Review

An appraisal of phytoremediation as an alternative and effective remediation technology for crude oil-contaminated soils: A review

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The review investigates phytoremediation as an alternative environmentally-friendly method of cleaning and restoring hydrocarbon contaminated soils. Phytoremediation is a ‘green’ technology that exploits the natural ability of green plants to remove, degrade or suppress contaminants in soils, sludges, sediments, surface-water and ground-water in an ecologically-friendly manner. Its processes are stimulated by sunlight and microbial biota in the contaminated medium. The use of various mechanisms of phytoremediation is reviewed along with the criteria used in the selection of plant species for phytoremediation exercises. The importance of soil amendments in phytoremediation experiments is also considered. The usefulness of phytoremediation as a viable tool for the remediation of contaminated soils in the crude oil bearing regions of the world, and particularly in Nigeria, have been assessed through the work of previous authors to verify its suitability for the remediation and restoration of contaminated soils.

Key words: Crude oil, phytoremediation, pollution, plant species, soil.

INTRODUCTION

Pollutants are often released into the environment (such as the atmosphere, soil and water) through human actions, such as agricultural and industrial activities, and these substances cause environmental pollution (Ikhuoria and Okieimen, 2000; Erakhrumen, 2007; Jadia and Fulekar, 2008; 2010; Oyedeji et al., 2015). The remediation of such environments after pollution incidents is often necessary and can be effectively achieved using phytoremediation (Erakhrumen, 2007). Phytoremediation is the methodology that exploits the natural ability of green plants to remove, degrade or suppress contaminants in soils, sludges, sediments, surface-water and ground-water in an ecologically-friendly manner and it is stimulated by sunlight. This technology operates on the concept of using ‘nature to cleanse nature’ following contamination of the environment (Osam et al., 2011).

Some plant species are capable of tolerating a wide range of environmental conditions and this ability can be
used to modify these conditions (Susarla et al., 2002).

Phytoremediation technology enhances the amelioration and restoration of contaminated environments, such as soils and waters, by growing green plants that have the ability to tolerate and/or remove contaminating substances, thereby restoring the soil and its functions (Peer et al., 2008). It is a non-destructive, cost-effective in situ technology that utilizes plants and their associated micro-organisms to remediate contaminated soils. Cunningham et al. (1996) described it as an in situ use of plants and their associated micro-organisms to degrade, contain or render harmless, contaminants in soil or ground-water. The use of phytoremediation techniques can either be through naturally growing plants in the contaminated soil or by artificial cultivation of selected plant species (Erakhrumen, 2007) and has emerged as a viable option for the remediation of petroleum hydrocarbon polluted sites (Frick et al., 1999; Tanee and Kinako, 2008). A considerable number of regions in the global community continue to record substantial economic growth. In the clean-up of contamination by petroleum hydrocarbons, plants enhance the microbial degradation of contaminants in the rhizosphere (Merkl et al., 2004a, b, 2005; Atagana, 2011).

The use of phytoremediation as a remediation option may not only be to degrade contaminants but can also be used to enhance habitat recovery through the stimulation of vegetative plant growth. Plants can enhance bioremediation processes by absorbing, translocating or sequestering the organic contaminant and removing them from the soil system (Cunningham et al., 1995; Glick, 2003). In a situation where the contaminant, in its present concentration, is not phyto-toxic, the cultivation of plants can be a valuable tool in soil remediation. The mechanism and efficiency of phytoremediation technology depend on the type of contaminant, its bioavailability and the surrounding soil properties (Cunningham and Ow, 1996).

Although the phytoremediation of contaminated soil may be moderately slow, it is, however, environmentally-friendly, inexpensive, requires little equipment and or labour, is easy to perform, and has the benefit that the contaminated sites can be cleaned without removing the polluted soil. The key factor for successful phytoremediation practise is the identification of a plant species that is tolerant of the contaminated site, and can tolerate high concentrations of contaminant(s) in the polluted site. Bamidele and Agbogidi (2006) described an effective phytoremediation plant species as one that thrives well in a contaminated habitat. Some plant species of the families Poaceae, Brassicaceae, Fabaceae, Euphorbiaceae, Asteraceae and Lamiaceae have been identified, and considered as being able to remediate contaminants, due to their extensive root systems and presence of root nodules which house microbes that help in degrading hydrocarbons (Jadia and Fulekar, 2009; Hall et al., 2011).

Phytoremediation technology presents considerable potential for the treatment of contaminated soils and has proved successful in several studies. For instance, Merkl et al. (2004b) reported that the grass, Brachiaria brizantha (Hochst ex A. Rich.) Stapf. and the legumes Centrosema brasilianum (L.) Benth. and Calopogonium mucunoides Desv. are good plant species for phytoremediation because in crude oil contaminated soil they combined high seedling emergence with good biomass production.

White et al. (2006) investigated phytoremediation of alkylated polycyclic aromatic hydrocarbons in a crude oil-contaminated soil and reported that there was enhanced degradation of complex aromatic hydrocarbons attributable to the phytoremediation process. Agbogidi et al. (2007) investigated the use and effectiveness of Tectona grandis (Linn.) and Gmelina arborea (Roxb.) forest tree species of family Lamiaceae for phytoremediation of crude oil contaminated soils and reported that the two plant species are good candidates for phytoremediation, especially when the concentration of the crude oil is low in the contaminated soil. Atagana (2011) reported the bioremediation of co-contamination of crude oil and heavy metals in soil by phytoremediation using Chromolaena odorata (L) King & H.E. Robins of the family Asteraceae in a pot experiment. At the end of the experiment, crude oil was reduced in the soil and the reduction was attributed to natural attenuation and microbial action in the root system (rhizosphere) of the plant. It was also observed that C. odorata (L) has the capability of thriving and remediating crude oil contaminated soil.

Allowing polluted soil to undergo natural self-remediation takes some time (Kinako, 1981). Therefore, polluted soil needs human intervention to accelerate its recovery process after a pollution incident. Pollution is a serious environmental problem in the oil-bearing region of Nigeria (Figure 1). The practise of phytoremediation in developed and developing countries (such as Nigeria) could offer a feasible and economic alternative to achieve the remediation of petroleum hydrocarbon contaminated soils.

MECHANISMS OF PHYTOREMEDIATION

Remediation of soils contaminated with organic substances, including petroleum hydrocarbons, occurs through one, or more, of the following primary mechanisms: phytostabilization, phytoextraction, phytodegradation, phytovolatilization, and rhizodegradation (Figure 2).

Phytostabilization

Phytostabilization is often referred to as the on-site
Figure 1. Map of Nigeria showing the Niger Delta oil-bearing region and numerically indicating the location of its member states Abia\(^1\), Akwa Ibom\(^2\), Bayelsa\(^3\), Cross River\(^4\), Delta\(^5\), Edo\(^6\), Imo\(^7\), Ondo\(^8\), and Rivers\(^9\).


activation of contaminants and is employed in the remediation of soil, sediment and sludges (Eapen and Dsouza, 2005; USEPA, 2000). In this process, plant roots limit contaminant mobility and availability within soils (Jadia and Fulekar, 2009; Mukhopadhyay and Maiti, 2010). The mechanisms involved may include absorption and accumulation by roots, adsorption onto root surfaces, or chemical precipitation within the root zone (Ghosh and Singh, 2005). Plant uptake and accumulation of petroleum hydrocarbons from contaminated soil, however, is generally quite small. Thus, in the case of petroleum hydrocarbons, phytostabilization may simply be involved in the establishment of vegetative cover to minimize potential migration of the contaminant through erosion, leaching or soil dispersion (Jadia and Fulekar, 2009; Raskin and Ensley, 2000). Plants (especially trees) can also act as organic pumps, transpiring water, and in turn retaining the contaminant in the root zone which helps prevent inter-site mobility (Berti and Cunningham, 2000). Phytostabilization has proved successful with low concentrations of contaminants in soil (Jadia and Fulekar, 2009). It involves accumulation of the contaminants in the root zone. The plants harbour and tolerate the contaminants within the root system and this is one of the major advantages of this process (USEPA, 2000).

Phytovolatilization

Phytovolatilization refers to the use of plants for the uptake of contaminants. The contaminants are taken up by plants, converted into volatile, less chemically toxic substances and transpired into the atmosphere (Jabeen et al., 2009; Jadia and Fulekar, 2009) through the open stomata on the leaf surface and some radial diffusion from the stem tissues and plant bark (Kamath et al., 2004). Some plants have the ability to absorb heavy metals and convert them to a gaseous form in plant tissues and thereafter release them into the atmosphere (Ghosh and Singh, 2005).

Phytoextraction

Phytoextraction involves the extraction of contaminants by plants through their root system and its subsequent accumulation in the harvestable aerial parts of the plant.
Rhizofiltration

Rhizofiltration relies on the capability of the plant root system to take up and sequester contaminants, or nutrients, in excess quantities from aqueous waste streams (Erakhrumen, 2007). This process has the ability to remediate metals including lead (Pb), cadmium (Cd), nickel (Ni), vanadium (V) and chromium (Cr) (Jabeen et al., 2009). Plants suitable for this technique should produce extensive root systems, root biomass and surface area. The plant species should have the capability to accumulate and tolerate substantial amounts of contaminants (Dushenkov and Kapulnik, 2000). Terrestrial plants are very appropriate for rhizofiltration. Plants such as Helianthus annuus (L.) of the family Asteraceae, Brassica juncea (L.) (Brassicaceae), Nicotiana tabacum (L.) (Salicaceae), Spinacia oleracea (L.) (Amaranthaceae) and Zea mays (L.) (Poaceae) have been investigated for their suitability to remove pollutants (Raskin and Ensley, 2000). Rhizofiltration can also be conducted both in situ and ex situ to remediate contaminated water bodies. This method can be used to remediate many metal contaminants. Dushenkov et al. (1995) recommended its commercialization and public acceptance for phytoremediation works.

Phytodegradation (sometimes referred to as phytotransformation)

Phytodegradation involves the breakdown of contaminants either internally, through metabolic processes, or externally, through the release of plant-produced enzymes into the soil using the relationship between plants and their associated micro-organisms in the rhizosphere (Jabeen et al., 2009; Oyedeji, 2016). Some plants are capable of detoxifying contaminants
(such as hydrocarbons) and transforming them into non-phytotoxic metabolites. These contaminants are detoxified in three phases: conversion, conjugation and compartmentalization (Kamath et al., 2004). Plants and micro-organisms are involved, both directly and/or indirectly, in the degradation of complex petroleum hydrocarbons into products that are generally simple, less toxic and less persistent in the environment than the parent compounds. Phytodegradation may occur internally in the rhizosphere (Mukhopadhyay and Maiti, 2010) and it is referred to as rhizodegradation or rhizoremediation. It is applied in the remediation of petroleum hydrocarbon contaminated soils.

Rhizodegradation or rhizoremediation

Rhizodegradation, otherwise referred to as rhizoremediation, is applied in the remediation of pollutants such as petroleum hydrocarbon contaminated soils. This process involves the use of tolerant plant species, and associated micro-organisms, in the rhizosphere to accelerate the remediation processes (Pajuelo et al., 2011). The root systems of plant species that are suitable for rhizodegradation support adequate microbial growth due to their ability to offer their root nodules as a habitat (for microbes, enzymes, nutrients and oxygen) as well as a large surface area for microbes to colonize in the soil layers (Anderson et al., 1993). The roots are capable of releasing ‘degradative enzymes’ to promote degradation of petroleum hydrocarbons (Wenzel, 2009). The root systems also play significant roles in transferring the contaminants to the degrading microbes and for the production of oxygen, either by transferring oxygen or creating a vacuum in the soil’s sub-surfaces that permit diffusion of atmospheric oxygen (Van Epps, 2006) to increase the degradation of contaminants in the remediation processes.

In the rhizosphere, a much higher microbial density (which could enhance rhizodegradation) is present in the surface soil layer than in deeper layers (Hingsinger et al., 2005, 2006) and this is associated with higher microbial numbers, diversity and bioactivity (Boopathy, 2000). Availability of numerous degrading microbes in the soil significantly determines their potential for remediation (Mikkonen et al., 2011). Bacteria in the soil rhizosphere are increased by organic contaminants (Chaineau et al., 2003; Chaudhary et al., 2012). This increased microbial population, and its availability, promote plant growth through the degradation of organic contaminants. The *Rhizobium* population helped increase the growth performance of *Tritium* species (L.) Fabaceae on hydrocarbon contaminated soil (Chiapusio et al., 2007). Rhizoremediation can be employed in the treatment of soil contaminated by petroleum hydrocarbons, but the choice and tolerance of plant species also influence its effectiveness.

TOLERANCE MECHANISMS OF PLANTS AND THEIR SUITABILITY FOR REMEDIATION

The physiological and molecular mechanisms of a plant species determine the suitability of such plants for remediation processes. A plant’s tolerance to a particular contaminant is governed by its ability to tolerate an increasing level of the contaminant (Jabeen et al., 2009). Kamath et al. (2004) identified some criteria for selecting plant species. This should follow the needs of the application, the contaminants concerned and the potential of such plants to thrive well on contaminated soil. It is preferable to use native plant species for remediation purposes to support soil ecosystem restoration (Pilon-Smits and Freeman, 2006), as introduced, or exotic species, may become invasive during, or after, the clean-up exercise which give rise to other associated ecological problems.

SELECTION OF PLANT SPECIES FOR PHYTOREMEDIATION

Some researchers (Merkel et al., 2004a, b, 2005; White et al., 2006; Agbogidi et al., 2007; Atagana, 2011) have investigated and reported on the selection of plants for the remediation of soils contaminated with hydrocarbons. It was observed that there was enhanced degradation of complex hydrocarbons within the root rhizosphere (Merkel et al., 2004b; Atagana, 2011). This suggests that a good plant candidate for phytoremediation must have an extensive root system.

The selection of suitable plant species is a fundamental step to be considered in the phytoremediation processes. Some plants do not tolerate the presence of contamination, while others do and effectively enhance the remediation of hydrocarbons within soil. This may be due to variation in plant morphology (e.g. roots), physiology and biochemistry (e.g. root exudates) and interactions between microbes and the plants in the rhizosphere (Walker et al., 2003). Some grasses, herbs, shrubs and trees are good candidates for phytoremediation as listed (Table 1) and some of these plants have extensive branched fibrous roots that are more likely to provide large surface areas for interaction (Yateem et al., 2007). The rhizospheres of certain trees (e.g. *Populus deltoides* × *nigra*) have the capability to enrich hydrocarbon degrading micro-organisms more than the soil outside the root zone (Hutchinson et al., 2003). To achieve maximum hydrocarbon reduction in soil, and to successfully establish a stable vegetation cover, various criteria must be considered. Any ideal plant species candidate for the phytoremediation of hydrocarbon contaminated soil should be selected to provide a large surface area per unit volume of soil (Aprill and Sim, 1990; Smith et al., 2006) which thus permits rhizosphere-contaminant-microbe interactions. Due to the
SUITABILITY OF FABACEAE FOR PHYTOREMEDICATION OF HYDROCARBON CONTAMINATED SOILS

The Fabaceae family is made up of plant species commonly referred to as legumes and consists of ~18,000 species across the world and grow in diverse terrestrial habitats. The potential and suitability of Fabaceae for phytoremediation of hydrocarbon polluted soil, with its unique adaptation and rhizodegradation mechanisms, is well known (Merkl et al., 2004b; Tanee and Akanye, 2009; Osam et al., 2011; Atagana, 2011; Hall et al., 2011). There are a number of reports on the use of legumes in hydrocarbon contaminated soils remediation and their ability to fix N (Nichols et al., 1997; Dzantor et al., 2000; Osam et al., 2011) has been known for some time.

Contaminated soils are usually particularly deficient in N and P (Wenzel, 2009) and competition for nutrients among the soil biota reduce nutrient availability. N fixing plant species, such as legumes, can be used in rhizoremediation work (Miller and Cramer, 2005). Microbes, such as *Rhizobium* species, can penetrate the root systems of leguminous plant species and form symbiotic interactions in their root nodules with which they are able to fix atmospheric N in the form of ammonium compounds (Suominen et al., 2000) and have also been found to increase potassium (K) and phosphorous (P) uptake in plants (Vershinina, 2012). Some of the common N-fixing microbes in soil include *Azotobacter* species, *Azospirillum brasilense*, *Rhizobium* spp. and Actinomycetes (Havlin et al., 2005) and these micro-organisms play vital roles in remediation work by degrading the contaminants. The amount of N fixation by microbes in plant root nodules is substantial, often >100 kg ha⁻¹ year⁻¹ (Vitosek et al., 2002). The interaction between microbes and leguminous plant species, such as alfalfa (*Medicago sativa*) and red clover (*Trifolium pratense*), have proven successful in the remediation of petroleum hydrocarbon contaminants (Frick et al., 1999). The use of woody leguminous plant species for phytoremediation in tropical areas is a reflection of their prevalence and abundance (Vitosek et al., 2002) and they can stimulate microbial growth, which increases oxidation of organic chemical substances (Peer et al., 2006).

THE USE OF PLANT SPECIES OF OTHER FAMILIES FOR REMEDIATION OF HYDROCARBON CONTAMINATED SOILS

Plant screening experiments have shown that some plant species, such as *Lolium multiflorum* Lam. and *Festuca arundinacea* Schreb are tolerant of hydrocarbon contamination (Frick et al., 1999). *B. juncea* L. is a useful plant species for phytoremediation and has been successfully used to remediate a 3 km Bulgarian
ecological zone contaminated with Pb (Simeonova and Simeonov, 2006). Pb can be one of the impurities in crude oil. The results of their one season planting showed a decrease between 0 and 25.9% in the initial Pb concentrations at various sample locations.

Günther et al. (1996) found that soils planted with Italian rye-grass (L. multiflorum Lam.) had reduced hydrocarbons than soil that was unplanted. In their 22 weeks phytoremediation experiment, the initial extractable hydrocarbon concentration of 4330 mg total hydrocarbon/kg soil was decreased to <120 mg/kg soil (97% decrease) in planted soil.

The examination of the phytoremediation potential of two cold-hardy grass species, Tall fescue (F. arundinacea Schreb) and annual Italian rye grass (L. multiflorum Lam.) planted together in potted soils contaminated with crude oil, found that the contaminated soils had significantly lower concentrations of total petroleum hydrocarbon compared to unplanted controls (Reynolds and Wolf, 1999). The initial crude oil concentration for planted treatments and untreated controls was ~6200 mg TPH per kg soil. After 640 days, crude oil-contaminated soils planted with both species had 1400 mg TPH per kg soil (77% decrease), while the unplanted control contained 2500 mg TPH per kg soil (60% decrease).

In a 6-month laboratory study, switch grass (Panicum virgatum) and little blue stem Schizachyrium scoparium (Michx.) Nash were capable of decreasing the concentration of total Petroleum Aromatic Hydrocarbons (PAHs) in contaminated soil collected from a manufacturing gas plant (Pradham et al., 1998). The initial soil concentration of total PAHs for the three plant treatments and an unplanted control was 184.5±14.0 mg total PAHs per kg of soil. After 6 months, the concentration in the unplanted control soil was 135.9±25.5 mg/kg, while the concentration in planted treatments was much lower (P. virgatum, 79.5±3.7 mg/kg and S. scoparium, 97.1±18.7 mg/kg).

THE ROLE OF SOIL AMENDMENTS IN PHYTOREMEDIATION PROCESSES

Fertilizers and natural zeolites can play vital roles in phytoremediation processes. White et al. (2003, 2006) and Tanee and Kinako (2008) reported the importance of fertilization in phytoremediation protocols. Chaineau et al. (2003) suggested that the addition of fertilizer (as a soil amendment) and periodic tillage are useful in the degradation of petroleum hydrocarbons in contaminated soil. However, excessive use of nitrogenous fertilizer can damage the environment and to avoid this problem, N-fixing plant species supplemented with soil amendments are encouraged in remediation work (Miller and Cramer, 2005). The environmental applications of natural zeolites such as clinoptilolite as a viable soil amendment has also been reported for contaminated soils (Ming and Allen, 2001; Bowman, 2003; Chmielewska, 2003; Tian et al., 2004; Englert and Rubio, 2005; Leggo et al., 2006; Misaelides, 2011) and for the restoration of soil nutritional qualities. Adebowale et al. (2005) reported environmental significance of Nigerian kaolin for adsorption and remediation of Pb2+, Cu2+, Zn2+ and Cd2+ metal ions in media. Trkova et al. (2004) affirmed that kaolin is effective in the amelioration of adverse effects of contaminants from both the living organisms and the environment.

COMPARISON OF PHYTOREMEDIATION WITH ALTERNATIVE REMEDIATION STRATEGIES

Phytoremediation has shown remarkable cost effectiveness and recent societal acceptance. Its advantages include low costs, according to various authors who have conducted a series of experiments (Frick et al., 1999; Macek et al., 2000; Glick 2003). Other advantages compared with other remediation processes include: Can be applied in situ; Cost-effective and, therefore, economically viable; Offers less disruption to the natural environment compared with mechanical methods; Avoids excavation and heavy damage to soils; Can be applied to large areas of terrestrial contamination; Relatively easy to apply; Preserves soil structure; Potentially quick to apply to the contaminated sites; No disposal site(s) is required; Can be applied to a diverse range of hazardous materials; Plants act as indicators of contamination; Plants help contain contaminants; Plants transfer oxygen and nutrients to the rhizosphere; Other additional advantages of providing plant cover are soil conservation, landscape aesthetics, improved habitat for fauna, carbon-sequestration, etc. (Frick et al., 1999; Oyedeji, 2016).

DISCUSSION

The use of phytoremediation as an alternative environmentally-friendly method of cleaning and restoring contaminated soils has been reviewed. The success of previous phytoremediation works conducted by different authors (Nichols et al., 1997; Dzantor et al., 2000; Tesar et al., 2002; Merkl et al., 2004b; Bamidele and Agbegidi, 2006; Osam et al., 2011; Atagana, 2011) using a range of plant species has shown that research on this emerging technology should be encouraged, strengthened and applied where applicable. This is especially the case in areas prone to hydrocarbon contamination such as the Niger Delta region of Nigeria. The findings of this work have revealed that phytoremediation, particularly rhizodegradation or rhizoremediation, could be employed in the remediation of hydrocarbon contaminated soils (Atagana, 2011; Osam et al., 2011; Oyedeji, 2016) and it also revealed that plants in the family Fabaceae have
been used for phytoremediation and found to be good candidates because of their extensive root system and ability to fix N within their root nodules. It is, therefore, hoped that land owners, farmers and governments at all levels will gain awareness of this viable ecosystem remediation technology for our ecosystems and support research on phytoremediation as a practical and effective technology for soil remediation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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