Cost reduction strategies in the remediation of petroleum hydrocarbon contaminated soil [version 1; peer review: 2 approved]

Ismail B. Ahmed, Eucharia O. Nwaichi, Ejikeme Ugwoha, John N. Ugbebor, Samuel B. Arokoyu

Centre for Occupational Health, Safety and Environment, University of Port Harcourt, Choba, Nigeria
National Oil Spill Detection and Response Agency (NOSDRA), Abuja, Nigeria
Department of Biochemistry, University of Port Harcourt, Choba, Nigeria
Exchange & Linkage Programmes Unit, University of Port Harcourt, Choba, Nigeria
Department of Civil & Environmental Engineering, University of Port Harcourt, Choba, Nigeria
Centre for Research Management and Administration, University of Port Harcourt, Choba, Nigeria
Department of Geography and Environmental Management, University of Port Harcourt, Choba, Nigeria

First published: 08 Apr 2022, 5:21
https://doi.org/10.12688/openresafrica.13383.1

Abstract
Petroleum hydrocarbon spill on land pollutes soil and reduces its ecosystem. Hydrocarbon transport in the soil is aided by several biological, physical, and chemical processes. However, pore characteristics play a major role in the distribution within the soil matrix. Restoring land use after spills necessitates remediation using cost-effective technologies. Several remediation technologies have been demonstrated at different scales, and research is ongoing to improve their performances towards the reduction of treatment costs. The process of removing the contaminants in the soil is through one or a combination of containment, separation, and degradation methods under the influence of biological, physical, chemical, and electrically-dominated processes. Generally, performance improvement is achieved through the introduction of products/materials and/or energy. Nevertheless, the technologies can be categorized based on effectiveness period as short, medium, and long term. The treatment cost of short, medium, and long-term technologies are usually in the range of $39 – 331/t (tonne), $22 – 131/t, and $8 – 131/t, respectively. However, the total cost depends on other factors such as site location, capital cost, and permitting. This review compiles cost-saving strategies reported for different techniques used in remediating petroleum hydrocarbon polluted soil. We discuss the principles of contaminant removal, performance enhancing methods, and the cost-effectiveness analysis of selected technologies.

Open Peer Review

Approval Status

1. Mojisola Christiana Owoseni, Federal University of Lafia, Lafia, Nigeria
2. Chukwuma Ogbonnaya, The University of Manchester, Manchester, UK

Any reports and responses or comments on the article can be found at the end of the article.
Keywords
Petroleum hydrocarbon, soil remediation, treatment cost, contaminated soil, cost effectiveness

Corresponding author: Eucharia O. Nwaichi (nodullm@yahoo.com)

Author roles: Ahmed IB: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Writing – Original Draft Preparation; Nwaichi EO: Conceptualization, Funding Acquisition, Supervision, Validation, Writing – Review & Editing; Ugwoha E: Funding Acquisition, Resources, Supervision, Visualization; Ugbebor JN: Investigation, Project Administration, Resources; Arokoyu SB: Funding Acquisition, Methodology, Project Administration

Competing interests: No competing interests were disclosed.

Grant information: This work was supported by a grant from BW Offshore Nigeria Limited under Nigerian Content Research and Development. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Copyright: © 2022 Ahmed IB et al. This is an open access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

How to cite this article: Ahmed IB, Nwaichi EO, Ugwoha E et al. Cost reduction strategies in the remediation of petroleum hydrocarbon contaminated soil [version 1; peer review: 2 approved] Open Research Africa 2022, 5:21 https://doi.org/10.12688/openresafrica.13383.1

First published: 08 Apr 2022, 5:21 https://doi.org/10.12688/openresafrica.13383.1
Introduction

Onshore production of crude oil necessitates transportation of petroleum hydrocarbon across vast lands to loading terminals or facilities for further processing. The process of production, transportation, and processing had resulted in several spills either as a result of attacks on facilities or operational reasons, such as equipment failure. When an oil spill occurs on land, several natural processes are activated, and depending on prevailing environmental conditions, type of oil, spill volume, and soil type, hydrocarbons could percolate into the soil matrix and reach the groundwater. The migration of oil in the soil is also affected by physical processes such as volatilisation, adsorption, and dissolution in soil pore water. All these factors and time to human intervention determines the extent of the impact on the soil.

Oil spills intensify rapid depletion of nutrients in the soil, thereby rendering it infertile for agricultural purposes. It also affects the biodiversity of microorganisms in such a way that only tolerant ones are present after the spill. Oil coats surfaces, so limiting gas and moisture transport across plants. Likewise, the plant is starved of nutrient uptake due to the unfavourable C/N ratio induced by oil. This could stress the plant and possibly lead to its death. Human exposure to oil spill contaminants has been reported to have caused lung diseases, cancer, and skin problems. Furthermore, run-off from contaminated areas could transport contaminants to nearby water bodies and serve as pathway through which aquatic animals are exposed. Studies have shown the accumulation of polycyclic aromatic hydrocarbons (PAH) in seafood species. Therefore, an intervention must be made in the form of soil remediation to minimise damage to the environment.

Several methods have been researched and/or implemented in the remediation of petroleum hydrocarbon polluted soil. While some are still at laboratory scale, there have been records of field applications at large scale. Soil remediation methods are categorised based on the contaminant removal approach and these include containment, separation, and degradation. Therefore, the choice of remediation technology is determined by other factors, including regulatory clean-up level, permitted time, and cost.

This review aims to compile cost-saving strategies reported for different techniques used in remediating petroleum hydrocarbon polluted soil. This was based on (1) principles of contaminant removal, (2) performance enhancement method, (3) and cost-effectiveness analysis of selected technologies.

Transport processes of spilled oil in soil

The cost of soil remediation from the impact of petroleum hydrocarbon is majorly dependent on the volume of the impacted soil and hydrocarbon content. These factors are in turn dependent on the volume of spill petroleum hydrocarbon and soil type. The fate of oil in the soil is described by various processes that are categorised as transport, mass transfer, and natural attenuation. Oil spill in unsaturated soil displaces air from pores and, depending on the connectivity of the pores and gravity head of oil, the migration continues until groundwater is encountered. While oil migration occurs both vertically and horizontally, vertical transport is faster. When a spill occurs, continuous transport towards the water table is determined by residual retentive capillary forces within soil pores and percolating oil volume head. Depending on the soil profile before the water table, less porous soil, such as clay, may be encountered, which retards downward migration of oil and forms a pool of free-phase oil. Within porous media that have experienced an oil spill, there may exist sections of residual hydrocarbon held by capillary force, discontinuous free phase within pores held by water films, or pool of free phase due to restricted migration by high capillary pore pressures.

The transport of oil is accompanied by other mechanisms, such as sorption, dispersion, volatilisation, dissolution, and biodegradation. Sorption of petroleum hydrocarbon to soil particles is influenced by organic matter content, and depending on the age of the spill, bioaccessibility could be hampered. Soluble fractions of petroleum hydrocarbon could dissolve in pore water and undergo diffusion and dispersion depending on the water flow. Volatilization of lighter fractions could cause vapour intrusion into nearby buildings or be locked up in soil pores, while biodegradation could occur with or without the presence of oxygen.

The method and cost of remediation are greatly dependent on the fate of petroleum hydrocarbon described by the transport, mass transfer, and natural attenuation mechanisms. This then requires thorough contaminated soil characterisation to identify the extent and content of petroleum contamination before clean-up or remediation is initiated.

Soil remediation technology selection factors

Arriving at the technology in decontaminating petroleum polluted soil involves considering several factors including remediation limit, duration, and cost.

Remediation limit

Petroleum facilities traverse several kilometres of land subjected to different uses, and spills at different areas may call for different remediation approaches. Ultimately, the remediation approach could depend on the contaminant level that threatens identified ecological receptors. All these factors are considered in determining the residual content of petroleum contaminant allowed within an area after a spill. The choice of remediation technology could be determined by the residual level. For remediation of soil contaminated by petroleum hydrocarbon, by Lien et al., have described that their choice of technology was guided by future land use, which eliminated the risk of receptor exposure through ingestion and dermal contact, which proffered a strategy based on vapour migration only. Duan et al. suggested that residual level may not be fixed based on total contaminant level but bioavailability, especially when dealing with aged soil contamination. Thavaman et al. further suggested that other soil physico-chemical parameters could impose toxicity on biota even if residual total petroleum hydrocarbons (TPH) do not, and caution is
necessary when fixing remediation limits based on toxicity. Stringent site-specific limits imposed in some sites, such as recreational areas, may warrant the use of technology that achieves a very high performance within a short time or complete removal and replacement of soil.

**Duration**

Current or intended land use of the spill area determines how soon the impacted area needs to be remediated, and hence influences the technology to be adopted. In urban areas with high commercial activities, soil replacement could be the best approach, while in remote rural areas with available land and limited activities, other technology, such as land farming, could be adopted. When time is a primary factor, the cost could play a role when several technologies can achieve remediation objectives within the allowable time.

**Cost**

Cost is of the essence in adopting remediation technology. However, this factor plays a role where several technologies are capable of achieving remediation level within the allotted time frame. Several factors determine the cost of remediation and these include treatment mode (in-situ or ex-situ), amendment type, energy input, post-remediation waste management, and equipment.

**Treatment mode.** The cost of excavation and backfilling of soil, as well as haulage between impacted sites and treatment centres, take a chunk of remediation cost if ex-situ is an option. However, this cost could be saved with in-situ approaches if effectiveness is guaranteed within the expected period. In-situ microwave heating was demonstrated to treat hydrocarbon polluted soil, and Falciglia et al. reported an energy cost of €18–27/tonne (t), however Nagkiri et al. documented $50–330/t for using ex-situ thermal desorption.

Depending on the site characteristics, most in-situ approaches, such as electrokinetic, bioventing, and soil flushing, could require the injection of enhancers. However, secondary contamination in groundwater has to be avoided, and if that is not guaranteed, ex-situ treatment is usually adopted. In most cases, ex-situ has more control over factors that enhance remediation to achieve a higher performance within a short period.

**Soil amendment.** Enhancement of remediation performance is usually done through the inclusion of products or energy that aids contaminant separation, fixation, or degradation. However, some remediation methods, such as bioventing, soil vapour extraction or thermal treatment, could proceed without soil amendment. Where an amendment is applied, the nature and cost of the product could increase the general cost of remediation. In the long run, the cost could be offset by increased performance and reduced duration of treatment. In bioremediation, several propriety products are in the market with varying costs. In a case study reported by Lehr, a consortium of hydrocarbon utilizing bacteria was employed in remediation of petroleum contaminated soil that was initially earmarked for incineration, and approx. $200,000 was saved after bioremediation. Different from propriety products, the use of organic amendments has also proved successful and cost-effective in soil remediation.

**Energy input.** The cost of providing energy to drive the remediation varies with the soil treatment method. The thermal approach of decontamination is considered energy-intensive due to elevated temperatures that need to be achieved for oil desorption and volatilisation. In aerobic bioremediation where air is needed for effective biodegradation, the energy input could be in form of air supply into the soil matrix within biopile or in-situ during bioventing. Other treatment energy input could be in operation of processing or soil handling equipment as well as man-hour. The cost of energy is usually covered under Operation and Maintenance.

**Post-remediation waste management.** Varying types and quantities of wastes are generated during soil remediation depending on the adopted method. Different wastes recorded in soil remediation include off-gas, wastewater, treatment residue, and other forms of industrial wastes. For example, a high volume of wastewater is generated during soil washing remediation, and it is passed through wastewater processes after the contaminated soil has been cleaned. Also, depending on the soil type handled by the soil washing technique, a significant sludge could be generated, and hence requires further treatment and disposal.

**Soil remediation technology**

Soil remediation takes place on or off-site, through in-situ or ex-situ technology. While in-situ is carried out on-site, ex-situ can be achieved on or off-site. Remediation is regarded on-site, where the impacted soil is decontaminated in position or excavated and treated in an adjoining land, cell or facility within the same site. However, off-site remediation involves excavation of contaminated soil and haul over a distance to a treatment facility.

As shown in Figure 1, remediation technology can be generally categorised in terms of method (containment, degradation, and separation) and dominant processes of decontamination (physical, chemical, biological, and electrical).

**Containment**

**Stabilization and solidification.** Containment involves fixing the contaminant in place, thereby eliminating leaching or migration to receptors. Stabilization and solidification fall in this category, and these are mostly achieved ex-situ. However, the products are rarely returned for backfilling. They are diverted for other purposes such as bricks/concrete blocks, road construction, or landfilling. The operation always involves the physico-chemical process of mixing the contaminated media with other materials, such as binders and other additives, to ensure immobilization of the target contaminants.

In solidification and stabilization practice, the resulting solids must have minimum requirements to qualify them for different final disposal or applications. Crucial requirements include leachability, compressive strength and permeability.
Several binders and stabilizers have been used at different proportions to stabilize petroleum contaminated soil; however, the inclusion of industrial waste materials could be adjudged a low-cost method and waste recycling strategy. Furthermore, using the stabilized solids for different applications, such as civil construction, is an additional waste recycling strategy compared to landfills. Ahmad et al.\textsuperscript{32} compared the performance of two industrial waste materials, Cement Kiln Dust (CKD) and Limestone Powder (LP), in supplementing cementitious properties of Ordinary Portland Cement (OPC) to stabilize petroleum hydrocarbon contaminated sandy soil. All the proportions of CKD and LP added to 2.5% OPC resulted in permeability and heavy metal leachability below USEPA standard; however, CKD performed poorer than LP in unconfined compressive strength in not meeting USEPA standard of 340 kPa most especially at a hydrocarbon content above 5%. Considering the suitability of the stabilized material for road construction, LP supplements above 20% for up to 10% diesel contaminated sand displayed Unconfined Compressive Strength (UCS) > 1400 kPa, hence could be used as subbase materials for paved and unpaved roads. However, in the case of crude oil contamination, it would take 40% of LP supplement to produce stabilize material with UCS > 700 kPa that could be used as a subbase for only unpaved roads. Ahmad et al.\textsuperscript{32} revealed that the required type and proportions of cementitious materials are determined by the type and concentration of petroleum hydrocarbon in the contaminated soil.

\textbf{Phytostabilization.} Different from the physico-chemical approach of containment, there has been evidence of contaminant stabilization within the rhizosphere of plants employed for phytoremediation\textsuperscript{31}. This could be as a result of plant enzyme influencing the fixation of the contaminant with soil organic matter thereby hampering mobility and bioavailability\textsuperscript{35}. Phytostabilization is common with remediation of metal-polluted soil than petroleum hydrocarbon\textsuperscript{36,37}. Several phytoremediation studies reported a decrease in TPH within the soil rather than concentrating and fixing it within the soil matrix\textsuperscript{35,36}.

\textbf{Separation} Separation is achieved when petroleum hydrocarbon contaminants are desorbed from soil through a biological, physical, chemical or electrical process. In some situations, further recovery and treatment could be initiated.

\textbf{Thermal treatment.} Thermal desorption technology (TDT) achieves soil decontamination through heat application to facilitate desorption and volatilisation of petroleum hydrocarbon constituents, which are then carried in a stream of sweep gas. The removal efficiency of TDT has been largely dependent on temperature and residence time\textsuperscript{39,40}. Other factors include heating rate, initial contaminant concentration and sweep gas flow rate\textsuperscript{29}. Due to the binding potential of different soil types, desorption temperature could also be varied for different soils. Leontari \textit{et al.}\textsuperscript{39} treated petroleum contaminated soil with thermal desorption technology at a varying temperature from 60 to 250°C for 10 and 30 minutes. The study recorded about 94% TPH reduction after residence time of 30 minutes at 250°C, while about 13% TPH reduction was achieved at 100°C at the same time range. However, 10 minutes of holding time recorded less TPH reduction with pronounced difference observed at the higher temperature.

Aside from modification of operational parameters, improved contaminant desorption by the inclusion of additives has been shown to have increased removal efficiency\textsuperscript{41}. Chen \textit{et al.}\textsuperscript{42}
demonstrated the influence of eggshell and plant ash on desorption efficiency during treatment of PAH contaminated soil by thermal desorption. The proportions of the additives varied from 2.5% to 20%, and the mixed soil was subjected to a temperature of 300°C at a residence time of 20 minutes with nitrogen as a carrier gas. Chen et al. reported the highest desorption efficiencies of 96.6% and 95.9% at 15% plant ash and 10% eggshell inclusion respectively. However, further increase in proportion resulted in reduced efficiency. The performances of the additives were attributed to their improved desorption characteristics, but their poor thermal conductivities contributed to reduced desorption efficiencies when proportions were above optimum.

The type and flow rate of carrier gases can affect the cost and performance of TDT. Carrier gas facilitates the transport of volatilized hydrocarbon from the soil compartment to off-gas treatment facilities. The common carrier gases in use are nitrogen and helium, but the presence of oxygen can influence the oxidation of hydrocarbon and in turn improve removal performance. Better still, the cost of running TDT may be offset by recycling desorbed volatile organic compounds (VOC) into the combustion chamber of the heating unit.

Performance of TDT has been reported based on removal efficiency without recourse to input energy. Considering offsetting of operational cost, off-gas recovery could be considered an option, provided the recovered gas has an economic value. Several off-gas treatment methods are reviewed by Zhao et al.

Also, the reuse of waste heat could be utilized for several heating purposes.

**Soil washing.** Soil washing achieves contaminant separation through solvent interaction with contaminated soil particles. Depending on the solvent used, desorption is initiated and followed by dissolution or flotation for further recovery or treatment of effluent. Soil washing is done *ex-situ* in a facility, while wash liquid is properly contained and treated before being discharged or recycled. The performance of this technology is influenced by various factors: soil type, initial contaminant concentration, residence time, type of solvent, and mode of treatment. This method is suitable for sandy or gravel dominated soil, which has less clay/silt and organic matter. However, Li et al. has reported up to 86% removal performance for illite clay while chlorite dominated clay has a poor removal performance of about 13%. There is a general opinion that bench-scale setup precedes field application to identify the best surfactant for a targeted polluted soil towards cost-saving and achievement of better performance.

Several surfactants have been applied in soil washing technology and they are grouped as cationic, anionic, nonionic, and mixed. However, a mixed surfactant that contains anionic and non-ionic properties have been adjudged better in achieving higher removal performance because of high mixed micelles. Operational cost recovery is largely covered by hydrocarbon separation or degradation from wash liquid to achieve recyclable solvent. In a field application of soil washing to remediate 24,620 m³ contaminated soil having an initial TPH of 65,756 mg/kg, Kang et al. reported reuse of water-based wash liquid after passing through treatment made-up of sedimentation, oil/water separator, air floatation, and activated carbon adsorption. In another field application, reported by Iturbe et al., water-based surfactant, TW80, was added to water at 0.5% to wash excavated contaminated soil from decommissioned petroleum product distribution and storage site. Rather than ordinary water, TW80 dissolves the petroleum hydrocarbon at every wash. However, the wash water was treated with FeCl₃ to aid flocculation and sedimentation of surfactant. The treated water was further returned to the plant for further washing. There had been other reports of hydrocarbon degradation from used surfactant, thereby promoting reuse and increase in overall performance per volume of surfactant.

Rather than dissolution, mobilization and recovery of petroleum hydrocarbon were demonstrated by Wilton et al. through the use of biopolymer and polystyrene foam pellets (PF) as mobilizers and recovery agents, respectively. 25 mL (1% biopolymer) solvent and 300 mg of PF were mixed with 20 mg contaminated soil and agitated at 200 rpm at 22°C for 30 minutes, after which the floating PF was skimmed off. Wilton et al. reported higher TPH removal efficiency of 94% at this combination compared to 58% achieved when water and PF were used. Furthermore, the authors suggested cost recovery could be achieved by using the recovered PF as fuel. Also, the biopolymer was derived from plants, while PF was made from recycled material, hence making the method cost-effective.

**Phytextraction.** In a plant assisted contaminant separation, phytextraction describes the translocation of soil contaminants such as petroleum hydrocarbon to the above-ground parts. The accumulation of the contaminants may occur in the stem and becomes part of plant tissue structure or volatilised through the leaves’ stomata. The latter is referred to as phytovolatilization and various volatile organic compounds could be removed from soil through this process. However, integrating contaminant in plant tissue is called phytoaccumulation, and heavier hydrocarbon such as PAH has been reportedly removed through this process. Nwaihi et al. studied phytoremediation of crude oil contaminated soil using four different plant species for 90 days. The effect of two soil amendments (cow dung and NPK fertilizer) was also tested. The authors reported improved PAH removal (>80%) from all planted soil. However, amended soil recorded higher removals. Nwaihi et al. identified plant uptake as one of the removal mechanisms, though soil amendments significantly hampered PAH accumulated by the plants.

Transplanting of plants from one contaminated site to another may be possible provided the accumulation capacity of the plant has not been exhausted. However, plants for phytovolatilization and other processes of phyto remediation could be transplanted across several contaminated media without being stressed as long as toxicity level is not exceeded. Ayuba et al. reported that the initial concentration of TPH in the soil did not record a significant difference in bioaccumulated content during phyto remediation of crude oil impacted soil. Also, Liao et al. detected lighter PAH in maize tissue during phyto remediation.
of crude oil polluted soil, and that the level did not increase with crude oil content in the soil. Possibly transplanting from light impacted soil to heavier impacted soil may not record significant improvement in bioaccumulation, but this requires further study.

Petroleum hydrocarbon constituent accumulation in plants has been established in the literature and is comprehensively reviewed by Hunt et al. However, evidence of bioaccumulation in animal or human tissue through the ingestion of plants is limited. Therefore, plant recycling by turning it to animal feed may be more sustainable than other conventional treatment, except it has established that petroleum hydrocarbon contaminants could be transmitted up the food chain. Open burning may also not be appropriate because of evidence of PAH release into the soil after bush burning.

**Electrokinetic.** Electrokinetic technology involves the introduction of direct current through electrodes into contaminated soil to induce transport of charged particles and/or soil fluid towards electrodes. The transport of soil fluid facilitates contaminant desorption and migration to the cathode in a process called electroosmosis. However, the removal of hydrophobic constituents of petroleum hydrocarbon is improved by the introduction of surfactant that is capable of solubilizing or aiding desorption of the constituents. This is one of the strategies of improving electrokinetic performance in remediating petroleum hydrocarbon polluted soil. Other strategies for improved contaminant removal include electrode type and spacing, applied potential difference, polarity switching, and source of energy. Gidudu and Chirwa carried out lab-scale electrokinetic remediation to compare the influence of electrode spacing, voltage supplied, and presence of biosurfactant on oil removal performance from contaminated soil. The authors experimented with 30V and 10V at electrode spacing of 185 and 335 mm arranged in soils contaminated with lubricating oil. In addition, each setup was with or without a biosurfactant. The combined application of 30V, 185 mm electrode spacing and biosurfactant recorded a higher oil recovery of 75%. However, this was achieved at the expense of an increased number of electrodes and energy consumption. Gidudu and Chirwa justified the choice of adopting the 30 V and 185 mm configuration with increased performance that offsets the increased cost. Invariably this could disadvantage the period of remediation and time spent on site thereby reduces the amount spent on manpower and machinery. Detail review of electrode configurations to address pH problems and enhance petroleum hydrocarbon removal from contaminated soil can be found in Saini et al.

The mode of power supply in electrokinetic has also been reported to have enhanced contaminant removal. Asadolahfardi and Rezaee studied the impact of interrupted and continuous power supply on remediation efficiency of diesel contaminated soil. The researchers used sodium dodecyl sulphate and sodium sulphate as catholyte and anolyte respectively with graphite electrodes. The setup was operated with 1 and 2 V/cm continuously for 7 days, while the same voltages were also operated for 5 days followed by 2 days interruption, and then 2 days reconnection. Asadolahfardi and Rezaee reported enhanced removal performance of 57.6 and 63.86% at 1 and 2 V/cm, respectively, for interrupted power supply, while continuous supply recorded 52.48 and 58.62% at 1 and 2 V/cm, respectively. The authors attributed the higher performance of interrupted supply mode to re-equilibration at the solid-liquid interface during the power-off period, and this influenced more dissolution of the hydrocarbon.

**Degradation**

**Bioventing.** Bioventing is an *in-situ* bio-physical activity where air is pumped or injected in subsurface soil to enhance aerobic biodegradation of petroleum hydrocarbon. This technology involves the installation of wells that are terminated within the vadose zone, and the air is injected to enhance the biodegradation of petroleum constituents. The performance of contaminant biodegradation is dependent on other factors, such as available nutrients, distribution of contaminants, moisture content, permeability, and groundwater level. Preliminary site characterisation conducted by Dominguez et al. indicated that available nutrient in the soil was in the excess of what would be needed for effective biodegradation, and the only limiting condition was oxygen. In other studies, need for a nutrient supplement may be required to ensure abundance microbes for contaminant degradation. In a pilot-scale bioventing experiment conducted by Mosco and Zytnier, NH₄Cl was used as a source of nitrogen to stimulate indigenous microbes. Yang et al. conducted a lab-scale bioventing remediation to study effects of initial concentration, moisture content, CNP ratio, pore volume number, and venting mode on removal performance of diesel from contaminated soil. The authors reported that the driving factors of performance are in the order of: initial concentration, pore volume number, CNP ratio, and moisture content. However, the mode of venting (injection or pumping) recorded the least influence on the TPH removal. Yang et al. thereafter determined optimum condition for remediating contaminated soil of 40 mg diesel/ g soil as 20% field capacity, 100:20:1, and 4 v/v/day for moisture, C:N:P, and pore volume number, respectively.

The major factor that drives the budget of bioventing is the cost of energy to drive blowers or air pumps. Therefore, methods could be designed to minimize this cost. Dominguez et al. designed and implemented a device that injected air captured from the wind into bioventing wells. The device was able to supply air within the vadose zone to meet up with predetermined 5% O₂ utilization per day for effective biodegradation. This was adjudged to have contributed to 90% VOC reduction after the second month of the 15 months operation. The authors reported that the system could have gulped energy of 12,000 kWh/year from the grid if an electric power blower was used. It is a point to note that an adequate preliminary study is necessary to ensure available wind speed within the area will be enough to generate the air pressure required for injection into the wells considering the soil permeability. In addition to air presence, supply rate is also very important to minimize contaminant volatilization, which could increase the
cost of off-gas treatment or secondary air pollution. Khan and Zytnier reduced VOC loss from 2.5% to 0.03% of initial content when the flow rate was reduced from 0.75 mL/min to 0.40 mL/min.

**Bioaugmentation.** Bioaugmentation is a biological approach of degrading soil petroleum hydrocarbon through the inclusion of exogenous petroleum hydrocarbon degrading microbes (PHDM). This method has proved effective most especially where indigenous microbes are less abundant in achieving the targeted reduction within the allowed time frame. The PHDM are usually isolated from previous spill areas or oily waste dumps. Aside from the aforementioned, controlled culture do occur in the laboratory, where colonies of microbes from different sources such as waste treatment plants are treated with petroleum hydrocarbon, and the tolerant ones are isolated for further exposures.

The PHDM are added to the contaminated media through the inoculum and in some cases, the performance is enhanced by the addition of nutrients in form of fertilizers, or compost. However, there could be initial competition with indigenous microbes. A means of eliminating such competition was demonstrated by Leal et al. in the treatment of mature compost with diesel and allowed to stand for 21 days purposely to ensure an abundance of PHDM before mixing with diesel contaminated soil. Also, Nwankwegu and Onwosi suggested that immobilized PHDM on biocarriers has improved remediation performance and eliminates competition with indigenous microbes. Zhang et al. used biochar as a biocarrier in remediating soil contaminated with petroleum hydrocarbon. The authors recorded the highest TPH reduction of 26.85 g/kg in soil treated with immobilized PHDM, while sequential addition of PHDM and biochar resulted in a reduction of 20.74 g/kg. However, PHDM only recorded 17.68 g/kg reduction. The authors suggested that immobilized PHDM were more adapted within a short period and hence improved bioactivity.

Aside from growing and isolating PHDM before applying to contaminated soil, there have been records of direct treatment with animal manure, and in the course of acclimatization, some microbes die off due to petroleum hydrocarbon toxicity, while others adapted to the new source of carbon. This method could be considered low cost because the rigorous laboratory culturing and isolation is eliminated. However, the disadvantage of using animal manure include transportation difficulties, inability to store for a long time, and pathogen threat. In addressing the aforementioned, the manure and other organic wastes are stabilized through composting to derive compost rich in nutrients and microbes. This has been successfully utilized in soil bioremediation and yielded good performance.

**Biotostimulation.** Biotostimulation is a biochemical process of introducing limiting nutrients required by PHDM into the petroleum-contaminated soil for enhanced biodegradation. Several sources of nutrients have been developed and tested at different scales, and reportedly achieved higher TPH degradation compared to natural attenuation. Spill areas that consist of indigenous microbes would require microbial stimulants to sustain growth towards enhanced hydrocarbon removal. Soil characterisation would reveal limiting nutrient that needs to be supplemented to avoid excessive products that may inhibit the growth of degrading microbes. The CNP ratio commonly adapted for effective growth of PHDM are 100/5/1 and 100/10/1. Koolivand et al. investigated how varying CNP ratios affected TPH removal in the treatment of oily sludge. After 12 weeks of composting setup with CNP ratios of 100/5/1 and 100/10/1, the authors did not record a significant difference in the TPH. However, Koolivand et al. proposed adoption of 100/5/1 for an economical reason as less nutrient is required. There are several nutrient propriety formulated products for bioremediation of petroleum impacted soils. These products contain mainly nitrogen and phosphorus with or without other simple organic compounds in different combinations. Considering the less expensive approach of bioremediation, animal manure, sewage sludge and organic waste materials have also been judged as effective biostimulants. However, Cunningham et al. cautioned against the use due to them being potential sources of antibiotics resistant genes (ARGs) that could enter food chain. Several studies have shown that organic waste composting goes a long way to reduce ARGs, and compost could be considered safer as biostimulants in bioremediation.

**Rhizodegradation.** Tolerant plant roots have been implicated in secreting exudates that stimulate microbes within the rhizosphere to degrade petroleum hydrocarbons. This is regarded as one of the processes of phytoremediation, and it is called rhizodegradation. The exudates released into the soil contain organic nitrogen, enzymes, simple organic acids, and organic compounds that have a similar structure with some petroleum hydrocarbon constituents. With this, several mechanisms are suspected to be responsible for TPH degradation based on exudates composition. Among these include the release of enzymes, such as Laccases and Peroxidases, that enhance the bioavailability of petroleum hydrocarbon constituents. Similarly, simple organic acid desorbs strongly adsorbed TPH constituents from soil particles and hence improve microbial degradation.

Co-metabolism could also be induced by exudates constituents that mimic the structure of petroleum hydrocarbon constituents such as PAH. Several plants have been demonstrated to have the potential of TPH removal from petroleum contaminated soil through these processes, however, using indigenous plant species is preferable to avoid the introduction of invasive plants. In addition, indigenous plants have existing adaptation to soil microbiomes, which is an important factor in phytoremediation. Lastly, the cost of transportation and preservation could discourage the introduction of foreign plants.

TPH removal through rhizodegradation by exudate-stimulated microbial-plant root nexus has been adjudged a time-consuming process. In addition, the radius of influence is few centimetres away from the root, and also the performance decreases with distance from the root. Several efforts have been demonstrated to have improved the performance of this process. These include the introduction of biostimulants, biosurfactant, or plant-growth enhancing microbes. Seo and Cho investigated the influence of soil amendments (compost and NPK formulation), and plants (maize and tall fescue)
on the reduction of TPH from artificially contaminated potting soil. The authors reported a lag phase of 12 days in unplanted pots when insignificant TPH change was recorded. However, planted pots recorded a rapid drop in TPH and higher removal performance after the experiment. Moreover, compost amended pots showed improved performance than a chemical nutrient, and this was attributed to exogenous microbes and nutrients introduced into the rhizosphere. Nwaichi et al.28 also reported enhanced phytoremediation in the presence of poultry dung and NPK fertilizer as amendments. The authors attributed the higher performance of animal manure to increase organic matter content that invariably led to improved bioactivity.

Modified electrokinetic remediation. The principle of electrokinetic remediation is based on the mobility of soil fluids. However, the degradation of petroleum hydrocarbon contaminants is facilitated by the introduction of fluids that contain microbial limiting nutrients, hydrocarbon degraders, biosurfactants, or oxidants.96-100 Fan et al.101 mixed PHDM suspension with artificially contaminated soil and subjected it to an electrokinetic setup (B-EK). Other setups the authors studied included electrokinetic in contaminated soil untreated with microbial suspension (EK), soil treated with microbial suspension but no electrokinetic arrangement (B), and control under natural attenuation (NA). Fan et al.101 attributed the highest TPH removal by B-EK to improve mixing and distribution of PHDM and contaminants during electromigration as polarity changes. However, the TPH removal performance was spatially different within the soil matrix of EK and B-EK setups. The highest performance was recorded close to the electrodes. At the end of 98 days, Fan et al.101 recorded TPH removal performance of 8.8, 36.6, 47.7, and 72.3% from NA, B, EK, and B-EK respectively. It is a point to note that the increased cost associated with the provision of PHDM in the experiment could be offset by the increased performance, which could be a justified reason.

Aside from soil amendments, electrode type has a major influence on the cost and performance of modified electrokinetic remediation. In the Fenton modified electrokinetic system demonstrated by Adhami et al.99 using copper or iron electrode, higher TPH removal from oil base drilling mud was recorded for the Fenton modified system compared to conventional electrokinetics. The authors attributed the performance of the Fenton modified system to the initial oxidation of heavy hydrocarbon by radicals produced in anolyte spiked with hydrogen peroxide, which further increased the biodegradability of the intermediates. The Fenton modified electrokinetic recorded TPH removal of about 120% higher than what conventional electrokinetic recorded. However, while Fenton modified system with copper electrode caused an increase in energy consumption by 9.27% compared to conventional, the modified system with iron electrode recorded less energy consumption by 20% relative to the conventional one. The iron electrode, nevertheless, corroded due to low pH and was deposited within the electrode compartment. This is of concern, especially when considering in-situ applications in the field.

Cost effectiveness analysis
The effectiveness of technology in remediating petroleum contaminated soil is not defined in isolation without considering parameters that define the acceptability of the work. Local Regulatory Standards play a major role in this aspect by specifying allowable limits and periods at which a contaminated site is to be remediated. While several technologies are effective in delivering the work within the required time, a remediation engineer still considers cost in selecting the appropriate method. Table 1 shows varying performances of different technologies with different effective periods, and it is obvious that high efficiencies are achieved at varying periods. Several studies have compared different technologies that have wide effective periods. In Table 1, all remediation technologies that involve enhanced natural processes achieved good performance after

| Category      | Process                          | Soil qty | Performance enhancement strategy                                                                 | Efficiency (%) | Period | Reference                  |
|---------------|----------------------------------|----------|----------------------------------------------------------------------------------------------------|----------------|--------|----------------------------|
| Degradation   | Chemical oxidation               | 10 g     | Persulphate activated by ultrasonic and zero valent iron                                           | 56.28          | 3 d    | Li et al.103               |
| Degradation   | Chemical oxidation and bioaugmentation | 2.3 kg  | Hydrogen peroxide + Cultured hydrocarbon-degrading bacteria (Acinetobacter sp.) + NPK fertilizer | 86             | 30 d   | Bajagain et al.75          |
| Degradation   | Solvent extraction + chemical oxidation | 5 g      | Ethyl lactate + Hydrogen peroxide                                                                  | 96.8           | 4 h    | Jallilian Ahmadkalaei et al.104 |
| Degradation   | Bioaugmentation                   | 500 g    | Cultured hydrocarbon-degrading bacteria immobilised on biochar                                     | 56.2           | 60 d   | Zhang et al.107            |
| Degradation   | Phytoremediation                  | 13,000 m²| Plant growth-promoting rhizobacteria                                                               |                |        | Murray et al.108           |
| Degradation   | Chemical oxidation                | 20 g     | Persulphate+Soil minerals                                                                         | 94.14          | 48 h   | Satapanajaru et al.109     |
| Degradation   | Bioaugmentation and biostimulation | 1 kg     | Hydrocarbon degrading consortium + NH₄NO₃ and K₂HPO₄                                               | 5              | 112 d  | Wu et al.106               |
| Degradation   | Biostimulation                    | 500 g    | Intermittent spray NH₄NO₃ and K₂HPO₄                                                              | 53.5           | 90 d   | Wu et al.106               |

Table 1. Remediation enhancement strategies and their performances.
several days or months, while other processes such as thermal, soil washing, or chemical oxidation achieved high performance within a very short time. Meuser\textsuperscript{12} categorised remediation periods based on time to decontaminate 3 ha of land, and these are; “weeks to few months”, “more than 4 months to 2 years”, “3–10 years” and “decades”. Rather, this review considers the period to remediate a unit volume of soil, and therefore categorised as short term (< 1 day), medium term (several days but less than one month), and long term (> 1 month). Furthermore, all cost analyses are uniformly expressed in USD/t assuming soil bulk density of 1500 kg/m\(^3\). Where necessary, currency conversion at the rate of €1.19/USD was adopted.

### Short term

Some remediation technologies such as thermal desorption and soil washing are capable of delivering high removal performances within minutes or hours\textsuperscript{44,49,104,108,113}. These have been applied at various scales and proved effective within the context in which they were tested. In the \textit{ex-situ} approach, the processes involved include excavation, transportation, treatment, backfilling/landfilling, and waste management. However, the \textit{in-situ} application, which involves only treatment and waste management, is considered less costly, but is disadvantaged due to non-uniform performance due to heterogeneity of soil\textsuperscript{8}. Therefore, the common activities for all the technologies are treatment and waste management. The thermal approach generates gaseous waste, which is handled by an off-gas treatment setup. However, soil washing generates liquid waste that is handled by wastewater treatment processes. For example, chemical oxidation generates much less treatment waste compared to others; therefore, its cost of waste management could be less. \textit{Ex-situ} chemical oxidation is a fast degradation process depending on the oxidant employed, though several activating agents had been used to enhance the

| Category       | Process                                      | Soil qty | Performance enhancement strategy                                                                 | Efficiency (%) | Period | Reference       |
|----------------|----------------------------------------------|----------|---------------------------------------------------------------------------------------------------|----------------|--------|-----------------|
| Degradation    | Bioaugmentation and biostimulation           | 1 kg     | Hydrocarbon degrading consortium + \( \text{NH}_3\text{NO}_3 \) and \( \text{K}_2\text{HPO}_4 \)       | 93.14          | 42 d   | Varjani et al.\textsuperscript{107} |
| Degradation    | Chemical oxidation                           | 10 g     | Ultraviolet + ultrasonic + Fenton process                                                          | 99             | 3 h    | Gharae et al.\textsuperscript{108} |
| Degradation    | Phytoremediation and Electrokinetic          | 4 kg     | Reverse polarity                                                                                    | 84             | 20 d   | Rocha et al.\textsuperscript{109} |
| Degradation    | Bioaugmentation                              | 250 tons | Hydrocarbon degrading bacteria consortium                                                            | 95.9           | 63 d   | Poi et al.\textsuperscript{110}   |
| Degradation    | Biostimulation                               | 2 kg     | Poultry manure + plam bunch ash + granite dust                                                     | 96.7           | 70 d   | Chikere et al.\textsuperscript{111} |
| Degradation    | Biostimulation                               | 50 g     | Biochar + N (Urea) + rhamnolipid                                                                   | 80.9           | 50 d   | Wei et al.\textsuperscript{112}   |
| Degradation    | Biostimulation                               | 250 g    | Poultry manure + Avocado peer seed cake                                                            | 89.6           | 70 d   | Olatunji et al.\textsuperscript{113} |
| Degradation    | Biostimulation                               | 150 g    | Poultry manure                                                                                     | 73.4           | 8 wks  | Aghalibe et al.\textsuperscript{114} |
| Degradation    | Bioaugmentation and biostimulation           |          | Immature compost                                                                                   | 79.5           | 16 wks | Farzadkia et al.\textsuperscript{115} |
| Degradation    | Bioaugmentation and biostimulation           | 60 g     | Diesel modified compost + NPK                                                                       | 99.4           | 20 d   | Leal et al.\textsuperscript{116}   |
| Degradation    | Bioaugmentation and biostimulation           | 3 kg     | Autoclaved compost + Petroleum degrading bacteria                                                    | 84.3           | 12 wks | Abtahi et al.\textsuperscript{117} |
| Separation     | Thermal desorption (fast pyrolysis)          | 10 g     | Nitrogen carrier gas and temperature of 500°C                                                      | 100            | 5 mins | Li et al.\textsuperscript{118}   |
| Separation     | Soil washing                                 | 20 g     | Biopolymer + Polystyrene Foam Beads                                                                | 94             | 30 mins | Wilton et al.\textsuperscript{119} |
| Separation     | Microwave                                    | 30 g     | Spent graphite as a susceptor                                                                      | 91.18          | 60 mins | Sivagami et al.\textsuperscript{120} |
| Degradation    | Phytoremediation                             |          | Harvested and replanted                                                                            | 96             | 100 d  | Mita et al.\textsuperscript{121}   |
| Degradation    | Vermiremediation                             | 1 kg     | Earthworm                                                                                            | 84.99          | 90 d   | Ekperusi and Aigbodion\textsuperscript{122} |
| Degradation    | Bioelectrochemical                           | 340 g    | Glucose                                                                                             | 63.86          | 9      | Asadollahfardi and Rezaee\textsuperscript{123} |
| Degradation    | Phytoremediation                             | 2 kg     | Compost                                                                                            | ca. 75.5       | 79     | Seo and Cho\textsuperscript{124}   |
| Degradation    | Electrokinetic                               |          | Surfactant Sodium dodecyl sulphate as catholyte and sodium sulphate as anolyte                      | 63.86          | 9      | Asadollahfardi and Rezaee\textsuperscript{125} |
performance. Moreover, soil treatment costs may encompass associated waste decontamination, and separate quotation may not be presented for off-gas or wastewater treatment.

In thermal treatment, several factors could determine cost of decontamination. Hyman and Dupont factored in moisture effect on cost and quoted a range of $52 – 69/t depending on moisture content between 10 and 30% for about 4,500 tonnes of contaminated soil. Meuser quoted a range of $55 – 138/t for treatment cost that excludes excavation and permitting. Meuser reported an estimate between $23 and $152/t for thermal remediation.

In soil washing, cost includes wastewater treatment but not sludge disposal, and it ranges between $88 and $276/t depending on whether the soil is co-contaminated with other pollutants such as heavy metals. Leehr reported a range of $110 – 221/t and the cost is dependent on proportions of silt, clay, and organic content. Meuser quoted a range of $53 – 76/t.

The treatment costs for thermal desorption and soil washing are relatively within the same range. However, sludge disposal is not captured for soil washing cost analysis, and depending on the type of soil being treated, sludge volume could be significant. This may invariably cause an increase in the cost. For thermal desorption, it was suspected that higher oil content in soil could result in reduced cost of treatment due to reduced fuel consumption, while moisture content could lead to an increase. For coarse sandy or gravel contaminated media generating less sludge, soil washing could be preferred, especially when an existing hazardous wastewater treatment plant is nearby to reduce the cost of setting up an on-site plant.

Medium term
Several technologies such as modified electrokinetic remediation, bioremediation, in-situ chemical oxidation (ISCO), as shown in Table 1, achieve high performance in less than a month. Lehr estimated a cost range of $110 – 221/t and the cost is dependent on proportions of silt, clay, and organic content. Meuser quoted a range of $53 – 76/t.

Bioremediation is perceived to take a long time in decontaminating polluted soil, but recent improvements in biostimulation and bioaugmentation, as well as active aeration, have been changing the narrative. Likewise, the performance of electrokinetic remediation has recently been improved by integration with other methods such as phytoremediation, chemical oxidation, and bioremediation. On the other hand, ISCO may take a longer time to achieve high removal performance because of soil permeability and the uneven distribution of contaminants in comparison with the ex-situ approach that is faster due to improved soil-oxidant homogenisation.

Lehr projected that the cost of electrokinetic remediation could be within $44 – 131/t. For composting, Lehr reported a range of $22 – 88/t. These costs depend on initial concentration, clean-up level, soil composition, type of amendments, utilities, sampling and analysis among others. ISCO depends on oxidants in use, and Aurora and Juana estimated between $9 – 80/t. Also, Lehr quoted a range of $22 – 66/t for ISCO.

Long term
Some remediation technologies are effective after several months or years. Notably among these are natural processes dependent approaches such as bioventing, biopiling, landfarming, and phytoremediation. However, several efforts have been demonstrated to enhance their performance.

Bioventing is usually operated for more than one month depending on the area of impact and scale. Dominguez et al. reported the operation of wind-driven bioventing for 13 months. For bioremediation approaches such as biopiling, landfarming, and composting that adopt biostimulating and/or bioaugmenting agents to enhance the performance of contaminant removal, their operations can take few months in treating a batch of soil to achieve clean-up targets. Phyto remediation application takes years to reach the clean-up level depending on the initial concentration. However, its application in petroleum hydrocarbon polluted soil is less expensive compared with other contaminants such as metals or radioactive elements.

The cost of bioventing is mostly dependent on mode of introducing air into the soil, actively or passively. Dominguez et al. saved equivalent energy cost of 20 kWh/year when active wind driven equipment was used to supply air. Generally, Lehr estimated a cost range of $7 – $20/t for bioventing with soil volume below 11,000 m³. Meuser reported a common range of $14 – 40/t.

In a bioremediation pilot study conducted by Ighilahriz et al., treatment cost was estimated at $13/t of oily sludge. For the use of some propriety products, Lehr quoted treatment cost of $18 – 131/t for bioaugmentation products, while biostimulators are between $13 – 79/t. Meuser recorded a range of $21 – 119/t for landfarming and biopiling.

Gerhardt et al. reported a range of $28 – 111/t for general phyto remediation remediation. Furthermore, the authors estimated reduced range $13 – 26/t when plant growth promoting rhizobacteria enhanced phyto remediation is adopted. Lehr reported a range of $11 – $39/t.

Conclusion
Different land use warrants different approaches of remediation when spills occur. The need to save costs while achieving remediation goals has necessitated different performance enhancement strategies for remediation technologies. Importantly, enhancement is in the form of speeding contaminant separation, degradation or containment through physically, electrically, chemically, or biologically dominated processes. In most cases, product or energy is introduced into the contaminated soil matrix to enhance pollutant’s desorption and dissolution or volatilization towards facilitation of free phase separation, oxidation or degradation. Despite the improvement, the period of effectiveness varies and could be categorised as short, medium, and long terms. For example, thermal desorption, soil washing, and chemical oxidation are capable of achieving high removal performance within a few minutes or hours and are categorised as short term technologies. However,
contaminated soil characteristics, clean-up level, and site location may determine additional cost of treatment and the final choice of technology.

Generally, short term technologies have treatment costs in the range of $39 – 331/t, excluding excavation, transportation, permitting, samples analysis, equipment rentals, and other special activities. On the other hand, the medium-term technologies achieve high removal performance after several days within a month. These include modified electrokinetic remediation, in-vessel composting, and in-situ chemical oxidation. These technologies have a treatment cost range between $22 – 131/t, excluding other capital costs. Lastly, long term technologies, such as phytoremediation, biopiling, landfarming, and bioventing, could incur treatment costs in the range of $8 – 131/t of a contaminated site. In comparing technologies in terms of cost-effectiveness, it is suggested that comparison be made within respective effective period.

Data availability
No data are associated with this article.

Acknowledgments
Eucharia Nwaichi is a Fellow of the African Academy of Sciences.

References
1. Aroh K, Ubong L, Eze C, et al.: Oil spill incidents and pipeline vandalism in Nigeria: impact on public health and negation to attainment of Millennium Development Goal: the Ibiagwe example. Disaster Prevention and Management: An International Journal. 2010; 19(1): 70–87. Publisher Full Text
2. Ugwoha E: Modeling the Biodegradation of Used Engine Oil in Soil. J Eng. 2020; 10(7): 19–28. Publisher Full Text
3. Azigbe et al.: Seasonal variation of nutrient composition in an oil spill contaminated soil: a case of Rumuolukwu, Eneka, Port Harcourt, Nigeria. Biotechnol Res. 2016; 2(4): 179–186. Reference Source
4. Nwaichi EO, Chuku LC, Igboagwogwo E: Polycyclic aromatic hydrocarbons and selected heavy metals in some oil polluted sites in Delta state Nigeria. J Environ Prot. 2016; 7(10): 1389–1416. Publisher Full Text
5. Kuppusamy S, Maddela NR, Megharaj M, et al.: Total Petroleum Hydrocarbons: Environmental Fate, Toxicity, and Remediation. Cham: Springer International Publishing. 2020. Publisher Full Text
6. Nwaichi EO, Fac M: Evaluation of soil microbial communities as influenced by crude oil pollution. Afr J Biotechnol. 2015; 14(19): 1632–1639. Reference Source
7. Nwaichi EO, Ntorgbo SA: Assessment of PAHs levels in some fish and seafood from different coastal waters in the Niger Delta. Toxicol Rep. 2016; 3: 167–172. PubMed Abstract | Publisher Full Text | Free Full Text
8. Kuppusamy S, Palanisami T, Megharaj M, et al.: Total Petroleum Hydrocarbons: Environmental Fate, Toxicity, and Remediation. In: Reviews of Environmental Contamination and Toxicology. Pd. Voogt, (Eds.). Switzerland: Springer International Publishing, 2016; 1–115.
9. Kuppusamy S, Palanisami T, Megharaj M, et al.: Ex-Situ Remediation Technologies for Environmental Pollutants: A Critical Perspective. In: Reviews of Environmental Contamination and Toxicology. Pd. Voogt, (Eds.). Switzerland: Springer International Publishing, 2016; 236: 117-238. Publisher Full Text
10. Caliman FA, Robu BM, Smaranda C, et al.: Soil and groundwater cleanup: benefits and limits of emerging technologies. Clean Technol Environ Policy. 2011; 13(2): 241–268. Publisher Full Text
11. Dunea D, Jordache S, Pohota A, et al.: Investigation and Selection of Remediation Technologies for Petroleum-Contaminated Soils Using a Decision Support System. Water Air Soil Pollut. 2014; 225(7): 2035. Publisher Full Text
12. Meuser H: Remediation Planning. In: Soil Remediation and Rehabilitation. Springer, 2013; 23: 357-381. Publisher Full Text
13. Ugwoha E, Amah VE, Agharese-Adu PE: Modelling the Transport of Crude Oil in Sandy Soil. International Journal of Chemistry and Chemical Engineering Systems. 2021; 1: 37–51. Reference Source
14. Balzarro-Romero M, Monterroso C, Casares J: Environmental Fate of Petroleum Hydrocarbons in Soil: Review of Multiphase Transport, Mass Transfer, and Natural Attenuation Processes. Pedosphere. 2018; 28(6): 833–847. Publisher Full Text
15. Abbasi Maedeh P, Nasratabadi T, Wu W, et al.: Evaluation of oil pollution dispersion in an unsaturated sandy soil environment. Pollution. 2017; 3(4): 701–711. Publisher Full Text
16. Essaid HI, Bekins BA, Cozzarelli IM: Organic contaminant transport and fate in the subsurface: Evolution of knowledge and understanding. Water Resour Res. 2015; 51(7): 4861–4902. Publisher Full Text
17. Tomlinson DW, Rivett MO, Wealchal GP, et al.: Understanding complex LNAPL sites: Illustrated handbook of LNAPL transport and fate in the subsurface. Environ Manage. 2017; 204(4 Pt 2): 748–756. PubMed Abstract | Publisher Full Text
18. Truskewycz A, Gundry TD, Khudur LS, et al.: Petroleum hydrocarbon contamination in terrestrial ecosystems—fate and microbial responses. Molecules. 2019; 24(18): 3400. PubMed Abstract | Publisher Full Text | Free Full Text
19. Yang M, Yang YS, Du X, et al.: Fate and Transport of Petroleum Hydrocarbons in Vadose Zone: Compound-specific Natural Attenuation. Water Air Soil Poll. 2013; 224(3): 1439. Publisher Full Text
20. Yihdego Y, Al-Weshah RA: Treatment of world’s largest and extensively hydrocarbon polluted environment: experimental approach and feasibility analysis. Int J Hydroal Sci Technol. 2018; 8(2): 190–208. Publisher Full Text
21. Nielsen DM, Nielsen GL, Presio LM: Environmental site characterization. In: Practical handbook of environmental site characterization and ground-water monitoring. D.M. Nielsen, (Eds.). Boca Raton, FL: CRC Press, 2006; 35–205.
22. Lien BR, Huang WH, Shue YT, et al.: Risk-Based Approaches for the Remediation of a UST Site: A Case Study. In: Applied Mechanics and Materials. Trans Tech Publ, 2014; 496-500: 2959–2962. Publisher Full Text
23. Duan L, Naidu R, Thavamani P, et al.: Managing long-term polycyclic aromatic hydrocarbon contaminated soils: a risk-based approach. Environ Sci Pollut Res. 2015; 22(12): 8927–8941. PubMed Abstract | Publisher Full Text
24. Thavamani P, Smith E, Kavitha R, et al.: Risk based land management requires focus beyond the target contaminants—A case study involving weathered hydrocarbon contaminated soils. Environ Technol Innov. 2015; 4: 98–109. Publisher Full Text
25. Falcioppa PP, Scardatta P, Vagliasindi FGA: Modelling and preliminary technical, energy and economic considerations for full-scale in situ remediation of low-dielectric hydrocarbon-polluted soils by microwave heating (MWH) technique. J Soils Sediments. 2016; 16(5): 2350–2360. Publisher Full Text
26. Nagkoti P, Shaik K, Vasudevan G, et al.: Bioremediation of terrestrial oil spills: Feasibility Assessment. In: Optimization and applicability of bioprocesses. H.J. Purohit, V.C. Kalia, A.N. Vaidya, and A.A. Khardenavis, (Eds.). Singapore: Springer Nature Singapore Pte Ltd, 2017; 141–173. Publisher Full Text
27. Lehr JH: Wiley’s remediation technologies handbook: major contaminant
67. Dominguez RC, Leu J, Bethahar M: Sustainable wind-driven bioventing at a petroleum hydrocarbon-impacted site. Remediation Journal. 2012; 22(3): 65–78. Publisher Full Text

68. Khan AA, Zytner RG: Degradation Rates for Petroleum Hydrocarbons Undergoing Bioventing at the Meso-Scale. Bioremediat. 2013; 17(3): 159–172. Publisher Full Text

69. Nwankegu AS, Onwosi CO: Microbial cell immobilization: a renaissance to bioaugmentation inadequacies. A review. Environmental Technology Reviews. 2017; 6(1): 186–198. Publisher Full Text

70. Koolvand A, Abasab A, Parhamfar M, et al.: Biodegradation of high concentrations of petroleum compounds by using indigenous bacteria isolated from petroleum hydrocarbons-rich sludge: Effective scale-up from liquid medium to composting process. J Environ Manage. 2019; 248: 109228. Publisher Full Text

71. Abbasi H, Parhamfar M, Saedee R, et al.: Effect of competition between petroleum-degrading bacteria and indigenous compost microorganisms on the efficiency of petroleum sludge bioremediation: Field application of mineral-based culture in the composting process. J Environ Manage. 2020; 258: 110013. Publisher Full Text

72. Silva NM, de Oliveira A, Pegorin S, et al.: Characterization of novel hydrocarbon-degrading Gordonia paraffinivorans and Gordonia siliwensis strains isolated from composting. Plos One. 2019; 14(4): e0215396. Publisher Full Text

73. Verjani S, Upasani VN: Influence of biotic factors, natural attenuation, bioaugmentation and nutrient supplementation on bioremediation of petroleum crude contaminated agricultural soil. J Environ Manage. 2019; 245: 358–366. Publisher Full Text

74. Poi G, Aburto-Medina A, Mok PC, et al.: Large scale bioaugmentation of soil contaminated with petroleum hydrocarbons using a mixed microbial consortium. Ecol Eng. 2017; 102: 64–71. Publisher Full Text

75. Bajagaj R, Park Y, Jeong SW: Feasibility of oxidation-biodegradation serial foam spraying for total petroleum hydrocarbon removal without soil disturbance. Sci Total Environ. 2018; 626: 1236–1242. Publisher Full Text

76. Leal AJ, Rodrigues EM, Leal PL, et al.: Microbial inoculants produced from solid waste compost for bioremediation of diesel-contaminated soils. Boletim do Museu Paraense Emilio Goeldi-Ciências Naturais. 2019; 14(2): 233–244. Publisher Full Text

77. Zhang B, Zhang L, Zhang X: Bioremediation of petroleum hydrocarbon-contaminated soil by petroleum-degrading bacteria immobilized on biochar. RSC Adv. 2019; 9(60): 35304–35311. Publisher Full Text

78. Chikere CB, Obieze CC, Chikere BO: Biodegradation of artisinally refined diesel and the influence of organic wastes on oil-polluted soil remediation. Sci Afr. 2020; 8: e00385. Publisher Full Text

79. Ren X, Zeng G, Tang L, et al.: The potential impact on the biodegradation of organic pollutants from composting technology for soil remediation. Waste Manag. 2018; 72: 138–149. Publisher Full Text

80. Uzyiyez OC, Thiet RK, Knorr MA: Effects of community-accessible biochar and compost on diesel-contaminated soil. Bioremediat. 2019; 23(2): 107–117. Publisher Full Text

81. Farzadkia M, Esrafil M, Gholami M, et al.: Effect of immature and mature compost addition on petroleum contaminated soils composting: kinetics. J Environ Health Sci Eng. 2019; 17(2): 839–846. Publisher Full Text

82. Ventorino V, Pascale A, Fagnano M, et al.: Soil tillage and compost amendment promote bioremediation and biofertility of polluted area. J Clean Prod. 2019; 239: 118087. Publisher Full Text

83. Ugwoha E, Arham VE, Oweh GO: Bioremediation of Crude Oil Contaminated Soil Using Pig Droppings and Bone Char. Adv Biol Biotechnol. 2020; 28(3): 13–84. Publisher Full Text

84. Wu M, Ma C, Wang D, et al.: Nutrient drip irrigation for refractory hydrocarbon removal and microbial community shift in a historically petroleum-contaminated soil. Sci Total Environ. 2020; 713: 136331. Publisher Full Text

85. Koolvand A, Rajaei MS, Ghanatzedeh M, et al.: Bioremediation of storage tank bottom sludge by using a two-stage composting system: Effect of mixing ratio and nutrients addition. Bioresour Technol. 2017; 235: 240–249. Publisher Full Text

86. Cunningham CJ, Kuyukina MS, Ishvina IB, et al.: Potential risks of antibiotic resistant bacteria and genes in bioremediation of petroleum hydrocarbon contaminated soils. Environ Sci Process Impacts. 2020; 22(5): 1110–1124. Publisher Full Text

87. Babaei AA, Safdari F, Alavi N, et al.: Co-composting of oil-based drilling cuttings by bagasse. Biosyst Eng. 2020, 43(1): 1–12. PubMed Abstract | Publisher Full Text

88. Adams G, Tawar-Fufuyin P, Igelyenah E: Bioremediation of spent oil contaminated soils using poultry litter. Research Journal in Engineering and Applied Sciences. 2014; 2(2): 124–130. Reference Source

89. Bao J, Wang X, Gu J, et al.: Effects of macroscopic adsorption resin on antibiotic resistance genes and the bacterial community during composting. Bioreoros Technol. 2020; 295: 121997. PubMed Abstract | Publisher Full Text

90. Zuzzolo D, Guarino C, Tartaglia M, et al.: Plant-Soil-Microbiota Combination for the Removal of Total Petroleum Hydrocarbons (TPH): An In-Field Experiment. Front Microbiol. 2021; 11(3611): 621581. PubMed Abstract | Publisher Full Text | Free Full Text

91. Hassain I, Punchannreter M, Gerhard S, et al.: Rhizoremediation of petroleum hydrocarbon-contaminated soils: Improvement opportunities and field applications. Environ Exp Bot. 2018; 147: 202–219. Publisher Full Text

92. Zamani J, Hajiabassi MA, Mosaddeghi MR, et al.: Experimental on Degradation of Petroleum in Contaminated Soils in the Root Zone of Maze (Zee Mays L.) Inoculated with Pifirmorosspora Indica. Soil Sediment Contam. 2018; 27(1): 13–30. Publisher Full Text

93. Zhen M, Chen H, Liu Q, et al.: Combination of rhamnolipid and biochar in assisting phytoremediation of petroleum hydrocarbon contaminated soil using Spartina anglica. Environ Sci (China). 2019; 85: 107–118. PubMed Abstract | Publisher Full Text

94. Seo Y, Cho KS: Effects of Plant and Soil Amendment on Remediation Performance and Methane Mitigation in Petroleum-Contaminated Soil. J Microbiol Biotechnol. 2021; 31(1): 104–114. PubMed Abstract | Publisher Full Text

95. Murray EW, Greenberg BM, Cryer K, et al.: Kinetics of phytoremediation of petroleum hydrocarbon contaminated soil. Int J Phytoremediation. 2019; 21(1): 27–33. PubMed Abstract | Publisher Full Text

96. Prakash AA, Prabhu NS, Rajasekar A, et al.: Bio-electroremediation of crude oil contaminated soil enhanced by bacterial biosurfactant. J Hazard Mater. 2021; 405: 124061. PubMed Abstract | Publisher Full Text

97. Gibudu B, Chirwa EM: Biosurfactants as demulsification enhancers in bio-electroremediation of petroleum contaminated soil. Process Saf Environ Prot. 2020; 143: 332–339. Publisher Full Text

98. Vaishnavi J, Devanesan S, AlSaihi MS, et al.: Biosurfactant mediated bioelectroremediation of diesel contaminated environment. Chemosphere. 2021; 264(Pt 1): 128377. PubMed Abstract | Publisher Full Text

99. Adhimi S, Jamshed-Zanjani A, Darban AK: Remediation of oil-based drilling waste using the electrokinetic-Fenton method. Process Saf Environ Prot. 2021; 149: 432–441. PubMed Abstract | Publisher Full Text

100. Xu H, Cang L, Song Y, et al.: Influence of electrode configuration on electrokinetic-enhanced persulfate oxidation remediation of PAH-contaminated soil. Environ Sci Pollut Res Int. 2020; 27(35): 44355–44367. PubMed Abstract | Publisher Full Text

101. Fan R, Ma W, Zhang H: Microbial community responses to soil parameters and their effects on petroleum degradation during bio-electrokinetic remediation. J Environ Manage. 2020; 240: 110463. PubMed Abstract | Publisher Full Text

102. Bianco F, Monteverde G, Race M, et al.: Comparing performances, costs and energy balance of ex situ remediation processes for PAH-contaminated marine sediments. Environ Sci Pollut Res Int. 2020; 27(16): 19363–19374. PubMed Abstract | Publisher Full Text

103. Li YT, Li D, Lai LJ, et al.: Remediation of petroleum hydrocarbon contaminated soil by using activated persulfate with ultrasound and ultrasound/Fenton. Chemosphere. 2020; 238: 124567. PubMed Abstract | Publisher Full Text

104. JalilianAhmadkalaie SP, Gan S, Ng HK, et al.: Evaluation of ethyl lactate as solvent in Fenton oxidation for the remediation of total petroleum hydrocarbon (TPH)-contaminated soil. Environ Sci Pollut Res Int. 2017; 24(21): 17779–17789. PubMed Abstract | Publisher Full Text

105. Satapananjaro T, Chokejaroenrat C, Sakulthaew C, et al.: Remediation and Restoration of Petroleum Hydrocarbon Containing Alcohol-Contaminated Soil by Persulfate Oxidation Activated with Soil Minerals. Water Air Soil Pollut. 2017; 228(6): 345. Publisher Full Text

106. Wu M, Ye X, Chen K, et al.: Bacterial community shift and hydrocarbon transformation during bioremediation of short-term petroleum-contaminated soil. Environ Pollut. 2017; 223: 657–664. Publisher Full Text

107. Varjani S, Pandey A, Upasani VN: Petroleum sludge polluted soil remediation:
Integrated approach involving novel bacterial consortium and nutrient application. Sci Total Environ. 2021; 763: 142934.

108. Gharaee A, Khosravi-Nikou MR, Anvaripour B: Hydrocarbon contaminated soil remediation: A comparison between Fenton, sono-Fenton, photo-Fenton and sono-photo-Fenton processes. J Ind Eng Chem. 2019; 79: 181-193.

109. Rocha IMV, Silva KNO, Silva DR, et al.: Coupling electrokinetic remediation with phytoremediation for depolluting soil with petroleum and the use of electrochemical technologies for treating the effluent generated. Sep Purif Technol. 2019; 208: 194-200.

110. Wei Z, Wang JJ, Gaston LA, et al.: Remediation of crude oil-contaminated coastal marsh soil: Integrated effect of biochar, rhamnolipid biosurfactant and nitrogen application. J Hazard Mater. 2020; 396: 122595.

111. Olatunji OM, Horsfall IT, Ekiyor TH: Comparison of bioremediation capabilities of poultry droppings and avocado pear seed cake in petroleum polluted soil. Journal of Engineering and Technology Research. 2018; 10(5): 38–45.

112. Aghalibe CU, Igwe JC, Obike AI: Studies on the Removal of Petroleum Hydrocarbons (PHCs) from a Crude Oil Impacted Soil Amended with Cow Dung, Poultry Manure and NPK Fertilizer. Chemistry Research Journal. 2017; 2(4): 22-30.

113. Li DC, Xu WF, Mu Y, et al.: Remediation of petroleum-contaminated soil and simultaneous recovery of oil by fast pyrolysis. Environ Sci Technol. 2018; 52(9): 5330-5338.

114. Sivagami K, Padmanabhan K, Joy AC, et al.: Microwave (MW) remediation of hydrocarbon contaminated soil using spent graphite - An approach for waste as a resource. J Environ Manage. 2019; 230: 151-158.

115. Mita M, Ikeura H, Kari T, et al.: Effect of Replanting Zinnia Plants for Remediation of Oil-Contaminated Soil. In: E3S Web of Conferences. EDP Sciences, 2018; 65: 05009.

116. Ekperusi OA, Aigbodion FI: Bioremediation of petroleum hydrocarbons from crude oil-contaminated soil with the earthworm: Hyperodrilus africanus. 3 Biotech. 2015; 5(6): 957-965.

117. Li X, Wang X, Wan L, et al.: Enhanced biodegradation of aged petroleum hydrocarbons in soils by glucose addition in microbial fuel cells. J Chem Technol Bioc. 2016; 91(1): 267-275.

118. Florie J, Patrick H, Cohen G, et al.: Comparing the Efficiency of Oxidization, Sparging, Surfactant Flushing, and Thermal Treatment at Different Scales (Batch, Column, Metric Pilot). In: Environmental soil remediation and rehabilitation: Existing and innovative solutions. D.v.H. Eric, H. David, P. Yoan, S. Marie-Odile, and C. Stefan, (Eds.). Switzerland: Springer. 2020; 211-238.
Open Peer Review

Current Peer Review Status: ✅ ✅

Version 1

Reviewer Report 14 November 2022

https://doi.org/10.21956/openresafrica.14531.r29399

© 2022 Ogbonnaya C. This is an open access peer review report distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

✅ Chukwuma Ogbonnaya

Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, UK

The article is well presented and Table 1 is very valuable in substantiating the title of the article. However, I recommend the following for the authors to consider:

1. At the Introduction Section, the authors should highlight the contribution of the study. Why is this work worth publishing? Justify the new ideas in the article beyond compiling cost saving strategy for remediation.

2. It appears that there is a need to state the outline/overall structure of the article at the end of the introduction section. There were some sections that were not completely on cost and readers may need to get an overview.

3. Can you be more explicit on what you mean by "fate of petroleum hydrocarbons" on page 2. It was used twice.

4. Can you create a section before the conclusion to present the research gaps that other researchers can consider? In other words, what are the effective cost reduction strategies that are yet to be fully explored? Or other aspects beyond cost that should be explored. Comment on the roadmap for future research regarding the topic of the review.

Overall, the paper is an interesting read.

Is the topic of the review discussed comprehensively in the context of the current literature?

Yes

Are all factual statements correct and adequately supported by citations?

Yes
Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Energy, Manufacturing, Sustainability, Polymers, Engineering

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 26 May 2022

https://doi.org/10.21956/openresafrica.14531.r29196

© 2022 Owoseni M. This is an open access peer review report distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

✅ **Mojisola Christiana Owoseni**
Department of Microbiology, Federal University of Lafia, Lafia, Nigeria

The review of cost reduction strategies in the remediation of petroleum hydrocarbon contaminated soil expounds on the various cost reduction strategies available for effective remediation of soils. The review was well written providing adequate information.

Statements were supported with citations and the reader can connect each remediation approach to the cost of each technique. The conclusion compares the cost within each group of strategies.

The authors should address the following areas:
1. The authors should provide possible comparisons among the various cost-reduction strategies to enable a robust conclusion to be drawn in relevance to the topic.

2. The authors expatiated on the effect of the soil type and other factors on the treatment strategies. Considering the climatic and economic constraints influencing cost effectiveness of each treatment strategy in each environment, can the authors discuss regions or areas where each cost-reduction strategy can be applicable and the reasons for their specifications?

Is the topic of the review discussed comprehensively in the context of the current literature?
Yes

Are all factual statements correct and adequately supported by citations?
Yes

**Is the review written in accessible language?**
Yes

**Are the conclusions drawn appropriate in the context of the current research literature?**
Yes

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Environmental microbiology and public health, remediation, water quality.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.