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Review

Challenges and opportunities for low-carbon remediation in the Niger Delta: Towards sustainable environmental management

Ikeabiama Ndubuisi Azuazu [a], Kabari Sam [b], Pablo Campo [a], Frederic Coulon [a,*]

[a] *School of Water Energy and Environment, Cranfield University, MK430AL, UK*
[b] *School of the Environment, Geography and Geosciences, University of Portsmouth, PO1 3QL, UK*

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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.

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; Smith, 2019). 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 environmental remediation strategies that are designed to minimise greenhouse gas (GHG) emissions, thus mitigating climate change while addressing environmental contamination and delivering net societal

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* Corresponding author.
E-mail address: f.coulon@cranfield.ac.uk (F. Coulon).

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benefits (Hu et al., 2023).

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., 2023), 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 6000 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). 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 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 and 2021, with 2895 t 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 and 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 and 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 (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 (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. Overview of remediation approaches in the Niger Delta region

2.1. The Niger Delta context

The Niger Delta has a landmass of approximately 70,000 km^2, 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° north of the Equator and longitudes 5 and 7° 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)

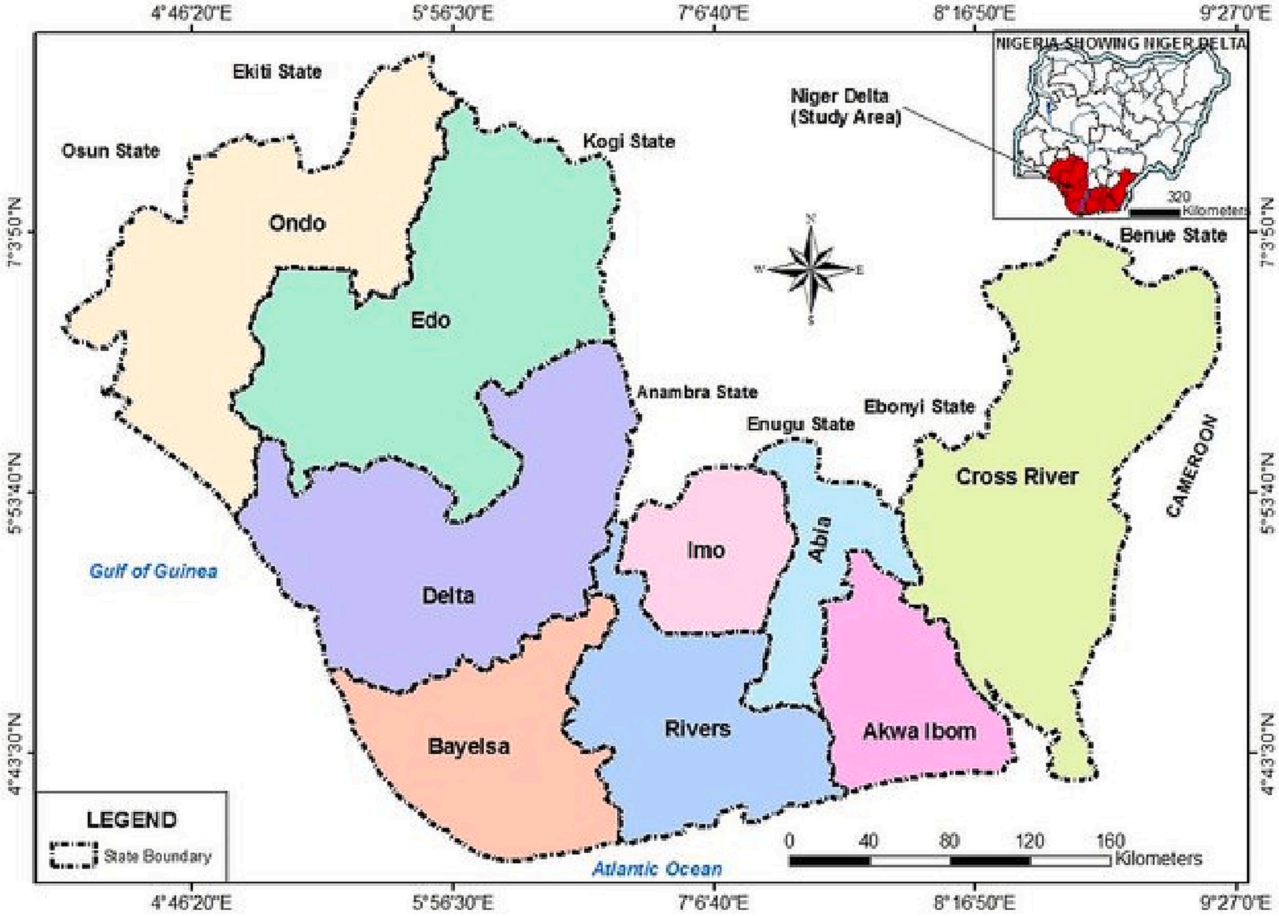

Fig. 1. Map of Niger Delta showing states (Oweikeye, 2017).

(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. (2018). 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., 2010). 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, 2008a). 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 (Fig. 1).

2.2. *Remediation of contaminated sites in Nigeria*

Several sites including water and soil contamination have been reported in Nigeria (UNEP, 2011). 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

Table 1
Biological remediation strategies and their respective challenges.

Remediation technique	Drawbacks	Region Applied	Ways to better manage the technique	References
Biostimulation	• 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	• India, South Africa, Nigeria, UK	• 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.	Coulon et al. (2012), Wang et al. (2012), Sarkar et al. (2016), Chikere (2012), Orji et al. (2012), Atagana (2008), Adesodun and Mbagwu (2008)
Bioaugmentation	• 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.	• China, Australia, Nigeria, Malaysia, Brazil	• 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.	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)
Bioventilation	• 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.	• USA, Mexico, Estonia, Nigeria, China, Taiwan	• 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.	Hahn (1997), Azubuike et al. (2016), Kunukcu (2007), Landmeyer et al. (2001), Rojas-Avelizapa et al. (2005), Goi et al. (2011)

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Table 1 (*continued*)

Remediation technique	Drawbacks	Region Applied	Ways to better manage the technique	References
Remediation by enhanced natural attenuation (RENA)	• 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	• Nigeria	• An ex-situ form of RENA can be adopted where leachate collection systems and high-density polyethene membrane 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	Orji et al. (2012), Okparanma et al. (2017)
Land farming	• 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)	• Nigeria	• 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.	Brown et al. (2017)

(Rumaila, 2020). However, Rylott and Bruce (2020) propose that multidisciplinary 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 enable microorganisms degrade contaminants at a faster rate to clean up contamination such as Total Petroleum Hydrocarbon (TPH). However, there are indications that RENA 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). Within the bioremediation technology, different approaches have different suitability and challenges that need to be considered depending on the desired remediation outcome (Table 1). Also, these different approaches require different manipulations (e.g., available nutrients and oxygen) and control to achieve desired remediation outcomes (Table 2). This is critical as the rate of microbial degradation of hydrocarbons in the soil is primarily determined by the availability of nutrients and oxygen (Uloaku et al., 2022). 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 fertiliser applications and windrows to provide nutrients and oxygen, respectively, accelerating oil spill degradation. However, the cost of acquiring large quantities of fertiliser 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). Andersson et al. (2003) investigated the potential of wood-rotting fungi, *Pleurotus ostreatus* and *Antrodia vaillanti*, 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, 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,

Table 2
Conditions that maximise bioremediation strategies.

Remediation strategy	Summary	Conditions that maximise the result	Reference
In situ	• 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.	• 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 CO_2, 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 (2023)
Ex situ	• 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	• 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), Bolan et al. (2023)

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 is 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).

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 prioritizes 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 biodegradation of contaminants. Given 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 (Mayakaduwage 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; Nwankwegu et al., 2022). 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 is 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., 2019a). 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 is 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, 2014). 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., 2016). 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; Sam et al., 2023). 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 CO_2 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 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. These methods, RENA, landfarming, engineered biocells, stabilisation & solidification, thermal desorption, phytoremediation, and bioremediation, each offer unique ways to mitigate the effects of oil pollution. RENA harnesses natural processes to degrade contaminants over time, further accelerated by nutrient amendments (Okparanma et al., 2017; Orji et al., 2012). Landfarming involves the use of tilling to promote the biodegradation of contaminants in the soil, with the opportunity to optimise tilling frequency and method to minimise GHG emissions (Mmom et al., 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 6 m to 10 m 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). Also, the benefits of stabilisation & solidification in mixing contaminants with a binding agent to prevent their spread, with a high potential for exploring lower carbon footprint materials and processes has been documented (Opete et al., 2010; Table 3).

Table 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

Table 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 et al. (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)

Table 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	Kriipsalu et al. (2007)
Lubricating oil and diesel oil-contaminated soil	150	Bioremediation: commercial fertiliser and soil/spruce bark	70 % and 71 % TPH removal	Finland	Jùrgensen et al. (2000)
Crude oil-contaminated soil	1825	Phytoremediation: alfalfa (*Medicago sativa* L.), ryegrass (*Lolium perenne* 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_2HPO_4	45 % and 73 % TPH removal	USA	Bonte et al. (2019)
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. (2019b)

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.

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 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

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

Themes	Developed countries	Developing countries
Management	Efficiency in identifying contaminated sites.	There is a significant deficiency in the identification of contaminated sites.
	Conduct risk assessments before commencing remediation activities	Risk analysis is employed in a few remediation processes.
	In most countries, remediation of contaminated sites is a normal development process.	The contaminated site remediation occurs mainly due to the need imposed by public power.
	The principle of "suitable for future use" is adopted as the standard for evaluating and remediating contaminated sites.	The lack of a database of these sites affects the remediation process, and the quality and validity of the conclusions reached both at the end of a restoration project and in the impact assessment.
	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 concern for the restoration of "soil quality" for the remediation of contaminated sites is still used.
Regulation	A clear definition of contaminated land.	No clear description of contaminated land.
	Clear regulations on the issue of contaminated sites.	Lack of a clear political framework applicable to the reality of developing countries.
	Clear and applicable policy framework.	Soil quality standards are often defined based on international guidelines, which may be inappropriate for developing countries.
	Soil quality standards are defined according to scientific analysis.	Lack of professionals with knowledge and experience in public positions.
	Presence of professional knowledge and experience in public positions, 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	Managers of contaminated sites are often trained.	Lack of periodic training and technical training for professionals.
	Encourage sharing knowledge and information. In developed regions such as the UK and the US, regular training platforms are established for contaminated land management professionals to encourage sharing of knowledge and information.	Lack of knowledge and technical capacity to implement a successful remediation technology considering the level of contamination
	Public bodies are equipped with specialised technical personnel	Lack of specialised professionals responsible for contaminated sites in public agencies at all levels of government.
Responsibility	In some countries, local authorities are responsible for dealing with the effects of soil contamination on public health and the development of contaminated sites.	Lack of clarity in the structure of the authorities responsible for the contaminated sites.
	Well-coordinated and competent local authorities with a clear and well-defined role. They develop quality standards considering regional characteristics and local authorities' primary regulators.	Shared responsibility among agencies and levels of government (national, regional, and local), generating governance conflicts in remediation.
	The interconnection of various legislative regimes regulates contaminated sites.	Weak regulatory framework. Responsibility for contaminated sites is scattered across government departments—lack of an integrated legislative regime on contaminated sites at the national level. Thus, different, and conflicting interventions and target values are used to regulate the remediation 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, the current owner/occupier, and the government, leading to delays and disputes in remediation actions.
Financing	Government incentive through funding for the remediation of contaminated sites. For example, the Superfund in the United States is a fund for the remediation of contaminated sites.	Little governmental incentive in financing for the remediation of contaminated sites.
	Political incentive in voluntary remediation by private site owners	Remediation of contaminated sites depends on the voluntary actions of site owners or through public pressure. Resources for remediation are limited, hampering the provision of incentives for the remediation of contaminated sites.
	A sustainable financing mechanism is developed to ensure immediate attention to sites threatening human health and the environment.	The responsibility for remediation of the contaminated sites is not very clear. Thus, in many places, the polluter ends up being blamed. However, the public places end up being for the government to remedy.
Sustainability	They incorporate social benefits while seeking to reduce environmental costs and damages in the managemental and decision-making of contaminated sites.	There is little consideration in terms of the cost-benefit analysis of remediation processes. It is that the concern with the social benefits is little considered.
Public consultations	Conscientisation of the population in participating in the decision-making processes of the remediation projects.	There is a lack of public awareness and participation in managing contaminated land.
Stakeholders	Greater involvement of stakeholders in the decision-making process on managing contaminated sites. In the United Kingdom, for example, stakeholder engagement has already become a mandatory component of the policy development process (Cundy et al., 2013).	Lack of involvement of different stakeholder groups in discussing the mechanisms to ensure the remediation of contaminated soil
	Integrated and robust approaches that ensure stakeholder participation.	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	Numerous countries already have programs that seek to integrate national inventories of contaminated sites with remediation strategies.	Lack of national remediation programs.
	More excellent knowledge of contaminated sites of countries.	Difficulty in dealing with historical contamination due to inapplicable policies or lack of available information about the contaminated area, problems in the remediation process.
	Consolidated databases on remediable contaminated sites.	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

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.

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 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.

The journey towards sustainable remediation in the Niger Delta, as depicted in Fig. 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 (Fig. 3). 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).

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. 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.

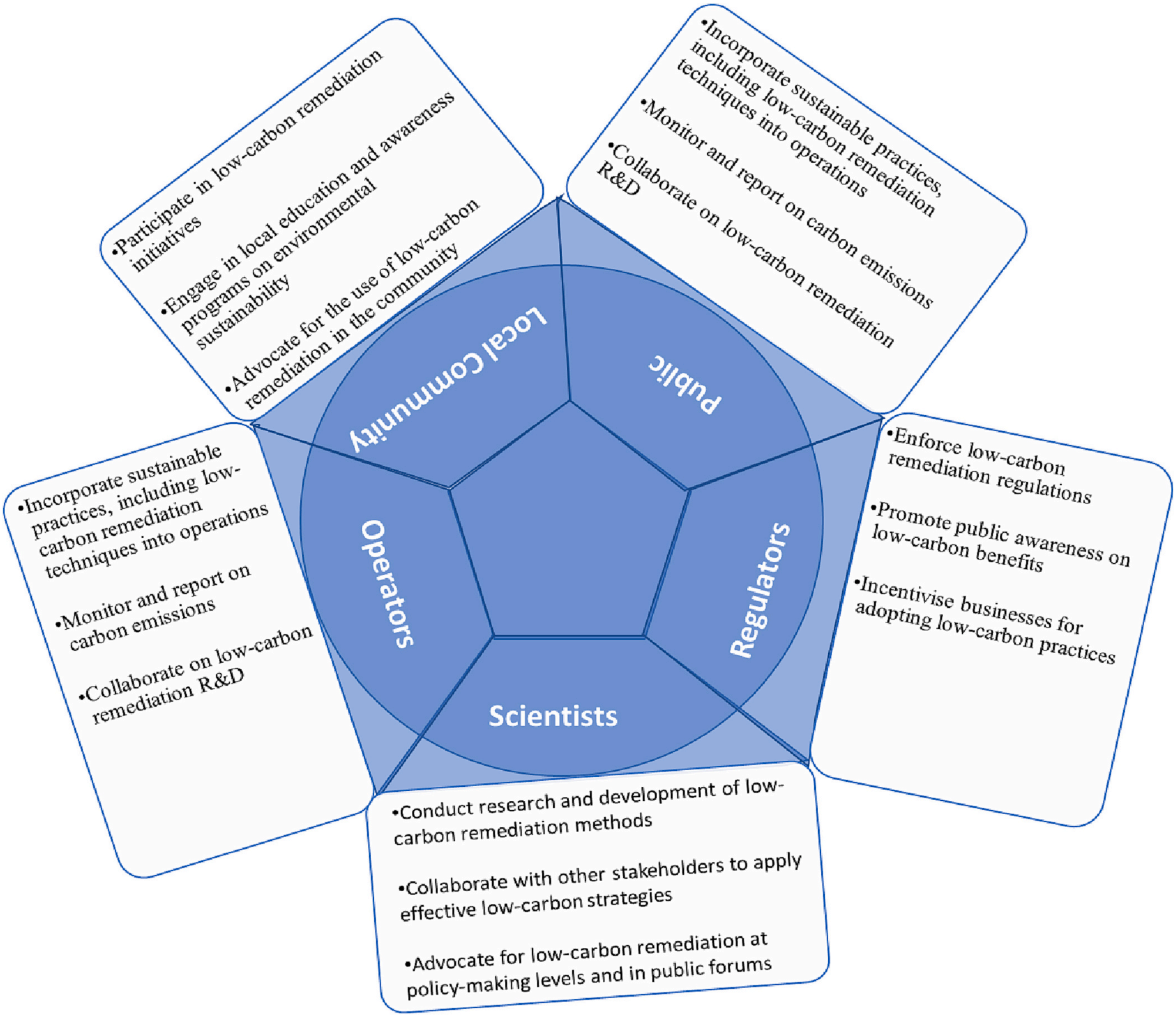

Fig. 2. Stakeholders' roles in promoting low-carbon remediation practices.

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 6, which provides an overview of the current state and prospects for various aspects of sustainable

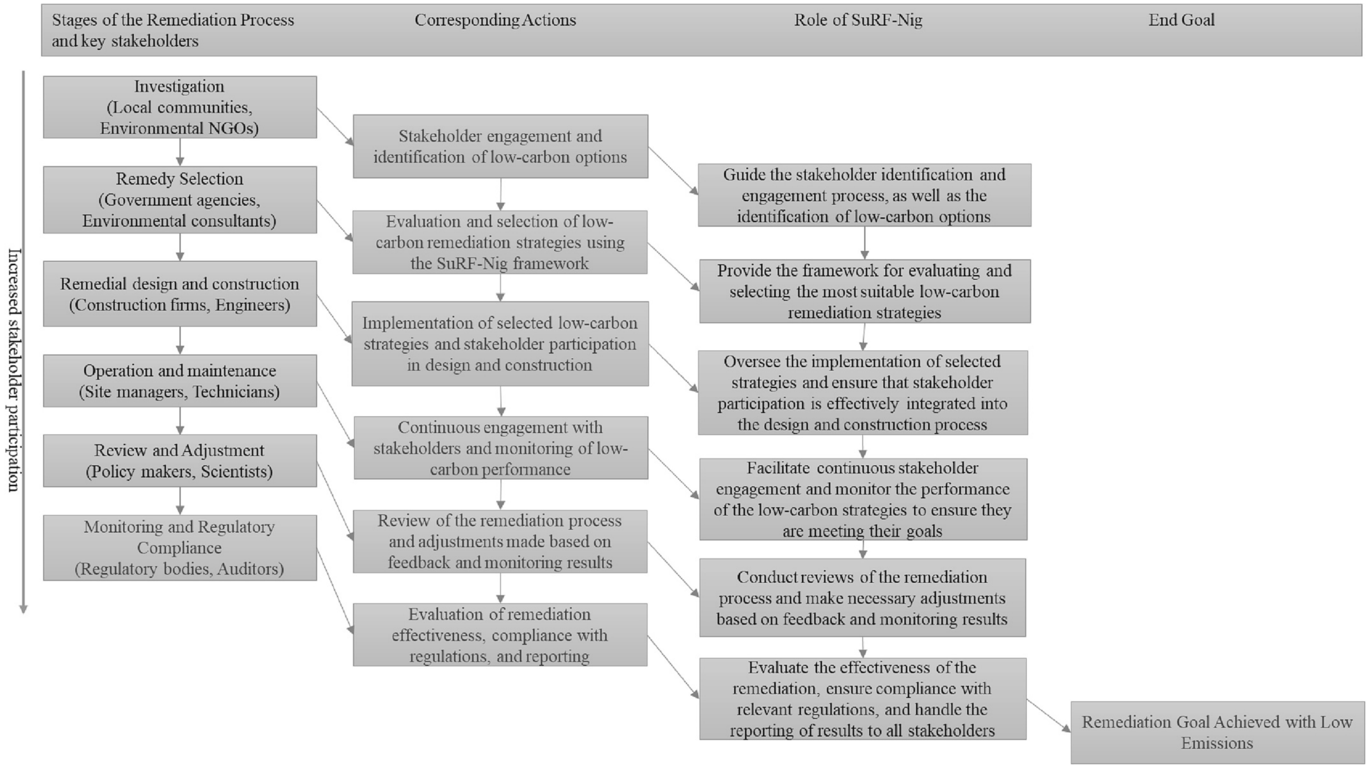

Fig. 3. Conceptual framework for integrating sustainable remediation approaches for achieving low carbon remediation in the Niger Delta.

Table 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.

remediation in the Niger Delta.

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 5, 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.

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, 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 therefore provides insights for achieving low-carbon remediation in regions addressing land contamination by different contaminants. The study will also serve as exemplar for regions with similar experience as Nigeria, as it will prevent trial and error in the adoption of remediation technologies that considers contextual socio-economic and environmental indices for sustainable development.

CRediT authorship contribution statement

Conceptualisation, I.N.A and F.C.; Writing, original draft preparation, I.N.A.; Writing, review, and editing, F.C., P.C. and K.S.; Supervision and feedback, F.C. and P.C.; project administration, F.C., Funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Azuazu, Ikeabiama Ndubuisi

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