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A Review on the Phytoremediation of Petroleum Contaminated Environment

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Abstract: The discharge of petroleum and its products into the environment has attracted global attention owing to its adverse effects on ecosystems and human health. This is not a new problem and has been a big challenge for more than a century. Several remediation strategies have been in use globally to address these environmental problems emanating from hydrocarbon contaminations with little or no success recorded as either in some methods, complete remediation is not achieved or they have negative impact on the environment, which consequently leads to air and water pollution. The efficacy of any available remediation approach depends on the amount of oil spilled, soil type, extent of oil penetration into the soil, the age and level of contamination. Because the conventional remediation methods such as physical and chemical process are harmful to the environment than the petroleum spill itself, thus the need for the development of a more eco-friendly approach that cleans up the environment and restores the contaminated ecosystems to their original state. Hence, phytoremediation, a process whereby green plants are used to remediate petroleum polluted soils has proven to be a good remediation option as it is most efficient, less financial intensive and environmentally friendly, although it has some constraints. In this paper, thorough attention has been given to the enhancement of phytoremediation, environmental factors affecting phytoremediation, plants/legumes associated with phytoremediation, mechanisms of phytoremediation, merits and demerits of phytoremediation technique. Therefore, phytoremediation has been recommended as a sustainable soil remediation approach. Also, brief accounts of other remediation methods have been provided in this paper.

Keywords: Petroleum, Contamination, Environment, phytoremediation, rhizodegradation, phytoextraction, phytodegradation, phytostabilization, phytovolatilization, pneumatophores.

Introduction

Environmental (air, soil, water) contamination owing to crude oil exploration has attracted global concern as it threatens public health. According to [1], between 1.7 and 8.8 million metric tonnes of petroleum oil are released into global water bodies annually. Soil contaminated with petroleum causes contamination of local ground water, threatens the safety of potable water, limits the use of ground water, causes tremendous economic loss and ecological damage, and obstructs agricultural production.[2, 3] Previous studies by scholars have shown that as a result of crude oil pollution, agricultural soils have been made less productive and the creeks and the fishing waters have become almost dead.[4, 5, 6] In the early 70's, soil contamination caused by petroleum spill was perceived in terms of rare cases, with poor understanding but great devastating impacts on human health and ecosystems systems.[7] However, several cases such as Gulf War Oil Spill, BP's Deepwater Horizon Oil Spill and the Exxon Valdez Oil Spill have drawn media attention to the issue of soil contamination. [8,9,10] In addition, naturally occurring oil spills and bitumen release without human cause from the world's Tar Pits particularly the largest in Athabasca, Northern Alberta, Canada have been an historical source of pollutants for the 2nd largest river basin in North America, the Mackenzie River, since first recorded in 1719.

Presently, the perception has changed to issues relating to enormous infrastructural damage, ecosystem devastation and adverse impacts on public health, emanating from contaminated sites and current waste disposal techniques. Currently, the problem of soil contamination by petroleum is gaining global attention as it poses significant challenge to the present and future generations. In light of this, different countries, like the UK and USA have developed strategies and policies for addressing the challenges associated with contaminated sites. Many developed countries have gone ahead in the implementation of such policies, and some of these countries are; Australia, USA, UK and the Netherlands.

In previous years, several conventional methods such as physical, chemical and thermal processes have been employed in the clean-up of sites contaminated with oil.[11] However, these techniques have been known to have some adverse effects on the environment and are quite expensive.[12] However, the method of steam injection for bitumen removal in the Athabasca Tar Sands has dramatically reduced the naturally occurring flow of oil, bitumen and alluvial deposits into water bodies in the affected areas. The region around the Athabasca deposits have proven challenging while trying to incorporate phytoremediation as it cannot be sustained due to the short growing seasons, lower mean temperatures and high levels of naturally occurring and persistent pollutants.

Figure 1: Region in Athabasca river basin Alberta, Canada

But we also need to address the levels of contamination to which phytoremediation can withstand the toxicity levels that permeate the soil in any particular contaminated site, as in aerobic or anaerobic qualities of the soil. We need to find the balancing point where airflow in the soil is adequate enough for plant growth.

In order to address the challenges of the use of the conventional, biological techniques like phytoremediation are now used for the remediation of sites contaminated with petroleum. Phytoremediation (phyto – meaning plant in Greek) is a general term used to describe the process through which plants remove contaminants from soil and water.[13,14] This technique has proven to be effective for different kinds of contaminants like radionuclides, heavy metals and a wide range of organic pollutants.[15,16] Report has it that, plants that are to be used for phytoremediation should have the ability to withstand the climatic and soil conditions of the contaminated sites. Such plants should also have the capacity to tolerate stress conditions.[17]

Impact of Petroleum Spill on the Environment

The increasing and constant dependence of the economy of oil-producing nations on crude oil exploration and extraction has caused serious adverse effects on the ecosystems of these nations due to accidental discharge of petroleum and its products into man's environment. So the Athabasca Oilsands in Alberta, Canada have a reverse ideology in being forced to remediate natural oil spills in order to alleviate the persistent introduction of oil related deposits into fresh waterways. As shown in figure 1, the level, degree, and persistence of the contaminants will dictate whether phytoremediation will even survive in such conditions. So oil exploration is a lesser case in Alberta as the problem is ever present. In this case mechanical/steam removal of the bitumen is the only option at present.

The global environmental contamination resulting from crude oil exploration has become known and has attracted international concern as it affects local farmers and fishermen whose source of livelihood depends on fertile soil and rivers. There is increasing public outcry as high concentrations of deleterious substances from crude oil constantly enter ecosystems through various routes such as exploration, extraction, refining, transportation, distribution and storage. These routes involve anthropogenic activities, which can be controlled or even prevented to reduce oil spills mainly with adequate surveillance of state-of-the-act technology used in crude oil production operations, although crude oil discharge cannot be totally eliminated till credible regulatory framework is set up and modern technology for oil spills detection are implemented. The immediate causes of oil spills have been linked to one or a combination of the following: break up of pipelines or damage to or leakage of oil pipelines, oil tank overflow; rupture or failure of loading, floating or under-busy hose; broken flange connections or flow line As well as naturally occurring chronic upsurges from subcutaneous tar pits.[18] Majority of spills happen during the process of transportation of crude oil through pipelines or tankers from one location to another[19] But in the case of oilsand and bitumen related remediation, it becomes a case of what to do with the oil once removed from the tar sands so transportation is the only option.

To better understand this section, this paper has presented the impacts of crude oil spill into two sub-topics namely, social and public health impacts and ecological and economic impacts.

Social and Public Health Impacts

In many countries of the world, pollution from oil spills has negatively impacted on the biodiversity, soil and water resources. This pollution may continue for many years if inappropriate remediation technologies and unskilled staff are deployed. The main objective on public health has been to promote, protect and sustain the health of man and his environment. It has never been a new report that many epidemiological studies have been carried out to determine the impacts of certain exposures on the health and living condition of concerned populations.[20] Hydrocarbon compounds are made up of substances that are harmful to human health, causing a broad range of symptoms in different human body systems.[21] Therefore, oil spills are hazardous to human health in a multiple ways. For instance, the Niger delta region of Nigeria (the oil producing hub of Nigeria) has had several cases of oil spills (1969 Ejama-Ebubu, 1998 Jesse Pipeline explosion etc) resulting from the militating activities of oil exploration and producing companies. The region is currently bedeviled with several socioeconomic, public health and environmental challenges. Public health issues such as various illnesses, birth defects, cancer and death have been associated to petroleum hydrocarbon contamination.[22] Many legacy sites and current spills have made the region to be regarded as one of the most impacted deltas in the world, destroying surface and ground water, agricultural soil and the regional economy.[23,24] Studies have revealed and suggested reduction in some species of benthic fauna including molluscs and crabs, and the local death of fish species.[25] Economic loss owing to the land contamination by oil spills has adversely impacted farming and fishing (livelihoods) activities, thereby prompting the indigenes into oil pipelines vandalism and militancy to enable them meet societal needs.[25,26]

More so, a study conducted on the Prestige oil spill in Spain showed adverse health impacts owing to exposure to hydrocarbon.[27] In addition, severe exposures to aromatic hydrocarbon caused respiratory illness and cancer to humans, while high molecular polycyclic-aromatic hydrocarbon

(PAH) caused gene mutation and bioaccumulation in tissues owing to their lipophilic character.[28] With these testaments, acute exposure of humans to hydrocarbon could cause respiratory and chromosomal defects. Moreover, polycyclic-aromatic hydrocarbon (PAH) could cause bronchial disease in children, skin tumours and skin damage.[29]

Ecological and Economic Impacts

Crude oil spill has deeply penetrated the ecosystems, food chains, land and water bodies, making it a stressful incident and depriving many oil-producing regions of the world of their environmental benefits. These have consequently led to the disappearance of many ecosystem services such as wood, areas for fish breeding and mangrove forest.

Ecologically, many regions of the world have been gravely affected due to crude oil spills. The freshwater wetland and mangrove forest degradation by oil spills mars the suitability of the ecosystems for wildlife and biodiversity. Several studies have been performed on the impacts of petroleum and its products on the environment. The severe and chronic consequences of oil spills are depletion of environmental resources which may lead to death of living organisms in the environment, either instantly or with time.[21,30,31] The negative impact of oil spill in the oceans is particularly concerning. This causes the world's coastlines pollution, contamination of aquatic lives, extirpation of colonies of sea birds and other adverse effects on affected animals which lead to dead. For example, the Exxon Valdez oil spill that happened at Alaska, USA in March, 1989 caused severe localized ecological damage to nearby community.[32] More than 250 thousand seabirds were killed due to this spill.[9] In addition, the Deepwater Horizon (DWH) oil spill decreased the biodiversity of the vertebrates and metazoan meiofauna. The cleaning cost of this spill was estimated to be 10 billion USD.[33] In the oil producing region of Nigeria, increase in land contamination as a result reduces the available land for agricultural purposes.[26,34] This creates situations where farmers migrate to neighboring communities for farmlands and this leads to increased pressure on limited fertile land.[35] Similarly, fishes can be affected if the crude oil toxicity which suffocates fishes, and reduces the ability of the rivers to support valuable fish species.[34] Thus, fishers will become jobless and will be financially incapable.

1.5 Characteristics and the Fate of Petroleum/Oil Spill

It should be noted that whenever petroleum compounds are released into the environment, they undergo physical, biological and chemical transformations. And thousands of compounds, mainly hydrocarbons with a small amount of nitrogen, sulfur and oxygen, in different proportions are produced.[36] Soil can readily degrade most chemicals and make the components return to their natural cycles, in which way it can reduce the environmental troubles caused by pollution. With the relationship between mixtures of chemicals, soil and soil biota, the fate of chemicals in soil may be different from that of separate Petroleum Hydrocarbon (PHC) chemicals.[37] However the interactions between PHCs and soil are extremely complex. As PHC pollution affects soil properties, soil properties in turn have remarkable impacts on PHC degradation. According to a report, Petroleum hydrocarbons are extremely complex mixtures of hundreds of compounds.[38] It is important to know that the major hydrocarbon fractions have differing environmental fates, and the extent to which the various petroleum hydrocarbons degrade is dependent on their physical and chemical properties.[37,39,40] Low molecular weight hydrocarbons are relatively easy to biodegrade. Straight-chain hydrocarbons degrade more readily than the corresponding branched chain hydrocarbons. Whereas naturally occurring extra-heavy oils such as those found in tar pits or in particular; the Athabasca Oilsands, oils which have a viscosity as termed by the World Energy Council (WEC) higher than 10,000 centipoises or a semi-solid form of oil which are non-dispersant, whereas oil exploration has viscosities lower than 2000 centipoises making them optimal for dispersants. What this means is that low viscosity oils (2000 centipoises & lower) have a higher probability of massive ecological damage in a very short period of time, but high viscosity solids (10,000 centipoises & greater) labeled as "Asphaltenes" pollute at a slower steady rate through constantly leaking alluvial deposits. Pressure from far below the earth's surface constantly force these Asphaltenes up from below and spill into waterways. Plant growth on these anomalies is impossible.

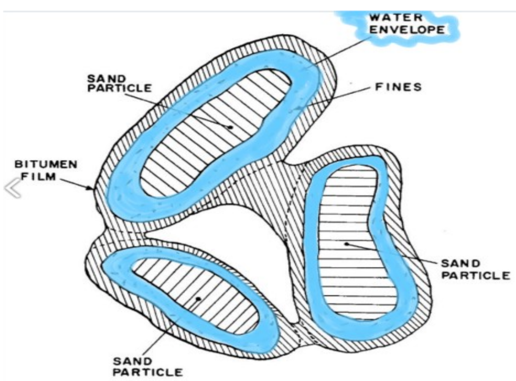

Figure 2: Microscopic view of a sample of Alluvial Deposit from Athabasca Tar Sands (Oilsands), Alberta, Canada.

In 1870, John Macoun took particular note of the structure of the tar sands deposits (Alluvial Deposits) detailing that water trapped within the bitumen film is extremely toxic.[41] He also noted that the Canadian tar sands are the thickest on record. These samples are on the highest end (Asphaltenes) of the solubility scale well over 10,000 centipoises and consequently fall into waterways as Alluvial Deposits. As weather elements break down the individual tar sand structure then the entrapped aromatic hydrocarbons and other toxins are released in a constant natural state. Current Phytoremediation methods are not effective with this condition, so In-situ Steam Removal and open mining are the only current options.

Generally, the rate of biodegradation decreases as molecular size increases. Furthermore, the lighter mixture of hydrocarbon compounds such as gasoline can be easily biodegraded and the two-, three-, four-, and five ring compound hydrocarbon compounds are less readily biodegraded than the monoaromatic compounds.[42,43]

As the size (ie number of aromatic rings) and complexity (ring linkages pattern) of chemicals increase, their insolubility in water, hydrophobicity and sorptive properties increase. Polycyclic aromatic hydrocarbons, (PAHs) with three or more rings tend to be firmly absorbed to the soil.[44,45] This is better illustrated in figures 3 and 4 below.

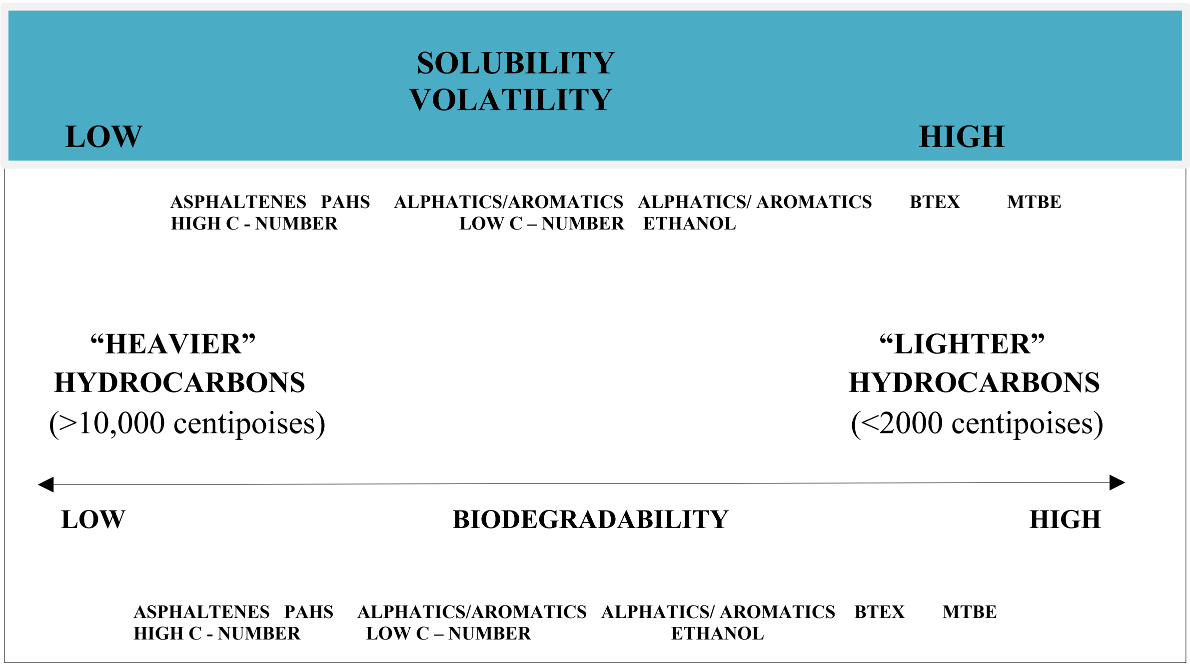

Figure 3: Summary of Characteristics of Petroleum Hydrocarbons.[46]

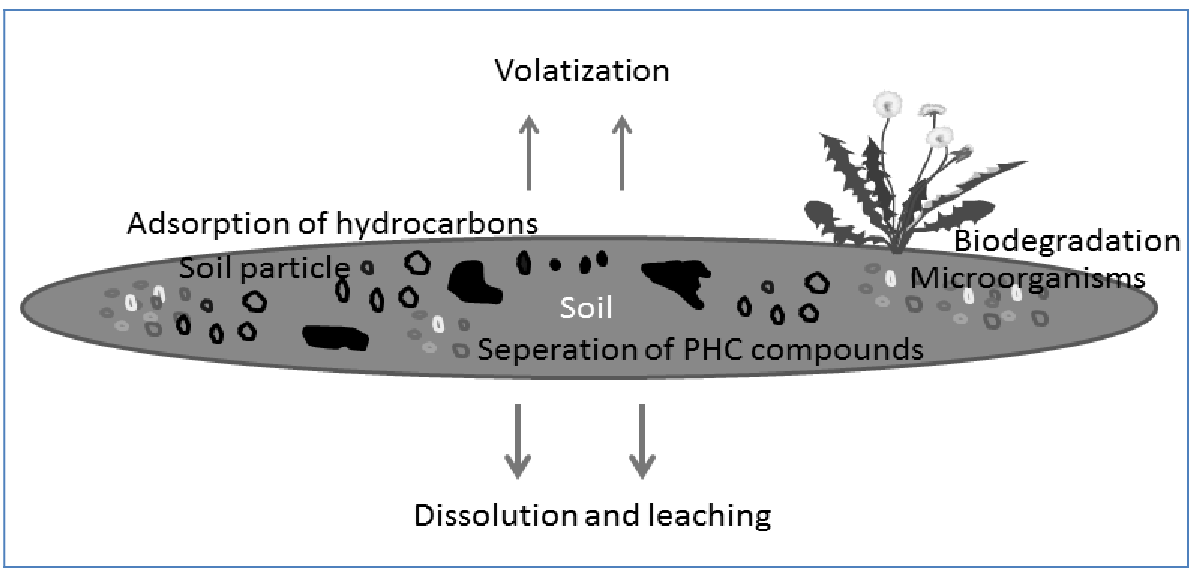

Figure 4: Physical and biochemical behavior (Fate) of petroleum hydrocarbons in soil, as modified.[37]

Remediation Strategies for Petroleum-polluted Environment

Remediation is a process of restoring back soil, water or air status that existed before contamination. This is achieved through the degradation and transformation of contaminants into less harmful and even harmless forms. Several methods exist for remediation which depends on the media (e.g. air, water, or soil) and contaminant type (e.g. heavy metals, PCB).[47] These methods could be biological, physical (or mechanical), or chemical.[48-51] Hence, it is very necessary to utilize a technique or a combination of techniques that would be suitable and sustainable for affected environments. The oil type, its location and size of spill, environmental impacts, local regulation and standards should be considered in the choice of the best clean-up strategy. It is important to note that for selecting the best methods, various criteria such as efficiency, time, cost, reliability, effect on oil characteristic, and necessity of the post-remediation treatment of the applied method must be considered as well.[52]

Physical/Mechanical Remediation Strategy

Physical/mechanical strategy is a process that principally involves replacement of soil and thermal desorption. The commonly used mechanical methods are: booming and skimming, manual removal (wiping), mechanical removal, water flushing, sediment relocation and tilling.[53] This method is fast and effective in cleaning up polluted environment, however, the process is labour intensive, expensive and suitable for small contaminated sites.[49] But we must keep in mind the difference between lighter hydrocarbons and a regionally sized, spill v/s heavy hydrocarbons in the form of Asphaltenes in a constant localized contamination.

Chemical Remediation Strategy

This strategy involves washing contaminated soil using clean water, reagents, and solvents that can leach the contaminants from the soil.[48,50,51] The chemical method could be done via chemical leaching, chemical fixation, electrokinetic remediation, vitrify technology, chemical immobilisation, oxidation, chemical fluid extraction and photodegradation among others. Specifically, the chemical method is fast at cleaning-up contaminants, but the major constraint to this approach is emission of harmful wastes such as carbon dioxide and other greenhouse gases into the environment.[54] In addition, the chemical method is expensive and has the potential to contaminate other environmental media including air and water bodies through the introduction of solvents and reagents during remediation.[50]

Biological Strategy

The biological approach is the use of biological agents such as plants and microorganisms in cleaning up environment polluted with contaminants like petroleum. This technique has been of great research interest in the last decade owing to its various advantages. When compared to the physical and chemical remediation methods, biological strategy is regarded as a better remedial technology in soil contamination. The preference of this approach to other conventional methods stem from the fact that the process cleans up contaminated environment with little or no adverse environmental effects on the terrestrial and aquatic habitats. More so, biological remediation presents a potentially low-technology, cheaper option than physicochemical strategies.[55,56]

There two principal forms of biological treatment which are bioremediation and phytoremediation. While bioremediation involves the use of microorganism in degrading contaminants, phytoremediation is the use of living green plants or its roots to absorb contaminants during the clean-up process.[57,58]

In bioremediation, five known mechanisms are involved which are bioventilation, natural attenuation, bioaugmentation, biostimulation and a combination of bioaugmentation and biostimulation.[59,60-67] On the other hand, phytoremediation technique has seven mechanisms which include; phytostabilization, phytovolatilization, phytoextraction, phytodegradation, phytohydraulics, rhizofiltration and rhizodegradation.[59,68]

In this paper, a comprehensive study of the phytoremediation approach has been presented.

Phytoremediation Strategy

Phytoremediation involves the use of living green plants to absorb contaminants from soil. Put in another way, phytoremediation is the use of plants to contain, sequester, remove or degrade organics in polluted soils.[11,69] This method uses enzymes present in plant roots to aid degradation of contaminants. It reduces the concentration of contaminant in soil and consequently reduces risk posed by such contaminants to the environment and human health. Furthermore, it is suitable for sites where other remediation options are not cost effective, less contaminated sites, or in combination with other remediation strategies. Plants that are used clean-up different kinds of pollutants as well as pesticides, explosives, oil and metals. More so, the plants also help prevent wind, rain, and groundwater from transferring contaminants away from sites to other areas.[70] Phytoremediation is very effective at sites with low to medium levels of contamination.

In this approach, plants take away harmful chemicals from the ground when their roots take in water and nutrients from polluted soil, streams, and groundwater. The plants are allowed to grow and absorb chemicals. Thereafter, the plants are harvested and destroyed, or recycled if pollutants (e.g. metals) stored in the plants are reusable. Studies have shown that phytoremediation approach works effectively when combined with nutrient enrichment since crude oil pollution leads to nutrient deficiencies in the contaminated sites.

The addition of fertilizers could accelerate oil degradation rate by native micro-organisms in the rhizosphere and simultaneously stimulate plant biomass production, and thus increasing the effectiveness of phytoremediation process.[71] The main organic pollutants that can be contained using phytoremediation approach are; crude oil, gas condensates, pesticides and explosive compounds. Also, the inorganic pollutants such as radioactive materials, heavy metals, metalloids and radioactive materials can be addressed using this approach. Phytoremediation is also applied in the decontamination of some affected media such as surface water, ground water sediments and soils. More so, different emerging applications of phytoremediation technologies are being developed, including the potentials of vegetation in capturing atmospheric carbon emissions for greenhouse gas mitigation.[72-76]

Enhancement of phytoremediation Strategy

In spite of the fact that phytoremediation process is the in-situ use of vegetation in the remediation of petroleum contaminated soils, the use of vegetation alone presents constraints in the use of the technology. Recently, especially in the laboratory scale, studies and researches have been focused on the enhanced phytoremediation so as to improve the effectiveness, as well as the reduction in the time in the treatment of petroleum polluted soils. The known processes are; amendment of soil, inoculation of plants with microorganisms, plants growth-promoting rhizobacteria, genetic engineering technology and combined approaches.

Soil Amendment:

The use of soil amendment to enhance the phytoremediation process is one of the promising options for phytoremediation of petroleum polluted soil. This process, if adequately carried out will enable great vegetative coverage and as well increase the rate of removal of contaminants in soil. Report has shown that the addition of compost to petroleum contaminated soil helps in the reduction of the negative impacts of petroleum hydrocarbons on ryegrass growth and accelerates the removal of the chemicals from the soil.[77] More so, a research has confirmed that in the amendment of soil using NPK fertilizer yielded 65% hydrocarbon removal from contaminated soil while the addition of municipal biowaste recorded 60% hydrocarbon removal in 39 months.[78]

However, there is no significant decline of concentration hydrocarbons in non-amended soil. The addition of Jatrophacurcas modified with organic wastes to contaminated soil significantly increases the removal of 89.6% and 96.6% waste lubricating oil in soil contaminated with 2.5% and 1.0% oil, respectively. Though, the loss of 67.3% and 56.6% was recorded in the corresponding contaminated soils without amendment over 180 days.[79] In furtherance to this, a report has revealed that although traditional enhancements such as NPK fertilizer application have contributed to the effective degradation of hydrocarbon pollutants and plant productivity, when excessively utilized, the remaining fertilizers in the soil, not absorb by the plants usually damage the plants and are capable of causing environmental devastation.[80] Natural biosurfactants such as rhamnolipids, which are not toxic to plants and can increase the bioaccumulation of petroleum hydrocarbon, have been shown to enhance degradation of petroleum hydrocarbon pollutants.[81] The benefits of applying biosurfactants have proven that biosurfactant-enhanced phytoremediation has the prospects of becoming a rewarding approach for remediation of contaminated soil.[82]

Inoculation of Plants with Microorganisms:

Scientific studies have proven that inoculation of plants with microorganisms isolated from vegetated soils improves the performances of phytoremediation processes. Different plants may improve rhizodegradation through the selection of microorganisms from various microbial communities.[83] In addition, grasses are more preferred for phytoremediation process because of the large surface areas of their roots that establish strong microbial activity and populations.[84] Besides, research has revealed that microorganisms extracted from grass planted on soils were better in the degradation of petroleum hydrocarbons than the ones from non-vegetated soils. Consequently, inoculation of plants rhizosphere with microbes protects plant roots from contaminant toxicity and at the same time enhances phytoremediation efficiency. Currently, a lot of studies have been channeled on the enhancement of rhizodegradation efficacy via microbial inoculation, more especially using native microorganisms isolated from polluted habitats. Autochthonous microbes have more compatibility with local polluted sites than allochthonous microbes, occupying no functional niche.[85] The promising options for phytoremediation process are potential petroleum-degrading bacterial strains that have the capacity to compete favourably with the indigenous habitat and are associated with plants. Furthermore, the inoculation process using hydrocarbon-degrading bacteria to improve phytoremediation has been the main focus of previous researches and studies. However, plants with inoculated fungal strains such as *F. equiseti, F. solani, F. oxysporum, F.reticulatum* and *Fusariumacuminatum* are also more efficacious at increasing decontamination of petroleum hydrocarbon than phytoremediation alone.[86] Studies have indicated that mutual benefits exist between plants and inoculated hydrocarbon-degrading microbes which enhance phytoremediation of petroleum hydrocarbons.

Plant Growth-Promoting for Phytoremediation Enhancement:

Plant growth-promoting rhizobacteria are bacteria that have the ability to promote plant growth through the colonization of the plant root surface and close adherence onto soil interfac.[87] Certain rhizosphere bacteria are necessary for plant growth. They can offer protection to plants against pathogens, enhance benefical plant-microbe symbioses, increase nutrient uptake via phosphate dissolution and nitrogen fixation, stimulate plant growth via phytohormone secretion, induce systemic resistance and exhibit antifungal activity.[88,89] These bacteria are known as plant growth-promoting bacteria (PGPB). Plant growth-promoting bacteria (PGPB) such as *Nocardia, Pseudomonas, Rhizobium, Acinetobacter, Achromobacter, Flavobacterium,* and *Bacillus* species have been shown to increase plant yields and solid organic matter contents. They have also proven to be effective in the enhancement of rhizoremediation of contaminated soils.[88-90]

Genetic Engineering Technology:

The application of plants for the cleanup of harmful compounds in soils is limited by slow plant growth action, because several years are usually required to restore polluted sites. It has been reported that the efficiency of using plants can be greatly enhanced via genetic engineering technologies.[91] Several efforts have been made towards the development of transgenic plants for phytoremediation. These transgenic plants when effectively modified substantially assist in the remediation of heavy metal and organic compound polluted sites.[92] However, phytoremediation of petroleum contaminated soils utilizing transgenic weeds has not been given proper consideration.

Combined Approaches:

In most cases, phytoremediation with one enhancement approach may not be effective. For a phytoremediation approach to produce positive results, plant tolerance towards contaminants and the total crude oil degradation needs to be enhanced by combinative use of all the strategies earlier discussed. An all-inclusive phytoremediation technology has been suggested for the combination of processes such as inoculation using pollutant degrading bacteria, agronomic treatment and the growth of the pollutant-tolerant plants such as tall fescue (*Festucaarundinacea*) with rhizobacteria (plant-growth promoting bacteria).

A report from a study has revealed that within the first four months of culture, successful removal of total petroleum hydrocarbons and sixteen polycyclic aromatic hydrocarbons using multi-process phytoremediation approach was 50% more than inoculation with microbes, 45% more than phytoremediation and twice that of agronomic treatment.[93] A combination of methods constituting phytoremediation, addition of surfactant, flushing and microbial remediation effectively removes oil from contaminated soil, and it is ideal for fast restoration of sites contaminated with petroleum hydrocarbon compounds.[94] More so, the application of multi-process phytoremediation approach involving aromatic hydrocarbon-degrading bacteria, mycorrhizal fungi and rhamnolipids for the bioremediation of polycyclic aromatic hydrocarbons has been reported.[81] With reference to this report, the multi-process approach was successful in removing the total polycyclic aromatic hydrocarbon after 90 days and was 251.83% greater than that of phytoremediation alone. This study shows that the application of multi-process more effective that a single approach in the quest for better remediation process. Therefore, phytoremediation in combination with multi-process technique may be an ideal solution for the enhancement of petroleum hydrocarbon removal from contaminated sites. It would be interesting to see the results of adding to this multi-process one more layer of effectiveness with plants displaying pnuematophoric capabilities such as the Black Mangrove or *Avicennia germinans*. These plants grow in very wet soil that is not heavily oxygenated which is why their roots grow straight up into the air. These roots are called **pneumatophores** and look like tiny snorkels that help with gas exchange. With the introduction of vents and ability to exude extremely heavy volumes of salts and contaminates onto the back of their leaves, how complimentary would this addition be if the Mangrove or similar genus could survive in diverse climates, soil types, and varying levels of contamination? [95]

Environmental factors influencing phytoremediation of petroleum polluted-lands

The phytoremediation approach is affected by many environmental factors. These factors are:, pH, organic matter content, water and available oxygen, temperature, sunlight, nutrients, soil type and soil quality. Some factors directly impact degradation processes while others affect phytoremediation by altering the bioavailability of the pollutants.[96,97]

Soil Type:

The influence that soil type (structure, texture and organic matter content) has in phytoremediation process is that it can limit petroleum contaminants' bioavailability to plants and may affect the quality of root exudates and thus may have impact on phytoremediation process. More so, microorganisms need low clay or silt content for optimum activity. Again, a reasonable volume of petroleum hydrocarbon pollutants are firmly adsorbed on organic matter present in the soil. Plant root exudates have been found to increase the amount of organic matter in contaminated soils, which may affect pollutant bioavailability through sorption.[98,99] But, petroleum hydrocarbons are not easily desorbed in some cases, and hence, not available for phytoremediation. Also, increase in the concentration or volume of soil petroleum hydrocarbon will have a negative effect on plant growth, and at the same time deteriorate human and animal health through use of soil, water and food produced on the contaminated soils. Furthermore, high volumes of contaminants will even result in plants death.[100]

Soil Quality:

Soil quality is an essential factor that fosters successful germination, growth and health of plants. Highly polluted soil causes poor physical conditioning which negatively affect rapid rhizosphere bacteria and growth of vegetation as well. Therefore, it is of greatest importance to apply amendments in order to enhance the quality of soil before planting. Some known drawbacks are inadequate aeration, nutrient deficiencies, poor water retention ability and low permeability. Organic additives such as sewage sludge, compost, aged manure, mulch or straw can be used to enhance the water-retention ability of a contaminated soil. Sulphur and lime are respectively utilised to decrease and increase the soil pH.[101-103] There is usually deficiency of micro-and macro nutrients in petroleum contaminated soils (as shown in Table 1) required for rapid and healthy growth of plants and for the stimulation of biodegradation by microbes. In addition, the ratio of carbon to Nitrogen (C: N) is usually altered when soil is polluted with hydrocarbon-rich compounds and which can cause immobilisation of nitrogen.[104] Frequent report has revealed that phosphorous and nitrogen (i.e. inorganic mineral nutrients) content restricts the degradation of petroleum hydrocarbons in contaminated soil.[99]

Micronutrients (1ppm)	Macronutrients (100ppm)
Iron (Fe)	Nitrogen (N)
Boron (B)	Phosphorus (P)
Zinc (Zn)	Potassium (K)
Copper (Cu)	Magnesium (Mg)
Manganese (Mn)	Calcium (Ca)
Molybdenum (Mo)	Sulfur (S)

Table1: Micronutrients and Macronutrients Requirements for Healthy Plant Growth.[105]

Soil moisture content:

This refers to the quantity of water present in the soil or the amount it can hold. For optimum microbial activity and hydrocarbon breakdown, 25 to 28% and 30 to 90% of percentage soil moisture are respectively required.[97] This is indicated in table 2.

Temperature:

The prevailing temperature and sunlight impact greatly on the weathering processes of the soil such as evapotranspiration, photomodification, volatilization, hydrolysis and biotransformation. These processes selectively reduce the amount of easily degradable contaminants with the more intractable compounds remaining in the soil. Temperature influences the rate at which the various processes occur. Hence, phytoremediation might be suitable for tropical regions where plant growth occurs all year round than in temperate regions, where effective contribution of phytoremediation is limited to the plants growing period only. Seasonal conditions, for instance, the winter can create challenges for phytoremediation approach as broad-leaved (deciduous) vegetations lose their leaves. Because of this, transformation and uptake may stop, hindering transpiration. The optimum temperatures required for microbial activity and for hydrocarbon degradation are respectively 5 – 45ºC and 20 – 30ºC as presented in Table 2. Generally, an elevated temperature increases biological degradation processes in contaminated environment, especially in contaminated soil. On the other-hand, low temperature decreases hydrocarbon degradation owing to the fact that low temperature retards microbial growth. The summary of the optimum conditions necessary for the degradation of petroleum contaminants have been presented in Table 2

Parameter	**Optimum value for hydrocarbon Degradation**	**Condition required for microbial activity**
Soil Type		Low clay or silt content
Soil Moisture	30-90%	25-28% water retention/holding Capacity
Temperature (°C)	20-30	15-45
Soil pH	6.5-8.0	5.5-8.8
Nutrient Content	C:N:P = 100:10:1	N and P for microbial Growth
Oxygen Content	10-40%	Aerobic

Table 2: Summary of the Optimum Environmental Conditions for the Degradation of Petroleum Contaminants in Soil.[99,106]

Plant/Grasses/Legumes Applied in the phytoremediation of petroleum Contamination.

Several plants have been found to have the capacity in facilitating the phytoremediation of environments contaminated with petroleum hydrocarbon. These plant species for phytoremediation are selected on the basis that their roots can extend throughout the entire contaminated environment. Many criteria have been identified in the selection of plants for phytoremediation.[68] Basically, the selection of plant species should be in respect to the application requirements, contaminants involved and their ability to thrive on contaminated environment. Preferably, they should be indigenous plants in order to avoid the introduction of invasive species. For example, in Nigeria, two native plants, vetiver (V*etivera Zizanioides*) and kenaf (*Hibiscus Cannabinus*) have shown to have the potentials in cleaning up petroleum contamination.[107]

Various studies by researchers and authors have singled out grasses and legumes for their potentials in cleaning up petroleum contaminated environment.[108,109] Grasses, herbs, shrubs as well as deciduous and coniferous trees are potential plant species based on the environmental condition and the contaminants. Grasses (e.g. ryegrass, wheatgrass and sunflowers), legumes (e.g. clover, alfalfa, reed canary grass and peas) and trees (e.g. *Thespesia populnea, Populus* sp*., Salix* sp*., Scaevola serica, Cordia subcordata* and *Prosopis pallida*) have been proven to tolerate crude oil contaminated soil.[11,68] Tolerance is the ability of a plant to grow in hydrocarbon contaminated soil, but this is not necessarily a sign that the plant is healthy.[11]

Grasses in Phytoremediation:

Grasses, often planted with trees are extensively used as primary remediation species in oil-contaminated sites owing the fact that they provide tremendous fine roots in the surface soil. Grass species have the ability at binding and transforming hydrophobic contaminants such as PAHs and BTEX owing to large fine root biomass which can hold a higher microbial population than other species of comparable sizes.[110]

Legume – rhizobium Symbiosis in Phytoremediation:

The interaction between legume plants and rhizobia has proven to be successful in remediating PHC and heavy metal contaminated soil.[89] As mentioned earlier, legumes such as rye (*Elymus sp.*), alfalfa (*Medicago sativa*), reed canary grass (*Phalaris arundinacea*), Fescue (*Vulpia myuros*) and clover (*Trifolium sp*.) have been successfully applied in remediating contaminated sites, particularly petrochemical waste contaminated soils.[68,110] The use of woody legumes in tropical regions is as a result of their abundance there.[111] More so, legumes are associated with different microbial populations. Like grass, legumes have the ability of creating an aerobic soil environment and stimulating microbial activity, leading to the enhancement in oxidation of organic chemical residues.

Trees and their Hybrids in Phytoremediation:

Trees are widely used in the remediation of Petroleum hydrocarbon contaminated soils. Fast growing plant hybrids with desirable characteristics (e.g. resistant to diseases, pests, contaminants, harsh climates and soil conditions) have been selected as prospective candidates in phytoremediation.[112] For instance, hybrid trees such as those from poplars and willows have been successfully and broadly utilised in the phytoremediation of both organic and inorganic polluted environments.

Table 3 and table 4 are respectively the lists of plants that have potential to phytoremediate petroleum hydrocarbon and the plants that have shown the potential in tolerating petroleum hydrocarbons. They are predominantly grasses and legumes. The uniqueness of these grasses in phytoremediation is due to the fact that they possess fibrous root systems which enhance their contact with the contaminant as a result of large surface area.[84] In addition, legumes are a good option for phytoremediation owing to their ability to fix atmospheric nitrogen. Consequently, they do not compete with microorganisms and other plants for the limited nitrogen in the soil and thus, can grow and have enough biomass which will enhance their phytoremediation capabilities.

S/N	Details
1	Western wheatgrass (Agropyron smithii)
2	Big bluestem (Andropogon gerardi)
3	Side oats grama (Boutelona curtipendula)
4	Blue grama (Boutelouna gracilis)
5	Common buffalograss (Buchloe dactyloids)
6	Praire buffalograss (Buchloe dactyloids var. Prairie)
7	Bell rhodesgrass (Chloris gayana)
8	Bermuda grass (Cynodon dactylon L.)
9	Carrot (Daucus Carota)
10	Canada wild-rye (Elymus canadensis)
11	Tall fescue (Festuca arundinacea schreb)
12	Arctared red fescue (Festuca rubra var. Arctared)
13	Soybean (Glycine max)
14	Duckweed (Lemna gibba)
15	Annual ryegrass (Lohum multiflorium)
16	Ryegrass or perennial ryegrass (Lolium perenne. L.)
17	Alfalfa (Medicago sativa L.)
18	Verde kleingrass (Panicum coloratum var. Verde)
19	Switchgrass (Panicum virgatum)
20	Bush bean (Phaseolus vulgaris L.)
21	Poplar trees (Populus deltoids x. nigra)
22	Winter rye (Secale cereal L.)
23	Little bluestem (Schizochryrium scoparius)
24	Indiangrass (Sorghum nutans)
25	Sorghum (Sorghum bicolor) or Sudangrass (Sorghum vulgare L.)
26	Meyer zoysiagrass (Zoysia japonica var. Meyer)
27	Sudangrass (Sorghum vulgare L.)

Table 3: Plants with a demonstrated potential to phytoremediate petroleum hydrocarbon.[11]

S/N	Details
1	Crested wheatgrass (Agropyron desertorum)
2	Tilesy sage (Artemisia tilesu)

3	Oat (Avena sativa)
4	Canola (Brassica rapa)
5	Water sedge (Carex aquatilis)
6	Round sedge (Carex rotundata)
7	Rock sedge (Carex rupestris)
8	Carrot (Daucus carota)
9	Bering hairgrass (Deschampsia beringensis)
10	Quackgrass (Elytrigia repens or Agropyron repens)
11	Tall cotton-grass (Eriophorum angustifolium)
12	Soybean (Glycine max)
13	Sunflower (Helianthus annuus)
14	Barley (Hordeum vulgare)
15	Birdsfoot trefoil (Lotus corniculatus)
16	Black medick (Medicago lupulina)
17	Alfalfa (Medicago sativa L.)
18	Melilotus altissima)
19	Reed canary grass (Phalarus arundinacea)
20	Reed grass (Phragmites australis)
21	Jack pine (Pinus banksiana)
22	Field pea (Pisum arvense)
23	Alpine bluegrass (poa alpine)
24	Psoralea bituminosa)
25	Robinia Pseudacacia
26	Arctic willow (Salix arctica)
27	Snow willow (Salix reticulata)
28	Three-square bulrush (Scirpus pungeus)
29	Senecio glaucus)
30	Spartina alterniflora
31	Spartina patens
32	Alsike clover (Trifolium hybridum)
33	Red clover (Trifolium pretense)
34	White clover (Trifolium repens)
35	Wheat (Triticum aestivum)
36	Cattails (Typha latifolia)
37	Fababean (Vicia faba)
38	Vicia tetrasperma)
39	Maize (Zea mays L.)
40	Black Mangrove (Avicennia germinans)

Table 4: Plants with a demonstrated potential to tolerate petroleum hydrocarbons.[11]

Mechanisms of Phytoremediation

Phytoremediation has several mechanisms which include phytostabilization, phytovolatilization, phytoextraction, phytodegradation, rhizodegradation, rhizofiltration and phytohydraulics.[52,68,113-117]

Rhizodegradation:

This approach involves the breakdown of contaminants via enhanced microbial activity in the rhizosphere zone (1–5 mm) of the soil. It is enhanced by the presence of the rhizosphere and is a much slower process than phytodegradation. In this process, certain microorganisms (yeast, fungi, or bacteria) consume and digest organic contaminants such as crude oil or solvents that are toxic to man and break them down into harmless substances via biodegradation. These harmless substances become sources of food and energy for microorganisms. Natural products produced by plant roots are sugars, alcohols, and acids which constitute organic carbon that provides food for soil microorganisms. The additional nutrients enhance microbial activity. Various reports have revealed that whenever petroleum compounds such as crude oil are released into the environment, the compounds undergo physical, chemical and biological changes. The extent to which the various types of petroleum hydrocarbons degrade is dependent on the physical and chemical properties of the hydrocarbons.[118-120]

Phytoextraction (Phytoaccumulation):

This process entails the translocation/concentration of organic contaminants in the soil by plant roots into the above ground portion of the plants (shoots and leaves). Simply put, phytoextraction involves the use of tolerant and accumulating plants to absorb contaminants from soil, which are transferred and stored in over-ground parts.[51] There are two forms of phytoextraction. First, is the continuous phytoextraction, where hyperaccumulating plants, accumulate high concentrations of contaminants throughout their lifetime. Second, is the induced phytoextraction, which involve enhancement of contaminants accumulation at a single time point by addition of 'accelerants' or 'chelators' Unusually, hperaccumulators or hyperaccumulating plants absorb enormous amount of contaminants into their shoots during normal growth and reproduction. These plants absorbed 100 fold more than non-accumulating plants. Furthermore, hyperaccumulators have additional detoxification mechanisms.[76,120]

(iii) Phytodegradation (or Phytotransformation):

This is the breakdown of contaminants through the metabolic processes of the plant with enzymes. In phytodegradation, the breakdown of contaminants is via internal and external plant processes. The internal process takes place within the plant through metabolic processes, while in the external process, contaminants are broken down via compounds (enzymes) produced by plants.[106,120] Once these contaminants are taken up into plant system, they are made harmless or detoxified through a number of reactions in three phases: conversion, conjugation and compartmentation.[68]

Unlike microbes which metabolize organic contaminants to carbon (iv) oxide and water, phytodegradation relies on plant enzymes in metabolizing or mineralizing chemicals completely into carbon (iv) oxide and water.[112] For instance, a research has revealed that dehalogenase, an enzyme produced by algae and parrot feather (*Myriophyllum aquaticum*) and hybrid poplars (*Populus* spp.)

can breakdown organic compounds (e.g. dehalogenates chlorinated solvents) which encourages the use of these plants in remediating oil-contaminated soils.[96]

(iv.) Phytostabilization (Phytosequestration):

Phytostabilization is the use of plant roots to absorb and precipitate contaminants thereby fixing them to a point and reducing their bioavailability and migration to other ecological systems such as food chain and underground water. This process is capable of re-establishing vegetative cover at sites where natural vegetation is lacking owing to high contaminant concentrations. The three mechanisms of phytostabilization are phytochemical complexation in the root zone, transport protein inhibition and vacuolar storage in the root cells, decreasing the mobility of the contaminants and restricting migration to soil, water, and air.[112] Phytostabilization process is widely performed using sedges, forage plants, grasses and reeds with high rate of transpiration.[60]

Unlike other phytoremediation techniques, phytostabilization is not used to remove contaminants from a site, but rather to stabilize them by accumulation in roots or precipitation within root zones, reducing the risk to human health and the environment. It is applied in situations where there are potential human health impacts, and exposure to substances of concern can be reduced to acceptable levels by containment. Phytostabilization is most efficient for fine-textured soils with high organic-matter content, but it is suitable for treating a broad range of sites where large areas are subject to surface contamination.[74,121] Report has revealed that the combinative use of hardy, perennial, dense rooted plants or deep rooting trees (e.g. poplar, cottonwoods) have a particularly positive effect on the remediation of soil contamination.[60] However, phytostabilization is not carried out on some highly contaminated sites because plants cannot growth or survive in such environment.

Phytovolatilization:

Phytovolatilisation is the conversion or transfer of contaminants (e.g. mercury) to a gaseous state using special matters secreted by plant roots.[122] Once contaminants are taken up by plants, they are modified or broken down into volatile forms and thus diffuse from the plants to the atmosphere through open stomata on leaves together with a small amount of redial diffusion through stem tissues and bark.[68,113]

Various researches and studies have revealed that trees, particularly poplars (*Populus* spp.) and willows (*Salix* spp.), can successfully dissipate or attenuate fuel contaminants such as methyl tertiary-butyl ether (MTBE) and benzene-toluene-ethylbenzene-xylene (BTEX) in contaminated groundwater and soils, because they have a relative short half-life in aerobic environment compared to saturated anaerobic conditions.[68,123] Report has it that hybrid poplar trees (*Populus deltoids x nigra*) has 5 times more benzene-toluene-xylene (BTX) degraders in rhizosphere soil compared to bulk soil. Compounds that possess double-bonds such as perchloroethylene (PCE) and trichloroethylene (TCE) can also be readily oxidized in the atmosphere by hydroxyl radicals following the emission from plant leaves.[68]

Nonetheless, phytovolatilizaiton is not a terminal solution, especially under circumstances when the air circulation is poor. Some volatile organic compounds such as MTBE can exist in atmosphere for a long period of time. And they will pose a threat to the ecosystem as they do in soil and water. However, the emission rate of VOCs from plant tissues is rather small and it is a potentially viable remediation strategy for many volatile organic compounds, VOCs.

Phytohydraulics:

This, also known as hydraulic control and plant uptake is the ability of plants to capture and evaporate water off the plant and thus prevent migration of contaminants to the groundwater. Deep-rooted, high-transpiring, water-loving phreatophytes are extremely useful for this process. Trees in the *Salicaceae* family, such as cottonwood, hybrid poplars and willows are often used. In this process, water as well as contaminants from soils and aquifers is drawn upwards and either oxidized into harmless or volatile forms in aerobic soil or taken up and modified into volatile forms in plants, preventing further dispersion and migration.[123] The contaminants must be dissolved in the soil water before they can be extracted by the plant roots through the transpiration stream. The rate of contaminant removal is highly associated with transpiration rate, contaminant concentration and uptake efficiency in soil water. Factors that affect the potential uptake of organic chemicals into plants through the transpiration stream include hydrophobicity, polarity, sorption properties and solubility.[112]

Rhizofiltration:

Rhizofiltration is the adsorption or precipitation onto plant roots (or absorption into the roots) of contaminants that are in solution surrounding the root zone. It can also be defined as the use of plants to clean-up water by absorbing or precipitating contaminants onto or into their roots. This approach is similar to phytoextraction, but the plants are used to clean up contaminated groundwater rather than soil. The plants to be used for clean up are raised in greenhouses with their roots in water. Contaminated water is either collected from a waste site, and brought to the plants or the plants are grown in the contaminated area, where the roots then take up the water and the contaminants dissolve in it. As the roots become saturated with contaminants, they are harvested. For example, sunflowers were successfully used to remove radioactive contaminants from pond water in a test at Chernobyl, Ukraine.

The Summary of the phytoremediation mechanisms has been shown in figure 3 and presented in table 7 below

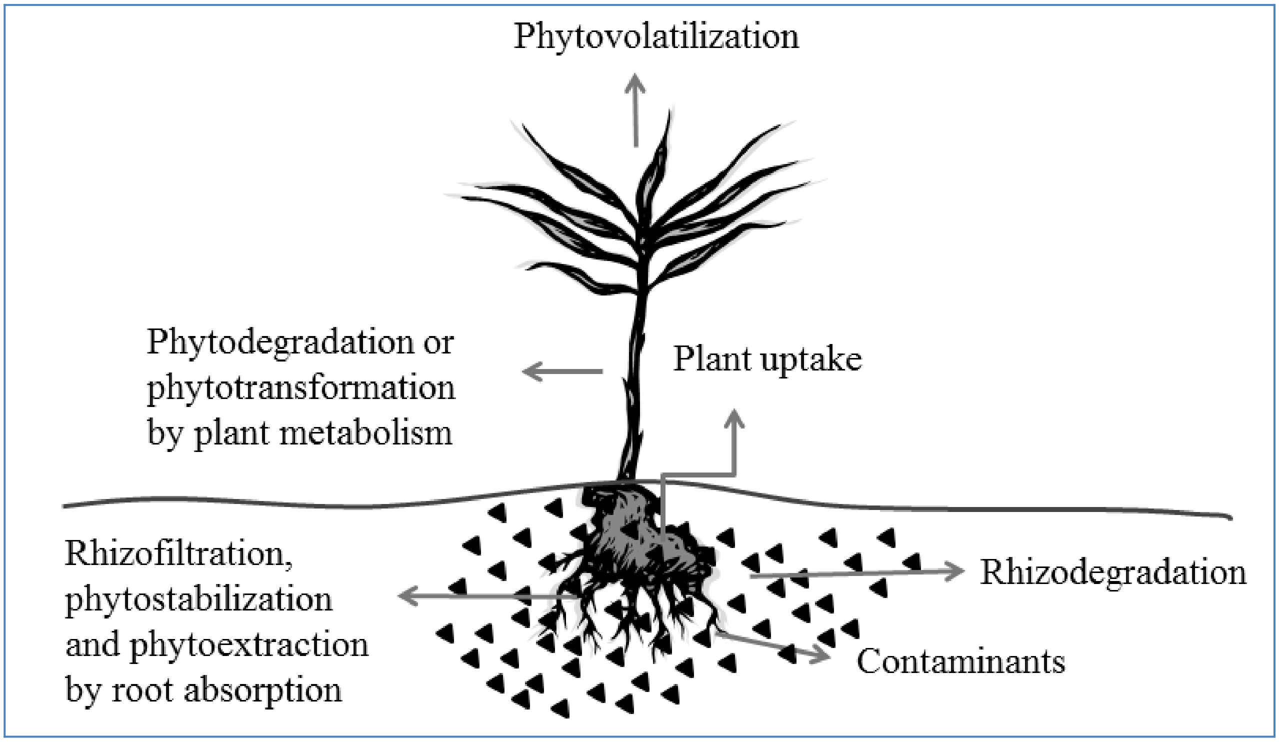

Figure 5: Modified Mechanisms of Phytoremediation.[68]

Location	Mechanisms	Definition	Contaminants and media	Cleanup goals
Plant shoots	Phytoextraction or phytoaccumulation	Plants absorb and accumulate contaminants, especially heavy metals, from soil into aboveground part of the plants.	Metals and other toxic inorganics in soil, sediment and surface water.	Remediation by removal of plants containing the.
	Phytodegradation or phytotransformation	Breakdown of contaminants through metabolic processes with enzymes.	Mobile organics: herbicides, TNT, MTBE, TCE in soil, sediment and surface water.	Remediation by destruction.
	Phytohydraulics	Plants act as 'pumps' to pull-in large volumes of contaminated water as part of transpiration process, resulting in reduced migration of contaminants.	Organics and inorganics in ground and surface water.	Containment by controlling hydrology.
	Phytovolatilization	Uptake and release of contaminants to atmosphere which always happens along with transpiration.	VOCs such as TCE and MTBE, and volatile inorganics such as Se and Hg in surface water or surface soil.	Remediation by removal through plant.
Rhizosphere	Rhizofiltration.	Use of plants to clean up water by absorbing or precipitating contaminants onto or into their roots.	Organics and inorganics such as heavy metals in surface water.	Containment.
	Phytostabilization or phytosequestration.	Certain plant species immobilize contaminants through absorption and accumulation to prevent contaminants from migrating to the groundwater or air.	Organics and inorganics in soil and water.	Containment.
	Rhizodegradation	Plant-assisted bioremediation which mainly relies on breakdown of contaminants through metabolic activity of microorganisms (fungi, yeast, or bacteria) in soil	Hydrophobic organics such as PCBs and PAHs, and other petroleum hydrocarbons in soil and water	Remediation by destruction

Table 5: Summary of Phytoremediation mechanisms.[38,68,112,114-116]

Merits and Demerits of Phytoremediation

Phytoremediation has numerous merits which makes it an ideal remediation approach for petroleum contaminated environment. In spite of the various demerits of phytoremediation approach, there remain several challenges which have led to continuous search for more sustainable means for the enhancement of the technique.

Concisely, table 8 below has presented the merits and demerits of phytoremediation.

MERITS OF PHYTOREMEDIATION
Phytoremediation is economically competitive (less costly) as substantial costs savings are attainable.
It has higher general public acceptance owing to the use of environmentally-friendly "green" and low-tech remedial technology. This is because the plants can also improve air quality and sequester greenhouse gases.
It has relatively low maintenance, easier implementation, self-repairing and does not require highly specialized personnel.
Phytoremediation can be less invasive and destructive than other technologies.
With phytoremediation, organic contaminants adsorbed or trapped within the micro-pores in the soil matrix can be effectively removed. Hence, it can be applied to multiple and mixed contaminants and media.
Vegetation (Plants) can help to reduce or prevent erosion and fugitive dust emissions.
Phytoremediation can create habitat or supplement the existing ones, promote biodiversity and help speed up the restoration of ecosystems that were previously disrupted by anthropogenic activities.
Trees planted may also provide shade to buildings, helping to decrease energy.
This approach preserves natural structure and texture of the soil thereby improving soil quality, prevents soil erosion, and thus minimizes the leaching of contaminants.
Final stages of a phytoremediation approach can provide a land reuse/restoration asset upon completion.
DEMERITS OF PHYTOREMEDIATION
Phytoremediation method may not be appropriate for sites with contamination at significant depths due to the generally shallow distribution of plant roots. This shows that this approach is most effective only at contaminated sites with shallow ground water, soils and sediments.
Phytoremediation can be applied only under warmer climates for one year remediation, hence the system can lose its effectiveness during winter (when plant growth slows or stops) or when damage occurs to the vegetation owing to weather, disease, or pests. A back-up remedial technology may be necessary.
It is not applicable in high concentrations of contaminants. For example, specific phytoremediation prescription could not be applicable to diverse site conditions, as concentration levels could be toxic to the intervention plants

which may prevent plant growth or cause death of plant. In addition, this technique may not be applicable for highly hydrophobic contaminants due to the tendency of the contaminants to remain adsorbed to the soil particles.
Phytoremediation is a slow remediation strategy and could only be considered for long-term clean-up. It is often in need of supplementary treatments such as nutrient supply.
Identification and selection of plant species which could withstand the toxicity of the contaminants is usually a primary challenge of phytoremediation approach. There is usually bioaccumulation of hydrocarbon in plants. Thus, phytotoxic plants can transfer contaminants to another medium in the environment, and/or the food chain, with possible introduction of an inappropriate or invasive plant species.
Phytoremediation may require the use of a greater land area than other remedial methods. This might interfere with other remediation or site activities.
Plant tissues (e.g. roots) responsible for contaminant uptake must be able to access contaminants in soil; thus, where contaminants have percolated into soil layers out of reach of plant root system, the approach might be feasible.
Safe disposal of used plants is a challenge yet to be resolved in many regions. Hence, a risk analysis may be necessary before disposal of any contaminated plant material.
Amendments and cultivation practices might exert unintended effects on contaminant mobility.
Sampling and analysis of plant and core tissues may be required to verify contaminant transfer issues occurring within the plant.

Table 6: Merits and Demerits of Phytoremediation Approach.[43,52,96,112,120,122-130]

Conclusion and Recommendations

Petroleum polluted soils are common sites all over the world especially in areas where there are oil exploration activities. Several methods have been devised and used in the time past to treat petroleum contaminated soils. However, great success has been recorded in the application of phytoremediation strategy in the clean-up of terrestrial and aquatic environments. This approach is preferred over other traditional methods such as chemical and physical process because it cleans up petroleum contaminated sites without much negative environmental impacts. Although phytoremediation approach is in its early stage, without much information, yet it is a remediation approach that holds splendid prospects for the future. Currently, a lot of studies and researches are in progress in the following areas of phytoremediation; the utilization of genetically modified plants that offer greater speed of crude oil uptake, site specificity of phytoremediation strategy, the influence of microbial population and the phytoremediation mechanisms by plants as they may vary. For this approach to be safely and effectively implemented, we strongly recommend that future research on this approach deals with safe disposal of plants after phytoremediation.

One recommendation is that these discarded plants/trees be made available for use in the construction of building materials such as Oriented Strand Board (OSB), which is a type of engineered wood similar to particle board, formed by adding adhesives and then compressing layers of wood strands (flakes) in specific orientations. Using this process would allow the chemical compositions trapped within the tree fibers to become an integral part of the newly formed board. [131] A second alternative would be to use the trees in the formation of tar paper which is a water proofing material used in building construction. [131] The third recommendation is to collect water and algae blooms from lakes with high concentrations of nutrients and blend with contaminated soils while implanting remediation plants in affected oil spill sites. This will help reduce algae blooms in water bodies while providing a fuel source to the phytoremediation site, and not have to add additional manufactured fertilizers to our atmosphere. With the use of Algae to create biofuel, the VOC's trapped within the remediating plants could be reused and incorporated back into an ethanol fuel product. [132]

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References

1) National Research Council (1985) Oil in the Sea: Inputs, Fates and Effects. National Academy Press, Washington DC, pp: 7-10.
2) Xu S.Y; Chen Y.X; Wu W.X, (2006). Enhanced dissipation of phenanthrene and pyrene in spiked soils by combined plants cultivation: Science of Total Environment. 363: pp. 206-215.
3) Wang J; Xu H. K; Guo S. H. (2007) Isolation and characteristics of a microbial consortium for effectively degrading phenanthrene; Petroleum Science, 4(3): pp. 68-75.
4) Dabbs, W.C., (1996). Oil Production and Environmental Damage; http://www.american.edu.TED/hpl.htm.
5) Odokuma, L.O. ; Ibor, M.N. (2002) Nitrogen fixing bacteria enhanced bioremediation of crude oil polluted soil. Global Journ. Pure Appl. Sci., **8** (4): pp. 455-468.
6) Okpokwasili, G.C. ; Odokuma L.O. (1990) Effect of salinity on Biodegradation of oil spills dispersants. Waste Management, 10: pp. 141 – 146.
7) Döberl, G., Ortmann, M., Frühwirth, W., (2013) Introducing a goal-oriented sustainability assessment method to support decision making in contaminated site management; Environ. Sci. Policy 25: pp. 207–217.
8) Michel J., (1991) Gulf War Oil Spill," in Oil Spill Science and Technology, ed. by M. Fingas (Gulf Professional Publishing, 2010), p. 1127.

9) Mapelli F. ; Scoma A.; Michoud G.; Aulenta F.; Boon N.; Borin S.; Kalogerakis N.; Daffonchio D (2017) Biotechnologies for marine oil spill cleanup: indissoluble ties with microorganisms. Trends Biotechnol 35(9): pp. 860–870.

10) Jain P.K ; Gupta V.K; Gaur R.K; Lowry M; Jaroli D.P; Chauhan U.K (2011) Bioremediation of petroleum oil contaminated soil and water. Acad J Inc p 5(1): pp. 1–26.

11) Frick, C. M.; Farrell, R. E.; Germida, J. J. (1999) Assessment of Phytoremediation as an in situ technique for cleaning oil-contaminated sites; Petroleum Technology Alliance Canada, Calgary: http://www.rtdf.org/pub/phyto/phylinks.htm.

12) Lundstedt, S. (2003) Analysis of PAHs and their transformation products in contaminated soil and remedial processes; Solfjodern Offset AB, Umea, Sweden, p 55.

13) U. S. Environmental Protection Agency (USEPA) (1998). A citizen's guide to phytoremediation, EPA – 542-F- 98-011, Office of Solid Waste and Emergency Response: Washington DC. p. 6.

14) U.S. Department of Agriculture (USDA) (2000). Conservation buffers work – economically and environmentally. Program Aid 1615: Washington, D.C. p. 4.

15) Schnoor, J.L. (2002). Phytoremediation of Soil and Groundwater: Technology Evaluation Report TE-02-01. Groundwater Remediation Technologies Analysis Centre (GWRTAC). www.gwrtac.org.

16) Schroder, P., Harvey, P.J. ; Schwitzguebel, J.P. (2002). Prospects for the phytoremediation of organic pollutants in Europe, Environ. Sci. Pollut. Res. 9(1): pp 1-3.

17) Siciliano, S.D. ; Germida, J.J. (1998a). Biolog analysis and fatty acid methyl ester profiles indicate that Pseudomonas inoculants that promote phytoremediation alter the root-associated microbial community of Bromus biebersteinii. Soil Biol. Biochem. 30: pp. 1717-1723.

18) Mobil Producing Nigeria (1998). January 1998 Idoho – QIT 24 pipeline oil spill, Short term environmental impact assessment report Nigeria: Mobil Producing Nigeria.

19) Ogbogbo C.B.N. (2004). The Niger delta and the resource control conflict since 1960 –1995 [Ph.D. Institute of African studies dissertation]. Nigeria: University of Ibadan. United Nations Development Programme, 2006, Niger delta human development report. Abuja: UNDP.

20) Moeller D.W. (1997). Environmental Health: Revised Edition, Cambridge Mass Harvard University Press.

21) Hofer J (1998). Environmental and Health effects resulting from marine bulk liquid transport; Environ. Sci. Pollut. Res. Int. 5(4): pp. 231-7.

22) Amaize, E. (2016). Strange ailments in Niger-Delta: "oil pollution deforming, killing Ogoni babies" - Vanguard news. Vanguard Spec. Rep. 20.

23) Zabbey, N.; Uyi, H., (2014). Community responses of intertidal soft-bottom macrozoobenthos to oil pollution in a tropical mangrove ecosystem, Niger Delta, Nigeria Mar. Pollut., Bull. 82: pp.167–174.

24) United Nation Environment Programme, UNEP, (2011). Environmental Assessment of Ogoniland UNEP, Switzerland.

25) Raji, A.O.Y. ; Abejide, T.S., (2013). An Assessment of Environmental Problems Associated With Oil Pollution and Gas Flaring in the Niger Delta Region Nigeria, C. 1960s–2000. 3 pp. 48–62.

26) Orubu, C.O. ; Odusola, A. ; Ehwarieme, W., (2004). The Nigerian oil industry: environmental diseconomies, management strategies and the need for community involvement. J. Hum. Ecol. 16, pp. 203–214.

27) Suárez, B., Lope, V., Perez-Gomez, B., Aragones, N., Rodriguez-Artalejo, F., Marques, F., Guzman, A., Viloria, L.J., Carrasco, J.M., Martin-Moreno, J.M., (2005). Acute health problems among subjects involved in the cleanup operation following the Prestige oil spill in Asturias and Cantabria (Spain). Environ. Res. 99: pp. 413–424.

28) Ite, A.E., Semple, K.T., (2012). Biodegradation of petroleum hydrocarbons in contaminated soils. Microb. Biotechnol. Energy Environ. pp. 250–278.

29) Rodríguez-Trigo, G. ; Zock, J.P. ; Pozo-Rodríguez, F., Gómez, F.P. ; Monyarch, G. ; Bouso, L., Coll, M.D. ; Verea, H.C. ; Antó, J.M. ; Fuster, C. ; Barberà, J.A., (2010). Health changes in fishermen 2 years after clean-up of the Prestige oil spill. Ann. Intern. Med. 153:489–498.

30) MacFarland HN (1998). Toxicology of Petroleum Hydrocarbons Occup. Med. 3(3): pp. 445-454.

31) Cole HA (1997) Pollution of the Sea and its Effects, Proc. R. Soc., Lond., B. Biol. Sci. 205(1158): pp. 17-30.

32) Atlas RM (1995). Petroleum Biodegradation and Oil Spill Bioremediation, Marine Pollut. Bull. 31: pp. 178-182.

33) Alessandrello MJ; Juárez Tomás MS; Raimondo EE; Vullo DL; Ferrero MA (2017). Petroleum oil removal by immobilized bacterial cells on polyurethane foam under different temperature conditions. Mar Pollut Bull 122(1–2): pp. 156–160.

34) Umukoro, N., (2012). Governance and environmental inequality in Nigeria: implications for conflict management strategies in the Niger Delta. Int. J. Environ. Stud. 69: pp. 913–920.

35) Olawuyi, D.S., (2012). Legal and sustainable development impacts of major oil spills. J. Sustain. Dev. 9: pp.1–15.

36) Canadian Council of Ministers of the Environment (CCME) (2001b). Backgrounder - Petroleum Hydrocarbons in Soil - Canada-Wide Standard. 2 pp. Available at: http://www.ccme.ca/assets/pdf/phc_backgrounder_e.pdf.

37) Agency for Toxic Substances and Disease Registry (ATSDR) (1999). Toxicological profile for total petroleum hydrocarbons (PHC) Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service. Available at: http://www.atsdr.cdc.gov/ToxProfiles/tp123.pdf.

38) Epps, A. V. (2006). Phytoremediation of Petroleum Hydrocarbons. U.S. Environmental Protection Agency. Available at: http://clu-in.org/download/studentpapers/A_Van_Epps-Final.pdf.

39) Collins, C.; Laturnus, F ; Nepovim, A. (2002). Remediation of BTEX and Trichloroethene: Current Knowledge with Special Emphasis on Phytoremediation Environ. Sci. & Pollut. Res. 9 (1): pp. 86-94.

40) Mueller, K.E. ; Shann, J.R. (2006). PAH dissipation in spiked soil: Impacts of bioavailability, microbial activity, and trees. Chemosphere 64: pp. 1006-1014.

41) Alberta Provincial Archives.

42) Phillips, L.A.; Greer, C.W.; Farrell, R.E.; Germida, J.J. (2009). Field-scale assessment of weathered hydrocarbon degradation by mixed and single plant treatments. Appl. Soil Ecol. 42: pp. 9–17.

43) Radwan, S.N.; Sorkhoh, C.; El –Nemr, I. (1995). Oil Biodegradation around roots, Nature, 376: p. 302.

44) Alexander, M. (2000). Aging, bioavailability, and overestimation of risk from environmental pollutants. Environmental Science and Technology 34, 4259–4265.

45) Reilley, K.A.; Banks, M.K.; Schwab, A.P. (1996). Dissipation of Polycyclic Aromatic Hydrocarbons in the Rhizosphere, J. Environ. Qual. 25: pp. 212-219.

46) Nwoko, C.O. (2010). Trends in phytoremediation of toxic elemental and organic pollutants, African Journal of Biotechnology, 9: pp. 6010 – 6016.

47) Gomes, H.I.; Dias-Ferreira, C.; Ribeiro, A.B., (2013). Overview of in situ and ex situ remediation technologies for PCB-contaminated soils and sediments and obstacles for full scale application Sci. Total Environ. 445–446: pp. 237–260.

48) Hamby, D.M., (1996). Site remediation techniques supporting environmental restoration activities—a review: Sci. Total Environ. 191: pp. 203–224.

49) Khan, F.I.; Husain, T.; Hejazi, R., (2004). An overview and analysis of site remediation technologies. J. Environ. Manag. 71: pp. 95–122.

50) Yao, Z., Li, J., Xie, H., Yu, C., (2012). Review on remediation technologies of soil contaminated by heavy metals. Procedia Environ. Sci. 16: pp. 722–729.

51) Lim, M.W.; Lau, E.; Von, Poh, P.E., (2016). A comprehensive guide of remediation technologies for oil contaminated soil — present works and future directions. Mar. Pollut. Bull. http://dx.doi.org/10.1016/j.marpolbul.2016.04.023.

52) Marzan LW; Sultana T; Mahbub Hasan M; Akter Mina S; Islam R; Rakibuzzaman AGM; Hassan Khan I (2017). Characterization of furnace oil bioremediation potential of hydrocarbonoclastic bacteria isolated from petroleum contaminated sites of the Sundarbans, Bangladesh. J Genet Eng Biotechnol 15(1): pp. 103–113.

53) Zhu, X.; Venosa A.D.; Suidan M.T.; Lee K. (2001). Guidelines for the bioremediation of marine shorelines and freshwater wetlands, Report under a Contract with office of Research and Development, U.S. Environmental Protection Agency.

54) Cappuyns, V., (2013). Environmental impacts of soil remediation activities: quantitative and qualitative tools applied on three case studies. J. Clean. Prod. 52: pp.145–154.

55) Obuekwe, C. O. ; Al-Muttawa, E. M. (2001). Self-immobilized bacterial cultures with potential for application as ready-to-use seeds for petroleum bioremediation Biotechnology Letters, 23: pp. 1025–1032.

56) Shukla, K. P.; Nand K.S.; Shivesh S. (2010). Bioremediation: Developments, Current Practices and Perspectives. Genetic Engineering and Biotechnology Journal, Volume 2010: GEBJ-3.

57) Kapley A. ; Purohi, H. J. (2009). Genomic tools in bioremediation. Indian Journal of Microbiology 49: pp. 108–113.

58) Boopathy, R. (2000). Factors limiting bioremediation technologies, Bioresource Technology 74: pp. 63-67.

59) Zabbey, N. ; Sam, K. ; Onyebuchi, A.T. (2017). Remediation of contaminated lands in the Niger Delta, Nigeria: Prospects and challenges. Science of Total Environment. http://dx.doi.org/10.1016/j.scitotenv.2017.02.075

60) Peer, W. A.; Baxter, I. R.; Richards, E. L.; Freeman, J. L.; Murphy, A. S. (2006). Phytoremediation and Hyperaccumulator Plants. Chapter 7 in Molecular Biology of Metal Homeostasis and Detoxification. Springer, Berlin. ISBN-10: 3-540-22175-1, p. 299-340.

61) Zahed MA, Aziz HA, Isa MH, Mohajeri L (2010). Effect of initial oil concentration and dispersant on crude oil biodegradation in contaminated seawater. B. Environ. Contam. Tox. 84 (4): pp. 438-442.

62) Sheppard PJ; Adetutu EM; Makadia TH; Ball AS (2011). Microbial Community and Ecotoxicity of Bioremediated, weathered hydrocarbon-contaminated soil. Soil Research 49: pp. 261-269.

63) Makadia TH; Adetutu EM; Simons KL; Jardine D; Sheppard PJ; Ball AS (2011). Re-use of remediated soils for the bioremediation of waste oil sludge. J. Environ. Manage. 92: pp. 866-71.

64) Yousefi Kebria D.; Khodadadi A.; Ganjidoust H.; Badkoubi A.; Amoozegar M. A. (2009). Isolation and characterization of a novel native *Bacillus* strain capable of degrading diesel fuel. Int. J. Environ. Sci. Tech. 6 (3): pp. 435-442.

65) Abdulsalam S.; Bugaje I. M.; Adefila S. S.; Ibrahim S. (2011). Comparison of biostimulation and bioaugmentation for remediation of soil contaminated with spent motor oil. Int. J. Environ. Sci. Tech. 8 (1): pp. 187-194.

66) Andreoni V.; Gianfreda L. (2007). Bioremediation and monitoring of aromatic-polluted habitats. Appl. Microbiol. Biot. 76: pp. 287-308.

67) Gennaro P. D.; Morenoa B.; Annonib E.; García-Rodríguez S.; Bestetti G.; Beniteza E. (2009). Dynamic changes in bacterial community structure and in naphthalene dioxygenase expression in vermicompost-amended PAH-contaminated soils. J. Hazard. Mater. 172 (2-3): pp. 1464-1469.

68) Kamath, R. ; Rentz, J.A. ; Schnoor, J.L. ; Alvarez P.J.J. (2007). Phytoremediation of hydrocarbon-contaminated soils: principles and applications, Department of Civil and Environmental Engineering, Seamans Center, University of Iowa, Iowa City, Iowa, U.S.A. – 52242.

69) Banks, M.K.; Govindaraju, R.S.; Schwab, A.P.; Kulakow, P. (2000). Part 1: Field Demonstration. In: Phytoremediation of Hydrocarbon Contaminated Soil, pp 3-88. (Fiorenza, S., Oubre, C.L. and Ward, C.H. Eds). Baton Rouge, LA, Lewis Publishers.

70) Khan, A.G.; Kuek, C.; Chaudhry, T.M.; Khoo, C.S.; Hayes, W. J. (2000). Role of Plants, Mycorrhizae and Phytochelators in Heavy Metal Contaminated Land Remediation. Journal of Chemosphere 41: pp. 197-207.

71) Zhu, Y.L.; Zayed, A.M.; Qian, J.H.; De Souza, M.; Terry, N. (1999). Phytoaccumulation of Trace Elements by Wetland Plants: Water hyacinth. Journal of Environmental Quality 28(1): pp. 339-344.

72) U. S. Environmental Protection Agency (EPA) (2000). Introduction to phytoremediation EPA/600/ R-99/107.Office of Research and Development, Washington, DC.

73) Cunningham, S.D.; David W. ow (1996). Promises and prospects of phytoremediation. Plant Physiol. 110: pp. 715-719.

74) Cunningham, S.D.; Shann, J.R.; Crowley, D.E.; Anderson, T.A. (1997). Phytoremediation of contaminated water and soil. p. In E.L. Kruger, T.A. Anderson, and J.R. Coats (ed.) p. 2-19.

75) Mattina, M.J. I.; Lannucci-Berger, W.; Musante, C. ; White, J.C. (2003). Cocurrent plant uptake of heavy metals and persistent organic pollutants from soil. Environmental Pollution, 124: pp. 375–378.

76) Ndimele, P.E. (2010). A review on the phytoremediation of petroleum hydrocarbon. Pakistan Journal of Biological Sciences, 13(15): pp. 715–722.

77) Vouillamoz, J.; Milke, M.W. (2001). Effect of compost in phytoremediation of diesel-contaminated soils. Water Science Technology, 43: pp. 291–295.

78) Palmroth M.R.T.; Koskinen P.; Pichtel J. (2006). Field-scale assessment of phytotreatment of soil contaminated with weathered hydrocarbons and heavy metals. Phytoremediation 6(3): 128-136. Available at: http://link.springer.com/article/10.1065%2Fjss2006.07.170.

79) Agamuthu, P.; Abioye, O.P.; Aziz, A.A. (2010). Phytoremediation of soil contaminated with used lubricating oil using Jatrophacurcas. Journal of Hazardous Materials, 179: pp. 891–894.

80) Kang, B.G.; Kim, W.T.; Yun, H.S.; Chang, S.C. (2010).Use of plant growth promoting rhizobacteria to control stress responses of plant roots. Plant Biotechnology Reports, 4: pp. 179–183.

81) Zhang, J.; Yin, R.; Lin, X.G.; Liu, W.W.; Chen, R.R. ; Li, X.Z. (2010). Interactive effect of biosurfactant and microorganism to enhance phytoremediation for removal of aged polycyclic aromatic hydrocarbons from contaminated soils. Journal of Health Science, 56: pp. 257–266.

82) Zhu, L.Z.; Zhang M. (2008). Effect of rhamnolipids on the uptake of PAHs by ryegrass. Environmental Pollution, 156: pp. 46–52.

83) Euliss, K.; Ho, C.H.; Schwab, A.P.; Rock, S.; Banks, M.K. (2008). Greenhouse and field assessment of phytoremediation for petroleum contaminants in a riparian zone. Bioresour. Technol. 99: pp. 1961–1971.

84) Aprill, W.; Sims, R.C. (1990). Evaluation of the use of prairie grasses for stimulating polycyclic aromatic hydrocarbons treatment in soil. Chemosphere, 20: pp. 253–265.

85) Atlas, R.M. and Bartha, R. (1998). Microbial ecology: Fundamentals and applications. Redwood City, CA: Cummings Science Publishing.

86) Hashem, A.R. (2007). Bioremediation of petroleum contaminated soils in the Arabian Gulf region: A review. Kuwait Journal of Science and Engineering, 19: pp. 81–91.

87) Kloepper, J.W. ; Schroth, M.N. (1981). Relationship of in vitro antibiosis of plant growth-promoting rhizobacteria to plant growth and the displacement of root microflora. Phytopathology, 71: pp. 1020–1024.

88) Bhattacharyya, P. N.; Jha, D. K. (2011). Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World Journal of Microbiology and Biotechnology 28(4): pp. 1327-1350.

89) Pajuelo, E. ; Rodriguez-Liorente I.; Lafunte A.; Caviedes M.A. (2011). Legume–Rhizobium Symbioses as a Tool for Bioremediation of Heavy Metal Polluted Soils. Biomanagement of metal-contaminated soils. Environmental Pollution 20: pp. 95-123.

90) Vershinina, Z. R.; Baymiev, A.K.; Blagova, D.K.; Chubukova, O.V.; Baymiev, K.A.; Chemeris, V.A. (2012). Artificial colonization of non-symbiotic plants roots with the use of lectins. Symbiosis 56(1): pp. 23-33. DOI 10.1007/s13199-012-0156-4.

91) Kawahigashi, H. (2009). Transgenic plants for phytoremediation of herbicides. Current Opinion in Biotechnology, 20: pp. 225–230.

92) Doty, S.L.; James, C.A.; Moore, A.L.; Vajzovic, A.; Singleton, G.L.; Ma, C.; Khan, Z.; Xin, G.; Kang, J.W.; Park, A.Y.; Meilan, R.; Strauss, S.H.; Wilkerson, J.; Farin, F.; Strand, S.E. (2007). Enhanced phytoremediation of volatile environmental pollutants with transgenic trees. P. Natl. Acad. Sci. *USA*, 104: pp. 16816–16821.

93) Huang, X. D.; El-Alawi, Y.; Gurska, J.; Glick, B.R.; Greenberg, B.M. (2005). A multi process phytoremediation system for decontamination of persistent total petroleum hydrocarbons (TPHs) from soils. Microchemical. Journal, 81: pp. 139–147.

94) Zhu, K.; Chen, H.; Nan, Z. (2010). Phytoremediation of loess soil contaminated by organic compounds. NATO Science for Peace and Security, pp. 159–176.

95) "Mangroves: Definition, Types & Facts." Study.com, https://study.com/academy/lesson/mangroves-definition-types-facts.html 19 December 2016, study.com/academy/lesson/mangroves-definition-types-facts.

96) Susarla, S.; Medina, V.; McCutcheon, S. (2002). Phytoremediation: An ecological solution to organic chemical contamination. Ecological Engineering. 18: pp. 647-658.

97) Infante C.; Hernandez – Valencia, I.; Lopez, L.; Toro, M. (2013). Phytoremediation of Petroleum Hydrocarbon – Contaminated Soils in Venezuela. In: Naser et al (Eds.) Phytotechnologies: Remediation of Environmental Contaminants, CRC Press, Florida, USA. pp. 99 - 112.

98) Issoufi, I.; Rhykerd, R.; Smiciklas, K. (2006). Seedling growth of agronomic crops in crude oil contaminated soil. Journal of Agronomy and Crop Science 192: pp. 310-317.

99) Hutchinson S.L.; Banks, M.K.; Schwab, A.P. (2001). Phytoremediation of aged petroleum sludge: Effect of inorganic fertilizer. J Environ Qual. 30: pp. 395-403.

100) Adam, G.; Duncan, H. (2003). The Effect of Diesel Fuel on common Vetch (*Vicia sativa L.*) plants. Environmental Geochemistry and Health 25: pp. 123- 130.

101) Gerhardt, K.E.; Huang, X.D.; Glick, B.R.; Greenberg, B.M. (2009). Phytoremediation and rhizoremediation of organic soil contaminants: potential and challenges. Plant Sci. 176: pp. 20–30.

102) Smith, M.J.; Flowers, T.H.; Duncan, H.J.; Alder, J. (2006). Effects of polycyclic aromatic hydrocarbons on germination and subsequent growth of grasses and legumes in freshly contaminated soil and soil with aged PAHs residues. Environmental Pollution, 141(3): pp. 519–525.

103) Alkorta, I.; Garbisu, C. (2001). Phytoremediation of organic contaminants in soils. Bioresour. Technol. 79: pp. 273–276.

104) Newman, L.A.; Reynolds, C.M. (2004). Phytodegradation of organic compounds. Current Opinion in Biotechnology, 15: pp. 225–230.

105) Prasad, M.N.V. (2006). Stabilization, remediation and integrated management of metal contaminated ecosystems by grasses (Poaceae) In, Prasad, M.N.V. Sajwan, K.S. and Naidu, Ravi (Eds) Trace elements in the environment: Biogeochemistry, Biotechnology and Bioremediation. CRC Press, Florida, USA (Taylor and Francis) Chap. 21: pp. 405-424.

106) McGill, W. B.; Rowell, M.J.; Westlake, D.W.S. (1981). Biochemistry, ecology, and microbiology of petroleum components in soil. In Soil Biochemistry, Vol. 3 (eds. Paul, E.A. and Ladd, J.N.), Marcel Dekker, New York: pp. 229–296.

107) MERCK (2002). "Indigenous Plants to the Rescue." Science in Africa. Available at: http://www.scienceinafrica.co.za/2002/february/oil.htm.

108) Qiu, X.; Leland, T.W.; Shah, S. I.; Sorensen, D. L.; Kendell, E.W. (1997). Field Study: grass remediation for clay soil contaminated with polycyclic aromatic hydrocarbons. In Kruger E.L. et al. (eds). Phytoremediation of Soil and Water Contaminants. American Chemical Society, Washington DC. ACS Symposium Series. 664: pp. 189-199.

109) Gunther, T.; Dornberger, U.; Fritscher W. (1996). Effects of ryegrass on biodegradation of hydrocarbons in soil. Chemosphere, 33: pp. 203-216.

110) Chiapusio, G.; Pujol S.; Toussaint, M.; Badot, P. (2007). Phenanthrene toxicity and dissipation in rhizosphere of grassland plants (Lolium perenne L. and Trifolium pratense L.) in three spiked soils. Plant Soil 294: pp. 103–112. DOI: 10.1007/s11104-007-9234-4.

111) Vitosek, P. M.; Cassman K.; Cleveland C.; Crews T.E. (2002). Towards an ecological understanding of biological nitrogen fixation. Biogeochemistry 57/58: pp. 1–45.

112) Interstate Technology & Regulatory Council (ITRC) (2009). Phytotechnology Technical and Regulatory Guidance and Decision Trees, Revised. Phyto-3. Available at: http://www.itrcweb.org/Documents/PHYTO-3.pdf.

113) Wang, J.-Z.; Zhang, G.-H.; Mu, H.-D.; Yan, M.-J., (2011). Quantitative valuation and validation of the influence degree of human activities on shallow groundwater. Shuili Xuebao (J. Hydraul. Eng.) 42: pp. 1445–1451.

114) U. S. Environmental protection agency (USEPA) (1999). Phytoremediation Resource Guide, EPA 542-B-99-003, solid waste and emergency response (5102G). Available at: http://clu-in.org/download/remed/phytoresgude.pdf.

115) U. S. Environmental Protection Agency (USEPA) (2010). Phytotechnologies for Site Cleanup. EPA 542-F-10-009.

116) Jussila, M. M.; Jurgens, G.; Lindström, K.; Suominen, L. (2006). Genetic diversity of culturable bacteria in oil-contaminated rhizosphere of Galega orientalis. Environmental Pollution 139: pp. 244–257.

117) Interstate Technology & Regulatory Council (ITRC) (2001). Phytoremediation Online Decision Tree Document. http://www.itrcweb.org/, user/webphyto/envdept/phyto/wwwphyto/index.htm.

118) Banks M.K.; Schwab, A. P.; Liu, B.; Kulakow, P.; Smith, J.S. ; Kim, R. (2003). The effect of plants on the degradation and toxicity of petroleum contaminants in soil: A field assessment. Adv Biochem Eng/Biotech 78: pp. 75-96.

119) Shirdam, R.; Zand, A.D.; Nabibidhendi, G.; Mehrdadi, N. (2009). Enhanced biodegradation of hydrocarbons in the rhizosphere of plant species in semi arid regions. Asian J. Chem. 21(3): pp. 2357–2368. Siqueira, J.O., Nair, M.G., Hammer schimidt, R., Safir.

120) Aisien, F.A.; Oboh, I.O.; Aisien, E.T. (2013). Phytotechnology - Remediation of Inorganic Contaminants In: Naser et al (Eds.) Phytotechnologies: Remediation of Environmental Contaminants, CRC Press, Florida, USA. pp. 75 - 82.

121) Shimp, J.F.; Tracy, J.C.; Davis, L.C.; Lee, E.; Huang, W.; Erickson, L.E.; Schnoor, J.L. (2009). Beneficial Effects of Plants in the Remediation of Soil and Groundwater Contaminated with Organic Materials. Crit. Rev in Env. Sci. and Tech, 23: pp. 41-77.

122) Watanabe, M.E., (1997). Phytoremediation on the brink of commercialization. Environ. Sci. Technol. 31: pp. 182–186.

123) Cook, R. L.; Landmeyer, J. E.; Atkinson, B., Messier, J. P.; Nichols, E. G. (2010). Field note: successful establishment of a phytoremediation system at a petroleum hydrocarbon contaminated shallow aquifer: trends, trials, and tribulations. International Journal of Phytoremediation, 12: pp. 716-732.

124) Merkl, N.; Schultze-Kraft, R.; Infante, C. (2005). Assessment of tropical grasses and legumes for phytoremediation of petroleum contaminated soils. Water Air Soil Pollut 165: pp. 195-209.

125) Newman, L. A.; Doty, S.L.; Gery, K.L.; Heilman, P.E.; Muizieks, I.; Shang, T.Q.; Siemieniec, S. T.; Strand, S.E.; Wang, X.; Wilson, A.M.; Gordon, M.P.(1998). Phytoremediation of organic contaminants: a review of phytoremediation research at the University of Washington. Journal of Soil Contamination. 7(4): pp. 531-542.

126) Nowak, D.J.; Crane, D.E., (2002). Carbon storage and sequestration by urban trees in the USA. Environmental Pollution 116 (3): pp. 381-389.

127) Flathman, P.E.; Lanza, G.R. (1998). Phytoremediation: Current views on an Emerging Green Technology. J. Soil Contam., 7: pp. 415–432.

128) Wilson, M.A. (2004). Ecosystem Services at Superfund Redevelopment Sites. Prepared for U.S. EPA. Office of Solid Waste and Emergency Response, Policy Analysis and Regulatory Management Staff. (http://www.sswm.info/glossary/2/letterp).

129) Peng, S.; Zhou, Q.; Caia, Z.; Zhanga, Z. (2009). Phytoremediation of petroleum contaminated soil by Mirabilis Jalapa L. in a greenhouse plot experiment," Journal of Hazardous Materials, 168: pp. 1490-1496.

130) Sas-Nowosielska, A.; Kucharski, R.; Małkowski, E.; Pogrzeba, M.; Kuperberg, J.M.; Kryński, K., (2004). Phytoextraction crop disposal — an unsolved problem. Environ. Pollut. 128:373–379. http://dx.doi.org/10.1016/j.envpol.2003.09.012.

131) Canadian Wood Council: CSA O86 Engineering design in wood, Technical Publications, National Building Code of Canada

132) J.M.K.C. Donev et al. (2018). Energy Education - Harvesting algae [Online]. Available: https://energyeducation.ca/encyclopedia/Harvesting_algae.

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