

A Technical Review of the Effects of Bone Char, Spent-palm Bunch, and Inorganic Fertilizer in the Biodegradation of Hydrocarbon-Polluted Soil

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ABSTRACT

This paper critically reviews the comparative mechanisms of bone char, Spent-Palm-Bunch (SPB), and NPK (Inorganic) fertilizers in driving the biodegradation of saturated, aromatic, resin, and asphaltene fractions in polluted tropical soils. Following a transparent search of relevant literatures, we identify the primary studies that report bone char, SPB, or NPK amendment of hydrocarbon-contaminated soil, extract their soil type, contaminant loading, amendment dose, trial duration, microbial response, hydrocarbon-fraction removal, pH shift, and stated limitations. Only one identified study places bone char and NPK head-to-head on the same soil under the same protocol; no identified study places all three amendments together. Kinetic modelling (first- and second-order decay) and Response Surface Methodology (RSM) have been applied within single-amendment studies to optimize dose and predict half-life, but never across amendments to test whether bone char, SPB, and NPK differ significantly in mechanism or outcome. We identify critical knowledge gaps in comparative field validation, bio-char/waste matrix optimization, and long-term ecosystem recovery. Finally, an integrated conceptual framework is proposed to guide scalable, bioremediation strategies, critical field-validation, dose-standardization, and joint-modelling work for hydrocarbon degraded tropical soils.

Keywords: Biodegradation, Bone-char, Spent-Palm-Bunch, NPK fertilizer, Biostimulation, Contaminated soil.

INTRODUCTION

Petroleum hydrocarbon degradation is the breakdown of complicated hydrocarbons by bacteria, fungi and yeast. Degradation depends on the hydrocarbon type and concentration. Bioavailability is a key limiting factor because hydrocarbons are prone to bind to soil components. Susceptibility to microbial attack generally decreases in the order: linear alkanes; branched alkanes; small aromatics; cyclic alkanes, with high-molecular-weight polycyclic aromatic hydrocarbons (PAHs) being potentially completely resistant to degradation. Bioremediation helps in this process by providing optimum conditions for the microbes to grow. The removal of hydrocarbons from the contaminated environment is mainly done by microbial degradation.

Biodegraded petroleum-derived aromatic hydrocarbons have been found in marine sediments, with the breakdown of alkylaromatic hydrocarbons preceding the breakdown of the crude oil's n-alkane profile, with key degraders identified as *Arthrobacter*, *Burkholderia*, *Mycobacterium*, *Pseudomonas*, *Sphingomonas* and *Rhodococcus* (Nilanjana and Preethy, 2010). Nine bacterial strains capable of degrading crude oil were isolated from a polluted tropical stream in Lagos, Nigeria, *Pseudomonas fluorescens*, *P. aeruginosa*, *Bacillus subtilis*, *Bacillus* sp., *Alcaligenes* sp., *Acinetobacter lwoffii*, *Flavobacterium* sp., *Micrococcus roseus* and *Corynebacterium* sp. (Adebusoye et al. 2007). Reported biodegradation efficiencies vary greatly among microbial groups: 6–82% for soil fungi, 0.13–50% for soil bacteria, and 0.003–100% for marine bacteria. The chemical complexity of crude oil typically requires the presence of mixed populations of microbes with broad

enzymatic capacity for effective degradation in soil, freshwater and marine environments. (Rahman & Rahman, 2018).

THEORETICAL FRAMEWORK

Factors Affecting Biodegradation of Hydrocarbons

Multiple interacting parameters govern the rate of hydrocarbon biodegradation in soil, and understanding these is essential for optimizing remediation. They are:

Temperature: Temperature influences both the chemistry of the pollutant and the physiology of degrading microorganisms (Venosa and Zhu, 2003). At low temperatures, oil viscosity rises and volatilization of toxic low-molecular-weight fractions declines, delaying biodegradation onset (Atlas, 1981), while solubility is also temperature-dependent. Optimal degradation generally occurs at 30–40°C in soils, 20–30°C in freshwater, and 15–20°C in marine systems though biodegradation in psychrophilic environments is also documented (Delille et al., 2004). Cold-adapted (psychrotolerant/psychrophilic) degraders of alkanes, aromatics, and chlorophenols are widespread (Aislabie et al., 2000; Margesin et al., 2005), predominantly Gram-negative, with adaptations in membrane lipids, enzymes, and protein synthesis. Hydrocarbon degraders make up <0.1% of unpolluted microbial communities but can reach 100% of cultivable organisms in polluted sites (Atlas, 1981). Consortium studies show optimal growth near 35°C for toluene degraders and higher metabolic rates at 25°C than 10°C for benzene-aquifer bacteria.

Nutrients: Heterotrophic degraders require carbon, nitrogen, phosphorus, and trace vitamins/amino acids, which are often limiting in soils, including Arctic soils. An optimal C:N ratio of 2–200 has been reported, with paraffinized urea and octyl phosphate serving as effective slow-release N and P sources (Atlas and Bartha, 1998); field/microcosm work has used a C:N:P ratio of 100:3.25:0.75. Biodegradability also depends on oil composition: kerosene is almost fully biodegradable, whereas heavy asphaltic-naphthenic crude is degraded to only approximately 11% under favorable conditions. Reported ranges include 8.8–29% degradation of Maya crude in 15 days by mixed consortia (Okoh, 2002, 2003) versus approximately 89% by axenic *Burkholderia cepacia* RQ1 (Okoh et al., 2001). Although degradation efficiency can fall as oil concentration rises, e.g., from 78% to 52% as concentration increased from 1–10% (Rahman et al., 2003); degradation may plateau independent of growth rate once a biomass threshold for enzyme production is reached (Okoh, 2002). Photo-oxidation can increase bioavailability and biodegradability (Maki et al., 2005; Jacquot et al., 1996), and nutrient supplementation, including fertilizers, poultry manure, and other organic amendments, consistently enhances degradation, although excessive NPK can be inhibitory, particularly for aromatics (Chaillan et al., 2006).

Chemical Composition, Solubility, and Bioavailability: Petroleum hydrocarbons comprise saturates, aromatics, asphaltenes, and resins, with susceptibility to attack ranked: n-alkanes > branched alkanes > low-molecular-weight aromatics > cyclic alkanes. Biodegradability correlates with water solubility, since bacteria act mainly within soil interstitial water. Bioavailability—the physicochemically accessible fraction of a pollutant—is a key rate-limiting factor (Parales, 2008); growth on crystalline naphthalene shows linear kinetics limited by solubilization, and uptake likely proceeds via membrane attachment or diffusion coordinated with enzymatic oxidation. Surfactants (chemical or biological) can stimulate, inhibit, or have no effect on degradation (Rahman et al., 2003; Lindstrom and Braddock, 2002). Synthetic and biological surfactants have been shown to enhance bioavailability, while soil organic matter, humic/fulvic acids, mineral composition, pH, salinity, and weathering all affect contaminant sorption and availability over time.

Oxygen, Moisture, and pH: Oxygen serves as the principal electron sink in the initial and subsequent oxidative attack on hydrocarbons; in its absence, nitrate or sulfate reduction may partially support degradation, but little occurs under strictly anoxic conditions. Soil moisture, which governs the interstitial water microbes inhabit, similarly limits degradation rate when scarce. Soil pH ranges from 2.5 to 11 in nature; most heterotrophic bacteria favor near-neutral pH while fungi tolerate more acidic conditions. Raising pH from 4.5

to 7.4 doubled gasoline degradation, though further increase to 8.5 reduced rates, and an optimum of pH 7.8 (range 5.0–7.8) was found for oily sludge mineralization.

Mechanistic Background

The study review physicochemical and enzymatic background needed to interpret why bone char, SPB, and NPK act on hydrocarbon-contaminated soil in different ways, rather than surveying bioremediation technology generally.

Factors Governing Amendment Performance

Four factors recur across the bone-char, SPB, and NPK literature and structure the comparison in Section 4.

Nutrient stoichiometry: heterotrophic hydrocarbon degraders are carbon-rich but nitrogen- and phosphorus-poor relative to their substrate, and an optimal C:N:P ratio near 100:10:4 (or a C:N ratio not exceeding about 25:1) is repeatedly cited as the target that nutrient amendments are meant to restore (Atlas and Bartha, 1998). **Soil pH:** most heterotrophic hydrocarbon-degrading bacteria favor near-neutral conditions (pH 5.2–7.8), and amendments that shift soil pH toward this range, as bone char’s alkalinity and NPK’s acidifying tendency both can, in opposite directions, change degradation rate independently of any nutrient effect. **Carbon/porosity structure:** bone char and SPB are both particulate, high-surface-area carbon matrices that can adsorb hydrocarbons and host microbial biofilm, a mechanism NPK, as a soluble mineral salt mixture, does not share. **Cost and availability:** bone char and SPB are waste-derived and locally available in Niger Delta agro-processing and abattoir operations, whereas NPK is a purchased input whose price in Nigeria has been reported to limit its field-scale application (Okwonna and Otaraku, 2022).

Enzymology of Hydrocarbon Oxidation

Aerobic biodegradation is the dominant pathway for the hydrocarbon fractions these amendments target, proceeding through oxygenase- and peroxidase-initiated attack that feeds peripheral pathways into central metabolism. Cytochrome P450 alkane hydroxylases are a heme-thiolate monooxygenase superfamily central to this oxidation, alongside the di-iron AlkB-type alkane hydroxylases and methane monooxygenases summarized in Table 1 (Van Beilen and Funhoff, 2007). None of these enzyme systems is specific to any one amendment; bone char, SPB, and NPK are hypothesized to act by relieving different rate-limiting constraints, nutrient supply, pH, sorption, or carbon-source diversity, on the same underlying enzymatic machinery, which is why a direct comparison of amendments, rather than a further survey of the enzymology, is the more informative next step.

Table 1: Enzymes involved in biodegradation of petroleum hydrocarbons

Enzymes	Substrates	Microorganisms	References
Soluble Methane Monooxygenases	C1–C8 alkanes, alkenes, cycloalkanes	Methylococcus, Methylosinus, Methylocystis, Methylomonas, Methylocella	McDonald et al.
Particulate Methane Monooxygenases	C1–C5 (halogenated) alkanes, cycloalkanes	Methylococcus, Methylocystis	McDonald et al.
AlkB-related Alkane Hydroxylases	C5–C16 alkanes, fatty acids, alkyl benzenes, cycloalkanes	Pseudomonas, Burkholderia, Rhodococcus, Mycobacterium	Van Beilen et al. (2003)
Eukaryotic P450	C10–C16 alkanes, fatty acids	Candida maltosa, C. tropicalis, Yarrowia lipolytica	
Bacterial P450	C5–C16 alkanes,	Acinetobacter, Caulobacter,	Van Beilen et al.

oxygenase system	cycloalkanes	Mycobacterium	(2003)
Dioxygenases	C10–C30 alkanes	Acinetobacter sp.	Maeng et al. (1996)

Commercially Available Bioremediation Agents

The U.S. EPA defines bioremediation agents as microbiological cultures, enzymes, or nutrient additives that accelerate biodegradation, classified as bioaugmentation or biostimulation agents (Venosa et al., 2004). Fifteen agents were originally listed under the NCP Product Schedule (Clean Water Act; Oil Pollution Act, 1990), later reduced to nine (Table 2).

Table 2: Bioremediation agents in NCP product schedule (Adapted from USEPA)

Name or Trademark	Product Type	Manufacturer
BET BIOPETRO	MC	BioEnviro Tech, Tomball, TX
BILGEPRO	NA	International Environmental Products, LLC, Conshohocken, PA
INIPOL EAP 22	NA	Societe CECA S.A., France
LAND AND SEA	NA	Land and Sea Restoration LLC, San Antonio, TX
RESTORATION MICRO-BLAZE	MC	Verde Environmental, Inc., Houston, TX
OIL SPILL EATER II	NA/EA	Oil Spill Eater International Corp., Dallas, TX
OPPENHEIMER FORMULA	MC	Oppenheimer Biotechnology, Inc., Austin, TX
PRISTINE SEA II	MC	Marine Systems, Baton Rouge, LA
STEP ONE	MC	B & S Research, Inc., Embarrass, MN
SYSTEM E.T. 20	MC	Quantum Environmental Technologies, Inc., La Jolla, CA
VB591 WATER, VB997 SOIL, BINUTRIX	NA	BioNutraTech, Inc., Houston, TX
WMI-2000	MC	WMI International, Inc.

MC = Microbial Culture; EA = Enzyme Additive; NA = Nutrient Additive.

Laboratory efficacy does not reliably translate to field performance due to spatial heterogeneity, biological interactions, and climatic effects, making field trials essential. Notable nutrient products include Inipol EAP22 (urea, sodium laureth phosphate, and oleic acid; reduces emulsification and provides controlled N/P release; used in Prince William Sound) and Oil Spill Eater II (nitrogen, phosphorus, carbon, and vitamins). The EUREKA BIOREN trial showed that biosurfactant-containing BIOREN 1 outperformed BIOREN 2, indicating biosurfactant presence as the key active ingredient enhancing bioavailability and degradation rate.

MATERIALS AND METHODS

Materials Used in Remediation of Crude-Oil-Contaminated Soil

The materials used for remediation of crude-oil contaminated soil are disaggregated into: Biological, Chemical and Physical materials.

Biological: Bacterial genera (*Pseudomonas*, *Bacillus*, *Acinetobacter*, *Alcanivorax*, *Rhodococcus*, often as consortia) and fungi (white-rot species, *Aspergillus*, *Penicillium*) producing laccase and manganese peroxidase; NPK biostimulation agents; organic amendments/biocarriers (peanut hull powder, sawdust, rice-straw biochar, compost, manure); and phytoremediation species (ryegrass, alfalfa, tall fescue, maize, vetiver, *Mirabilis jalapa*).

Chemical: Oxidants (hydrogen peroxide, Fenton's reagent, persulfate, permanganate, ozone); surfactants/solvents for soil washing (SDS, saponin, rhamnolipid, ethanol-water); and solidifying/stabilizing agents (cement, lime, bentonite).

Physical: Natural sorbents (peat moss, straw, coconut coir, human hair); physical barriers (slurry walls, geomembranes); and thermal treatment, sometimes assisted by CaO or red mud.

Methods of Remediation of Crude-Polluted Soil

Remediation refers to treatments that restore contaminated soil/water and prevent or mitigate harm (Peter and Ayolagha, 2012; Ebuehi et al., 2005), offering faster recovery than natural attenuation.

Information Sources and Search Dates

Records were located through general academic web search covering, among others, ScienceDirect, SpringerLink, PubMed Central, and ResearchGate, together with citation-chasing from the reference lists of the retrieved papers (backward snowballing). The search was carried out on 26 September 2026. No date restriction was applied to publication year, since the aim was to locate every available primary study on these three specific amendments rather than only recent work; in practice, all bone-char and SPB primary studies located were published between 2013 and 2024.

Search Strings

Separate query sets were run for each amendment, combined with hydrocarbon- and soil-related terms: "bone char" AND ("crude oil" OR "petroleum hydrocarbon" OR TPH) AND (soil OR bioremediation OR biodegradation). ("spent palm bunch" OR "palm bunch" OR "empty fruit bunch" OR "oil palm empty bunch" OR "palm bunch ash") AND ("crude oil" OR hydrocarbon OR TPH) AND (soil OR bioremediation). NPK AND fertilizer AND ("crude oil" OR "petroleum hydrocarbon" OR TPH) AND (soil OR bioremediation OR biostimulation). (bone char OR "spent palm bunch") AND NPK AND (comparison OR "kinetic model" OR "half-life") AND soil

Eligibility Criteria

Records were included if they (i) applied bone char, palm-bunch-derived material (empty fruit bunch, palm bunch ash, or a palm-bunch-ash extract/stimulant), or NPK fertilizer as a soil amendment; (ii) targeted petroleum hydrocarbon, crude oil, or spent-oil-contaminated soil rather than a different contaminant class; and (iii) reported at least one quantitative outcome — hydrocarbon-fraction removal, TPH or THC concentration, a degradation rate constant or half-life, microbial count, or pH change. Records were excluded if they addressed bone char or palm-bunch material only in a non-hydrocarbon context (for example, fluoride adsorption from water, or agricultural soil fertility unrelated to contamination), if they were conference abstracts without extractable data, or if full outcome data could not be retrieved from the abstract, preview, or citing literature within the scope of this search.

Screening and Records Retained:

Title/abstract screening was applied to the records returned by the four query sets above; records meeting the eligibility criteria were retained for full-abstract or preview-level data extraction. Table 2 summarizes the outcome of this screening by amendment.

Table 3: Screening summary by amendment (Review, 2026)

Amendment	Records screened	Records meeting eligibility criteria	Notes
Bone char	~8	3	Includes one study by a co-author of this review (Okwonna and Otaraku, 2022) not cited in earlier drafts
Spent-palm-bunch / palm-bunch-derived	~7	3	Includes an earlier study by a co-author of this review (Otaraku and Anozie, 2013) not cited in earlier drafts
NPK	~10	4	Overlaps partly with organic-amendment comparison studies already present in the original draft
Direct multi-amendment comparison	—	1	Okwonna and Otaraku (2022): bone char vs NPK, same soil, same protocol

From Table 3, only one study places any two of the three named amendments side by side on the same soil under the same protocol, and none places all three together.

Data Extraction:

For each retained record, the following fields were extracted where reported: soil type and origin, hydrocarbon contaminant and its starting concentration, amendment identity and dose, experimental duration, microbial response variable(s) measured, the hydrocarbon-fraction or TPH/THC outcome reported, any soil-pH effect, and limitations stated by the original authors or evident from the study design. Fields not reported in the source are marked "NR" in Table 1 rather than estimated, so that the comparative table does not imply data that do not exist.

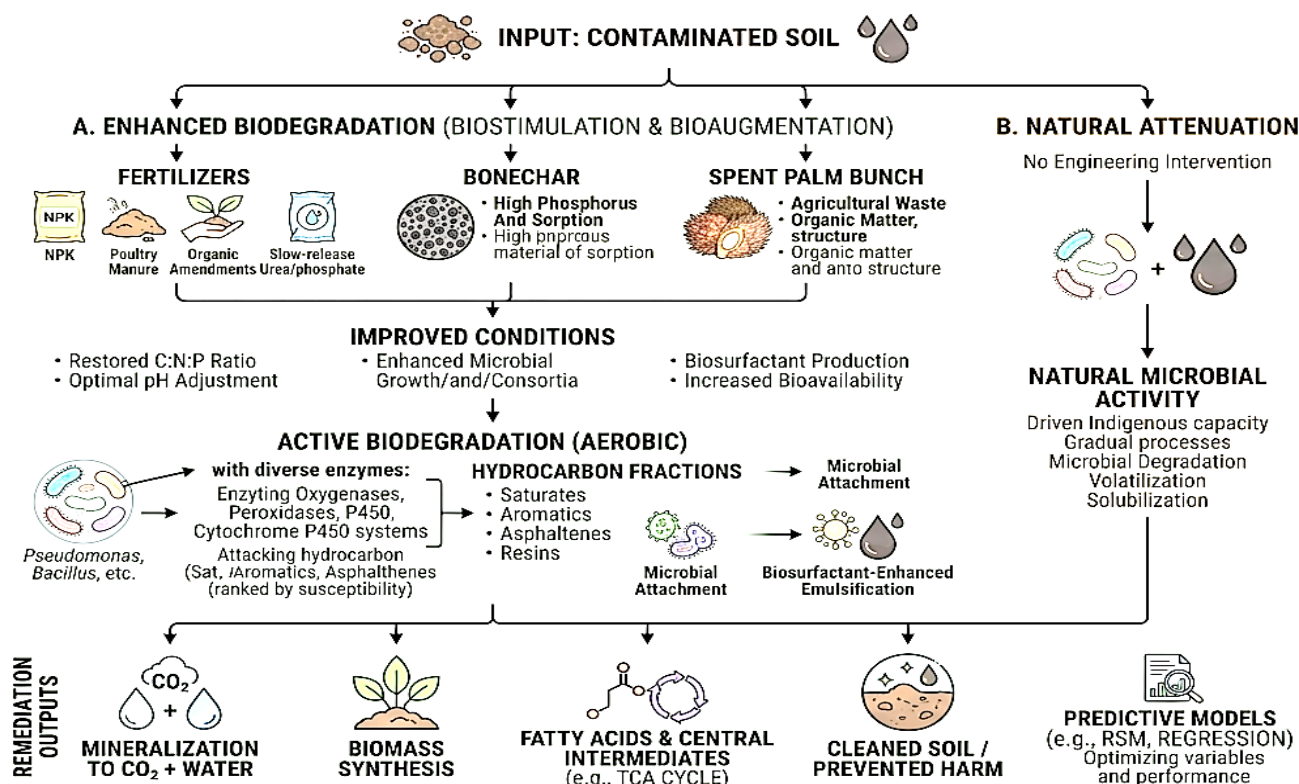


Figure 1: Diagrammatic Framework for Integrated Biodegradation of Hydrocarbon-Polluted Soil

Bioremediation Method

Bioremediation uses living organisms, native or introduced, to degrade pollutants, often at >60% cost savings over conventional treatment. It is widely applied to petroleum hydrocarbons, solvents, pesticides, and wood preservatives in soils, sludges, and groundwater (USEPA, 1994), typically via nutrient addition to stimulate indigenous organisms and/or inoculation with non-indigenous strains (Daniels and Thomas, 2009; Venosa, 2012). It is generally cost-effective relative to thermal desorption, incineration, chemical treatment, and pump-and-treat approaches (Atlas, 1995), though limitations include poor soil-contaminant contact, preferential flow paths, toxicity from heavy metals or high salt/chlorinated-organic loads, cold-temperature slowdown, and the need for groundwater management where mobility increases (Atlas, 1995). Historical accounts (e.g., the 1990 Gulf War oil spill recovery) illustrate the natural prevalence and resilience of hydrocarbon-degrading consortia (Atlas, 1995). Outcomes depend on contaminant type/concentration, depth, degree of environmental optimization, and technology.

Fertilizer Use in Bioremediation: NPK and organic fertilizers (bone char, palm bunch, poultry manure) have enhanced hydrocarbon degradation in Niger Delta soils, including restoring optimal carbon:nutrient ratios and pH (6.0–6.5) at oil-impacted sites in Owaza.

In-Situ Bioremediation: In-situ treatment avoids excavation costs but is harder to monitor and control than ex-situ methods (Daniel and Thomas, 2009; Khan et al., 2004; FRTR, 2000). Key techniques include:

Bioventing: Low-flow air injection stimulates aerobic degradation and volatilization of adsorbed hydrocarbons in the vadose zone; effective for petroleum hydrocarbons, non-chlorinated solvents, and wood preservatives, though limited by low soil permeability and moisture depletion. In use since the 1980s at over 1,000 sites.

Biostimulation: Addition of nutrients/electron acceptors to boost indigenous activity (Leung, 2012; Daniels and Thomas, 2009). A 16-month pilot found biostimulation reduced NAPL leachate by 19–31% versus untreated/oxidation controls. Cow dung as a nutrient source raised degradation to 62% versus 20% for controls over 70 days in mangrove soils; NPK reduced paraffin/isoprenoids by 40–60% within ten weeks (Chorom et al., 2010); combined NPK and nonionic surfactant achieved 67.2% TPH degradation (Agarry and Ogunleye, 2012).

Electroremediation: Uses low-voltage direct current to mobilize charged contaminants toward electrodes via electro-migration and electro-osmosis, effective for metals (Pb, Cd, Cu, Cr) and, to a lesser extent, organics (phenol, atrazine, PAHs) (Ribeiro et al., 2005; Maini et al., 2000).

Bioaugmentation: Addition of degrading microbial strains to supplement indigenous populations (Leung, 2012; Venosa, 2004; Daniels and Thomas, 2009), most effective where seed organisms can withstand competition and hostile conditions synergy (e.g., *Cyclocasticus* and *Alcanivorax borkumensis*) can enhance PAH degradation, while antagonism between species can reduce it.

Air Sparging / Biosparging: Pressurized air injected below the water table volatilizes and biodegrades contaminants, volatilization dominates early, biodegradation later.

Land Treatment: Periodic tilling of contaminated media using conventional farming equipment to aerate and stimulate degradation.

Phytoremediation (in situ context): Uses plants and rhizosphere microbes for extraction, stabilization, or volatilization of contaminants (USEPA, 1999/2000; White et al., 2012), including metal phytoextraction, rhizofiltration, phytostabilization, and phytovolatilization, and organic-pollutant metabolism of PCBs, TCE, and PAHs (Edema et al., 2010). Costs are substantially lower than excavation/incineration (\$162/m³ vs. \$810/m³; White et al., 2009).

Laboratory-optimized conditions often fail to translate to field performance, with contaminant half-lives 4–10 times longer in situ.

Ex-Situ Bioremediation: Ex-situ ("pump and treat") methods excavate contaminants into controlled environments, offering faster, more uniform treatment at higher cost (Leung, 2012; Daniels and Thomas, 2009). Techniques include landfarming (tilled lined beds with controlled moisture, aeration, pH, and amendments), biocells/biomounds (space-efficient covered units with aeration), composting (thermophilic, 54–65°C), and bioreactors (engineered tanks for water/air treatment).

Chemical Oxidation

In-situ chemical oxidation (ISCO) destroys organic contaminants via injected oxidants without material removal, offering rapid treatment (weeks rather than years) but at higher cost and with non-selective reactivity (Karpenko et al., 2009). Key oxidants: **Hydrogen peroxide/Fenton's Reagent:** Reacts rapidly with organic contaminants and ferrous iron under low pH (2–4); fast but costly (Karpenko et al., 2009). **Permanganate:** Effective across a wide pH range but weaker than peroxide and ineffective against benzene; can cause MnO₂ precipitate plugging. **Ozone:** Strong oxidant (approximately 1.2× peroxide's potential) requiring on-site generation and closely spaced injection points (Karpenko et al., 2009). **Sodium Persulfate:** Thermally/iron-activated to form sulfate radicals (oxidation potential 2.6V, exceeding hydroxyl, permanganate, and ozone), applied at over sixty sites for chlorinated and petroleum hydrocarbons.

Natural Attenuation: Natural attenuation relies on indigenous microbial capacity without engineering intervention, driven by microbial degradation, volatilization, and solubilization. Favorable conditions include year-round groundwater flow, adequate electron acceptors/nutrients, and absence of toxicants. Indigenous populations can increase substantially within 24 – 48 hours of hydrocarbon exposure (Daniels and Thomas, 2009); hydrocarbon-degrader proportions typically rise from <1% to approximately 10% of the community following contamination (Atlas, 1995).

Bioremediation of Hydrocarbon-Polluted Soil: Process Overview

Contaminated soil poses hazards through volatilization, plant uptake, leaching, chemical reaction, microbial breakdown, and food-chain transfer. Both indigenous hydrocarbon-utilizing bacteria (HUB) and genetically engineered strains are used; the basic process, microbial consumption, conversion to fatty acids, and eventual mineralization to CO₂ and water is mediated primarily by genera such as *Pseudomonas*, *Bacillus*, *Serratia*, and *Micrococcus*. Physicochemical and biological soil factors jointly govern decomposition, and lignin-decomposing white-rot fungi show notable capacity to transform recalcitrant PAHs (Barr and Aust, 1984), while low nutrients, low moisture, and alkaline pH constrain degradation (Aislabie et al., 1998). Refinery sludges, rich in aliphatic and cyclic/aromatic hydrocarbons, represent a particularly recalcitrant waste stream (Baheri and Sami, 2001).

Bone Char

The most directly relevant bone-char evidence is Okwonna and Otaraku (2022), which applied bone char in situ to petroleum-hydrocarbon-contaminated soil over an eight-week trial, using 0.5–3.5 kg of amendment across separate treatment plots. A first-order kinetic model was fitted to both total hydrocarbon content (THC) and total organic carbon (TOC) decay to obtain a degradation rate constant and half-life for each, and total bacterial count, hydrocarbon-utilizing bacteria, and hydrocarbon-utilizing fungi were tracked in parallel across the same plots. Treated soil differed significantly from untreated control ($p < 0.05$), establishing that bone char is an effective biostimulant on this soil, though the study does not report a standalone bone-char pH trajectory distinct from the treated-versus-control THC/TOC comparison.

The clearest quantitative benchmark for bone char's relative effectiveness comes from Amin and Zahran (2024), an incubation study that is not Niger Delta soil and not crude oil — it uses artificially spent-engine-oil-contaminated soil, but that is the only identified study placing bone char alongside other carbon amendments

under one protocol. At a 3% w/w dose, bone char, banana-leaf biochar, wood-chip biochar, and zeolite were compared against an unamended control over a full incubation-to-second-order-kinetics cycle. Effectiveness ranked banana-leaf biochar above bone char, which ranked above wood-chip biochar, control, and zeolite in that order; expressed as second-order half-lives, control soil carried a 4.0-year half-life, zeolite-amended soil 5.3 years, bone-char-amended soil 2.7 years, banana-biochar-amended soil 1.0 year, and wood-chip-biochar-amended soil 3.6 years. Bone char therefore roughly halved the TPH half-life relative to no amendment in this system, while underperforming a lignocellulosic biochar of comparable dose, a finding this review's comparative frame makes visible precisely because the source study included a like-for-like alternative amendment, which most single-amendment Niger Delta field trials do not.

Baniviga et al. (2019) is an adjacent rather than a pure bone-char study: it optimizes the proportion of cow dung to cow bone char in combination, rather than testing bone char alone against a control, and is included in Table 1 to flag that most bone-char field applications in the Nigerian literature are combined with an organic co-amendment rather than deployed as a single input.

Spent-Palm-Bunch (SPB) and Palm-Bunch-Derived Amendments

The oldest of the three amendment literatures traced here is Otaraku and Anozie (2013), which used empty oil palm bunch (OPEB) to remediate crude-oil-polluted soil across two field plots, monitoring hydrocarbon content weekly and fitting regression models to the resulting time series. This is the direct antecedent of the "SPB" material named in the present review's title, though the 2013 study used whole empty fruit bunch rather than the ash or aqueous extract forms tested more recently.

Two more recent studies work with processed palm-bunch material rather than the whole bunch. Abonyi et al. (2022) derived a "palm bunch enhanced stimulant" from palm-bunch ash, characterized by an appreciable phosphate, sulphate, and nitrate content that the authors argue makes it both a bulking agent and a nutrient source for crude-oil-degrading microbes, and fitted kinetic and half-life models to the resulting bioremediation. Udo et al. (2021) combined palm bunch ash with the nonionic surfactant Tween 80 to remove TPH from crude-oil-polluted arable soil, reporting removal efficiency and kinetics for the combined treatment rather than for palm bunch ash alone, which limits how cleanly its result isolates the amendment's standalone contribution. Across all three SPB-family studies, the common finding is that palm-bunch-derived material supplies nutrients and bulking/sorption capacity simultaneously, mirroring bone char's dual carbon-plus-nutrient action, but none of the three reports a microbial count alongside the hydrocarbon outcome, which is a gap Table 1 marks explicitly.

NPK (Inorganic) Fertilizer

NPK is the amendment with the largest number of quantitative outcomes in the literature located here, though most report it as one arm of a multi-treatment comparison rather than in isolation. Chorom et al. (2010) found that NPK fertilizer reduced the paraffin and isoprenoid indices of crude-oil-polluted soil by 40–60% within ten weeks. Agarry and Ogunleye (2012) combined NPK with a nonionic surfactant and reported 67.2% TPH degradation, again a combined rather than NPK-alone figure. A biostimulation comparison summarized in a 2023 review (PMC9921818) reports NPK (20:10:10) alone achieving 86% TPH biodegradation against a 4% natural-attenuation control, with a combined spent-mushroom-and-water-hyacinth compost treatment reaching 89%, the largest single-amendment NPK figure identified, and one that puts NPK's ceiling performance close to that of organic compost under favorable conditions. Rahman et al. (2003) is adjacent rather than a pure NPK study: it combines poultry litter, coir pith, and rhamnolipid biosurfactant, and is retained in Table 1 to mark how frequently NPK-family nitrogen sources are tested only in combination with an organic or surfactant co-amendment, the same pattern noted for bone char.

The Owaza-area finding already present that NPK and organic fertilizers, including bone char and palm bunch, restored soil pH to 6.0–6.5 at oil-impacted Niger Delta sites, is consistent with, but not identical to, the Okwonna and Otaraku (2022) trial discussed the two should not be treated as the same dataset without confirming they report the same field site.

Direct Head-to-Head Comparison: Bone Char versus NPK

Okwonna and Otaraku (2022) is, to the extent this search identified, the only study that places two of this review's three named amendments on the same contaminated soil, under the same eight-week protocol, with the same THC/TOC/microbial-count outcome measures. Both bone char and NPK produced a statistically significant reduction in THC and TOC relative to the untreated control ($p < 0.05$). The published abstract-level data available for this review does not, however, report a direct statistical test of bone char against NPK, only each against the control, so this review cannot state, on the evidence retrieved, whether bone char and NPK differ significantly from each other on this soil; that comparison would need to be confirmed from the full text of the paper, which one of this manuscript's own co-authors can supply. This is precisely the comparative gap Section 6 identifies as the review's central finding: even the one study built for a head-to-head test does not, on the evidence extracted here, settle the amendment-versus-amendment question, and no study was found that extends the same design to SPB.

Comparative Summary Table

Table 4 and Figure 2 consolidates on the eight comparative axes specified for this review: soil type, hydrocarbon concentration, amendment dose, experimental duration, microbial response, TPH/hydrocarbon-fraction outcome, pH effect, and major limitations. Entries marked "NR" indicate the field was not reported in the source rather than that no effect occurred.

Table 4: Comparative summary of bone char, spent-palm bunch (SPB), and NPK studies in hydrocarbon-contaminated soil, extracted against eight comparison axes

Study	Amendment / Soil type	Hydrocarbon & starting concentration	Amendment dose / Duration	Microbial response	TPH / Hydrocarbon-fraction outcome	Major limitations
Okwonna & Otaraku (2022)	Bone char / In-situ petroleum-hydrocarbon-contaminated soil, Niger Delta context	Petroleum hydrocarbon sludge; starting concentration NR in extracted data	0.5–3.5 kg per plot, separate experiments / 8 weeks	Total bacterial count, hydrocarbon-utilizing bacteria and fungi tracked; direction of change NR	First-order THC and TOC decay; treated vs. control significant at $p < 0.05$; rate constant/half-life reported but NR here	Single in-situ site; no reported statistical test of bone char vs. NPK directly; short 8-week window for a slow-degrading fraction
Amin & Zahran (2024)	Bone char / Artificial spent-engine-oil-contaminated soil, ex-situ incubation	Spent engine oil, not crude oil; starting concentration NR in extracted data	3% w/w / Full incubation to second-order kinetic endpoint	Not measured; CO ₂ -C emission tracked instead of microbial counts	TPHC second-order half-life: 2.7 yr (bone char) vs. 4.0 yr (control) vs. 1.0 yr (banana-leaf biochar)	Contaminant is spent engine oil, not crude oil; ex-situ artificial soil; no microbial data; bone char outperformed by lignocellulosic biochar

						comparator
Baniviga et al. (2019)	Bone char + cow dung / Crude-oil-polluted soil	Crude oil; starting concentration NR in extracted data	Cow dung;bone char ratio NR / Duration NR	NR in extracted data	NR in extracted data; optimization endpoint rather than a single removal percentage	Combination study; does not isolate bone-char-alone effect
Otaraku & Anozie (2013)	Crude oil + SPB (empty oil palm bunch) / Polluted field soil, two plots (A, B)	Crude oil; starting concentration NR in extracted data	Whole OPEB material; dose NR / Weekly monitoring over field-trial period	Not measured	Weekly hydrocarbon-content decline fitted by regression; specific % removal NR	No microbial data; regression rather than mechanistic kinetic model; older SPB study and less directly comparable to newer ash/extract forms
Abonyi et al. (2022)	Palm-bunch-ash “enhanced stimulant” / Crude-oil-contaminated soil	Crude oil; starting concentration NR in extracted data	Palm-bunch-ash-derived extract; dose NR / Duration NR	Not measured	Kinetic model and half-life fitted; specific % removal NR	No microbial data; positioned as a dispersant /stimulant, so mechanism may involve physical bulking as well as nutrient effects
Udo et al. (2021)	Palm bunch ash + Tween 80 / Crude-oil-polluted arable soil	Crude oil; starting concentration NR in extracted data	Palm bunch ash + Tween 80 surfactant; doses NR / Duration NR	Not measured	TPH removal efficiency and kinetics reported for combined treatment	Combined with surfactant; does not isolate palm-bunch-ash-alone effect
Chorom et al. (2010)	NPK / Crude-oil-polluted soil	Crude oil; starting concentration NR in extracted data	NPK fertilizer; dose NR / 10 weeks	NR in extracted data	Paraffin/isoprenoid indices reduced by 40–60%	Uses paraffin/isoprenoid indices rather than direct TPH; dose not specified in extracted data
Agarry & Ogunleye (2012)	NPK + surfactant / Soil contaminated	Crude oil; starting concentration NR in	NPK + nonionic surfactant; doses NR /	NR in extracted data	67.2% TPH degradation with combined treatment	Combined with surfactant; does not

	with crude oil	extracted data	Duration NR			isolate NPK-alone effect
Okwonna & Otaraku (2022)	Bone char vs. NPK / Same in-situ petroleum-hydrocarbon-contaminated soil, Niger Delta context	Petroleum hydrocarbon sludge; starting concentration NR in extracted data	0.5–3.5 kg per plot; each amendment tested separately / 8 weeks	TBC, HUB and HUF tracked for both amendments	Both bone char and NPK significantly different from control ($p < 0.05$); bone-char-vs-NPK statistical comparison not confirmed in extracted data	Only identified two-amendment head-to-head comparison; does not extend to SPB; direct bone-char-vs-NPK contrast not confirmed from abstract-level data

From Table 1, we examine across amendments rather than down single rows, shows duration, reported precisely only for the bone-char and NPK studies (8 and 10 weeks respectively), which are similar enough to be compared, whereas the SPB studies report weekly monitoring without a stated total duration, a reporting gap, not necessarily a shorter trial. Microbial response is tracked in both bone-char studies but in none of the SPB or single-amendment NPK studies located here, which means the mechanistic claim that SPB "produces biosurfactants" or "upregulates catabolic enzymes" made in this review's original abstract is not yet supported by microbial data from an SPB-specific trial, only inferred from the general enzymology of Section 3.2 and from organic-amendment studies using other carbon sources. Dose is reported in comparable units (kg per plot) only for the two bone-char/NPK trials from the same research group; the SPB and most NPK studies report dose in units that cannot currently be normalized against each other. See Figure 2.

PHYSICOCHEMICAL PROPERTIES OF SOIL

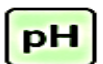


Soil Type & Texture

- Particle Size, Coarse vs. Fine

Sorption to Soil Colloids

- Limited bioavailability – continuous colloids:



pH

- Optimal Range (5.0–8.0)
- Heterotrophic bacteria favor neutral, fungi favor acidic



TEMPERATURE

- Optimal (15°C–40°C depending on system)
- Psychrophilic degraders exist
- Low Temp delays onset/increases viscosity



NUTRIENTS (N, P, K)

- Carbon:Nutrient Limitation
- Optimal C:N Ratio (2–200)
- Field C:N:P 100:3.25:0.75



OXYGEN & MOISTURE

- Aerobic is most rapid
- Oxygen as electron sink
- Optimal Moisture (~50–80% WHC)



HYDROCARBON CHARACTERISTICS

- Molecular Weight, Ring Number, Structure
- Recalcitrance: n-alkanes < Branched < Aromatics < Cyclics < Asphaltenes



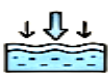
BIOAVAILABILITY

- Contaminant accessible fraction
- Restricted by hydrophobicity, solubility, sorption
- Enhanced by surfactants



INDIGENOUS MICROBIAL CAPACITY

- Adapts to contamination
- Increases from <1% to ~10% or more
- Presence often limits rate more than organism absence



SALINITY

- Elevated salinity causes stress
- Halophilic/halotolerant strains active

Figure 2: Governing Factors Affecting Biodegradation Rate

Remediation Efficiency

Efficiency varies by contaminant, method, and site conditions. Biological methods can reach 95–97% (rhamnolipids with nutrients), 93% (DNA-diagnosis-guided bioslurping), up to 100% (landfarming under favorable conditions), and 80% (fungal laccase bioaugmentation). Physical methods include microwave heating (approximately 90%) and thermal desorption (high efficiency but energy-intensive, degrades soil organic matter); radiofrequency heating can cut remediation time substantially. Chemical methods range widely: zero-valent-iron-activated persulfate (62–83% in 104 days), surfactant-aided soil flushing (approximately 53%), and Fenton's reagent (89–99%), with potential ecological trade-offs requiring careful management. Combined methods (e.g., soil washing with ozonation and biological treatment) can achieve high efficiencies, while electrokinetic-thermal combinations show moderate cost/complexity/effectiveness. Overall, contaminant type, method selection, soil properties, and environmental impact jointly determine outcomes.

Model Development and Output

Equations Governing Bioremediation: Bioremediation is modeled through coupled nonlinear partial differential equations describing fluid flow (Darcy's Law and mass conservation), contaminant/nutrient transport (advection, dispersion, sorption), biodegradation kinetics (commonly Monod or first-order kinetics), and biomass dynamics (growth, decay, and bio-clogging effects on porosity/hydraulic conductivity). A representative one-dimensional saturated-zone system includes:

Contaminant transport/degradation: relates substrate concentration change to retardation, porosity, advective velocity, dispersion, and degradation rate.

Nutrient transport/consumption: parallels the contaminant equation with a microbially linked consumption term.

Biomass growth/decay: tracks microbial concentration via growth and first-order decay, referenced against background indigenous biomass.

These systems are typically solved numerically (e.g., finite difference methods) under site-specific initial and boundary conditions. The mathematical model, often a quadratic polynomial regression model, which relates the independent variables (e.g., pH, N:P ratio) to the desired responses (e.g., percentage of TPH degraded, plant growth). A general form of the model equation is:

$$Y = \alpha^0 + \sum \alpha_i X_i + \sum \alpha_{ii} X_i^2 + \sum \alpha_{ij} X_i X_j + \epsilon \quad (1)$$

Where,

Y is the response,

X_i and X_j are the independent variables

α are the regression coefficient, and

ϵ is the model error

The software uses statistical analysis (like ANOVA) to determine the significance of each factor and their interactions.

Optimization and Validation: The primary utility of the Design-Expert model is its ability to predict the optimum point the ideal combination of all variables that yields the highest TPH degradation efficiency. Researchers validate the model's accuracy by conducting a physical laboratory experiment at the predicted optimal conditions. For comparison between the predicted and experimental results confirms the efficacy of the developed model, which can then be used as a reliable predictive tool for future applications or

up-scaling.

According to Honga et. al., (2023), the research modeled how pH affects biochar mix remediation of crude oil-polluted soil. Remediation decreased total petroleum hydrocarbons (TPH). The biochar blends PL-500, pW-500, and RS-400 were made by pyrolyzing poultry litter, pine wood, and rice straw at varied temperatures and times. Crude oil tainted soil pH was 4.72. Response surface experimental design mixed biochars to remediate TPH. Following 30 days of bioremediation, 15g PL-500, 6g RS-400, and 3g PW-500 removed a maximum of 46% TPH. The experimental data were statistically modeled and optimized using design expert software and response surface methods. Analysis of variance was used to determine the significance of each regression coefficient (ANOVA). Biochar mix improved soil pH to 6.9 following remediation. ANOVA indicated that PL-500 was significant for predicting TPH % degradation at $P = 0.0290$, suggesting that its high pH, nutrient, and soil water conservation values make it more effective at eradicating TPH.

A. Response Surface Methodology (RSM): Response Surface Methodology (RSM) is a statistical method used to optimize the processes for cleaning up crude oil-contaminated soil. It uses a series of experiments to find the most effective combination of variables, such as temperature, time, nutrient concentration, or pH, to maximize the desired outcome, like the removal of hydrocarbons. The results of these experiments are used to build a mathematical model, which predicts the optimal conditions and allows for a limited number of experiments to be performed, making the process efficient. How RSM is applied;

- i. Experimental design: RSM uses designs like Central Composite Design (CCD) or Box-Behnken Design (BBD) to systematically study the effects of multiple variables on the remediation process.
- ii. Variable identification: Researchers identify the key variables that affect the remediation outcome. These could include:
 - a. For physical extraction: Temperature, extraction time, water flow rate, or solvent type.
 - b. For bioremediation: Nutrient concentration (e.g., nitrogen), pH, dispersant addition, or bacterial dosage.
- iii. Mathematical modeling: After conducting experiments, the data is used to create a mathematical model, often a quadratic equation, that represents the relationship between the variables and the response (e.g., hydrocarbon removal efficiency).
- iv. Optimization: The model is used to find the combination of variables that yields the best results. For example, a temperature of 250°C with extraction time of 120 minutes, and water flow rate of 1 mL/min were optimal for crude oil removal and recovery.
- v. Validation: An additional experiment is performed using the predicted optimal conditions to confirm that the model's predictions are accurate.

Benefits of using RSM

Efficiency: It requires fewer experiments compared to traditional one-factor-at-a-time methods, which saves time and resources.

Interaction analysis: It can reveal how different variables interact with each other to affect the outcome.

Accurate prediction: It provides a predictive model that can be used to optimize the process and achieve a desired response.

B. Regression models: Regression models are used to predict outcomes in crude oil-contaminated soil, such as the rate of bioremediation, depletion of specific nutrients like potassium, or changes in soil properties like pH. These models are often developed using experimental data and can be either linear or more complex

(like polynomial regression) to capture the relationships between variables such as oil concentration, incubation time, and microbial activity.

Contaminant Degradation: Additional Process Factors

Degradation speed depends on contaminant type, oxygen, moisture, nutrients, pH, temperature, bioavailability, concentration, and toxicant presence (Atlas, 1995). Anaerobic conditions can degrade chlorinated compounds, sometimes requiring subsequent aerobic polishing; agro-industrial sludge amendment (as in landfarming) supports degradation by supplying nutrients (Atlas, 1995). Temperature strongly affects microbial activity and contaminant solubility, while oxygen supply governs aerobic breakdown rate (Atlas, 1995); biosparging is generally more effective than bioventing in low-permeability, saturated soils. Hydrogen peroxide supplementation can compensate for low oxygen availability but risks bactericidal effects in excess weathering reduces bioavailability of high-molecular-weight residues, though tailored fertilizers can accelerate degradation of these fractions. Biostimulation (nutrient addition) and bioaugmentation (high-density inoculation) both aim to accelerate degradation under controlled conditions in microbe-rich tropical soils such as the Niger Delta, biostimulation alone is often sufficient, and fertilizer application plus tilling can match the effectiveness of combined bacterial inoculation and tilling.

Optimal nutrient ratios (C:N:P $\approx$ 100:10:4, or 25:1:0.5) are essential; excess C:N ratios (>25:1) deplete soil nitrogen and delay decomposition. Sorption/desorption of hydrophobic compounds requires time to equilibrate, and compounds sequestered in soil micropores become effectively unavailable to microbes (Alexander, 2005; Atlas and Betta, 1993). Remediation mechanisms include bioaccumulation, bio-stabilization, and bio-volatilization, and nutrient partitioning across floating, soluble, and sludge oil phases affects delivery strategy.

CONCLUSION

Microbial response data (bacterial and fungal counts) accompany the bone-char studies but not the SPB or single-amendment NPK studies located here, so claims about which amendment most strongly stimulates specific degrader taxa cannot yet be supported comparatively.

Amendment dose is reported in incommensurate units across studies (kg per plot, % w/w, unspecified extract concentration), preventing pooled dose-response analysis without new, common-unit trials.

No RSM or kinetic model located in this search includes amendment identity as an explicit factor; existing models optimize within one amendment's design space and cannot, by construction, test whether amendment choice itself is significant. Most NPK and several bone-char/SPB field results are reported only for combined treatments (amendment plus surfactant, or amendment plus a second organic input), which inflates apparent effectiveness figures relative to what any one amendment could achieve alone.

A genuinely comparative evidence base for bone char, SPB, and NPK in Niger Delta hydrocarbon remediation would require a single multi-arm field trial, ideally the natural next step for the Okwonna and Otaraku (2022) research line, given that group's existing bone-char-versus-NPK design, that adds an SPB arm, reports dose in a common unit, tracks the same microbial and pH variables across all arms, and fits amendment identity as an explicit regression factor rather than as a fixed choice of which experiment to run. Until that trial exists, the honest state of the evidence, as this review's restructuring makes visible, is that bone char, SPB, and NPK are each independently effective against hydrocarbon-contaminated soil relative to no treatment, but the field cannot yet say which is more effective, under what conditions, or why.

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