Bioremediation of Hydrocarbon-Polluted Soils in the Niger Delta: A Comparative Review of Remediation Techniques and Biostimulation Products, With Emphasis on Clogen and Solpawa: A Comparative Review

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DOI: 10.56201/rjpst.vol.8.no11.2025.pg119.140

Abstract
Petroleum exploration, production and transportation activities in Nigeria's Niger Delta have generated an extensive legacy of hydrocarbon-contaminated soils that threaten soil fertility, plant growth, groundwater quality and human health. Numerous physical, chemical and biological techniques have been developed to remediate such soils, but bioremediation, and biostimulation in particular, has emerged as the most economical and environmentally compatible strategy for the large, diffuse contamination that characterises the region. This review compares the principal bioremediation strategies documented in the literature, namely biostimulation, bioaugmentation, phytoremediation and mycoremediation, in terms of mechanism of action, reported total petroleum hydrocarbon (TPH) degradation efficiency and operational constraints, and undertakes a focused comparative analysis of two indigenously manufactured Nigerian biostimulation products, Clogen and Solpawa, that are increasingly deployed by remediation contractors across the Niger Delta. Drawing on published field and laboratory studies, the review shows that although both products can independently achieve TPH degradation efficiencies exceeding 90%, they act through complementary rather than duplicate mechanisms: Clogen through soil conditioning, hydrocarbon emulsification and bioaugmentation, and Solpawa through concentrated nitrogen-phosphorus-potassium nutrient supplementation. This complementarity suggests that a combined application strategy may deliver more consistent and accelerated remediation outcomes than either product used in isolation. The review identifies the absence of published data on combined Clogen-Solpawa application as a significant research gap and outlines factors likely to govern the success of such a combined regime under Niger Delta field conditions.

Keywords: *bioremediation; biostimulation; hydrocarbon-polluted soil; Clogen; Solpawa; Niger Delta; total petroleum hydrocarbon degradation.*

1. Introduction

Petroleum is a hydrocarbon-based substance that, while indispensable to global economic development as an energy resource, is simultaneously one of the most pervasive sources of environmental pollution. Crude oil is a complex mixture of aromatic, aliphatic and heterocyclic hydrocarbons, asphaltenes and non-hydrocarbon compounds, of which between 60 and 90% are biodegradable (Falkova et al., 2016). Decades of oil exploration, transportation, storage and refining have caused widespread environmental contamination (Smith et al., 2015), and the high toxicity, carcinogenicity, mutagenicity and teratogenicity of petroleum compounds mean that their bioaccumulation in the food chain interferes with biochemical and physiological processes that affect human health both directly and indirectly (Atonye, 2023). Petroleum contamination alters soil chemical composition and nutrient availability, inhibits seed germination, and disrupts root growth and architecture (Nardeli et al., 2016; Nnadi et al., 2022). An estimated 0.6 metric tonnes of crude oil is released into the environment annually worldwide (Kvenvolden and Cooper, 2003), and because petroleum hydrocarbons are fundamentally carbon- and hydrogen-based, their presence in soil skews the carbon-to-nitrogen ratio at spill sites, depleting oxygen reserves and impeding microbial activity (Dindar et al., 2013). In humans, exposure to petroleum contaminants has been linked to depression of the nervous system, narcosis and mucous membrane irritation (Al Shami et al., 2017; Ameen et al., 2015; Bastida et al., 2016; Bezza et al., 2015).

Nowhere is this challenge more acute than in the Niger Delta of Nigeria, which has been identified among the most severely degraded oil-producing environments in the world (UNEP, 2011). As the largest river delta in Africa and the third largest globally, the Niger Delta covers approximately 70,000 km2, of which 36,000 km2 is land supporting mangroves, swamps and tropical rainforest ecosystems (Izah and Aigberua, 2023; Nnadi et al., 2022). The region has recorded major spills since the early 1970s, including the Escravos spill of 1978, the Funiwa-5 blowout of 1980, the Idoho spill of 1998, the Mogho spill of 2004, the Kpor spill of 2008, the Yorla spill of 2009, the K-Dere spills of 2009 and 2012, the Bodo spill of 2013 and the Eleme spill of 2023 (Ewim, Orikpete and Onuka, 2023). Using Sentinel-1 and Sentinel-2 satellite data, AbouSamra and Ali (2022) identified 29 distinct spills between 2019 and 2021 in the north-eastern Niger Delta alone, with oil theft, pipeline failure, poor facility maintenance, vandalism, artisanal refining and sabotage identified as the principal causes (Nnadi, Udokporo and Okolo, 2022).

Remediation of hydrocarbon-impacted soils in the region has historically combined physical, chemical and biological approaches (Shi et al., 2022), but physical and chemical detoxification technologies are frequently expensive and carry the risk of introducing secondary air or water pollution. Biological approaches, which exploit the diverse metabolic capabilities of microorganisms and plants, have therefore progressively gained favour as an effective, economical and eco-friendly alternative (Singha and Pandey, 2021; Sayara and Sanchez, 2020). Bioremediation is particularly attractive because it permanently destroys pollutants rather than merely transferring them, without generating toxic by-products (Roy et al., 2018), and because it restores soil to a condition supportive of continued agricultural and ecological use (Macaulay and Rees, 2014). Bacteria, fungi, algae and various plant species are known to mineralise petroleum hydrocarbons completely into carbon dioxide, water and simple organic compounds (Das and Chandran, 2011), although the rate and extent of this microbial activity is strongly governed by environmental variables such as energy sources, bioavailability, oxygen and nutrient availability, pH, temperature and metabolite inhibition (Kebede et al., 2021). Bibliometric analysis confirms that publication output on biological remediation of petroleum-impacted soils grew markedly between 2000 and 2022 (Mekonnen et al., 2024), reflecting the accelerating scientific and commercial interest in the field.

Within this broader biological remediation landscape, biostimulation, the enhancement of indigenous microbial activity through the addition of nutrients and other amendments, has become the most widely adopted strategy for accelerating the detoxification of petroleum hydrocarbon

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(PHC)-impacted soils (Guarino et al., 2017). In the Nigerian context, a distinct sub-literature has emerged around locally manufactured biostimulation products, most prominently Clogen and Solpawa, both developed to meet local content requirements of the Nigerian petroleum industry while offering a cost-effective alternative to imported remediation chemicals. Conventional excavation, incineration and chemical treatment methods remain expensive, technologically intensive and often unsuitable for the large-scale, low-resource settings typical of the Niger Delta, and can themselves introduce secondary pollution or leave remediation incomplete (Okoro et al., 2020; Nwankwegu et al., 2021).

The purpose of this review is threefold: to synthesise the literature on the sources, classification and environmental impacts of petroleum hydrocarbon contamination in the Niger Delta; to present a comparative analysis of the principal remediation techniques available for PHC-impacted soils, physical, chemical and biological, with particular attention to biostimulation, bioaugmentation, phytoremediation and mycoremediation; and, most centrally, to undertake a focused comparative review of Clogen and Solpawa, examining their composition, mechanisms of action and documented performance, and evaluating the scientific rationale for their combined application. In doing so, the review seeks to clarify where genuine complementarity exists between locally available remediation products and to identify the research gaps that must be closed before combined biostimulation regimes can be confidently deployed at field scale in hydrocarbon-impacted communities such as K-Dere, Gokana Local Government Area, Rivers State.

2. Oil Spillage and Petroleum Hydrocarbon Contamination in The Niger Delta

2.1 History, Causes and Trends of Oil Spillage in Nigeria

Oil spillage in Nigeria predates the discovery of the country's own petroleum reserves, with the earliest recorded spill occurring at Araromi in Ondo State in 1908 (Kadafa, 2012). Commercial crude oil was subsequently discovered at Oloibiri in present-day Bayelsa State in 1956 (Ordinioha and Brisibe, 2013), with exports commencing in 1958 and expanding substantially from 1965. Major historical incidents include the 1978 Escravos spill of approximately 300,000 barrels, the 1979 Forcados spill of about 580,000 barrels, the 1980 Funiwa-5 blowout of some 400,000 barrels, and the 1998 Jesse fire disaster, which released approximately 40,000 barrels (Tolulope, 2014; Ukoli, 2015). Nigeria's Department of Petroleum Resources recorded 4,647 spill incidents releasing roughly 2.37 million barrels between 1976 and 1986, rising to 6,817 incidents by 2001 (Kadafa, 2012), with a cumulative total exceeding 7,000 recorded incidents over five decades.

More recent data compiled by the National Oil Spill Detection and Response Agency (NOSDRA) indicate that 14,693 spill events occurred between January 2006 and June 2021, releasing an estimated 738,083 barrels of oil into the environment. Sabotage, principally through illegal pipeline tapping or bunkering, accounted for approximately 63% of these incidents, with equipment failure responsible for 12%, pipeline corrosion for 7%, and production operations for a negligible 0.02%; the remaining fraction is attributable to tanker accidents, explosions, structural failure and other causes (NOSDRA, 2021). By comparison, Nigeria recorded 9,343 spill incidents in a single decade, against only ten incidents recorded in Europe over four decades (Albert et al., 2018), underscoring the disproportionate scale of the Nigerian problem. Figures 1 and 2 summarise the principal causes and the year-on-year trend of these incidents.

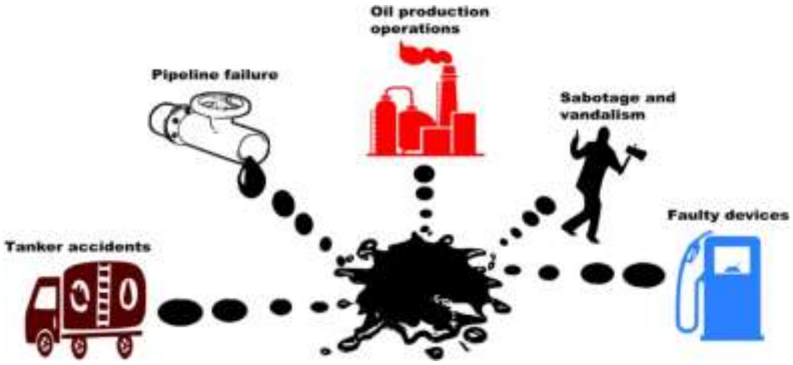

Figure 1. Major causes of oil spill incidents in Nigeria *(adapted from NOSDRA, 2021).*

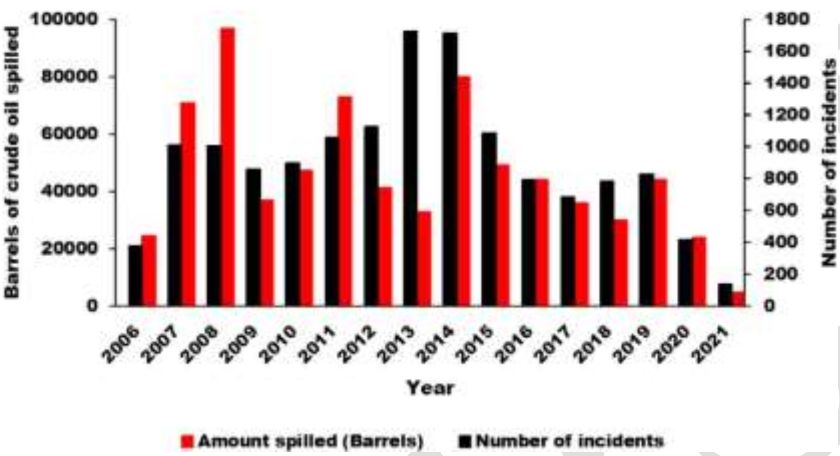

Figure 2. Recorded oil spill incidents and volume of crude oil spilled in Nigeria, January 2006 to June 2021 *(adapted from NOSDRA, 2021).*

2.2 Environmental, Soil Quality and Human Health Impacts

The environmental consequences of oil spillage are extensive and well documented. Depending on its chemical composition, spilled oil produces a range of physiological and toxic effects; benzene, for instance, is both carcinogenic and directly toxic to humans and wildlife (UNDP, 2006). Some hydrocarbon fractions are acutely toxic but degrade relatively quickly, whereas others persist for extended periods, producing long-term ecological damage (UNDP, 2006). When oil infiltrates soil, it percolates toward groundwater while its constituents interact with soil particles, altering structure and permeability and adversely affecting vegetation, microbial communities and water quality (Kakde and Sharma, 2024). Spilled oil is known to degrade forests, deplete aquatic fauna, damage mangrove swamps and contaminate groundwater; it coats birds, poisons algae, disrupts food chains and taints commercially valuable fish stocks (Badejo and Nwilo, 2014; UNDP, 2006). On soil quality specifically, crude oil contamination reduces available phosphorus while increasing soil pH, accelerating degradation in already fragile wetland soils (Wang et al., 2017), and raises daily maximum surface soil temperature relative to uncontaminated control sites (Aislabie et al., 2018). Oil smothers soil particles and blocks pore-space air diffusion, creating anaerobic conditions that disrupt microbial communities (Townsend et al., 2013; Sutton et al., 2013) and, in severe cases, cause complete mortality of marsh vegetation (Lin and Mendelssohn, 2021). Contaminated soils become more hydrophobic than pristine soils (Aislabie et al., 2018), while total organic carbon (Ekundayo and Obuekwe, 2020) and other physicochemical parameters (Hu et al., 2016; Wang et al., 2017; Arocena and Rutherford, 2015; Kisic et al., 2019) are measurably altered. On human health, ingestion of hydrocarbons through contaminated food and water leads to poisoning (Udoette, 2017), with documented toxic and carcinogenic effects of hydrocarbon exposure well established in the literature. Petroleum hydrocarbons are implicated in roughly 65% of contaminated groundwater sites worldwide (Ramos et al., 2014), and Nigeria's own historical record includes the 1980 Texaco spill, associated with approximately 180 deaths in a single affected community (Badejo and Nwilo, 2014).

2.3 Classification and Sources of Petroleum Hydrocarbons

Petroleum hydrocarbons (PHCs) are the primary constituents of crude oil, gasoline, diesel and numerous industrial solvents. They occur as complex heterogeneous mixtures containing hydrocarbons together with nitrogen, oxygen, sulphur and trace metals, and their accumulation in soil is now recognised as the leading cause of soil contamination worldwide (Popoola et al., 2022). PHC contamination reduces soil fertility, disturbs food-chain balance, and alters the physicochemical, biochemical and microbial properties of soil (Nassar and Said, 2021); soil particles coated with hydrophobic high-molecular-weight PHC films lose moisture-retention capacity, producing surface desiccation and anaerobic sub-surface conditions that inhibit nitrification and ammonification (Gaur et al., 2021; Stepanova et al., 2022). Owing to their high resistance to physical, chemical and biological degradation, PHCs persist in the environment for extended periods, bioaccumulate in living organisms, and biomagnify through the food chain (Chaudhary et al., 2021), with associated risks of genetic mutation, immunotoxicity, teratogenicity, neurotoxicity and carcinogenesis (Morillo et al., 2020; Chaudhary and Kim, 2019).

Kebede et al. (2021) classify PHCs into four principal structural groups, namely saturates, aromatics, asphaltenes and resins, while crude oil itself typically comprises 82 to 85% carbon, 10 to 14% hydrogen, 0.01 to 7% sulphur, 0.02 to 2% nitrogen and 0.1 to 1% oxygen, and may be categorised as light, intermediate or heavy according to density (Stepanova et al., 2022). Lighter fractions degrade more readily under microbial action than heavier fractions, which persist longer and cause more sustained ecological harm (Stepanova et al., 2022). At a finer structural level, PHCs comprise alkanes, monocyclic aromatic hydrocarbons (MAHs) such as benzene and phenol, and polycyclic aromatic hydrocarbons (PAHs), the latter subdivided into low-molecular-weight forms of two to three rings (such as naphthalene, phenanthrene and anthracene) and high-molecular-weight forms of four or more rings (such as pyrene and benzo[a]pyrene), with biodegradability decreasing as ring number increases (Abdel-Shafy and Mansour, 2016; Nzila, 2018). Figure 3 illustrates this classification, following Mekonnen et al. (2024).

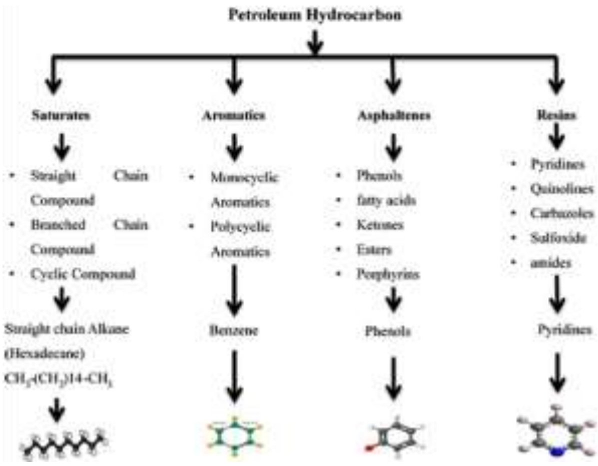

Figure 3. Structural classification of petroleum hydrocarbons into saturates, aromatics, asphaltenes and resins, showing representative degradation products *(adapted from Mekonnen et al., 2024).*

Sources of petroleum hydrocarbon contamination are similarly varied. According to Kakde and Sharma (2024), contamination arises from crude oil spillage during extraction, transportation or storage; from discharge of refined products such as petrol, diesel and their BTEX (benzene, toluene, ethylbenzene and xylene) constituents; and from chlorinated hydrocarbons such as trichloroethylene and perchloroethylene used in industrial processes, which persist in soil and groundwater with documented effects on the nervous system, liver and kidneys. Regardless of source, the persistence and toxicity of PHCs make their remediation a global environmental priority (Bicca et al., 2019), motivating the development of the physical, chemical and biological remediation techniques reviewed in the following section.

3. Remediation Techniques for Phc-Impacted Soils: A Comparative Overview

Remediation techniques for hydrocarbon-impacted soils are conventionally classified, on mechanistic grounds, into physical, chemical and biological categories (Chaudhary and Kim, 2019). Each category presents a distinct balance of cost, speed, scale-suitability and environmental compatibility, summarised comparatively in Table 1.

3.1 Physical and Chemical Techniques

Soil replacement involves the removal of contaminated soil and its substitution with clean soil, either wholesale, through deep spading to encourage dilution and natural attenuation, or through the importation of clean soil to dilute surface contaminant concentrations. The approach is effective for small, well-defined contamination footprints but becomes prohibitively costly at the scale of contamination typical of the Niger Delta. Thermal desorption exploits the volatility of hydrocarbon contaminants, applying heat via steam or infrared radiation to vaporise pollutants from the soil matrix; while the treated soil can often be reused, the equipment is expensive and desorption times can be lengthy for less volatile contaminants. Air sparging forces large volumes of air through contaminated soil to strip organic vapours, which are subsequently captured by filtration, while a related technique, encapsulation, does not remove contaminants but immobilises them in place by mixing the soil with lime, cement or concrete. These physical and chemical approaches share the common limitation of high cost and limited scalability, and chemical treatments in particular carry a risk of introducing secondary contamination.

3.2 Biological Techniques: The Case for Bioremediation

Bioremediation, in contrast, harnesses the metabolic capacity of bacteria, fungi and other microfauna to break down organic contaminants into carbon dioxide, water or methane, typically by enhancing naturally occurring biological oxidation processes through the addition of oxygen and nutrients that support the growth of indigenous, hydrocarbon-degrading bacteria (Guarino et al., 2017). Because biological treatment removes pollutants rather than merely relocating or immobilising them, and does so at comparatively low cost, it has become the preferred large-scale remediation strategy for diffuse, extensive contamination of the kind found across the Niger Delta (Gouda et al., 2017; Azubuike et al., 2016). Bioremediation techniques are classified by site of implementation into ex situ methods, comprising biopiles, composting, windrow treatment, land-farming and slurry-phase bioreactors, which require excavation and off-site or above-ground treatment; and in situ methods, comprising natural attenuation, bioventing, biosparging, phytoremediation, biostimulation and bioaugmentation, which treat contamination in place without excavation (Chaudhary and Kim, 2019; Eggen and Sasek, 2012; Leonardi et al., 2016). In situ techniques are generally more cost-effective and environmentally compatible, since they avoid the excavation, transport and disposal costs associated with ex situ treatment, although they are correspondingly more sensitive to site-specific environmental conditions and typically operate over longer timeframes (Bala et al., 2022).

Table 1. Comparative overview of remediation techniques for petroleum hydrocarbon-impacted soils.

Technique	Mechanism	Relative Cost	Key Limitation
Soil replacement	Dilution/removal of contaminated soil	High (large sites)	Impractical for extensive contamination
Thermal desorption	Volatilisation of contaminants by heat	High	Expensive equipment; long treatment time
Air sparging / encapsulation	Stripping or physical immobilisation of contaminants	Moderate-High	Does not always destroy contaminant
Bioremediation (ex situ)	Microbial degradation after excavation	Moderate	Excavation, handling and disposal costs
Bioremediation (in situ)	Microbial degradation in place	Low	Slower; highly site-condition dependent

4. Comparative Analysis of Bioremediation Technologies

Among in situ bioremediation techniques, biostimulation, bioaugmentation, phytoremediation and mycoremediation are the most widely adopted, owing to their comparatively low cost and demonstrated field effectiveness (Gogoi et al., 2013; Sang-Hwan et al., 2017). Figure 4 presents a classification of these bioremediation strategies according to their ex situ and in situ implementation, following Chaudhary and Kim (2019). The sub-sections that follow compare the four techniques on mechanism, representative performance data and operational constraints.

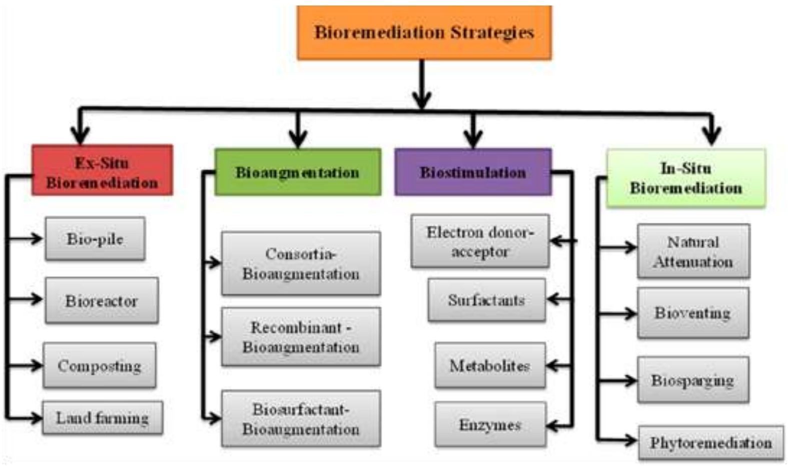

Figure 4. Classification of bioremediation strategies for petroleum hydrocarbon-impacted soils *(adapted from Chaudhary and Kim, 2019).*

4.1 Biostimulation

Biostimulation supports the natural degradative activity of the microorganisms already resident in contaminated soil, rather than introducing new organisms, by supplying carbon, nitrogen, phosphorus, oxygen and other growth-limiting nutrients (Guarino et al., 2017). Because it works with, rather than against, the existing soil microbiome, biostimulation is regarded as the most commonly deployed bioremediation technique for PHC-impacted soils, although the concentration of added nutrients must be carefully controlled to avoid inducing a nutrient imbalance in the microflora (Torlapati and Boufadel, 2014). Reported performance varies widely with soil type, amendment and duration. Komommo et al. (2025) recorded a TPH degradation efficiency of 99.61% for the Clogen product in a field evaluation at Eleme, reducing an initial TPH concentration of 6,600 mg/kg to 26 mg/kg. Koshlaf et al. (2019) found that pea-straw amendment enhanced PAH degradation by 66.6% over 102 days, with Proteobacteria, Bacteroidetes and Firmicutes dominating the amended soil microbiome. Al-Kindi and Abed (2016) demonstrated that spent mushroom compost and poultry manure raised hydrocarbon degradation from an untreated baseline of 19.3% to 34% over 96 days, while Qin et al. (2013) showed that rice-straw biochar amendment raised TPH removal efficiency to 84.8% relative to an unamended control value of 61.2%, confirming that nutrient addition measurably improves the development of hydrocarbon-degrading bacterial flora.

4.2 Bioaugmentation

Bioaugmentation introduces specific, beneficial microorganisms, whether bacterial, fungal or algal, into contaminated soil to supplement or substitute for an indigenous microbial community that is either absent or metabolically incapable of degrading the target contaminant (Nzila et al., 2016). The technique is particularly valuable where native microorganisms are too sparse or insufficiently adapted to achieve effective degradation, and has been successfully combined with chemical pre-treatment: Ahmad et al. (2023) reported that permanganate pre-treatment combined with bioaugmentation foam achieved 92.1% TPH reduction in diesel-contaminated unsaturated soil, with chromatogram analysis confirming 94% removal of the more persistent C18 to C22 hydrocarbon fraction. Composting-based bioaugmentation has proven effective even at very high contamination loads, with reported removal efficiencies exceeding 70%, and in some cases reaching 99%, for TPH concentrations of up to 380,000 mg/kg (Tran et al., 2020). Bacterial consortia are generally considered more effective than single-strain inocula, since complementary metabolic capabilities allow more complete degradation of complex hydrocarbon mixtures through synergistic and commensal relationships among species. Table 2 summarises representative microbial and consortium-based degradation outcomes reported in the literature across biostimulation, bioaugmentation and phytoremediation applications, illustrating the range of contaminant classes, treatment combinations and efficiencies documented to date.

Table 2. Representative degradation outcomes reported for microbial and plant-based bioremediation of petroleum hydrocarbons.

Agent / Consortium	Contaminant	Technique	Reported Efficiency
Rhodococcus spp.	TPH	Bioaugmentation	Effective across a wide range of temperature, salinity and pH
Bacillus sp.	TPH	Biostimulation	80.24% of aged TPH removed
Methylotrophicus + indigenous consortium	TPH	Biostimulation	100% degradation achievable within 6 days
Sophorolipids + Arthrobacter globiformis	PAH + DDT	Biostimulation	60.7% PAH and 29.3% DDT degradation, higher than control
Rhamnolipids + mixed surfactants + Pseudomonas brassicacearum	Naphthalene + PAH	Bioaugmentation	31.1% naphthalene removed; increased PAH degradation
MPDS + Serratia marcescens + Bacillus megaterium	PAH (acenaphthene, fluorene)	Bioaugmentation	98.92% fluorene and 98.16% acenaphthene degradation
Aeromonas hydrophila + Panicum virgatum + bacterial strains	TPH	Phytoremediation	Increased TPH degradation; most efficient in saturated anaerobic conditions
Actinomycetales + Melilotus officinalis (rhizosphere)	TPH + Aliphatic HCs	Phytoremediation + bioremediation	Improved TPH degradation by 32%; increased degradation of other HCs

A persistent challenge for bioaugmentation is the poor long-term survival of introduced microbial strains once released into an unfamiliar soil environment, with populations of exogenous microbes typically declining rapidly after inoculation (Mata et al., 2023). Effectiveness is further shaped by an interaction of biotic and abiotic factors; for example, Burkholderia sp. FDS-1 degraded the pesticide fenitrothion most efficiently at 30 degrees Celsius under slightly alkaline conditions, but performed poorly at 10 and 50 degrees Celsius and under strongly acidic conditions (Mata et al., 2023). These constraints mean that, while laboratory-scale bioaugmentation trials have been widely successful, translation to large-scale, real-world deployment remains an active area of ongoing research.

4.3 Phytoremediation

Phytoremediation exploits the capacity of plant root systems, and particularly the rhizosphere bacterial communities they support, to degrade petroleum hydrocarbons and BTEX compounds in situ (Fanaei et al., 2023). Root exudates provide readily accessible carbon substrates that support catabolism of aromatic compounds by rhizosphere microorganisms, predominantly from the Actinobacteria, Proteobacteria and Bacteroidetes phyla, and phytoremediation has been shown to achieve permanent hydrocarbon removal at former tank-farm sites (Lee et al., 2023). The technique is increasingly deployed in combination with bioaugmentation, since the two mechanisms address complementary pollutant classes: phytoextraction is particularly effective against metal contaminants, while bioaugmentation targets organic pollutants, and the physical interaction between plant roots and introduced microbial inocula in the rhizosphere increases both microbial activity and contaminant translocation (Alegbeleye et al., 2017). This combined approach also offers a longer-term, more sustainable remediation pathway than either technique alone, since phytoremediation provides persistent plant-driven contaminant uptake while bioaugmentation sustains microbial activity in the root zone (Simmer et al., 2022).

4.4 Mycoremediation

Mycoremediation employs fungal species to achieve complete mineralisation of petroleum hydrocarbons into carbon dioxide, water, nitrogen and microbial biomass (Rhodes, 2014), exploiting the unique morphology and metabolic versatility of fungi as effective bioremediation agents (Hawksworth and Lucking, 2017). Reported degradation efficiencies among fungal species are notably high and diverse. Dhailappan et al. (2022) achieved 87% TPH degradation within 21 days using the edible oyster mushroom Pleurotus ostreatus stimulated with paddy husk, while Marin et al. (2018) recorded a TPH removal rate of 98.78% for an endophytic Xylaria sp. isolate over 30 days. Kristanti et al. (2011) obtained 93% degradation of crude oil after 60 days using the white-rot fungus Polyporus sp. S133, and Daassi and Almaghribi (2021) reported approximately 92% TPH degradation after 60 days using Paecilomyces formosus. A synergistic combination of rhizospheric fungal strains with guinea grass (Megathyrsus maximus) roots achieved 95.36% total PAH mineralisation over 90 days (Asemoloye et al., 2017), illustrating that fungal-plant consortia can rival or exceed the performance of single-agent bioremediation strategies.

4.5 Comparative Synthesis

Taken together, the four bioremediation strategies exhibit distinct but overlapping strengths. Biostimulation offers the lowest cost and the least ecological disruption because it relies on indigenous organisms, but its efficiency is bounded by the metabolic competence of the native microbial community and can be limited where hydrocarbon-degrading populations are sparse. Bioaugmentation overcomes this limitation by introducing competent degraders, at the cost of variable strain survival and added logistical complexity. Phytoremediation offers the most durable, self-sustaining remediation pathway and the co-benefit of vegetative cover restoration, but generally acts over longer timeframes and is most effective against near-surface, root-zone contamination. Mycoremediation delivers some of the highest reported single-treatment degradation efficiencies in the literature, particularly against high-molecular-weight PAHs that resist bacterial attack, but its field-scale application remains less mature than the other three techniques. In practice, the strongest documented outcomes across all four categories tend to arise from combined or hybrid applications, whether biostimulation paired with bioaugmentation, or phytoremediation paired with fungal or bacterial inoculation, a pattern that directly motivates the combined-product analysis of Clogen and Solpawa presented in Section 6.

5. Factors Influencing Bioremediation Efficiency

Effective bioremediation depends on identifying and managing the site-specific factors that govern microbial degradation of PHCs (Kebede et al., 2021). Substrate properties and concentration determine the ease of degradation, with linear and low-molecular-weight hydrocarbons degrading more readily than branched or polycyclic aromatic structures, and excessively high initial TPH concentrations can themselves become toxic to the degrading microbial population. Temperature strongly influences microbial metabolic rate, with mesophilic hydrocarbon-degrading bacteria generally most active between 20 and 40 degrees Celsius. Nutrient availability, particularly of nitrogen and phosphorus, is frequently the binding constraint on bioremediation rate, since contamination itself depletes soil nitrogen and skews the carbon-to-nitrogen-to-phosphorus (C:N:P) ratio away from levels that support optimal microbial proliferation. Soil texture and organic matter content affect both contaminant retention and the diffusion of oxygen and nutrients, with clay-rich soils retaining contaminants more strongly but diffusing oxygen more poorly than sandy soils. The presence and diversity of competent hydrocarbon-degrading microorganisms determines the ceiling on achievable degradation, while soil pH and salinity influence microbial community composition, with most hydrocarbon-degrading bacteria favouring near-neutral pH and low to moderate salinity. Figure 5 summarises these major factor classes.

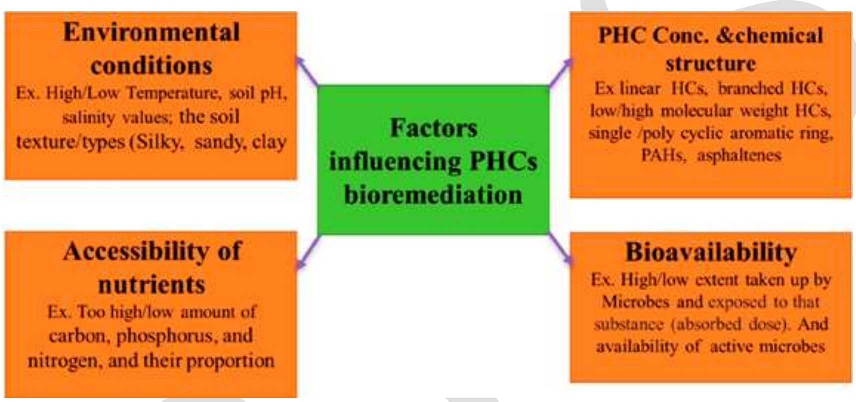

Figure 5. Major classes of factors influencing the bioremediation of petroleum hydrocarbon-impacted soils.

6. Comparative Case Study: Clogen And Solpawa Biostimulation Products

Among the locally formulated biostimulation products increasingly deployed for the amelioration of PHC-impacted soils in the Niger Delta, Clogen and Solpawa have emerged as two indigenously manufactured, non-imported nutrient formulations favoured by remediation contractors and researchers for their cost, availability and compliance with the local content policy of the Nigerian petroleum industry. Although a reasonable volume of literature exists on the individual application of each product, comparatively little has been documented on their combined or sequential deployment as a single biostimulation strategy. This section reviews the composition, mechanism of action and empirical performance of each product before evaluating the rationale for their combined application.

6.1 Overview and Composition of Clogen

Clogen is a liquid biostimulation and bioaugmentation product manufactured in Nigeria by Andelsta Limited and patented with the Federal Republic of Nigeria under Patent No. R.16273 (Komommo et al., 2025). It comprises electro-ionic biopolymers (14%), polysaccharide cellulose (16%), sodium poly-aromatic alkylated sulphonates (10%), hydrogen (14%) and carbon (45%), has a pH range of 8.5 to 9.5, and is highly soluble, non-flammable and non-hazardous under normal storage conditions. Field application typically involves diluting the product with water at a ratio of 1:6, applied at one litre per cubic metre of soil (Komommo et al., 2025). Mechanistically, the electro-ionic biopolymer and cellulose fractions bind soil particles together, improving physical structure and contributing organic carbon as the polymers decompose, while the sulphonate surfactant fraction emulsifies residual hydrocarbons, increasing their bioavailability to microbial attack. Because Clogen additionally contains cultured, locally isolated hydrocarbon-degrading microorganisms, it functions simultaneously as a biostimulant and a bioaugmentation agent. In a field-scale evaluation at Eleme, Ogoni-land, Clogen achieved a TPH degradation efficiency of 99.61%, reducing an initial concentration of 6,600 mg/kg to 26 mg/kg over approximately eighteen months, the highest efficiency recorded among four competing bioremediation products in that comparative study (Komommo et al., 2025).

6.2 Overview and Composition of Solpawa

Solpawa is an indigenous soil bioremediation system manufactured by Solpawa Bio-Remediation Products Limited and marketed under the trade name Solpawa SBR-X, comprising two complementary formulations: Solpawa Soil Conditioner, a liquid nutrient concentrate, and Solpawa Soil Booster, a granular nutrient blend (Okogbule-Wonodi and Nweke, 2023; Okogbule-Wonodi et al., 2023). The manufacturer describes the underlying mechanism as bio-emulstimulation, a combination of bio-emulsification and biostimulation that degrades TPH while simultaneously improving soil fertility. Laboratory characterisation shows the granular Booster to carry substantially higher fertilising value than the liquid Conditioner, with nitrogen content of 261.450 mg/kg versus 103.560 mg/kg, phosphorus content of 7.592 mg/kg versus 1.241 mg/kg, and potassium content of 569.191 mg/kg versus 180.903 mg/kg respectively (Okogbule-Wonodi and Nweke, 2023); both values considerably exceed the conventional agronomic N:P:K recommendation of 3:2.5:0.5, underscoring the products' suitability for nutrient-depleted, hydrocarbon-impacted soils. Okogbule-Wonodi and Nweke (2023) monitored TPH concentration in crude oil-contaminated sandy soil at depths of 0.3, 0.6 and 0.9 metres following sequential application of Conditioner, at dilution ratios of 1:4, 1:6 and 1:8, followed by Booster at a 1:12 ratio. Conditioner alone produced modest TPH reduction of between 9 and 11% after twelve days, but subsequent Booster application raised cumulative degradation to as much as 92.88% after forty days across the sampled depths, with treatment differences statistically significant at the 5% level. A related clay-soil trial (Okogbule-Wonodi et al., 2023) corroborated this sequential conditioner-then-booster dosing regime, and a field trial report commissioned to support product licensing by the Nigerian Upstream Petroleum Regulatory Commission, and funded by the Nigerian Content Development and Monitoring Board, further affirmed the products' field efficacy under Niger Delta conditions (Solpawa Bio-Remediation Products Limited, 2023).

6.3 Comparative Composition and Application Characteristics

Table 3 summarises the composition, physical form and application characteristics of Clogen and the two Solpawa formulations, highlighting their complementary rather than duplicate modes of action: Clogen supplies a biopolymer-surfactant-microbial consortium suited to soil conditioning, hydrocarbon emulsification and bioaugmentation, whereas Solpawa supplies a concentrated source of readily available nitrogen, phosphorus and potassium suited to stimulating the metabolic activity of indigenous hydrocarbon-utilising microorganisms.

Table 3. Comparative composition and application characteristics of Clogen and Solpawa products

Parameter	Clogen	Solpawa Conditioner	Solpawa Booster
Physical form	Liquid	Liquid	Granular
Nitrogen (N)	Not specified (biopolymer-based)	103.560 mg/kg	261.450 mg/kg
Phosphorus (P)	Not specified	1.241 mg/kg	7.592 mg/kg
Potassium (K)	Not specified	180.903 mg/kg	569.191 mg/kg
Key active components	Electro-ionic biopolymers (14%); polysaccharide cellulose (16%); sulphonate surfactants (10%); carbon (45%)	Indigenous liquid nutrient concentrate	Concentrated granular nutrient blend
pH	8.5 - 9.5	Not reported	Not reported
Primary mechanism	Bio-emulsification + bioaugmentation (cultured HC-degrading microbes)	Biostimulation (soil conditioning; initial nutrient release)	Biostimulation (concentrated nutrient boost)
Recommended application	1:6 dilution with water; 1 L/m3 of soil	1:4, 1:6 or 1:8 dilution with water	1:12 ratio (20 kg per 240 kg soil)

(Compiled from Komommo et al., 2025 and Okogbule-Wonodi and Nweke, 2023).

6.4 Empirical Performance Comparison

Figure 6 compares the TPH degradation efficiencies reported for Clogen and the two Solpawa formulations across the reviewed studies. It should be noted that the underlying studies differ substantially in soil type, remediation duration and scale, Clogen was evaluated at field scale in Eleme over approximately eighteen months, whereas the Solpawa trials were laboratory-scale studies of forty days or less, so the reported values indicate achievable performance rather than results obtained under strictly identical conditions. Nonetheless, the data show that both products, given sufficient contact time and appropriate dosing, are capable of driving TPH degradation efficiencies in excess of 90%, while the Solpawa Conditioner applied alone, without subsequent Booster application, achieved only modest degradation. This pattern reinforces the understanding that the conditioning stage functions primarily to prime soil porosity and microbial receptivity ahead of a nutrient-intensive booster stage, rather than to achieve substantial degradation in its own right.

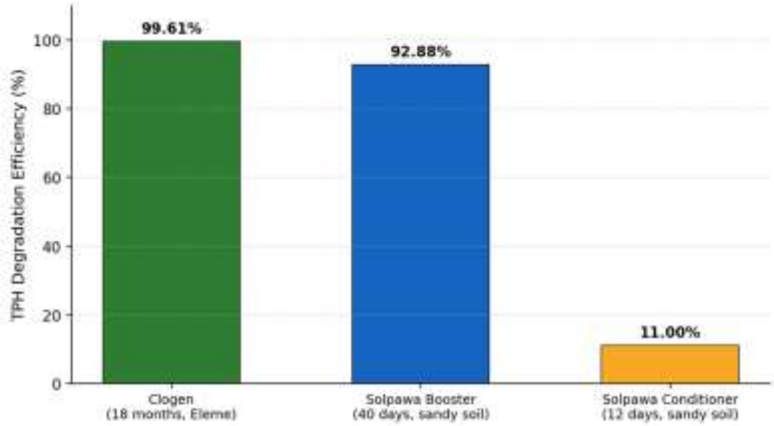

Figure 6. Comparative total petroleum hydrocarbon (TPH) degradation efficiency of Clogen and Solpawa formulations in prior field and laboratory studies *(data compiled from Komommo et al., 2025 and Okogbule-Wonodi and Nweke, 2023).*

6.5 Rationale and Synergistic Mechanism for Combined Application

The rationale for combining Clogen and Solpawa in a single biostimulation regime rests on the complementary, rather than overlapping, mechanisms of the two products. Whereas Clogen principally addresses soil physical structure, hydrocarbon emulsification and bioaugmentation through its biopolymer, surfactant and cultured-microbe components, Solpawa principally addresses the nitrogen, phosphorus and potassium deficiency that characteristically limits microbial proliferation in hydrocarbon-impacted soils. This complementarity is consistent with the wider biostimulation literature: a comprehensive review of 276 peer-reviewed studies published between 2000 and 2025 concluded that integrated or combined biostimulant treatments consistently outperform single-agent approaches in TPH removal efficiency (Li et al., 2025), a finding that echoes the earlier position of Adams et al. (2015), who argued that combining nutrient amendment with structural or microbial amendment typically outperforms either strategy applied in isolation, since nutrient supplementation alone cannot overcome unfavourable soil structure or the absence of competent hydrocarbon-degrading microbial populations, and vice versa.

Further indirect support for a combined-product approach can be drawn from Komommo et al. (2025), whose comparative field data showed markedly different degradation efficiencies among competing single-agent products at different Eleme locations, ranging from 73.89% for MicroSORB to 99.61% for Clogen, suggesting that no single product uniformly optimises every stage of the degradation pathway. Pairing products with complementary strengths, Clogen's emulsification-bioaugmentation capacity and Solpawa's concentrated nutrient supply, therefore offers a plausible route to more consistent and accelerated TPH removal. Figure 7 presents a conceptual schematic of this proposed synergistic pathway, in which the combined amendment simultaneously improves hydrocarbon bioavailability and soil physical structure via Clogen while relieving nutrient limitation on microbial growth via Solpawa, jointly enhancing the metabolic activity of the indigenous hydrocarbon-utilising microbial community.

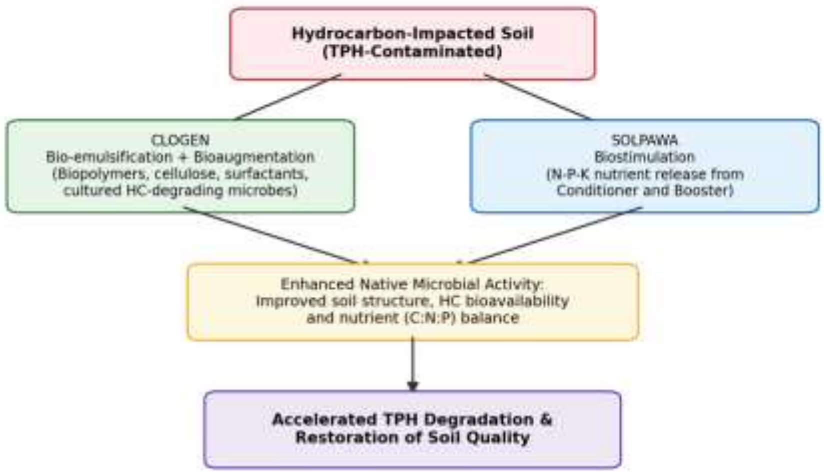

Figure 7. Conceptual schematic of the proposed synergistic mechanism of combined Clogen-Solpawa biostimulation for hydrocarbon-impacted soil remediation.

6.6 Factors Likely to Influence Combined Clogen-Solpawa Efficiency

The efficiency of a combined Clogen-Solpawa biostimulation process is expected to be shaped by several interacting factors. The sequencing and dosing ratio of the two products is likely to matter, since the Solpawa literature indicates that a conditioner-before-booster sequence outperforms either component applied alone, implying that a comparable staged or co-application protocol would need to be established for a Clogen-Solpawa combination (Okogbule-Wonodi and Nweke, 2023). Soil texture and structure will also influence performance, since biopolymer- and surfactant-based amendments such as Clogen behave differently in sandy, loamy and clay-rich soils, with clayey soils generally offering greater contaminant retention but poorer oxygen and nutrient diffusion (Abdulsalam et al., 2011). The carbon-to-nitrogen-to-phosphorus balance achieved after combined application must fall within the range known to support optimal microbial proliferation, since either excessive or insufficient nutrient loading can suppress rather than stimulate hydrocarbon-degrading activity. Ambient soil moisture, temperature, pH and oxygen availability will continue to modulate the rate at which the combined amendment's biostimulatory effect is expressed, and the initial TPH concentration together with the contact or incubation period will determine the degradation ceiling achievable within a given monitoring window, as reflected in the markedly different degradation percentages recorded for Clogen over eighteen months compared with Solpawa over forty days in the studies reviewed above.

Taken together, the reviewed literature indicates that Clogen and Solpawa are each independently capable of driving substantial TPH degradation in hydrocarbon-impacted soils, and that their combination is theoretically well justified on the grounds of complementary mechanism of action and the weight of evidence from the wider biostimulation literature favouring integrated over single-agent treatments. At the time of this review, however, no published study had specifically evaluated the combined, co-applied performance of Clogen and Solpawa on hydrocarbon-impacted soils of the Niger Delta, representing a clear and specific gap in the literature.

7. Discussion: Research Gaps and Future Directions

This review highlights several gaps that constrain confident field-scale deployment of combined biostimulation strategies in the Niger Delta. First, and most directly, no published study has evaluated the co-applied performance of Clogen and Solpawa, despite a strong theoretical rationale for complementarity between the two products; controlled trials directly comparing single-agent and combined-agent treatments under matched soil and climatic conditions are required to test this rationale empirically. Second, the performance data reviewed for both products, and indeed for most bioremediation techniques surveyed in Section 4, derive from studies that differ substantially in soil type, contamination level, duration and scale, which limits direct comparability and argues for standardised comparative protocols specific to Niger Delta field conditions. Third, relatively few studies track ecological and agronomic recovery beyond the point of TPH reduction, so that restoration of soil fertility and crop-supporting capacity, arguably the ultimate objective for farming communities, remains under-documented relative to contaminant removal efficiency alone. Fourth, the scale-up of promising laboratory and small-plot results to the scale of contamination found in communities such as K-Dere continues to present logistical and economic challenges warranting further operational research. Addressing these gaps through rigorously designed field trials, particularly of combined Clogen-Solpawa application, would meaningfully strengthen the evidence base available to remediation contractors, regulators and affected communities across the Niger Delta.

8. Conclusion and Recommendations

Hydrocarbon contamination of soil remains one of the most persistent environmental challenges facing the Niger Delta, driven by a long history of oil spillage from causes ranging from pipeline sabotage to equipment failure, and carrying substantial consequences for soil quality, ecosystem health and human wellbeing. Among the available remediation options, biological approaches, and biostimulation in particular, offer the most cost-effective and environmentally compatible pathway to restoring contaminated soils at the scale the region requires. This review has compared the four principal bioremediation strategies, biostimulation, bioaugmentation, phytoremediation and mycoremediation, finding that each offers distinct strengths and that the strongest outcomes in the literature typically arise from combined or hybrid applications rather than single-agent treatments. The focused comparison of Clogen and Solpawa reinforces this broader pattern. Both products are independently capable of achieving TPH degradation efficiencies exceeding 90% under appropriate conditions, yet they operate through genuinely complementary mechanisms, Clogen through soil conditioning, hydrocarbon emulsification and bioaugmentation, and Solpawa through concentrated nutrient supplementation, rather than through duplicate pathways. This complementarity provides a sound scientific rationale for combined application, but the absence of published field data specifically evaluating combined Clogen-Solpawa treatment means that this rationale remains, at present, a well-supported hypothesis rather than an empirically confirmed outcome. It is therefore recommended that future field trials directly test combined Clogen-Solpawa biostimulation against each product applied individually, under the soil and climatic conditions characteristic of impacted Niger Delta communities such as K-Dere, Gokana Local Government Area, Rivers State, with particular attention to product sequencing, dosing ratio, and the carbon-to-nitrogen-to-phosphorus balance achieved following combined application. Such trials, complemented by longer-term monitoring of soil fertility and ecological recovery rather than TPH reduction alone, would substantially strengthen the evidence base needed to guide remediation practice, regulatory policy and community-level restoration efforts across Nigeria's oil-producing regions.

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