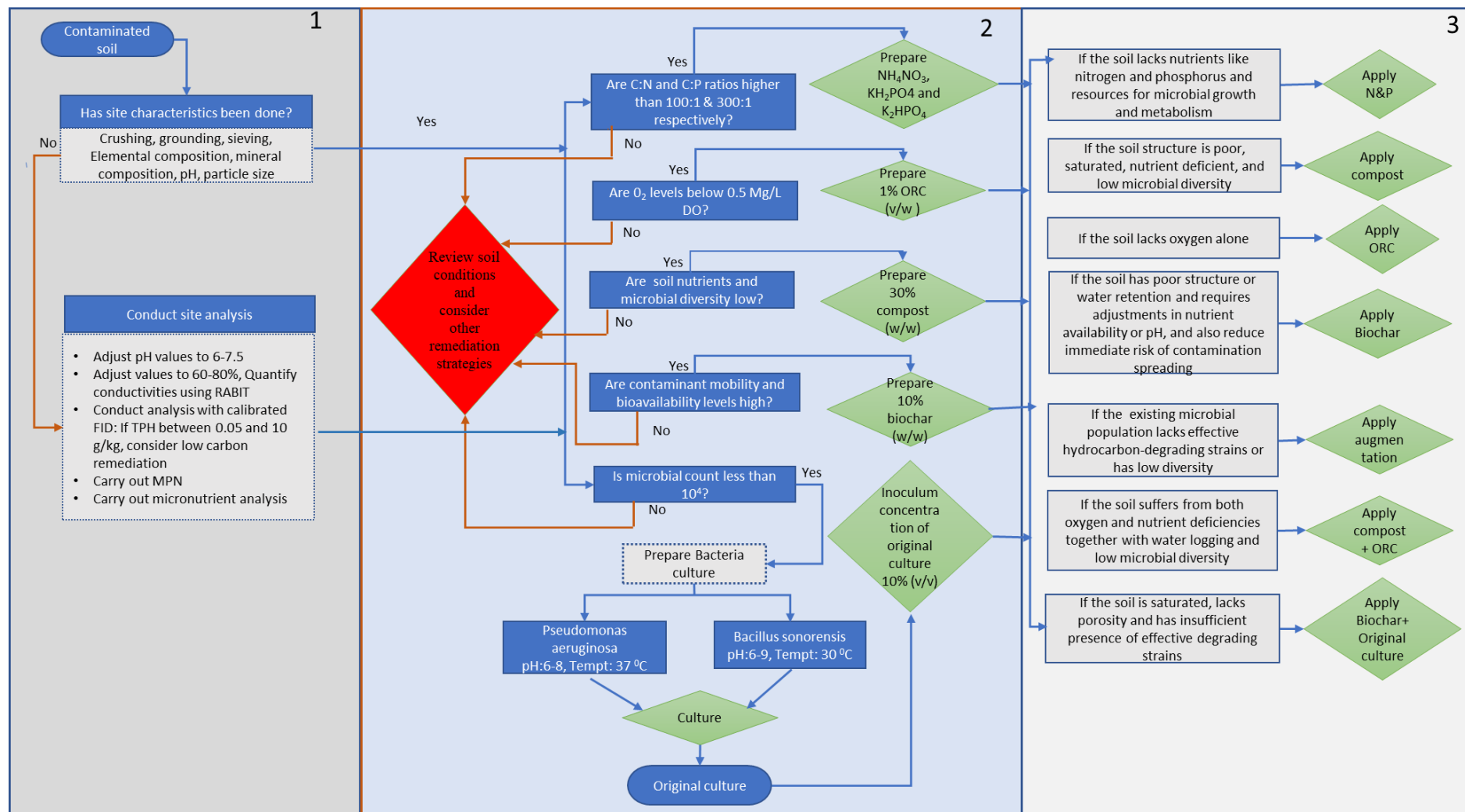


Figure 5. 2 Detailed Decision Tree for Bioremediation Strategy Selection and Implementation

Expanding on the preliminary process outlined in Figure 5.1, Figure 5.2 delves into the crucial points and considerations at each stage. It starts with an extensive site analysis, the foundation of which is a comprehensive evaluation of soil conditions. Parameters such as the soil's pH, WHC, oxygen level, TPH concentration, microbial count, and nutrient availability undergo rigorous evaluation. Additionally, other factors like elemental composition, mineral composition, and particle size are considered to provide an all-encompassing understanding of the soil's health. This assessment may highlight the need to modify certain parameters to render the soil suitable for bioremediation.

Following the verification of the soil's suitability with bioremediation, the decision-making process advances to the stage of quantifying the affected soil volume. Here, the scale of contamination and the volume of soil affected become the determining variables in outlining the scope of the remediation strategy required. The decision tree then deep dives into the meticulous evaluation of individual elements, specifically the presence of light and heavy aliphatic hydrocarbons, as well as light and heavy polyaromatic hydrocarbons. Depending on the outcomes of these assessments, distinct paths emerge, each leading to a potential bioremediation strategy. The selection of a bioremediation strategy marks a critical turning point in the process. At this juncture, the decision tree presents three potential pathways: low carbon bioremediation, CLCB, and biochar or bioaugmented biochar. The choice between these hinges on a nuanced understanding of the site's specific conditions and the nature of the contamination present.

Upon the selection of the most suitable strategy, attention is then directed towards its application, followed by methodical monitoring for evidence of TPH reduction. In instances where degradation is not observed, the process retraces its steps to the strategy selection stage. This return offers an opportunity to re-evaluate, modify, and reapply the strategy, reinforcing the iterative and dynamic nature of the bioremediation process. In essence, Figure 2 enhances and strengthens the overview that Figure 1 provides by delving more deeply into the specifics of each decision point. This layered, comprehensive decision tree encapsulates the complexity of considerations and the need for agile decision-making in the realm of bioremediation, enabling the implementation of effective and responsive remediation

strategies. This approach ultimately paves the way for more successful, sustainable efforts in the realm of soil bioremediation.

5.5. Analytical Hierarchy Process (AHP) for Optimal Bioremediation Strategy Selection

Given the substantial environmental and health hazards associated with oil contamination in the Niger Delta region, a comprehensive approach to decision-making is essential for sustainable remediation strategies. The application of the Analytical Hierarchy Process (AHP) analysis in this study represents a critical step towards an optimised approach for bioremediation strategy selection, offering practical applications for decision-makers and researchers alike.

In the application of the AHP, we involved ten experts from diverse fields, most of whom are integral stakeholders in the Niger Delta region's remediation process. These include representatives from environmental science, academia, industry operators, regulators, scientists, contractors, the local community, and the general public. Their multi-dimensional insights into the evaluation criteria, which encompassed effectiveness, cost, environmental impact, and social acceptability, greatly enhanced the comprehensiveness and legitimacy of our analysis. Notably, policymakers were not represented in our panel of experts, which we acknowledge as a potential limitation of our study, as their perspectives could further contribute to the robustness and practical applicability of the results. Future research should strive to include this crucial stakeholder group.

Two experiments were conducted, each utilising a distinct set of strategies. In the initial experiment, three treatments were examined: B1 employing ORC alone; B2 incorporating ORC with Nitrogen & Phosphorus (N&P); and B3 integrating ORC with Compost. The subsequent experiment involved an array of biochar-based treatments. These strategies incorporated Biochar 1 (B4) and Biochar 2 (B5) as the base, augmented with combinations of *Pseudomonas aeruginosa* (PA) and *Bacillus sonorensis* (BS), resulting in treatments B4PA, B4BS, B4PABS, B5PA, B5BS, and B5PABS.

The high social acceptability score of B3, derived from the judgements of the comprehensive panel of experts and stakeholders, echoes the importance of integrating socio-cultural factors into the decision-making process. Nonetheless, the inherent subjectivity of the AHP methodology must be acknowledged. Despite being a powerful tool, its results could ideally be used in conjunction with other decision-making tools and processes for a more comprehensive understanding. This underscores the need to recognise not only technical factors such as cost and effectiveness but also broader environmental impacts and societal perspectives. Despite its higher cost and environmental footprint in terms of CO₂ emissions, the B4PABS strategy's superior effectiveness coupled with its high social acceptability score rendered it the most viable option in the second experiment (Table 5.8). This result affirms that while cost and environmental impacts are critical considerations, they can be balanced with other important factors.

Table 5. 8 Weights and Scores of Bioremediation Strategies Based on the Analytical Hierarchy Process (AHP) Analysis

Strategy	Effectiveness (Weight: 0.4)	Cost (Weight: 0.1)	Environmental Impact (Weight: 0.3)	Social acceptability (Weight: 0.2)	Total Score
B1	0.120	0.049	0.099	0.080	0.348
B2	0.136	0.03	0.099	0.098	0.363
B3	0.148	0.021	0.099	0.172	0.440
B4	0.027	0.041	0.054	0.029	0.151
B4PA	0.049	0.046	0.038	0.010	0.143
B4BS	0.049	0.048	0.038	0.010	0.145
B4PABS	0.079	0.054	0.038	0.010	0.181
B5	0.027	0.036	0.021	0.029	0.113
B5PA	0.049	0.040	0.013	0.010	0.112
B5BS	0.079	0.043	0.013	0.010	0.145
B5PABS	0.079	0.050	0.013	0.010	0.152

It's noteworthy that the weighting assigned to each criterion was a critical element in our analysis. Even though the cost was given the least weight, this by no means dismisses its importance. Strategies such as B1 (ORC) performed well due to their lower cost. However, given our emphasis on sustainable and socially accepted environmental remediation practices, factors such as environmental impact and social acceptability were prioritized. Such apprehensions could stem from a lack of understanding about the safety and ecological implications of introducing these

bacteria into the environment. Although the bacteria we utilized in our study, *Pseudomonas aeruginosa* and *Bacillus sonorensis*, are naturally occurring and widely recognized for their oil degradation capabilities, we acknowledge that the public's perception may vary and contribute to lower social acceptability scores for these strategies. The application of these bioaugmented strategies indeed necessitates rigorous risk assessment, public communication, and ongoing monitoring to ensure that they do not pose unforeseen environmental or health risks. Therefore, the relatively lower social acceptability scores for these bioaugmented strategies underscore the importance of managing public perceptions and the need for strong stakeholder engagement processes. It is vital to engage the public and local communities in transparent and accessible discussions about these strategies to foster understanding, address potential concerns, and ensure their successful implementation.

It is a clear signal that implementing bioremediation projects goes beyond technical and economic feasibility and must consider the public's understanding, acceptance, and ownership of these solutions. These findings also provide valuable insights for decision-makers, including environmental engineers, policymakers, site owners, and funding bodies, allowing them to tailor bioremediation strategies to specific contexts. The multi-criteria decision analysis approach offers a comprehensive framework for evaluating different strategies, weighing their pros and cons, and aligning the chosen approach with the project's objectives and constraints. However, as the scores reflect averages across various experimental runs, actual results may vary depending on local environmental conditions, the specific type of contamination, and other context-specific factors. Consequently, the absolute values should not be viewed in isolation but rather as relative indicators of the potential performance of the various strategies.

This study provides a useful framework for both academic and practical decision-making in bioremediation strategy selection. It allows for the navigation of complex trade-offs, offering a balance between effectiveness, cost, environmental impact, and social acceptability. Future studies should continue to refine and validate this approach by incorporating additional criteria, exploring diverse weighting approaches, and applying the methodology to different contexts and case studies.

By doing so, the decision-making process for bioremediation strategy selection can become increasingly robust, versatile, and targeted.

5.6 Conclusion

This study presents a novel decision tree framework, rooted in the Analytical Hierarchy Process (AHP), for addressing crude oil-contaminated soil using combined low-carbon bioremediation (CLCB) and Bio2char strategies. The decision tree offers a systematic approach that considers various factors and conditions that may influence the feasibility and effectiveness of these strategies. The framework includes two sections: the application of CLCB in crude oil-contaminated soil and the application of Bio2char in cases of recurring spills on remediated soil. Based on the AHP analysis, it became evident that optimal strategy selection is not merely a function of cost or environmental impact but also involves balancing social acceptability and effectiveness. The decision tree considers site assessments, exposure levels monitored by natural attenuation, and factors influencing the acceptance of these strategies to ensure that the most effective and feasible method is implemented in each situation. While the success of this framework relies on the accuracy and comprehensiveness of site assessments, it represents a significant step forward in the development of more efficient and sustainable remediation practices for crude oil-contaminated soils. Furthermore, the application of the decision tree framework could be highly relevant to the Niger Delta, which has been heavily impacted by crude oil contamination. The systematic approach provided by the framework can guide practitioners and researchers in selecting appropriate remediation strategies based on site-specific factors and conditions. However, it is important to note that the framework does not explicitly address potential synergies or interactions between CLCB and Bio2char strategies, and some considerations should be taken into account when implementing this framework. The success of this approach will require the collaboration of stakeholders, policymakers, and researchers, as well as additional research and development to refine and expand the applicability of the framework to ensure its effectiveness in addressing soil contamination challenges in the Niger Delta and beyond. Overall, this work contributes to informed decision-making and improved environmental outcomes in soil remediation.

5.7 References

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6 Overall Discussion, Conclusion, and Recommendation

6.1 Overall Discussion

Beginning with Chapter 1, this research embarked on an in-depth exploration to confront the widespread problem of oil contamination in the Niger Delta region. This environmental dilemma, which poses serious socio-economic, health, and ecological consequences, necessitated a robust and multidimensional solution. This study encompassed four interconnected objectives: a critical review of low-carbon bioremediation technologies, an assessment of different biostimulation strategies, an evaluation of microbial responses to selected bioaugmentation approaches, and the development of a decision support tool. Each objective made a substantial contribution to the overarching aim of enhancing natural attenuation for crude oil-contaminated soils through an integrative approach of bioremediation techniques. Notably, the study achieved considerable progress in each of these areas, driving forward the understanding and application of low-carbon remediation strategies in the context of the Niger Delta's oil contamination problem.

Chapter 2 served as the pivotal starting point of the research project, guiding its trajectory and providing the focus needed to navigate the intricate issue at hand. This chapter entailed a comprehensive review of recent progress made towards low-carbon bioremediation technologies for sustainable remediation approaches. The study not only dissected various remediation technologies, including phytoremediation, bioremediation, chemical oxidation, and electrokinetic remediation (EKR), with their successful applications in different contexts but also highlighted the limitations such as cost, time, and environmental conditions that may restrict their effectiveness. Further to this, Chapter 2 emphasised the crucial role of stakeholder engagement in the remediation process, arguing for an integrated approach that involves local communities, government agencies, and environmental NGOs. This can result in more successful and sustainable outcomes. As a component of this integrated approach, the research introduced a novel framework, SuRF-Nigeria, which provides a systematic pathway for sustainable remediation in the region.

Identifying the obstacles to the implementation of sustainable remediation practices in Nigeria, such as a lack of awareness, an inadequate regulatory framework, illegal

refining, and insufficient funding, the study proposed potential solutions. These include strengthening regulations, establishing a long-term funding structure, developing a comprehensive database for contaminated lands, and building an integrated contaminated land management centre. In this foundational stage, the research not only laid the groundwork for the subsequent stages of the project but also provided an invaluable contribution to the scientific community's understanding of low-carbon remediation techniques in the context of the Niger Delta region. This enriched the body of knowledge available on this specific type of environmental contamination, setting the stage for further innovations in the field.

Building upon the insights gained from Chapter 2, Chapter 3 focused on the experimental design and execution of innovative bioremediation strategies to enhance the natural attenuation of crude oil-contaminated soils. In this endeavour, the research aimed to advance our understanding of the underlying mechanisms of microbial degradation processes, highlight the effectiveness of combined biostimulation strategies and enhance the natural attenuation effectiveness of crude oil-contaminated soils using different bioremediation approaches. The research delved into the field of novel low-carbon bioremediation technologies, with particular emphasis on oxygen- and nutrient-based biostimulation strategies. The core of the experimental investigation involved the use of three different biostimulation treatments: oxygen alone (B1), oxygen with nutrients (B2), and oxygen with compost (B3). These were compared against a passive set, represented by monitored natural attenuation (MNA). Each strategy's effectiveness was assessed over 180 days, employing metrics such as total petroleum hydrocarbon (TPH) degradation, microbial activity, and ecotoxicological bioassays.

The findings from these biostimulation experiments (B1, B2, and B3), constitute a substantial scientific contribution to the field of bioremediation. All three biostimulation strategies outperformed the MNA set in terms of hydrocarbon degradation and toxicity reduction. The highest degradation rate was noted in the B3 treatment, where the combination of oxygen and compost facilitated a synergistic effect, significantly decreasing TPH concentration and soil toxicity levels. Notably, chapter 3 revealed a dynamic interplay between TPH concentration and toxicity levels. As TPH degradation improved, toxicity levels concurrently decreased,

indicating an inverse correlation. This relationship was demonstrated through enhanced wheat seed germination rates, confirming the success of the biostimulation treatments in mobilising microbial communities and increasing TPH degradation, especially for the B3 strategy.

Furthermore, the research's significance extends beyond the experimental results to its broader implications for the fields of environmental science and soil remediation. It provides a basis for future large-scale field trials to validate these findings under real-world conditions, thereby potentially contributing to more effective remediation strategies for crude oil-contaminated soils. Thus, Chapter 3 effectively propelled the field of bioremediation forward by providing valuable insights into the role of oxygen and nutrients in bioremediation strategies.

Chapter 4 of this study sought to evaluate and optimise bioremediation strategies, focusing on the interaction between different types of biochar and selected bacterial strains (*Pseudomonas aeruginosa* and *Bacillus sonorensis*) in crude oil-contaminated soils. Over a 90-day period, the effects of biochar, bacterial strains, and their combinations on hydrocarbon degradation, microbial activity, and overall soil health were examined in depth. The B4PABS treatment, a combination of biochar, *P. aeruginosa*, and *B. sonorensis*, showed exceptional efficacy, facilitating a significant increase in soil respiration, microbial biomass, and total petroleum hydrocarbon (TPH) degradation, with a degradation rate of up to 93%. The chapter demonstrated that the different treatments led to diverse microbial communities, a crucial element in effective bioremediation. An observed positive correlation between increased microbial diversity and TPH degradation underscores the critical role of these diverse communities. The findings also revealed the adaptability and resilience of microbial communities in crude oil-contaminated soils, particularly under conditions of recurring oil spills. Furthermore, chapter 4 highlighted a 'priming effect', suggesting that microbial communities could respond more efficiently to oil spills due to previous exposure. This insight could serve as a basis for future research aimed at improving remediation strategies in environments experiencing repeated oil spills. In relation to objective 3 and the overall aim of the study, the findings of Chapter 4 provide compelling evidence of the potential of combined bioaugmentation approaches like B4PABS to enhance natural attenuation in crude oil-contaminated

soils, particularly for recurrent spills in the Niger Delta. Thus, the chapter directly addresses and supports the research's stated aim and objectives.

Chapter 5 focused on simplifying the intricate process of selecting sustainable bioremediation strategies. The research team developed a pioneering decision tree structure, based on the Analytical Hierarchy Process (AHP). This tool provides a pragmatic means for making informed decisions by considering a range of crucial variables, such as cost, environmental implications, social acceptability, and the efficacy of different strategies. This investigation sought to tackle the critical environmental challenge of oil contamination in the Niger Delta by exploring and comparing various bioremediation approaches. The research aimed to establish a comprehensive framework for choosing the most effective, cost-efficient, and socially accepted strategy using the AHP analysis. This new framework contributes significantly to the field of environmental management and decision-making, establishing a path for more balanced and effective decisions in the future. Two experiments were conducted, utilising a unique set of bioremediation strategies. The results showed that the B3 strategy, integrating ORC with compost, and the B4PABS strategy, combining wheat straw biochar with *Pseudomonas aeruginosa* and *Bacillus sonorensis*, were the most effective. Notably, the AHP analysis disclosed that social acceptability was a significant factor in decision-making, underscoring the importance of socio-cultural factors.

Additionally, the study in Chapter 5, offers practitioners and researchers innovative guidance for choosing the most suitable strategy based on site-specific factors, highlighting the importance of a multi-criteria decision-making process in the selection of optimal bioremediation strategies. This decision tree framework and the study's findings contribute to the project's aim to enhance the effectiveness of natural attenuation for crude oil-contaminated soils using a combination of different bioremediation approaches.

The chapters within this study have collectively advanced the field of low-carbon bioremediation through several significant accomplishments. The research critically reviewed and validated low-carbon bioremediation technologies, identifying the key role of oxygen and nutrients in biostimulation strategies. The findings revealed the synergistic effect of combined bioremediation approaches and the importance of

microbial diversity and resilience in biodegradation. Perhaps most impactful is the development of a pioneering decision tree structure based on the Analytical Hierarchy Process (AHP), a practical and comprehensive tool for choosing effective and socially accepted bioremediation strategies. These contributions collectively bolster the management and understanding of crude oil-contaminated soils, particularly in the Niger Delta region, underlining the necessity for comprehensive, multi-faceted approaches that integrate technical efficacy and socio-cultural considerations in environmental remediation.

This extensive research has made significant strides in advancing the understanding of oil contamination management in the Niger Delta in several significant ways by introducing low-carbon bioremediation technologies that bridge a critical gap in sustainable oil contamination solutions. These low-carbon technologies provide practical solutions, particularly highlighting the essential role of oxygen and nutrients in boosting bioremediation strategies. The findings underscore the importance of microbial diversity in biodegradation processes, offering insights into the adaptive capacities of microbial communities in oil-contaminated soils, especially under recurrent oil spill conditions. In meeting the project objectives, significant contributions have been made to environmental science, extending beyond academic discourse to practical applications. The development of a novel decision-support tool, based on the Analytical Hierarchy Process (AHP), is a major achievement of this research. This tool simplifies the complex process of selecting effective and socially accepted bioremediation strategies, paving the way for more nuanced, context-specific remediation approaches. Collectively, these advancements provide a detailed understanding of oil contamination management complexities and a clear direction for future work in the field.

6.2 Conclusion

These comprehensive studies have led to groundbreaking and significant advancements in understanding and managing oil-contaminated soils. The research has resulted in the critical review of low-carbon bioremediation technologies, the development of innovative biostimulation strategies, the uncovering of crucial interactions between biochar and bacterial strains, and the creation of a pioneering

decision support tool. These achievements collectively contribute to a more integrated and sustainable management of oil-contaminated soils. They have led to the creation of a unique framework for selecting effective and socially acceptable bioremediation strategies, potentially transforming future remediation projects in the Niger Delta region and similar environments globally. Additionally, the identification of the synergistic effect of oxygen and compost (B3 strategy) and the combination of wheat straw biochar with *Pseudomonas aeruginosa* and *Bacillus sonorensis* (B4PABS strategy) have set new benchmarks in the field of bioremediation. Each of these breakthroughs has not only met the study's objectives but also resulted in significant contributions to the field of environmental science, particularly in the fields of bioremediation and sustainable environmental decision-making. As a result, this research holds the promise of substantially improving the environmental health of oil-contaminated regions, leading to more effective and sustainable environmental remediation practices for years to come.

6.3 Future Research and Recommendations

Despite the groundbreaking achievements from this research, there are areas that require further exploration and refinement to extend the applicability of the developed strategies and the decision-making tool.

1. **Refinement of the AHP Decision-Making Process and Framework:** Future research should aim at refining the decision-making process and the decision tree framework. This can be achieved by incorporating additional criteria and diverse weighting approaches that take into consideration the complexity and variability of oil-contaminated environments.
2. **Context-specific Bioremediation Strategies:** Greater emphasis should be placed on considering local and context-specific factors when implementing bioremediation strategies. The unique needs and constraints of the specific environment should be taken into account to ensure that the selected strategy aligns with the remediation objectives and site conditions.
3. **Collaboration for Success:** Active collaboration among scientists, local communities, and policymakers is recommended to ensure the successful implementation of the bioremediation strategies. Scientists provide technical

expertise, while local communities and policymakers play a crucial role in decision-making and the practical implementation of the strategies.

4. Further Study of Biochar and Bacterial Strain Interactions: The interactions between biochar and bacterial strains uncovered in this research offer promising potential. Future research should delve deeper into understanding these interactions and optimising them for improved bioremediation outcomes.
5. Global Application: As the achievements of this research have the potential to transform future remediation projects, studies to validate and refine these strategies and tools in different global contexts are recommended.

The continued evolution of this research area, through the directions suggested above, will further strengthen the groundbreaking achievements of this study, thus furthering the field of bioremediation and sustainable environmental decision-making.

APPENDIX

Bioremediation Strategy Selection: Analytical Hierarchy Process (AHP) Questionnaire-Expert Responses

Expert 1

Section 1: Expert Demographics

1. Full Name (optional): Expert 1
2. Position/Job Title: Technical Expert
3. Organization: Okojoben Nigeria Limited
4. Field of Expertise: Restoration Scientist
5. Years of Experience in the Field: 11 Years of Experience
6. Highest Academic Qualification: MSc Land Reclamation and Restoration
7. Have you been involved in any bioremediation projects? If yes, please briefly describe your role and the project(s): Yes. Project management/coordination and technical reporting.

Section 2: Engagement with Stakeholders

8. What types of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)? Site owners/representatives, Policymakers, community representatives (Community development chairperson, women and youth leaders, chiefs including elders), NGOs head/representatives, professional colleagues, and the general public.
9. Can you share some examples of how you have engaged with these stakeholders in decision-making processes?

Section 3: Decision Criteria Weighting

This section seeks your input on the importance of different criteria in the selection of bioremediation strategies. These criteria include effectiveness, cost, environmental impact, and social acceptability.

Please rate the importance of each criterion on a scale of 1 (least important) to 9 (most important). Your responses will help in determining the weights assigned to each criterion in our Analytical Hierarchy Process (AHP) analysis.

10. Effectiveness (Ability of the strategy to remediate the oil contamination):

- **Rating:** 9
- **Justification:** Thorough scientific investigation must have been carried out.

11. Cost (Financial cost of implementing the strategy):

- **Rating:** 7
- **Justification:** A lot of factors are usually considered before arriving at the budget.

12. Environmental Impact (Environmental footprint, including CO₂ emissions, associated with the strategy):

- **Rating:** 8
- **Justification:** This is mostly approved at the initial stage of planning by the regulators.

13. Social Acceptability (Acceptance of the strategy by the local community and other stakeholders):

- **Rating:** 6
- **Justification:** Consider the input of the stakeholders, it was accepted by the community.

14. Could you please rank these criteria from least to most important?

Ranking: Cost > Social Acceptability > Environmental Impact > Effectiveness

Section 4: Additional Comments

14. Do you have any other comments or suggestions related to the decision-making process for selecting bioremediation strategies?

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone

- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 8

Justification: The effectiveness of this strategy you have presented in laboratory conditions is quite promising. Additionally, compost is a natural and readily available material, which makes this method potentially cost-effective.

Biochar with Strains

Rating: 9

Justification: The addition of bacteria that have been shown to degrade oil contaminants effectively significantly boosts the potential of this strategy. However, detailed explanations about the use of bacteria should be given to communities to ensure social acceptability.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their

social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: The use of compost, a natural and readily available material, could improve the social acceptance of this method. Clear communication about the process and involvement of the community in the implementation can further increase acceptability.

Biochar with Strains

Rating: 6

Justification: The introduction of bacteria in the process might raise concerns among the community. Clear communication, clarification, and education are necessary to improve acceptance.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Considering the criteria and the given ratings, both OC and BS strategies show significant potential. I would recommend a combination of both for field testing, with adjustments based on the results and feedback from the community. Proper engagement with the community and stakeholders is crucial to ensure understanding and acceptance of the strategies. The final decision should consider a balance between effectiveness, cost, environmental impact, and social acceptability.

Expert 2

Section 1: Expert Demographics

1. Full Name (optional): Expert 2
2. Position/Job Title: Oil spill response & Remediation Coordinator
3. Organization: Eroton Exploration & Production Company Limited
4. Field of Expertise: Oil Spill Response & Remediation
5. Years of Experience in the Field: 15 years
6. Highest Academic Qualification: MSc Environmental Management
7. Have you been involved in any bioremediation projects? If yes, please briefly describe your role and the project(s): Project management and clean-up of contaminated sites.

Section 2: Engagement with Stakeholders

8. What types of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)? Nigerian Upstream Petroleum Regulatory Commission (NUPRS), National Oil Spill Detection and Response Agency (NOSDRA), State & Federal Ministry of Environment, and host communities.
9. Can you share some examples of how you have engaged with these stakeholders in decision-making processes?
 - i. Development of appropriate risk assessment program for clean-up and remediation of any spill site
 - ii. Sharing knowledge and participating in the management and evaluation of spill sites.

Section 3: Decision Criteria Weighting

This section seeks your input on the importance of different criteria in the selection of bioremediation strategies. These criteria include effectiveness, cost, environmental impact, and social acceptability.

Please rate the importance of each criterion on a scale of 1 (least important) to 9 (most important). Your responses will help in determining the weights assigned to each criterion in our Analytical Hierarchy Process (AHP) analysis.

10. Effectiveness (Ability of the strategy to remediate the oil contamination):

a. **Rating:** 9

b. **Justification:** Effectiveness can influence price and improve the market.

11. Cost (Financial cost of implementing the strategy):

a. **Rating:** 9

b. **Justification:** Cost can influence usage. It can lead to comparative analysis. It can influence application.

12. Environmental Impact (Environmental footprint, including CO₂ emissions, associated with the strategy):

a. **Rating:** 4

b. **Justification:** It would have been considered at the approval stage.

13. Social Acceptability (Acceptance of the strategy by the local community and other stakeholders):

a. **Rating:** 5

b. **Justification:** If the technique is not approved by the regulators, it will not be accepted. Social acceptability is subject to regulatory acceptance. If it is approved by the regulatory agencies, it will be accepted by the community.

14. Could you please rank these criteria from least to most important?

o Social Acceptability → Cost → Environmental Impact → Effectiveness

Section 4: Additional Comments

1. Do you have any other comments or suggestions related to the decision-making process for selecting bioremediation strategies?

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 8

Justification: Considering the effectiveness of ORC with Compost in laboratory tests, I believe it would be a suitable strategy, especially as compost is a natural product and readily available. The organic nature of compost may also boost social acceptability.

Biochar with Strains

Rating: 9

Justification: The use of strains in synergy with Biochar 1 demonstrates high effectiveness in lab tests. The bacteria's ability to degrade oil contaminants efficiently is a significant advantage. However, the use of bacteria may need more clarification for the local communities to understand and accept the strategy

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification

for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: The use of compost, which is natural and organic, should be more socially acceptable, as it can be perceived as safer and less intrusive. Also, the availability of compost could encourage community participation in the process

Biochar with Strains

Rating: 6

Justification: Despite the effectiveness of B4PABS, its social acceptability could be challenging due to the use of bacteria. Clear communication with the community regarding the safety and benefits of the method would be crucial.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Given the high effectiveness of both OC and BS, I would recommend using a combination of both strategies. This approach would help us leverage the strengths of both strategies, namely, the readily available and organic nature of compost in OC, and the high degradation capability of the bacteria in BS. This recommendation is however subject to an in-depth cost-benefit analysis and community consultation to ensure their understanding and acceptance.

Expert 3

Section 1: Expert Demographics

1. Full Name (optional): Expert 3
2. Position/Job Title: Team Lead, Shoreline Clean-up & Mangroves Restoration
3. Organization: Hydrocarbon Pollution Remediation Project (HYPREP)
4. Field of Expertise: Environmental Assessment, Land Remediation, Shoreline Remediation, Assessment & Mangrove Restoration.
5. Years of Experience in the Field: 10 years
6. Highest Academic Qualification: Masters in Soil Science (Pedology)
7. Have you been involved in any bioremediation projects? If yes, please briefly describe your role and the project(s): Yes, as Remediation Site Supervisor

Section 2: Engagement with Stakeholders

8. What types of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Primarily site owners, environmental engineers, and funding bodies. I also interact with policymakers when advising on environmental legislation.

9. Can you share some examples of how you have engaged with these stakeholders in decision-making processes?

Response: I have conducted numerous workshops and seminars to share insights from my research and to foster dialogue around best practices for bioremediation.

Section 3: Decision Criteria Weighting

10. Effectiveness (Ability of the strategy to remediate the oil contamination)
 - **Rating:** 7

- **Justification for your rating:** The primary goal of any bioremediation strategy is to effectively remove or neutralize contaminants. If a strategy is not effective, its other attributes are moot.
11. Cost (Financial cost of implementing the strategy)
- **Rating:** 4
 - **Justification for your rating:** While cost is an important consideration, it should not overshadow other vital factors such as effectiveness, environmental impact, and social acceptability.
12. Environmental Impact (Environmental footprint, including CO₂ emissions, associated with the strategy)
- **Rating:** 9
 - **Justification for your rating:** A major goal of bioremediation is to restore the environment, and thus it is important to choose a strategy that minimizes negative environmental impact.
13. Social Acceptability (Acceptance of the strategy by the local community and other stakeholders)
- **Rating:** 6
 - **Justification:** The success of a bioremediation strategy is often dependent on its acceptance by the local community and other stakeholders. It's important to involve and consider their perspectives to ensure successful implementation and sustainability.
14. Could you please rank these criteria from least to most important?
- Cost → Social Acceptability → Effectiveness → Environmental Impact

Section 4: Additional Comments

15. Do you have any other comments or suggestions related to the decision-making process for selecting bioremediation strategies?

Response: Incorporating the perspectives of a diverse group of stakeholders, including local community members, can greatly enhance the decision-making process.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 8

Justification: The combination of ORC and compost can effectively address oil contamination.

Biochar with Strains

Rating: 8

Justification: The use of specific bacteria in bioremediation is a promising strategy.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 9

Justification: Using compost is socially accepted and does not raise significant concerns among the local population

Biochar with Strains

Rating: 7

Justification: The introduction of specific bacteria might cause initial apprehension, but with proper education, this strategy can be accepted.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

I would recommend the use of OC as the main strategy due to its effectiveness and high social acceptability. However, BS could also be used as a complementary approach, particularly in areas where contamination is more severe or persistent.

Expert 4

Section 1: Expert Demographics

1. Full Name (optional): Expert 4
2. Position/Job Title: Consultant, climate change and Green Growth
3. Organization: African Development Bank
4. Field of Expertise: Environmental Policy, Environmental Economics
5. Years of Experience in the Field: 12 years
6. Highest Academic Qualification: PhD in Environmental Biotechnology

7. Involvement in bioremediation projects: Yes, providing policy analysis and recommendations to inform decision-making.

Section 2: Engagement with Stakeholders

8. What types of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: I engage with policymakers, international organizations, and local communities within Africa.

9. Can you share some examples of how you have engaged with these stakeholders in decision-making processes?

Response: Public hearings, policy briefings, and stakeholder consultations.

Section 3: Decision Criteria Weighting

10. Effectiveness

- **Rating:** 9
- **Justification:** Effectiveness should be the main consideration but must be balanced with cost and impact on society and the environment.

11. Cost

- **Rating:** 5
- **Justification:** Cost is significant, especially in resource-constrained settings, but shouldn't compromise overall effectiveness or sustainability.

12. Environmental Impact

- **Rating:** 8
- **Justification:** Minimizing environmental impact is crucial to any remediation effort.

13. Social Acceptability

- **Rating:** 7
- **Justification:** Without community support, the best strategy might fail.

14. Could you please rank these criteria from least to most important?

o Cost → Environmental Impact → Social Acceptability → Effectiveness

Section 4: Additional Comments

15. Comments/Suggestions

Response: A more comprehensive cost-benefit analysis that quantifies environmental and social benefits could improve the decision-making process.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 7

Justification: The use of compost is a sound strategy, although it requires consistent quality control.

Biochar with Strains

Rating: 9

Justification: The joint action of these bacteria provides a strong approach to degrading oil contaminants.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 8

Justification: The use of compost is familiar and acceptable to most community members.

Biochar with Strains

Rating: 7

Justification: There might be some initial resistance to the use of bacteria, but with proper communication, this can be managed.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

I recommend a balanced approach between OC and BS, depending on the specific conditions of each remediation site. Both strategies have their strengths, and the final decision should take into account local context, stakeholders' perspectives, and resource availability.

Expert 5

Section 1: Expert Demographics

1. Full Name (optional): Expert 5
2. Position/Job Title: Environmental Scientist
3. Organization: Dexcom Solution Limited
4. Field of Expertise: Environmental Biotechnology
5. Years of Experience in the Field: 10 years
6. Highest Academic Qualification: Masters in Environmental Science
7. Involvement in bioremediation projects: Yes, Assessment, clean-up, and monitoring of remediation activities.

Section 2: Engagement with Stakeholders

8. What types of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Contractors, site owners, local communities, and regulators.

9. Can you share some examples of how you have engaged with these stakeholders in decision-making processes?

Response: Site visits, stakeholders' meetings, scientific briefings

Section 3: Decision Criteria Weighting

10. Effectiveness

- **Rating:** 9
- **Justification:** If the strategy doesn't work, other factors become irrelevant.

11. Cost

- **Rating:** 4
- **Justification:** Important, but secondary to effectiveness and environmental impact.

12. Environmental Impact

- **Rating:** 7
- **Justification:** The strategy should contribute positively to the environment.

13. Social Acceptability

- **Rating:** 6
- **Justification:** For long-term sustainability, social acceptance is crucial.

14. Could you please rank these criteria from least to most important?

- Cost → Social Acceptability → Environmental Impact → Effectiveness

Section 4: Additional Comments

14. Comments/Suggestions

Response: Rigorous field testing of strategies and long-term monitoring are important to validate lab results and to evaluate the true effectiveness of strategies.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the

synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 7

Justification: The combination of ORC with Compost has the potential to demonstrate good results, as ORC has been used in the past for cleaning which showed considerable results as well. Compost provides nutrients that stimulate microbial activity, making the process more effective. Nonetheless, the quality and availability of compost may influence the overall effectiveness.

Biochar with Strains

Rating: 9

Justification: Biochar and bacteria strains utilize the synergistic abilities of bacteria strains, which have been proven to be highly effective at degrading oil contaminants. While it may require a higher upfront investment, its effectiveness may result in long-term cost savings.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: The application of ORC with Compost, being a more organic approach, might be seen as a safer method and thus could have a higher social acceptance rate.

Biochar with Strains

Rating: 6

Justification: Justification of your rating: Despite the high effectiveness of BS, public perception towards the use of bacteria may affect its social acceptance. Clear communication and education on the safety and benefits of this strategy would be required.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Final Recommendation: While I understand that both OC and BS have their advantages, considering the high effectiveness of OC and its potential for long-term cost savings, I would lean towards recommending BS. However, this recommendation comes with the caveat that comprehensive stakeholder engagement, public education, and ongoing monitoring of the application's impact are crucial for this strategy to be successfully implemented and accepted.

Expert 6

Section 1: Expert Demographics

1. Full Name (optional): Expert 6
2. Position/Job Title: Chief Environmental Scientist
3. Organization: National Oil Spill Detection and Response Agency (NOSDRA)
4. Field of Expertise: Project Management, Site recovery

5. Years of Experience in the Field: 15 years
6. Highest Academic Qualification: Master's in Environmental Engineering
7. Involvement in bioremediation projects: Yes, regulating various bioremediation projects.

Section 2: Engagement with Stakeholders

8. What type of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Federal and state Ministry of Environment, site owners, local communities, Oil operators

9. Can you share some examples of how you engaged with these stakeholders in decision-making processes?

Response: Project meetings, site visits, stakeholder briefings

Section 3: Decision Criteria Weighting

10. Effectiveness

- Rating: 8
- **Justification:** A defective technology is sure to leave a negative environmental impact behind. Such a technology can't be said to be effective. Hence, this will naturally come behind the environmental impact.

11. Cost

- **Rating:** 6
- **Justification:** Cost is a major consideration in the feasibility of a strategy, especially for private site owners.

12. Environmental Impact

- **Rating:** 9
- **Justification:** The Niger Delta is already degraded by years of oil pollution. Any method used in the remediation of the environment must

never be seen to leave a negative environmental impact as that would be counterproductive.

- Then the cost of technology comes next. Of what use is a technology to me If I can't afford to bring it in? So this will come next after effectiveness. Then again why would for the sake of reducing cost choose a technology that leaves a gross negative impact on the environment, that would be penny-wise pounds foolish as they say. I use little cash to get the job done and look for big cash to undo the damage caused by trying to reduce cost. So while looking for affordable technology, its environmental impact and effectiveness remain foremost in my mind.
- Then comes social acceptability
- The society will go for any technology that is not seen to leave behind negative environmental impact.

13. Social Acceptability

- **Rating:** 6
- **Justification:** It's easier to implement a strategy that has the support of the community and other stakeholders.

14. Could you please rank these criteria from least to most important?

- Social Acceptability → Cost → Effectiveness → Environmental Impact

Section 4: Additional Comments

15. Comments/Suggestions

Response: Closer collaboration between academics, practitioners, and communities can enhance the understanding and acceptability of bioremediation strategies.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)

- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 8

Justification: ORC with Compost has the tendency to clean up contaminated soil that is deficient in nutrients and oxygen. The addition of compost provides essential nutrients that enhance microbial activity, thus improving remediation process

Biochar with Strains

Rating: 7

Justification: The combination of bacteria strains in BS shows potential, utilizing the synergistic abilities of these bacteria to degrade oil contaminants. However, the novel nature of this strategy may require more studies to fully understand its long-term impact.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their

social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: The application of ORC with Compost is likely to be more acceptable to the local community as it utilizes materials (compost) that are readily available and familiar to the people. It is a method that aligns well with the principles of sustainability.

Biochar with Strains

Rating: 5

Justification: Justification of your rating: While B4PABS demonstrates a high level of effectiveness, its social acceptability might be compromised due to potential concerns about the use of specific bacteria for bioaugmentation. It will require a lot of public education and engagement to assuage any fears and misconceptions that might arise

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

I would recommend OC for bioremediation in the Niger Delta region. The strategy is not only effective but also socio-culturally acceptable, cost-effective and aligns with the goal of sustainable environmental management. However, for BS to be fully deployed, extensive risk assessments, rigorous public engagement and education are necessary to mitigate concerns about the use of bacteria for bioaugmentation.

Expert 7

Section 1: Expert Demographics

1. Full Name (optional): Expert 7
2. Position/Job Title: Reader in Agricultural and Environmental Engineering
3. Organization: Rivers State University, Port Harcourt, Nigeria
4. Field of Expertise: Environmental Engineering
5. Years of Experience in the Field: 18 years of experience
6. Highest Academic Qualification: PhD
7. Involvement in bioremediation projects: Yes. Team Lead in the Field Trial of Locally Produced Soil Bioremediation Products, which was funded by the Nigerian Content Development and Monitoring Board (NCDMB).
<http://dx.doi.org/10.13140/RG.2.2.24873.57442/3>

Section 2: Engagement with Stakeholders

8. What type of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Policymakers, local communities, funding bodies, environmental engineers, site contractors, remediation product manufacturers

9. Can you share some examples of how you engaged with these stakeholders in decision-making processes?

Response:

- Policymakers: Logistics, HSE, Site Characterization, QA/QC, Monitoring & Evaluation, Reporting, Compliance Checks, Certification
- Local Communities: Site Access, Compensation, Homage, Security, Local Labour, Capacity Building
- Funding Bodies: Accountability, Logistics, Scoping, Supervision, Monitoring & Evaluation, Reporting, Advocacy for What Works

- Environmental Engineers: Logistics, HSE, Site Characterization, QA/QC, Implementation Strategy, Technology Applications, Supervision, Monitoring & Evaluation, Reporting
- Site Contractors: HSE, Technology Applications, Security, Information Sharing
- Product Manufacturers: Logistics, Implementation Strategy, Product/Method Application, Advisory, Reporting

Section 3: Decision Criteria Weighting

10. Effectiveness

- Rating:** 9
- Justification:** To achieve the remediation target value (screening value) for the contaminant

11. Cost

- Rating:** 9
- Justification:** Remediation cost and screening value are not linearly correlated

12. Environmental Impact

- Rating:** 9
- Justification:** Remediation footprint and environmental sustainability are not linearly correlated.

13. Social Acceptability

- Rating:** 6
- Justification:** Fosters peace and harmony and guarantees security

14. Could you please rank these criteria from least to most important?

- o Social Acceptability → Effectiveness → Environmental Impact → Cost

Section 4: Additional Comments

15. Comments/Suggestions

Response: Closer collaboration between academics, practitioners, and communities can enhance the understanding and acceptability of bioremediation strategies.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 8

Justification: Compost significantly enhances microbial activity, improving remediation results.

Biochar with Strains

Rating: 7

Justification: The combined action of the two bacteria can degrade contaminants effectively, but there are still some challenges with consistency.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 9

Justification: Compost is readily available and commonly used in agriculture in this region, leading to high acceptance

Biochar with Strains

Rating: 6

Justification: The use of specific bacteria may cause concern among some community members, reducing acceptance

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Considering all aspects, I recommend OC due to its high effectiveness and social acceptability. Although BS also shows promise, the higher acceptance of OC makes it more suitable for immediate implementation in the Niger Delta region.

Expert 8

Section 1: Expert Demographics

1. Full Name (optional): Expert 8
2. Position/Job Title: Environmental Scientist
3. Organization: Basic Nigeria Limited
4. Field of Expertise: Remediation and land reclamation
5. Years of Experience in the Field: 12 years of experience
6. Highest Academic Qualification: MSc in Environmental Biotechnology
7. Involvement in bioremediation projects: Yes. Supervise and coordinate remediation activities, soil and impact assessment

Section 2: Engagement with Stakeholders

8. What type of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Local communities, Regulators, site owners, and operators

9. Can you share some examples of how you engaged with these stakeholders in decision-making processes?

Response: Engaged with stakeholders on environmental impacts and the techniques applied within the communities and how best to minimize environmental impacts as well as ensure best practices and quality service delivery for the site owners through constant engagement

Section 3: Decision Criteria Weighting

10. Effectiveness

- a. **Rating:** 7
- b. **Justification:** An effective process is key to site owner satisfaction as well as local communities satisfaction

11. Cost

- a. **Rating:** 9
- b. **Justification:** All business decisions including remediation will ultimately be driven by affordability

12. Environmental Impact

- a. **Rating:** 8
- b. **Justification:** Local Communities are most affected by this and this also affects the perception of the site owners as well as their ability to freely operate in those local communities

13. Social Acceptability

- a. **Rating:** 7
- b. **Justification:** For implementation to even commence all stakeholders must be able to accept the strategy as being the best

14. Could you please rank these criteria from least to most important?

- o Social Acceptability → Effectiveness → Environmental Impact → Cost

Section 4: Additional Comments

15. Comments/Suggestions

Response: Closer collaboration between academics, practitioners, and communities can enhance the understanding and acceptability of bioremediation strategies.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 7

Justification: Compost is easily accessible and readily available and could prove cost-effective, however, the real-life effectiveness may differ from laboratory conditions

Biochar with Strains

Rating: 8

Justification: The combined action of the two bacteria can degrade contaminants effectively, but there are still some challenges with consistency.

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: While compost is a natural and available material, explaining the process to the community is necessary to increase acceptance

Biochar with Strains

Rating: 5

Justification: The use of bacteria might raise concerns in the community. Proper communication about the process and benefits is necessary to increase acceptance.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Recommendation: Both OC and BS strategies show potential. They should be field-tested with adjustments based on the results and community feedback. For implementation, the acceptance of all stakeholders is crucial. Ensuring a balance between cost, environmental impact, effectiveness, and social acceptability should guide the final decision. More collaboration between academics, practitioners, and communities would enhance the understanding and acceptability of bioremediation strategies

Expert 9

Section 1: Expert Demographics

1. Full Name (optional): Expert 9
2. Position/Job Title: Chief Microbiologist
3. Organization: Dexcom Solution Limited
4. Field of Expertise: Environmental Assessment
5. Years of Experience in the Field: 11 years of experience
6. Highest Academic Qualification: MSc Environmental Microbiology
7. Involvement in bioremediation projects: Yes. Coordinate site Assessment and remediation of crude oil polluted site

Section 2: Engagement with Stakeholders

8. What type of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Local communities, Regulators, site owners, and site engineers

9. Can you share some examples of how you engaged with these stakeholders in decision-making processes?

Response: Engaged with stakeholders on Joint Investigation Visits (JIV) and recommend the best available techniques (BAT) for remediation

Section 3: Decision Criteria Weighting

10. Effectiveness

- a. **Rating:** 9
- b. **Justification of your rating:** The method of remediation should reduce the contamination to the lowest level, as this is the main aim of remediating the soil

11. Cost

- a. **Rating:** 7
- b. **Justification of your rating:** The process should be cost effective, however cheap methods could prevent efficient remediation of contamination

12. Environmental Impact

- a. **Rating:** 9
- b. **Justification of your rating:** The environment should be able to accommodate living organisms (fauna and flora), and not cause harm either now or in the future.

13. Social Acceptability

- a. **Rating:** 8
- b. **Justification of your rating:** The strategy should be accepted by a large group, not breaking or defaulting any laws, traditions or beliefs

14. Could you please rank these criteria from least to most important?

o Cost → Social Acceptability → Effectiveness → Environmental Impact

Section 4: Additional Comments

15. Comments/Suggestions

Response: Closer collaboration between academics, practitioners, and communities can enhance the understanding and acceptability of bioremediation strategies.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 8

Justification: The use of compost can significantly increase the bioavailability of hydrocarbons, making them more accessible to the degradation process. Its application is also eco-friendly.

Biochar with Strains

Rating: 9

Justification: The implementation of specific bacteria known for their hydrocarbon degradation capacity can be highly effective. However, detailed communication and educational programs about the use of bacteria should be carried out to ensure acceptance by local communities

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: As compost is a naturally occurring material and easily accessible, it may be readily accepted by communities, especially if its benefits and implementation processes are thoroughly communicated.

Biochar with Strains

Rating: 6

Justification: Although using bacteria may raise concerns about safety and potential health risks, clear, transparent communication and education about the safety and efficacy of these bacteria can improve their social acceptability.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Recommendation: A key aspect to consider will be how to effectively communicate these strategies to the local communities and other stakeholders to ensure acceptance. For actual implementation, it will be crucial to take a balanced approach that takes into account cost, environmental impact, effectiveness, and social acceptability. Proper stakeholder engagement and communication will enhance the success of the chosen strategy.

Expert 10

Section 1: Expert Demographics

1. Full Name (optional): Expert 10
2. Position/Job Title: Soil and Groundwater Remediation Supervisor
3. Organization: 4GDOM Technologies Limited
4. Field of Expertise: Soil and Groundwater Remediation
5. Years of Experience in the Field: 10 years of experience
6. Highest Academic Qualification: PhD
7. Involvement in bioremediation projects: Yes. Site Supervisor; Remediation of Bomu Manifold, Norkpo, Egbalor, B-Dere, Gio, Biara oil spill sites

Section 2: Engagement with Stakeholders

8. What type of stakeholders do you typically engage with in your work (e.g., policymakers, local communities, funding bodies, environmental engineers, site owners, etc.)?

Response: Local communities, Regulators, site owners, site engineers, contractors, scientists and Academics.

9. Can you share some examples of how you engaged with these stakeholders in decision-making processes?

Response: Engage is closing out a site with Regulators and certifying the soil/water remediation exercise.

Section 3: Decision Criteria Weighting

10. Effectiveness

- a. Rating: 9
- b. **Justification of your rating:** The aim of remediation is getting the soil/water back to a form that can pose little or negative effect to receptors or the environment. The technique being employed should be better than what is out there.

11. Cost

- a. **Rating:** 7
- b. **Justification of your rating:** Despite the importance of this criterion, it needs the justification of the effectiveness of the technique,

12. Environmental Impact

- a. **Rating:** 9
- b. **Justification of your rating:** Living organisms should be able to thrive in an environment that has undergone remediation. This is as important as the technique's effectiveness

13. Social Acceptability

- a. **Rating:** 8
- b. **Justification of your rating:** The strategy must be able to be accepted by all stakeholders involved in the clean-up process

14. Could you please rank these criteria from least to most important?

o Social Acceptability → Cost → Environmental Impact → Effectiveness

Section 4: Additional Comments

15. Comments/Suggestions

Response: Closer collaboration between academics, practitioners, and communities can enhance the understanding and acceptability of bioremediation strategies.

Section 5: Evaluation of Bioremediation Strategies

For reference, here are some of the strategies used in our study:

- Oxygen release compound, ORC (O) alone
- ORC with Nitrogen & Phosphorus (ONP)
- ORC with Compost (OC)
- Biochar (B)
- Biochar with bacteria strains (BS).

We're focusing on OC and BS as they have shown to be the most effective in our lab experiments. The compost in OC enhances the availability of nutrients for microbial activity, improving remediation. Similarly, the bacteria strains in BS utilize the synergistic abilities of these bacteria to degrade oil contaminants more effectively than when used separately.

Based on your experience and knowledge, please rate the effectiveness of the following bioremediation strategies on a scale of 1 (not effective) to 10 (highly effective). Please provide a short justification for your rating.

ORC with Compost

Rating: 7

Justification: Compost can potentially enhance bioremediation processes, and it's environmentally friendly. However, it may not always be effective for complex contaminant mixtures or in different environmental conditions.

Biochar with Strains

Rating: 7

Justification: Specific microbial strains can target and degrade hydrocarbons, but their effectiveness can be influenced by environmental factors, which may limit their applicability

How would you rate the social acceptability of the OC and BS strategies on a scale of 1 (not acceptable) to 10 (highly acceptable)? Please provide a short justification for your rating. Again, we've chosen to highlight OC and BS due to their superior performance in lab experiments. We're particularly interested in your views on their social acceptability, as this is a crucial factor in the successful implementation of these strategies in the Niger Delta region.

ORC with Compost

Rating: 7

Justification: The use of compost is generally well-received as it is natural and sustainable. However, the perception may vary based on the community's knowledge of the process and results.

Biochar with Strains

Rating: 6

Justification: Despite the potential benefits, microbial bioremediation may not be easily accepted by the general public due to misconceptions about bacteria. Clear and transparent communication about the process and benefits is needed to increase acceptability.

Considering all aspects (effectiveness, cost, environmental impact, and social acceptability), which of the above strategies (OC or BS) would you recommend for bioremediation in the Niger Delta region? Why? We're asking you to consider these factors as a whole to reflect the multidimensional nature of decision-making in environmental remediation. Even though OC and BS were the most effective in lab experiments, other aspects like cost, environmental impact, and social acceptability can significantly influence their practical applicability in the field.

Recommendation: OC and BS both show potential for soil and groundwater remediation. The key aspect to consider will be how to effectively communicate these strategies to the local communities and other stakeholders to ensure acceptance. We must ensure a balanced approach that takes into account cost, environmental impact, effectiveness, and social acceptability. Effective stakeholder engagement and communication are necessary to guarantee the success of the chosen strategy..