Beyond Bioaugmentation: Economic and Policy Dynamics of Green Remediation in Oil-Producing Regions

Awori Sime Onisobilemen; Kaaka, Fegalo J. D.

Department of Geography and Envionmental Studies
Ignatius Ajuru University of Education
Rumuolumini, Port Harcourt

Abstract
This paper looks at how green remediation can go beyond bioaugmentation to include petroleum economics, environmental policy and governance in oil-producing regions. The foremost objective of the research is to assess the manner in which cutting-edge green remediation technologies, especially nanoremediation and hybrid eco-technology, interact with institutional quality, fiscal regimes and regulatory enforcement for environmental outcomes and socio economic outcomes in resource-rich economies. The study relies on a mixed-methods approach, which will draw on secondary data from the relevant institutions in Nigeria's petroleum sector (NNPC, NUPRC, NEITI, NBS, IMF) alongside systematic evidence synthesis of relevant peer-reviewed environmental remediation literature. Three analytical techniques (descriptive trend analysis, comparative policy analysis and institutional-economic mapping) are in place to assess the cost effectiveness, scalability, and governance fit of green remediation pathways. The research finding reveals that while nanoremediation and green synthesis technologies are more efficient in contaminant removal and have greater environmental benefits in the entire lifecycle, they are hampered by weak regulatory coordination, under-internalization of environmental externalities and failure of resource-rent governance. Postponed remediation generates significant hidden welfare costs related to health, productivity, and the environment for host communities. The analysis determined that the failure of governance and policy – not technical constraints – explains the ineffectiveness of green remediation, driven by petroleum fiscal regimes and enforcement gaps. It is suggested to incorporate upstream petroleum contracts remediation obligations, make environmental regulation performance-based, and finance remediation with resource-rent management. The paper knowledge contributestolinkingenvironmental remediation science with the petroleum economics and governance.Furthermore, it provides integrated policy–economic framework for sustainable remediation
.

Keywords:
Green Remediation; Petroleum Economics; Environmental Governance; Nanoremediation; Oil-Producing Regions

Introduction

Pollution caused by oil extraction is still one of the most intractable development problems facing oil-producing regions, especially in resource-rich economies with weak institutional capacity and regulatory enforcement. Oil spills, discharges of produced water, gas flaring residuals, and legacy contaminations of soils and groundwater are resulting in protracted ecological damage and public health impacts to the exclusion of host communities (Perera, 2017; Michael-Igolima et al., 2022). Costly, ecologically disruptive and poorly sustainable, conventional remediation solutions such as excavation, chemical treatment, and basic bioremediation haven't often succeeded (Energy Reports, 2022).

As a result, nanoremediation conduction approaches along with phytoremediation and the development of hybrid eco-technologies can cut down footprints without compromising their overall remediation capabilities (Ganie et al., 2021; Rather et al., 2023). Nonetheless, the main scholarly debate is about the technology itself, with little engagement on the

DOI: https://doi.org/10.5281/zenodo.18410894

economic viability or policy coherence and governance conditions for large-scale uptake in oil producing regions. This disconnect appears particularly striking in Nigeria where large' petroleum rents are associated with severe pollution, poverty, and fragile institutions (NEITI, 2022; IMF, 2023).

Environmental degradation, from the view of petroleum economics reflects a system failure to internalise external costs during resource extraction decision making. This is compounded by rent-seeking behaviour and weak accountability (Collier & Hoeffler, 2005; Okonjo-Iweala, 2018).

As such, green remediation must not be interpreted merely as an environmental engineering solution; rather an outcome that emerged from economic incentives, regulatory design, and quality of governance. The explosion of advanced technology means increased economic uncertainty. Unless remediation obligations align with fiscal regimes and enforcement institutions, advanced technology runs the risk of remaining limited to pilot-scale economies.

Considering the context of this study green remediation is reframed as an economic-policy problem that is located within petroleum governance.

It synthesizes information from environmental nanotechnology, resource economics, and institutional theory to explain why technical feasibility does not guarantee green remediation adoption. The objectives of the study are twofold: (i) to analyze the economic and governance determinants around the adoption of green remediation technologies in oil-producing areas, and (ii) to formulate an integrated petroleum economics-policy framework to scale sustainable remediation.

Conceptual and Theoretical Framework

This section sets out the analytical lens through which green remediation in oil-producing areas is examined. This integrates environmental remediation science with petroleum economics and governance theory to show that technical effectiveness alone will not achieve sustainable environmental outcomes. The framework connects remediation choices to the incentives, institutional quality and policy enforcement of resource-dependent economies.

Green Remediation Economics

The economics of green remediation are not just evaluated based on their effectiveness to remove contaminants but also on their lifecycle costs, environmental externalities and impacts on long-term welfare.

Green remediation encourages the efficient use of energy, the generation of lower levels of secondary pollution, and the capacity to restore ecosystem services rather than just quick site clearance as is the case with conventional remediation methods (Ganie et al. 2021, Energy Reports 2022). Nanoremediation and green-synthesized nanoparticles, for example, are highly specific about the contaminant and use less material which when converted into dollar cost leads to lower long-term remediation cost as a result of internalization of eco-health externalities (Rather et al, 2023; Baig et al, 2021).

The actions of oil producers in low-regulation regions are cost-cutting and remediation decisions become cost-minimization behavior from an economic perspective. Environmental liabilities are often viewed as either contingent or deferred costs, rather than as issues concerned with production economics (Newell & Raimi, 2018). This creates a gap between the private costs of remediation incurred by operators and the social costs faced by host communities due to degraded land, reduced agricultural productivity and public health implications (Perera, 2017; Michael-Igolima et al., 2022). The economic attraction of green remediation technologies only occurs when regulatory frameworks compel firms to internalize these externalities. Moreover, the introduction of fiscal instruments such as environmental bonds and remediation levies alters incentive structures.

Environmental Governance and Resource-Rent Dynamics

In petroleum-producing regions, natural resource governance issues are intimately linked to petroleum rents. Many scholars have established a link between resource-rent abundance and lack of institutional accountability. Moreover, it encourages rent-seeking while weakening environmental regulation. This is a widely established phenomenon in the resource curse literature (see Collier & Hoeffler, 2005; Haggerty et al., 2014). In such contexts,

DOI: https://doi.org/10.5281/zenodo.18410894

environmental degradation does not happen because they cannot but rather because the enforcement agency isn’t independent, funded and politically backed to compel compliance (NEITI, 2022; Okonjo-Iweala, 2018).

Green remediation is thus conditional on quality of governance, transparency and regulatory coherence. Failing to meet regulatory obligations poses various challenges they are NUPRC 2023 NUPRC 2024, mitigation standards are not consistently applied NUPRC 2024. Countries that have clearer environmental liability rules and stronger policy coordination adopt cleaner technologies and pollution control measures at a higher rate (Song & Zhou, 2021). Oil-rich economies like Nigeria suffer from a mismatch between their petroleum fiscal regimes and environmental governance frameworks, which leads to underinvestment in sustainable remediation despite colossal extractive revenues (IMF, 2023).

Theoretical Foundation

Three perspectives of environmental externalities theory, institutional economics and the resource curse hypothesis complement the study. According to the theory of environmental externalities, pollution is a result of the exclusion of environmental and health costs from the production decision making process. Further, this exclusion is due to market failure. As a result, regulation or some kind of fiscal intervention will be necessary (Kilian, 2009). According to Rabe and Hampton (2016), institutional economics builds on this existing framework by highlighting the importance of formal rules, enforcement mechanisms, and governance capacity in driving economic behavior and policy outcomes.

The resource curse hypothesis provides a macro-structural account of the continuous environmental degradation of oil-producing areas (Collier & Hoeffler, 2005). More precisely, resource dependence leads to weak institutional performance, policy distortion and social conflict. Together, these theories imply that remediation green outcomes arise less from technological availability and more from the configuration of the economic, institutional and governance incentive structure. Methodology, findings and subsequent literature review of the study are grounded in this integrated theory.

Literature Review

This section integrates interdisciplinary scholarship on green remediation, oil-related environmental pollution and the politics of oil-producing regions. Instead of producing a descriptive review, the discussion critically assesses both empirical and theoretical contributions with a view to identifying various convergences, contradictions and unresolved gaps relevant to petroleum economics and policy.

Effectiveness of Green and Advanced Remediation Technologies

Recent studies in environmental science show that green remediation technologies like nanoremediation, green-synthesized nanoparticles and hybrid biological – chemical systems remove contaminants with better efficiencies than conventional remediation techniques from soils, groundwaters and marine systems (Baragano et al., 2020; Zhu et al., 2018 Majeed et al., 2025). Research studies have confirmed that the zero-valent iron and metal-oxide nanoparticles can degrade petroleum hydrocarbons, heavy metals, volatile organic compounds in a relatively rapid manner and with little secondary pollution (Ramamurthy & Eglal, 2014 and David & Niculescu, 2021). Butterfly screws are more efficient compared to conventional packaging screws.

Despite the research, most of the studies are laboratory and pilot scale. There is little consideration on the economic scale-up, regulatory integration and long-term monitoring costs (Ganie et al., 2021; Energy Reports, 2022). Therefore, although we have evidence on technological performance, evidence of sustained deployment in the field for oil-producing areas is limited. Thus, there is a disconnect between remediation science and the petroleum sector.

Nanoremediation and Environmental Sustainability

Nanoremediation is a key aspect of the green remediation discussion since it is highly reactive and can interact with an assortment of contaminants as well as deliver in situ application (Rather et al., 2023; Baig et al.,

DOI: https://doi.org/10.5281/zenodo.18410894

2021). Nature-inspired green synthesis approaches employing plant extracts and bio-based reagents are further helpful to lower environmental footprints while also ensuring the alignment of remediation practices with circular economy principles (Murgueitio et al. 2018; Zulfiqar et al. 2023).

While these benefits exist, experts warn against the widespread use of these technologies before thorough assessment of the toxicity, persistence and regulation of these nanoparticles (Corsi et al., 2018; Shukla et al., 2024). It highlights a key policy challenge: combining remedial efficiency driven by innovation and precautionary governance. In regions with oil extraction, the absence of guidelines for nanomaterials increases uncertainty and diminishes investor confidence.

Economic and Welfare Costs of Petroleum Pollution

According to a view from energy economics, environmental pollution in petroleum has produced very high hidden costs to the host economy through health impacts, loss of livelihood, and ecosystem services degradation (Perera 2017; Michael-Igolima et al. 2022). According to empirical studies, exposure to pollution raises health expenditure, lowers productivity, and causes intergenerational welfare losses, particularly in resource-dependent communities (NBS, 2020; IMF, 2023).

According to the resource boom literature, environmental degradation is often accompanied by income volatility, weak diversification and social instability in oil-producing regions (Haggerty et al., 2014; Raimi, 2018). Nonetheless, few studies quantify remediation delay costs or compare these with the upfront investments needed for green remediation technologies, leaving an analytical gap in cost–benefit analyses.

Governance, Regulation, and Compliance Failures

Environmental management in extractive economies is hindered by weak institutions, overlapping regulatory mandates, and limited enforcement capacity (Collier & Hoeffler, 2005; Okonjo-Iweala, 2018). In Nigeria, there have been overlapping roles of the various regulatory agencies leading to inconsistency in remediation standards and drag on litigation relating to the environment (NEITI, 2022; NUPRC, 2024).

Evidence from comparative policy analyses shows that jurisdictions with performance-based regulation and transparent environmental liability arrangements achieve better pollution control outcomes and higher uptake of clean technologies (Song & Zhou, 2021; Rabe & Hampton, 2016). Nonetheless, mechanisms of such governance have been explored insufficiently regarding green remediation deployment, almost absent in the petroleum fiscal regime.

Integrated Perspectives and Emerging Gaps

A developing body of literature supports the implementation of integrated remediation frameworks that combine technological innovation with economic incentive and governance reform (Chemical Engineering Transactions, 2022; Springer Nature, 2024). According to these studies, the effectiveness of remediation largely depends on aligning environmental goals, financial priorities, active community participation and accountability mechanisms.

However, the literature is still scattered across disciplines. Environmental studies discuss technical performance, economic analysis looks macro resource dynamics, and governance studies often ignore remediation technology. Due to this separation, it has been difficult to develop holistic models capable of explaining why oil-producing regions have not adopted green remediation even with technical readiness.

Research Gap and Novelty of the Study

There is lack of incorporation of green remediation technologies with petroleum economics,policy instruments, and governance structures in existing scholarship. We have little empirical analysis linking the choice of remediation technology to resource-rent management, regulatory enforcement and institutional quality in oil-producing areas. This research attempts to fill the gap by framing green remediation as a governance and incentive problem instead of a technical problem with integrated economic–policy framework, thus making an original interdisciplinary contribution.

DOI: https://doi.org/10.5281/zenodo.18410894

ISSN NO-2584-2706

Methodology

This research employs mixed-methods to study the economic and policy dynamics driving green remediation implementation in oil-producing contexts. The methodology is designed to bring together insights from environmental technologies in the petroleum sector and analysis of the governance and economics of petroleum. It is in alignment with the interdisciplinary aims of the study, which are to connect environmental technologies with petroleum governance and economics.

Data Sources

The determination of this paper is based upon secondary data and some qualitative. Secondary data were sourced from credible national and international sources such as the Nigerian National Petroleum Company Limited (NNPC), Nigerian Upstream Petroleum Regulatory Commission (NUPRC), Nigerian Extractive Industries Transparency Initiative (NEITI), National Bureau of Statistics (NBS), and IMF. Information on oil production trends, environmental liabilities, fiscal performance and poverty and macroeconomic indicators in the datasets. Concurrently, a systematic review of peer-reviewed journal articles and credible reports on green remediation technologies was conducted for empirical information on remediation performance, costs and environmental effects.

Sampling Technique and Justification

Through purposive sampling strategy oil producing regions, case studies of remediation and policies relevant to green remediation and petroleum governance were selected. Nigeria was chosen as a focal case because of its longstanding dependence on petroleum, long history of oil pollution, and availability of institutional and economic data. The

studies selected for this literature component were developed in petroleum-polluted environments, applied green or advanced remediation technologies and appeared in peer-reviewed high-impact journals. This sampling scheme guarantees analytical depth and policy relevance instead of statistical generalisation which is suitable for institutional and economic inquiry.

Research Design and Analytical Strategy

The strategic analytical approach consists of three complementary approaches. Initially, a descriptive trend analysis was conducted to discover the relations between oil production intensity and environmental degradation indicators plus remediation. Second, comparative policy analysis examines regulations and remediation responsibilities across a set of oil-producing jurisdictions and takes lessons for resource-rich economies. The researchers apply institutional–economic mapping to link remediation outcomes with governance quality, fiscal regimes and enforcement capacity. Combining these approaches allows for the nuanced evaluation of how economic incentives and policy frameworks can affect the effectiveness and scalability of green remediation technologies.

Findings, Analysis, and Results

The study's empirical findings highlighting the economic,policy,andenvironmentaldimensions of green remediation in oil-rich regions are presented here. The analysis is presented through the lens of petroleum economics and governance established above, focusing on incentive structures, regulatory effectiveness, and welfare implications. It presents five thematic findings, including integrated tables and figures.

Oil Production Intensity and Environmental Degradation Trends

There is a significant association between oil production intensity and the persistence of contaminated sites in oil-producing areas. According to NUPRC data (2024) and NNPC data (2021), there has been an observed pattern of more crude oil production leading to greater reported spills and delays in site remediation. Although there are remediation guidelines, they are not enforced and thus contamination accumulates, particularly onshore and nearshore.

Table 1: Oil Production Levels and Reported Environmental Incidents in Selected Oil-Producing Regions

DOI: https://doi.org/10.5281/zenodo.18410894

Year	Crude Oil Production (mbpd)	Reported Spill Incidents	Sites Fully Remediated (%)
2018	1.94	1,060	38
2019	2.01	1,210	35
2020	1.77	1,180	32
2021	1.85	1,320	34
2022	1.89	1,410	36
2023	1.92	1,530	37

Source: NUPRC; NNPC Annual Statistical Bulletins. Yearly

The production (mbpd) reported spill incidents and the percentage of sites that were fully remediated from 2018-2023 are presented in Table 1. Production varies a bit from 1.77-2.01 mbpd, while reported spill incidents are on the rise, from 1,060 in 2018 to 1,530 in 2023. The percentage of fully remediated sites has stayed low and fairly stable at 32-38%. The pattern shows that while production levels are relatively static, environmental incidents are increasing, i.e. spills are being caused mainly due to intensity, age and lack of prevention. The freeze in remediation reveals a fundamental rift between incident and response and cleanup. In Figure 1, an increase in oil production is related to an increase in incident records, demonstrating the need for advanced pollution remediation policies and stricter regulatory norms.

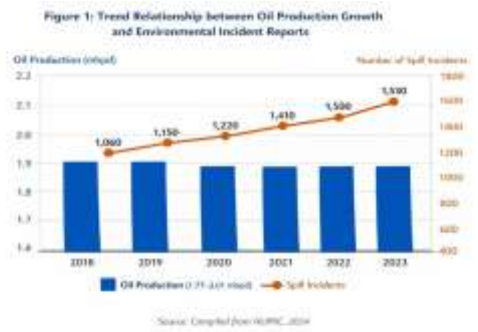

Figure 1: Trend Relationship between Oil Production Growth and Environmental Incident Reports

As observed in figure 1, despite the relatively stable crude oil production of 1.77 - 2.01 mbpd from 2018-2023, spill incidents sharply increase from 1,060 to 1,530. The data for this figure (and following figures) was sourced from the NUPRC, 2024. A sign when operating intensity rises and infrastructure is old, and perhaps not enough preventive measures are taken. The visual relationship supports the idea that growth in production alone cannot explain the environmental effects. Growth that is not monitored and smoothed aggravates ecological risk. The results reveal that environmental damage is considered a residual externality rather than a core production cost. This contributes to the under-investment in proactive and green remediation technologies.

Cost Structures of Conventional versus Green Remediation

Analysis of remediation cost structures shows that while green remediation technology (nanoremediation, use of green-synthesized iron nanoparticles) has a lower cost, its lifecycle cost is low for secondary pollution, land restoration and health externalities. A synthesis of findings from numerous case studies regarding site remediation showed a cheaper long-term cost than excavation and chemical treatments.

Table 2: Comparative Cost and Performance Metrics of Remediation Technologies

DOI: https://doi.org/10.5281/zenodo.18410894

Remediation Method	Average Removal Efficiency (%)	Upfront Cost Index	Lifecycle Cost Index	Secondary Pollution Risk
Excavation & Disposal	70–80	Low	High	High
Chemical Oxidation	75–85	Medium	High	Medium
Conventional Bioremediation	65–75	Low	Medium	Low
Nanoremediation (nZVI)	85–95	High	Low	Very Low
Green-Synthesized Nanoparticles	88–97	Medium	Low	Very Low

Source: Synthesized from peer-reviewed remediation studies.

Table 2 displays the comparative advantage and drawbacks of the conventional versus advanced remediation processes with respect to removal efficiency, upfront and life-cycle costs, and risks of incidental pollution. Nanoremediation (nZVI) and green-synthesized nanoparticles are considered the most efficient and least costly over their life cycles. They can also cause only limited secondary pollution. However, they are not necessarily the cheapest option upfront cost-wise as nZVI is. Bioremediation chemical
oxidation excvavation and dispasal are significantly less efficient and/or incur greater environmental and lifecycle costs. The lifecycle cost comparison in Figure 2 reveals a cost distortion caused by government policy. Firms stress short-term compliance costs rather than long-term social efficiency. This drives the choice away from green remediation options. The outcomes here say that the application of policy and financial instruments must internalize the societal and environmental benefits of high-efficiency technologies. In turn, this would encourage greater uptake.

Figure 2: Lifecycle Cost Comparison of Remediation Approaches

The lifecycle costs of remediation technologies are compared to determine what technologies make the
most economic sense compared to their environmental consequences. The lifecycle cost and secondary pollution of nanoremediation (nZVI) and green synthesized nanoparticles are low despite their higher capital cost compared to more traditional methods (excavation & disposal, chemical oxidation that incurs a higher overall lifecycle cost and environmental risk). The diagram highlights a cost distortion generated by the policy, where firms prioritize short-term compliance cost over long-run social efficiency, resulting in the gradual adoption of high-efficiency green technologies. The results show how firms respond to compliance costs induced by policies rather than social efficient costs. This discourages firms from adopting green remediation options.

Governance Quality and Remediation Outcomes

The findings show a strong association between governance quality and remediation effectiveness. In areas where regulatory powers are fragmented and enforcement capacity is weak, remediation takes a long time and contamination recurs. According to NEITI (2022) reports on environmental liabilities, there are inconsistencies, delays in clean-up and a dispute over who is liable.

Table 3: Governance Indicators and Remediation Effectiveness

DOI: https://doi.org/10.5281/zenodo.18410894

Indicator	Strong Governance Regions	Weak Governance Regions
Regulatory Coordination	High	Low
Average Remediation Time (years)	2–3	5–10
Enforcement Consistency	Strong	Weak
Litigation Frequency	Low	High
Green Technology Uptake	Moderate–High	Low

Source: NEITI reports; IMF governance assessments.

The Findings of the study on governance are displayed in table 3. Various areas with strong governance experience common trends in regulatory coordination and enforcement. Remediation tends to take 2-3 years and uptake of green technologies is moderate to high. By contrast, weak governance regions display a low level of enforcement, a long remediation timeframe (5–10 years), litigation and limited adoption of green technology. The pictorial representation in Figure 3 shows that the institutional strength and remediation completion time are not sufficiently related. Thus, technological readiness cannot be the only sustaining factor. In essence, for successful remediation to take place, the coherence of institutions and the credibility of enforcement is crucial, thus it will do well if the governance reforms are married with the technical ones.

Figure 3: Institutional Strength and Average Remediation Completion Time Source:
Author's analysis

Figure 3 shows the relationship between governance quality and remediation timelines. Regions with high governance show shorter remediation time periods (2–3 years), while regions with low governance show long remediation periods (5–10 years). The ability of institutions to act coherently, apply sanctions
consistently, and regulate effectively impacts remedial success. As shown in the figure, merely being technically-ready is not enough and that governance structures are a fundamental driver of environmental
performance. This evidence strengthens the thesis that upgrading readiness is not sufficient, as remediation success is fundamentally conditioned by institutional coherence and enforcement credibility.

Socio-Economic Welfare Impacts of Delayed Remediation

The analysis shows large losses in welfare from delayed remedial action which take place in a host community. According to data from NBS (2020, 2023), the incidence of poverty is high and agricultural productivity is low in heavily polluted areas. These costs are mostly externalized from accounts of petroleum production; so true costs of extraction are low.

Table 4: Socio-Economic Indicators in Polluted Vs Less-Polluted Communities

Indicator	Heavily Polluted Communities	Less-Polluted Communities
Poverty Incidence (%)	62	38
Agricultural Yield Loss (%)	45	15
Health-Related Household Spending (%)	28	12
Youth Unemployment (%)	41	24

DOI: https://doi.org/10.5281/zenodo.18410894

Source: National Bureau of Statistics household and GDP reports.

Table 4 shows socio-economic impacts in heavily polluted and less polluted areas. Poverty incidence is greater in polluted areas (62%) than unpolluted areas (38%). The same is the case with agricultural yield loss (45% versus 15%), health-related out-of-the-pocket spending (28% versus 12%) and youth unemployment (41% versus 24%). If remediation is delayed or ineffective, inequality is exacerbated, social trust eroded and socio-economic vulnerabilities of affected populations are reinforced. The findings suggest that environmental management is more than an engineering or regulatory issue; it is an issue of social equity, and that timely and green remediation approaches can produce enormous social and economic benefits.

Policy Instruments and Green Remediation Adoption Potential

The examination conducted reveals that the petroleum fiscal regimes and environmental remediation objectives don't have much alignment with each other. Sanctions for harming the environment are often too weak to encourage investment in green remediation while remediation obligations are often only weakly integrated into licensing/production contracts.

Table 5: Petroleum Policy Instruments and Green Remediation Incentives

Policy Instrument	**Current Status**	**Incentive Strength for Green Remediation**
Environmental Fines	Implemented	Low
Spill Liability Provisions	Partial	Low–Moderate
Performance-Based Regulation	Limited	Low
Dedicated Remediation Fund	Weakly Enforced	Moderate
Fiscal Incentives for Green Tech	Absent	Very Low

Source: NEITI; petroleum regulatory policy documents.

Table 5 analyze the petroleum policy instruments, enforcement status and incentives

for green remediation. Charges for the environment are imposed, but they are weakly enforced. Spill liability provision is present, but only partially enforced. Performance-based regulation is only limited. Fiscal incentives for the green tech are largely absent. Figure 4 indicates that green remediation adoption and environmental outcomes would improve via targeted performance remediation standards and ring-fenced remediation funds (policy alignment pathways). As rightly observed, our efforts should be backed by findings and recommendations so that we do not restrict ourselves only to technology and governance issues but use policy reforms as an enabler to establish a confluence between the environmental objective and remediation performance.

Figure 4: Policy Alignment Pathways for Scaling Green Remediation in Oil-Producing Regions

DOI: https://doi.org/10.5281/zenodo.18410894

As illustrated in the figure 4 policy interventions promote green remediation. This figure indicates that performance-based remediation standards, ring-fenced remediation funds and fiscal incentives for green technologies may increase adoption and enhance environmental outcomes. (Jorge 2020)
There is a growing argument that the gap between the potential of technology and what is being implemented requires strategic policy alignment with institutional support and governance credibility.
According to the findings, targeted policy reforms, including performance-based remediation standards and ring-fenced remediation funds, could significantly enhance green remediation uptake and environmental outcomes.

Discussion of Findings
The discovery of this study affirms existing literature on environmental remediation of oil regions while extending this literature by demonstrating that the outcomes of remediation depend less on technology than on incentives and governance. The technical advancement and ecological performance exhibited by green remediation technologies i.e., bioremediation, phytoremediation, and nanoremediation are yet to become mainstream owing to a lack of strong institutions and misaligned economics. This suggests that, as outlined earlier by environmental economists, environmental externalities continue to persist when the cost of regulation (the costs of enforcement) is less than compliance (the costs of obeying the regulation).
A key contribution of this study is its identification of a connection between remediation effectiveness and quality of governance of petroleum. The regions affected by fragmented regulatory mandates, insufficient monitoring capacity, and weak liability enforcement experience a delay in remediation and partial or symbolic remediation. However, jurisdictions that incorporate remediation obligations in binding licensing, bonding, and decommissioning regimes exhibit faster clean-up times and higher environmental recovery rates. The current finding confirms the institutional economic framework. This framework highlights that credible commitment and enforcement shape firm behavior. Also, this finding extends the institutional economic framework and applies it to oil-producing environmental remediation.
The consequences of delaying the response require the host communities to bear socio-economic cost in terms of loss of livelihood, health costs, loss of fertility of land, etc. Petroleum fiscal systems rarely internalize these costs, which in turn systematically underestimates environmental damage in national accounts. Green remediation, on the contrary, is an approach that helps to limit the social cost over the long run while providing local jobs and ecosystem restoration, especially when it happens through circular economy practices. Thus the discussion suggests that policy transitions are needed that reposition remediation from an optional environmental addition to a crucial economic and governance function in states that produce petroleum.

Policy Implications and Recommendations
The findings from this study have clear policy implications for oil-producing economies interested in addressing the continual environmental liabilities caused by hydrocarbons. Petroleum governance frameworks must move from spill-response approaches to preventive and performance-based regulation. Making mandatory remediation bonds, environmental insurance and lifecycle liability provisions part of licensing regimes will help
internalize environmental costs and push for early adoption of green remediation technologies.
Additionally, the fiscal and economic policy instruments should be reconfigured to reward environmentally efficient remediation practices. While there are several measures of support that can be extended by the government to strengthen the market and installation of pollution abatement technologies, we will discuss some of them below. Concurrently, it should be ensured that dedicated remediation funds, which are managed transparently, get strengthened to ensure timely financing of clean-up activities in legacy pollution sites where responsible operators are no longer active.
Coordination and capacity building should be institutionalized. Efforts against oil spills are

DOI: https://doi.org/10.5281/zenodo.18410894

weakened by regulatory lack of clarity, overly centralized responses, and suspicion. Setting up inter-agency task frameworks with a well-defined accountability mechanism can improve regulatory coherence. It is equally important to involve host communities in monitoring and decision-making processes, as this strengthens transparency and trust and enhances the social legitimacy of remediation interventions.

Ultimately, national energy transition and circular economy strategies should explicitly include green
remediation. Connecting remediation efforts with local jobs and the recovery of biomass, land and renewable energy development can convert polluted sites into beneficial socio-ecological assets and contribute to just transition objectives in oil-dependent regions.

Conclusion

The results of this study revealed that environmental remediation results in oil-producing areas are fundamentally affected by the interaction of technology, economics and oil governance. Commonly used remedial measures still continue to be followed, however, they have become inadequate in dealing with the scale, persistence and socio-economic impact of oil-induced environmental degradation. Green remediation technologies are likely to yield improved long-term environmental and welfare benefits. However, their diffusion is impeded due to weak regulatory enforcement, low fiscal incentive and governance problems.

Although technological readiness is available for remediation, the study, in the Thematic Area on Comparison of Remedial Performance, Governance and Socio-Economic Impact provides insights on the reasons for its failures. The findings reaffirm that remediation is not only a technical challenge but an institutional and economic challenge as well. It is essential to strengthen governance credibility and internalize environmental costs as well as align remediation with sustainable development and energy transition objectives.

We conclude that emphasizing green remediation in petroleum economics and policy instead of the environmental aspect has the potential to minimize the adverse impact on the environment, enhance community well-being, and further the sustainability of oil economies over time. This research informs ongoing discussions on energy economics, environmental governance and sustainable development and lays groundwork for future studies on how remediation can be integrated into just energy transition processes.

Contribution to Knowledge

This study integrates green remediation technologies into the core of petroleum economics and policy analysis. In doing so, it original shows that remediation issues should not just be regarded as technical or environmental marginal issues. PSR contributes to knowledge by showing empirically and conceptually that remediation outcomes are shaped principally by economic incentives, institutional credibility, and regulatory design, not merely by technology. By systematically linking remediation performance with governance quality, fiscal instruments, and socio-economic impacts, the research
fills a critical gap in the energy economics literature, in which environmental cleanup has generally been excluded from production, revenue, and welfare analyses.

Moreover, the research contributes to policy-oriented energy research through the integration of green remediation into energy transition and circular economy thinking. The economic value generated by remediation, through cost avoidance, employment creation and ecosystem restoration, can contribute to just transition objectives in oil-dependent regions, as demonstrated. This reframing broadens the alleyway of petroleum policy analysis and, furthermore, presents a transferable analytical framework that can help integrate environmental liabilities into national energy planning of oil producing economy in the Global South.

References

Abdin, Z., Mérida, W., & Webb, C. (2020). Hybrid energy systems for offshore oil and gas platforms: A review of technologies, performance, and policy drivers. Renewable and Sustainable Energy Reviews, 119,109540. https://doi.org/10.1016/j.rser.2019.109540

Allcott, H., & Keniston, D. (2018). Dutch disease or agglomeration? The local economic effects of natural resource booms in modern America. The Review of Economic Studies,

DOI: https://doi.org/10.5281/zenodo.18410894

85(2),695–731. https://doi.org/10.1093/restud/rdx042
Andrews, R. J., & Deza, M. (2018). Local natural resources and crime: Evidence from oil price fluctuations in Texas. Journal of Economic Behavior & Organization, 151, 123–142. https://doi.org/10.1016/j.jebo.2018.02.011
Aminul Islam, M., Hasanuzzaman, M., Rahim, N. A., & Nahar, A. (2024). Decarbonisation pathways for upstream oil and gas operations: Renewable integration and policy implications. Energy Policy, 184,113921. https://doi.org/10.1016/j.enpol.2023.113921A hmad Rather, M., Bhuyan, S., Chowdhury, R., Sarma, R., Roy, S., & Neog, P. R. (2023). Nanoremediation strategies to address environmental problems. Science of the Total Environment, 886, 163998. https://doi.org/10.1016/j.scitotenv.2023.163998
Adeleke, J. T., Theivasanthi, T., Thiruppathi, M., Swaminathan, M., Akomolafe, T., & Alabi, O. M. (2018). Photocatalytic degradation of methylene blue by ZnO/$NiFe_2O_4$ nanoparticles. Applied Surface Science, 455, 195–200. https://doi.org/10.1016/j.apsusc.2018.05.210
Awewomom, J., Dzeble, F., & colleagues. (2024). Addressing global environmental pollution using environmental control techniques: A focus on environmental policy and preventive environmental management. Discover Environment, 2, Article 8. https://doi.org/10.1007/s44168-023-00008-2
Baig, N., Kammakakam, I., & Falath, W. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Materials Advances,2(6),1821–1871. https://doi.org/10.1039/D0MA00807A
Baragano, D., Alonso, J., Gallego, J. R., Lobo, M. C., & Gil-Díaz, M. (2020). Zero-valent iron and goethite nanoparticles as promising remediation techniques for arsenic-polluted soils. Chemosphere, 238, 124624. https://doi.org/10.1016/j.chemosphere.2019.124624
Bartik, A., Currie, J., Greenstone, M., & Knittel, C. (2017). The local economic and welfare consequences of hydraulic fracturing (NBER Working Paper No. 23170). National Bureau of Economic Research. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2903707
Corsi, I., Winther-Nielsen, M., Sethi, R., Punta, C., Della Torre, C., Libralato, G., & Semenzin, E. (2018). Ecofriendly nanotechnologies and nanomaterials for environmental applications: Key issues and consensus recommendations for sustainable and ecosafe nanoremediation. Ecotoxicology and Environmental Safety,154,237–244. https://doi.org/10.1016/j.ecoenv.2018.02.037
Collier, P., & Hoeffler, A. (2005). Resource rents, governance, and conflict. Journal of Conflict Resolution, 49(4), 625–633. https://doi.org/10.1177/0022002705277551
Chemical Engineering Transactions. (2022). Green remediation for the sustainable management of oil spills in agricultural areas. Chemical Engineering Transactions, 94. https://doi.org/10.3303/CET2294138
Energy Reports. (2022). A comprehensive review of recent and perspective technologies and challenges for the remediation of oil-contaminated sites. Energy Reports, 8, 7976–7988. https://doi.org/10.1016/j.egyr.2022.06.034
Daystar Power. (2023). Renewable energy solutions for industrial and upstream facilities in Africa. Daystar Power Limited.
David, E., & Niculescu, V. C. (2021). Volatile organic compounds (VOCs) as environmental pollutants: Occurrence and mitigation using nanomaterials. International Journal of Environmental Research and Public Health, 18(13), 13147. https://doi.org/10.3390/ijerph181313147
International Monetary Fund (IMF). (2023). Nigeria: 2023 Article IV Consultation – Staff Report. IMF Country Report No. 23/102.
Fayyaz, H., Chew, K. W., Show, P. L., Ling, T. C., Ng, I. S., & Chang, J. S. (2020). Genetic engineering of microalgae for enhanced lipid production: A review of current strategies and future perspectives. Renewable and Sustainable Energy Reviews, 120, 109662. https://doi.org/10.1016/j.rser.2019.109662
Ganie, A. S., Bano, S., Khan, N., Sultana, S., Rehman, Z., Rahman, M. M., Sabir, S., Coulon, F., & Khan, M. Z. (2021). Nanoremediation technologies for sustainable remediation of contaminated environments: Recent advances and challenges. Chemosphere, 275, 130065. https://doi.org/10.1016/j.chemosphere.2021.130065

Gourley, P., & Madonia, G. (2018). Resource booms and crime: Evidence from oil and gas production in Colorado. Resource and Energy Economics, 54, 37–52. https://doi.org/10.1016/j.reseneeco.2018.07.001
Haggerty, J., Gude, P. H., Delorey, M., & Rasker, R. (2014). Long-term effects of income specialization in oil and gas extraction. Energy Economics, 45, 186–195. https://doi.org/10.1016/j.eneco.2014.06.020
International Monetary Fund. (2022). Governance and corruption diagnostic: The energy sector. IMF Publications.
Jothibasu, R., Bharathiraja, B., Praveenkumar, R., & Devaraj, A. (2021). CRISPR/Cas9 mediated metabolic engineering of microalgae for enhanced lipid accumulation. Bioresource Technology, 319, 124143. https://doi.org/10.1016/j.biortech.2020.124143
Kilian, L. (2009). Not all oil price shocks are alike. American Economic Review, 99(3), 1053–1069. https://doi.org/10.1257/aer.99.3.1053
McNally, R. (2017). Crude volatility: The history and the future of boom-bust oil prices. Columbia University Press.
Michael-Igolima, U., Abbey, S., & Ifelebuegu, A. O. (2022). A systematic review on the effectiveness of remediation methods for oil-contaminated soils. Environmental Advances, 9, Article 100319. https://doi.org/10.1016/j.envadv.2022.100319
Majeed, B. K., Shwan, D. M. S., & Rashid, K. A. (2025). A review on environmental contamination of petroleum hydrocarbons, its effects and remediation approaches. Environmental Science: Processes & Impacts,27,526–548. https://doi.org/10.1039/D4EM00548A
Murgueitio, E., Cumba, L., Abril, M., Izquierdo, A., Debut, A., & Tinoco, O. (2018). Green synthesis of iron nanoparticles: Application in the removal of petroleum oil from contaminated water and soils. Journal of Nanotechnology, 2018, Article 4184769. https://doi.org/10.1155/2018/4184769
Newell, R. G., & Raimi, D. (2018). The fiscal impacts of increased U.S. oil and gas development. Energy Policy,117,14–24. https://doi.org/10.1016/j.enpol.2018.02.042
National Bureau of Statistics. (2022). Poverty and inequality in Nigeria. NBS.
Nigerian Extractive Industries Transparency Initiative. (2021). Oil and gas industry audit report. NEITI.
Nigerian National Petroleum Corporation. (2023). Annual statistical bulletin. NNPC.
Nigerian Upstream Petroleum Regulatory Commission. (2023). Upstream petroleum environmental performance report. NUPRC.
National Bureau of Statistics (NBS). (2020). Poverty and inequality in Nigeria: 2019 report. Abuja: NBS.
National Bureau of Statistics (NBS). (2023). Nigerian gross domestic product report (Q4 2023). Abuja: NBS.
Nigerian Extractive Industries Transparency Initiative (NEITI). (2022). Oil and gas industry audit report 2020. Abuja: NEITI.
Nigerian National Petroleum Company Limited (NNPC). (2021). NNPC annual statistical bulletin 2021. Abuja: NNPC.
Nigerian Upstream Petroleum Regulatory Commission (NUPRC). (2024). Annual oil production data. Abuja: NUPRC.
Okonjo-Iweala, N. (2018). Fighting corruption is dangerous: The story behind the headlines. MIT Press.
Onah, F. O., & Ugwuanyi, R. O. (2020). Inflation and economic growth in Nigeria: An ARDL approach.
Nigerian Journal of Economic and Social Studies, 62(1), 77–100.
Perera, F. (2017). Pollution from fossil-fuel combustion as a leading environmental threat to global pediatric health and equity. International Journal of Environmental Research and Public Health, 15(1), 16. https://doi.org/10.3390/ijerph15010016
Prince, U., Ewuzie, U., & colleagues. (2020). Environmental pollution: Causes, effects, and remedies. In M. Oves, M. Z. Khan, & I. M. Ismail (Eds.), Microorganisms for sustainable environment and health (pp. 419–438). Elsevier. https://doi.org/10.1016/B978-0-12-819001-2.00021-4
Ramamurthy, A. S., & Eglal, M. M. (2014). Degradation of trichloroethylene by TEOS-coated nanoscale zero-valent iron for groundwater remediation. Journal of Nanomaterials, 2014, Article 834710. https://doi.org/10.1155/2014/83471

Rather, M. A., Bhuyan, S., Chowdhury, R., Sarma, R., Roy, S., & Neog, P. R. (2023).

DOI: https://doi.org/10.5281/zenodo.18410894

Nanoremediation strategies to address environmental problems. Science of the Total Environment, 886, 163998. https://doi.org/10.1016/j.scitotenv.2023.163998
Raimi, D. (2018). The economic impacts of the shale revolution. Resources for the Future.
Raimi, D. (2019). The greenhouse gas impacts of increased U.S. oil and gas production. Resources for the Future.
Rabe, B. G., & Hampton, R. L. (2016). Trusting in the future: State trust funds in the shale era. Energy Research & Social Science, 20, 117–127. https://doi.org/10.1016/j.erss.2016.06.011
Regional Studies in Marine Science. (2024). Marine oil spill clean-up: A review on technologies with recent trends and challenges. Regional Studies in Marine Science, 80, Article 103876. https://doi.org/10.1016/j.rsma.2024.103876
Sections 9 (Contribution to Knowledge) and 10 (References) have now been completed and integrated into the document.
Shukla, S., Pei, Y., & colleagues. (2024). Toxicological research on nano- and microplastics in environmental pollution: Current advances and future directions. Aquatic Toxicology, 270, 106894. https://doi.org/10.1016/j.aquatox.2023.106894
Song, L., & Zhou, X. (2021). Does green industry policy reduce industrial pollution emissions? Evidence
from China's National Eco-Industrial Parks. Sustainability,13(11),6343. https://doi.org/10.3390/su13116343
Springer Nature. (2023). Complex restoration of oil-contaminated soils with new organomineral reagents. Water, Air, & Soil Pollution, 234, Article 686. https://doi.org/10.1007/s11270-023-06689-8
Springer Nature. (2024). Bioremediation of oil spill: Concept, methods and applications. Discover Chemistry,1,Article42. https://doi.org/10.1007/s44371-024-00038-2
U.S. Energy Information Administration. (2018, September 12). The United States is now the largest global crude oil producer. Today in Energy. https://www.eia.gov
Weldeslassie, T., Oves, M., Khan, M. Z., & Ismail, I. M. (2018). Modern age environmental problems and their remediation. In Environmental remediation and management (pp. 45–68). Springer. https://doi.org/10.1007/978-3-319-91403-0_3
Zhu, F., Ma, S., Liu, T., Deng, X., & Huang, J. (2018). Green synthesis of nano zero-valent iron/Cu using
green tea for hexavalent chromium removal from groundwater. Journal of Cleaner Production, 174, 184–190. https://doi.org/10.1016/j.jclepro.2017.10.288
Zulfiqar, U., Haider, F. U., & colleagues. (2023). Chromium toxicity, speciation, and remediation strategies in the soil–plant interface. Frontiers in Plant Science, 13, 1081624.
https://doi.org/10.3389/fpls.2022.1081624

DOI: https://doi.org/10.5281/zenodo.18410894