International Journal of Bioinformatics and Biomedical Engineering
Vol. 1, No. 1, 2015, pp. 7-15
http://www.aiscience.org/journal/ijbbe

Rhizosphere Microorganisms as Inducers for Phytoremediation a Review

Abdel Ghany T. M.[1, 2, *], Mohamed A. Al Abboud[2], Moustafa E. Negm[3], Abdel-Rahman M. Shater[2, 4]

[1]Botany and Microbiology Department, Faculty of Science, AL, Azhar University, Cairo, Egypt
[2]Biology Department, Faculty of Science, Jazan University, Jazan, Kingdom Saudi Arabia
[3]AL Ghad International Colleges for Applied Medical Science, Riyadh, Kingdom Saudi Arabia
[4]Biology Department, Faculty of Science, Thamar, Thamar University, Yemen

Abstract

Phytoremediation is a relatively new technology that offers clear advantages over traditional methods for site cleanup. Plants and their associated rhizosphere microorganisms can be used in the cleanup of environmental pollution. Knowledge of the mechanisms involved may lead to the development of more efficient phytoremadiants and better management practices such as development of transgenic plants. In this review, current status of several subsets of phytoremediation are discussed which includes: Phytoextraction: the uptake and translocation of dissolved-phase contaminants from groundwater into plant tissue., Phytovolatilization: the transfer of the contaminant to air via plant transpiration. Rhizosphere degradation: the breakdown of organic contaminants within the microbe rich rhizosphere (soil surrounding the root). Phytodegradation: the breakdown of organic contaminants within plant tissue. Hydraulic control: the use of trees to intercept and transpire large quantities of groundwater or surface water in order to contain or control the migration of contaminants. There is need for further understanding on the processes that affect pollutant uptake and sequestration.

Keywords

Rhizosphere, Microorganisms, Inducers, Phytoremediation

Received: June 15, 2015 / Accepted: June 17, 2015 / Published online: July 7, 2015

@ 2015 The Authors. Published by American Institute of Science. This Open Access article is under the CC BY-NC license.
http://creativecommons.org/licenses/by-nc/4.0/

1. Introduction

The rhizosphere defined by Hiltner as the volume of soil that is influenced by the roots of plants (Vargas et al., 2002). and according to Lynch (1990), this term can be defined as the three units interacting: the plant, the soil and the microorganisms. The composition of rhizosphere structure is highly orientated by the type of plant, quantity and composition of root exudates and different root zones (Marschner *et al*., 2004). The root-associated microorganisms establish a synergism with plant roots and can help the plant to absorb nutrients improving plant performance and consequently the quality of soils (Tinker, 1984; Yang et al., 2009).

Phytoremediation has evolved to become a potential technology for cleanup of contaminated sites (Schnoor *et al.,* 1995*,* Macek *et al.,* 2000). Within just a few years, phytoremediation has bloomed into a number of interesting, potential applications for treating specific elemental and organic contaminants. Phytoremediation has several advantages, mainly of being a low-cost, ecologically superior process and having strong public acceptance. In the mid-1990s, reports of rapid Trinitrotoluene (TNT) disappearance in aquatic plant systems (Wolfe *et al.,* 1994) stimulated research and field evaluations of phytoremediation of explosives using aquatic and terrestrial plants. Commercial

---

* Corresponding author
E-mail address: tabdelghany@yahoo.com (Abdel G. T. M.)

success of phytoremediation for explosives contamination hinges on many variables (Burken *et al.,* 2000), including insights into the actual biochemistry of the process (the enzymes involved and definitive reaction network of pathways) and plant tolerance to contaminants. Phytoremediation utilizes physical, chemical, and biological processes to remove, degrade, transform, or stabilize contaminants within soil and groundwater. The disappearance of TNT from the medium was connected with the uptake of TNT into the plant tissues and its transformation into degradation products. Aminodinitrotoluenes were found to be the main degradation products of TNT (Vanek *et al*., 2006). A soil bacteria, Enterobacter cloacae, was found to be able to use nitrate ester explosives as its source of nitrogen. Two enzymes identified in this bacterium are able to perform the denitrification reaction: pentaerythritol tetranitrate reductase and nitroreductase (French *et al*., 1999; Hannink *et al*., 2001), both reductases use NADPH as a source of electrons to reduce TNT into less harmful compounds. Trichoroethylene (TCE) is a halogenated compound used in the industry as a degreasing agent. It is one of the most widespread organic pollutants and it is particularly hard to remove because of its high mobility (Evans and Furlong, 2001). While rhizospheric bacteria have long been known to degrade TCE, it is only recently that the direct role of plant enzymes in this process has been discovered. In experiments using isotopiclabeling, Gordon *et al*. (1998) were able to show that hybrid poplar cell cultures were able to absorb TCE present in the growth medium and subsequently degrade it to trichloroethanol, trichloroacetate and finally to CO_2. Most research to date on phytoremediation of explosives has concentrated on elucidating the capability of plants to transform TNT. Several small-scale studies show that plants possess an inherent capacity to remove TNT and other nitroaromatics from soil and water (Palazzoand Leggett 1986*, Larson 1997, Pavlostathis et al., 1998, Rivera et al., 1998, Salt et al., 1998, Scheidemann et al., 1998, Bhadra et al., 1999a, Bhadra et al., 1999b, Larson et al., 1999a, Larson et al., 1999b).* Although plant growth-promoting rhizobacteria (PGPR) was first used for prompting the plant growth and for the biocontrol of plant diseases, much attention has recently been paid on bioremediation with PGPR (Huang *et al*., 2004; Huang *et al*., 2005). In contrast with inorganic compounds, microorganisms can degrade and even mineralize organic compounds in association with plants (Saleh *et al*., 2004). Bacteria capable of degrading certain kind of organic pollutant, such as polychlorinated biphenyls (PCBs) have been isolated from a range of sites and the pathways and encoding genes have also been well studied (Brazil *et al*., 1995). But most of these bacteria cannot survive in the near-starvation conditions found in soils, including the rhizosphere (Normander *et al*., 1999).

Phytoremediation can be classified according to the method and/or nature of the contaminant (Eapen *et al*., 2003, Newman and Reynolds, 2004; January *et al*., 2008) so; there are several names as follows: a) Phytoextraction: a removal process taking advantage of the unusual ability of some plants to (hyper-) absorbing and accumulating or translocating metals or/metalloids to the shoots. b) Phytostabilization (and immobilisation): a containment process using plants often in combination with soil additives to assist plant installation to mechanically stabilizing the site and reducing pollutant transfer to other ecosystem compartments and the food chain; the organic or inorganic compound can be incorporated to the lignin or to soil humus. c) phytostimulation: the growing root promotes the development of rhizosphere microorganisms capable of degrading the contaminant, using exudates as carbon source. d) Phytovolatilisation/rhizovolatilisation: removal processes employing metabolic capabilities of plants and associated rhizosphere microorganisms to transform pollutants into volatile compounds that are released to the atmosphere. Some ions of elements of sub-groups II, V and VI of the periodic table like mercury, selenium and arsenic are absorbed by root, then converted into less toxic forms and released (Chowdhury *et al*., 2015; Teng *et al*., 2015) . e) phytodegradation: organic contaminants are degraded or mineralized by specific enzyme activity. f) rhizofiltration : use terrestrial plants to absorb, concentrate and/or precipitate contaminants in the aqueous system.

2. Phytoremediation

Phytoremediation of organic contaminants primarily occurs by one or more of the following five mechanisms:

1. Phytoextraction: the uptake and translocation of dissolved-phase contaminants from groundwater into plant tissue.
2. Phytovolatilization: the transfer of the contaminant to air via plant transpiration.
3. Rhizosphere degradation: the breakdown of organic contaminants within the microberich rhizosphere (soil surrounding the root).
4. Phytodegradation: the breakdown of organic contaminants within plant tissue.
5. Hydraulic control: the use of trees to intercept and transpire large quantities of groundwater or surface water in order to contain or control the migration of contaminants.

2.1. Phytoextraction

Phytoextraction is one of the phytoremediation's subareas based on the use of pollutant-accumulating plants for trace elements and organics removal from soil by concentrating them in the harvestable parts (Salt *et al.,* 1998). Phytoextraction is the uptake and translocation of contaminants from groundwater into plant tissue as the plant takes in water and micronutrients from soil through its root system. Plant uptake of chlorinated solvents is influenced by many factors including soil pH, clay content, water content, and organic matter content, as well as the properties of the chlorinated solvent (Ryan *et al*., 1988; Yasin *et al.*, 2015).

The plant–rhizosphere interactions controlling trace element uptake by roots are of primary interest. To what extent root exudates can mobilize trace elements or if microbial rhizosphere communities stimulated by these root exudates (Anderson, 1997) can contribute to trace element phytoavailability remains to be further examined. As certain plants can use microbial siderophores to improve their iron uptake, it has been hypothesized that bacterial trace element chelators, such as siderophores, can eventually improve the uptake of heavy trace elements by plants (van der Lelie *et al*., 1999).

There are several advantages of phytoextraction. The cost of phytoextraction is fairly inexpensive when compared to conventional methods. Another benefit is that the contaminant is permanently removed from the soil. In addition, the amount of waste material that must be disposed of is substantially decreased (up to 95%) (USEPA, 2000) and in some cases, the contaminant can be recycled from the contaminated plant biomass.

2.2. Phytovolatilization

Phytovolatilization is the transfer of a contaminant to air via plant transpiration. Plants normally transpire water as vapor, but volatile compounds can be transpired as well. Phytovolatilization occurs via diffusion from the tree's xylem (a tissue that begins at the root of the tree and continues through the tree to the upper side of the leaf (Kozlowski and Pallardy, 1997) through its bark or leaves. Volatilization of CVOCs from plant tissues to the atmosphere is a major pathway for CVOCs in phytoremediation applications. Although transpiration of chlorinated solvents has been confirmed in studies, researchers predict that transpiration from vegetation will not result in unacceptable levels of airborne CVOCs in the surrounding area (Narayanan et al., 1999; and McCutcheon and Schnoor, 2003). This hypothesis is supported by earlier studies that could not detect VOCs in the middle of the phytoremediation test plots. Furthermore, calculations show that during the slightest of wind velocities, the flux of VOCs to the atmosphere from a phytoremediation application leads to trivial concentrations in the atmosphere. Phytovolatilization also involves contaminants being taken up into the body of the plant, but then the contaminant, a volatile form thereof, or a volatile degradation product is transpired with water vapor from leaves (EPA, 2000). Phytovolatilization may also entail the diffusion of contaminants from the stems or other plant parts that the contaminant travels through before reaching the leaves (Raskin and Ensley, 2000). The most common heavy metal contaminants are Cd, Cr, Cu, Hg, Pb and Ni. Metals are natural components in soil with a number of heavy metals being required by plants as micronutrients. However, pollution of biosphere by toxic metals has accelerated dramatically since the beginning of the industrial revolution. As a result of human activities such as mining and smelting of metals, electroplating, gas exhaust, energy and fuel production, fertilizer, sewage and pesticide application, municipal waste generation, etc. (Kabata-Pendias and Pendias, 1989), metal pollution has become one of the most severe environmental problems today.

2.3. Rhizosphere Degradation

One of the reasons for the prevalence of remediation methodologies, utilizing microbial remediation which represent deep understanding of the biochemistry behind the action of microbes (Rieger and Knackmuss, 1995) and hence the consequential incorporation of that knowledge into engineering design criteria. For phytoremediation to reach a similar level of acceptance, much work is required in gleaning information about the enzymes involved, metabolites produced, and final fates of compounds in the transformation pathway. Progress in understanding pollutant transformation pathways, determining carbon fates *via* mass balances, and identifying associated metabolites formed will go a long way in helping phytoremediation evolve into an industrially accepted procedure (January et al., 2008, Yasin et al., 2015).

Rhizosphere degradation is the breakdown of organic contaminants within the rhizosphere— a zone of increased microbial activity and biomass at the root-soil interface. Plant roots secrete and slough substances such as carbohydrates, enzymes, and amino acids that microbes can utilize as a substrate. Contaminant degradation in the rhizosphere may also result from the additional oxygen transferred from the root system into the soil causing enhanced aerobic mineralization of organics and stimulation of co-metabolic transformation of chemicals (Anderson *et al*., 1993; Abdel Ghany *et al*., 2013). Many studies have indicated that wetland vegetation and rhizosphere microbial communities can effectively treat chlorinated compounds (Dhanker *et al*., 1999, Nzengung *et al*., 1999; Kassenga, 2003).

2.4. Phytodegradation

Phytodegradation is the breakdown of organic contaminants within plant tissue. Although data are limited, it appears that both the plants and the associated microbial communities play a five significant role in attenuating chlorinated compounds. Phytodegradation involves the partial or complete degradation of contaminants by internal or secreted plant enzymes (Chris, 2010). As in phytodegradation, phytostimulation also involves enzymatic breakdown, but through microbial activity. Plants can stimulate microbial biodegradation in several ways. Since most organic pollutants can be broken down enzymatically, phytodegradation and phytostimulation are particularly effective for this class of pollutants.

2.5. Hydraulic Control

A great deal of research has focused on the use of trees-poplar trees, in particular-to intercept shallow groundwater plumes (Thomas and Krueger, 1999, Quinn *et al*., 2001). Most of these studies have shown that trees can extract large enough quantities of groundwater to depress the water table, locally inducing flow toward the trees. This depression can be sufficient to create a hydraulic barrier or hydraulic control. Hydraulic control mitigates potential risks by controlling offsite transport of CVOCs and providing more opportunity for the other four mechanisms of phytoremediation to remediate the CVOCs. Proper hydraulic control involves the selection and planting of vegetation to intercept and transpire large quantities of groundwater or surface water.

3. Biodegradation of Petroleum Hydrocarbons in the Rhizosphere

3.1. Plant-Induced Changes in Soil

Growing plants have profound impacts on the physical and chemical properties of soil. Most plants have an extensive rooting system that extends into the soil, penetrates micropores, disrupts some soil aggregates, creates channels for air and water penetration, enhances the development of soil structure, and exposes more soil surface area for microbial interaction. Plants excrete amino acids, carboxylic acids, carbohydrates, nucleic acid derivatives, growth factors, enzymes, and other related products (Alexander, 1977, Abdel Ghany, 2014). These compounds can promote flocculation of clays in soil and solubilize metals through chelation. In response to the nutrient status of the soil, roots may decrease pH, increase pH, or alter the oxidation-reduction potential of the rhizosphere. All these root-related factors can impact the degradation of petroleum hydrocarbons and other recalcitrant organic pollutants. Stimulated activities of rhizosphere microorganisms and exploration of the soil are thought to be the most important root-induced factors in accelerating the degradation of soil contaminants. Thus, understanding the physiology, structure, and growth habit of roots is critical to optimizing phytoremediation systems. Under field conditions, roots are frequently more variable in appearance and development than shoots. Root proliferation in favourable portions of the soil can fully compensate for poor growth in other areas of the soil.

Some of the most important root properties that may contribute to phytoremediation include root length, surface area, mass, depth of penetration, quantity and composition of dead roots and exudates, proliferation of root hairs, and bacterial and fungal associations. Factors that affect these root properties include air temperature, soil temperature, water availability, nutrient concentrations, plant species and variety, and the physical properties of the soil.

For hydrophobic large molecular contaminants, such as polycyclic aromatic hydrocarbons (PAHs) and other petroleum hydrocarbons, the likely mechanism for removal from soil is rhizosphere degradation (also known as plant-assisted bioremediation, (*McCutchean* and *Schnoor*). Uptake of these large molecules into the plant is improbable. The uptake of an organic compound by plants is dependent on the water solubility and octanol water partition coefficient *(*K_{ow}*)*. Schwarzenbach *et al.* (1993) present these and other properties of selected PAHs.

Phytoremediation of PAHs occurs primarily in the rhizosphere, *i.e.,* the small volume of soil immediately surrounding and most influenced by the root. The rhizosphere cannot be defined unambiguously, but compared to the bulk soil, this root zone generally has larger concentrations of plant exudates, elevated carbon dioxide (CO2) gas pressures, greater microbial activities, and is strongly subject to the depletion of cations and anions due to plant uptake. As a result, strong concentration gradients are established, creating a chemically dynamic system. Bacteria degrade PAHs in the rhizosphere in the presence of oxygen and nutrients. In aged soils contaminated with PAHs, the contaminants may be strongly sorbed to soil surfaces and are often found in very small interstices (less than or equal to 1 micrometer in diameter) of the soil. Roots can enhance micro-bial degradation by exploring otherwise inaccessible microzones of the soil. The most important property controlling the uptake of organics by plant roots is lipophilicity, *i.e.,* the distribution of a chemical between the soil solution and the lipids in the plant cells (Trapp and McFarlane, 1995).

3.2. Effect of Microorganisms

The primary factor influencing the phytoremediation of petroleum hydrocarbon contaminants in soil is microbial activity (Alexander, 1977, Abdel Ghany *et al*., 2013). Microbial populations and activity are strongly associated with the water and nutrient contents of the soil, the plant species, and the type of contaminant. Microbial activity is affected by soil pH and by temperature. In addition, the extensive root surface area of monocot grasses creates an optimal environment for the contaminant-degrading microorganisms (Tate, 1995).

Total microbial activity varies with the available water in soil and varies from almost no activity at low water potential to maximum activity at an optimum water-filled pore space of 60 % (Tate*,* 1995). Soil bacteria have been found to function in soil with water potentials as low as three megapascals (Wilson and Griffin, 1975*,* Wildung *et al.,* 1975). As the water-filled pore space increases toward saturation and available oxygen becomes limited, microbial activity declines.

3.3. Soil Physical Properties and Contaminant Degradation

The physical properties of soil influence both oxygen and water transport. Soils with high clay content tend to have lower hydraulic conductivities and lower diffusion coefficients than soils with low clay content. Soils with high clay content also tend to be dominated by very small interstices in which contaminants may become trapped and are inaccessible to microorganisms. The presence of vegetation affects many physical properties of soil, including structure, porosity, hydraulic conductivity, and infiltration rate. These properties, in turn, influence microbial activity by regulating the transport of required water and nutrients through the soil profile and by controlling soil aeration. Understanding how the presence of vegetation impacts soil structure is an important step toward identifying the mechanisms of phytoremediation. Bioremediation and rhizodegradation of petroleum hydrocarbons are driven by microorganisms, which in turn depend heavily on adequate moisture and oxygen.

4. Degradation of Aromatic Hydrocarbons in the Rhizosphere

Bioremediation of petroleum hydrocarbons in soil by indigenous microorganisms has been established as feasible treatment option. The biodegradation rate of the more recalcitrant and potentially toxic petroleum hydrocarbon contaminants such as PAHs, however, is initially high but quickly declines as the PAH-contaminated waste ages. Biodegradation of PAHs is limited by the strong adsorption potential and low water solubility. Vegetation plays an important role in the biodegradation of these toxic organic chemicals in soil because the presence of rhizosphere microorganisms accelerates biodegradation.

Plants can influence the biodegradation of contaminants in several ways. A large fraction of petroleum hydrocarbon contaminants can be strongly adsorbed on organic matter. Plants exude appreciable quantities of carbon through the root system. By increasing the organic matter content in contaminated soils, plants may affect contaminant bioavailability through sorption. Many petroleum contaminants are not readily desorbed and, consequently, are not available for bioremediation (Hatzinger and Alexander*,* 1995). Also, the effect of humification in the rhizosphere may be considerable. Free radicals in humus may react with PAHs forming electron donor acceptor complexes which may initiate covalent bonding of the PAHs or the associated metabolites to humic material (Mahro *et al.,* 1994). Increased mineralization *,i.e.,* conversion into carbon dioxide and water) and formation of inextricable, bound residues have been observed after compost addition to soil. Metabolic by-products that are formed from PAH biodegradation *,e.g.,* hydroxyl carbonic acids and phenolic compounds) can chemically interact with soil organics and can be incorporated into humic material, thereby forming these bound residues. Roots of all plants have at least some capability to penetrate soil aggregates and small pores. The fine roots of aggressive plants can disrupt soil aggregates, increase exposed surface area, and enhance biodegradation of entrapped hydrophobic contaminants. Root biomass may be as high as 20 grams per kilogram of soil with total root length as high as 100 meters per kilogram of soil (Detling, 1979).

Plants may indirectly contribute to the microbial degradation of highly sorbed contaminants such as PAHs. Rhizosphere soil adjacent to plant roots has been observed to contain greater microbial densities than those observed outside the soil rhizosphere (Paul and Clark 1989). In fact, Rovira and Davey (1974) determined that the number of bacteria quantified in rhizosphere soil was as much as 20 times greater than that normally quantified outside the soil rhizosphere. Short, gram-negative rods (specifically *Pseudomonas* spp., *Flavobacterium* spp., and *Alcaligenes* spp.) are the most common microorganisms found in the rhizosphere (Barber*,* 1984). The presence of plant exudates and seasonal root dieback are primarily responsible for the increased microbial population densities generally observed in rhizosphere soil. These materials serve as sources of energy, carbon, nitrogen, and growth factors for these populations. The activity of microorganisms in the root zone stimulates root exudation that further stimulates microbial activity (Barber and Martin, 1976).The effect of plants and the associated rhizosphere on the fate of petroleum hydrocarbon contaminants has been evaluated in several studies (Aprill and Sims, 1990, Schwab *et al.,* 1995, Reilley *et al.,*1996). In general, plants enhanced the removal of contaminants from soil. Also, in studies using [^{14}C]-labelled contaminants in closed plant chambers, mineralization was observed to be greater in rhizosphere soils than in soils without vegetation (Lee, 1996).

Aprill and Sims (1990) investigated the effects of using deep-rooted prairie grasses for remediation of PAH-contaminated soil. They suggested that due to the fibrous nature, the roots of these perennial grasses might be more effective in stimulating microorganisms in the rhizosphere. Big bluestem *(Andropogon gerardii),* Indian grass (*Sorghastrum nutans*), switchgrass *(Panicum virgatum),* Canada wild rye *(Elymus canadensis),* little bluestem *(Schizachyrium scopar-ius),* side oats grama *(Bouteloua curtipenduld),* western wheatgrass *(Agropyron smithii),* and blue grama *(Bouteloua gracilis)* were evaluated. After 219 days of growth, PAH removal was greater in the rhizosphere soil than outside the soil rhizosphere. The order of removal among the four PAHs that were investigated correlated with the water solubility of the compound; the most water-soluble PAH exhibited the greatest extent of degradation.

Schwab and Banks (1994) investigated the degradation of PAHs in the rhizosphere of a variety of plants grown in petroleum hydrocarbon-contaminated soil. Alfalfa (*Medicago sativa*), tall fescue (*Festuca arundinaced*), big bluestem (*Andropogon gerardii*), and Sudan grass (*Sorghum vulgare* var *sudanense)* were used. Pyrene was one of the target PAH compounds assessed in this study. After 4 weeks of plant growth, pyrene concentrations had decreased from an initial level of 100 milligrams per kilogram of soil to less than 12.6 milligrams per kilogram of soil. During week 24, concentrations of pyrene were less than 2.4 milligrams per kilogram of soil. Pyrene degradation was appreciably greater in vegetated soil than in barren soil.

Qui *et al.* (1994) assessed the removal of naphthalene in the presence of prairie buffalo grass *(Buchloe dactyloides* var. *prairie)* in a field test. The rate of naphthalene removal was greater in the presence of plants. Additional data generated during the investigation suggested that the presence of Verde klein-grass *(Panicum coloratum* var. *verde),* common buffalo grass (*Buchloe dactyloides*), and Meyer zoysiagrass *(Zoysia japonica* var. *meyer)* might also be effective in reducing concentrations of PAHs in soil.

Gunther *et al.* (1996) reported that ryegrass *(Lolium multiflorum)* effectively enhanced the degradation of petroleum hydrocarbons in the rhizosphere. After 22 weeks of plant growth, the extractable hydrocarbon concentration in the phytoremediated soil had been reduced by 97 percent, while only an 82 percent reduction was noted in the soil control without vegetation. Microbial analyses established that microorganisms in the rhizosphere were responsible for the degradation. Pradhan *et al.* (1998) determined that alfalfa *(Medicago sativa* L.), switch-grass *(Panicum virgatum),* and little bluestem (*Schizachyrium scoparius*) were effective in enhancing the degradation of PAHs in soil from a manufactured gas plant. Their results showed that alfalfa *(Medicago sativa* L.) removed 56 percent, switchgrass *(Panicum virgatum)* removed 57 percent, and little blue-stem *(Schizachyrium scoparius)* removed 47 percent of the total PAHs in soil. The PAHs were reduced by only 26 percent in the control without vegetation. The microbial densities of petroleum hydrocarbon degraders have been shown to be consistently greater in the rhizosphere soil than in soil without vegetation (Nichols *et al.* 1997). In addition, the microbial densities of petroleum hydrocarbon degraders have historically been shown to be greater in rhizosphere soil exposed to petroleum hydrocarbon contaminants than in soil with no or very little prior exposure (Radwan *et al.,*1998). Enhancement of petroleum hydrocarbon degradation in the rhizosphere is possible using a variety of plants. In addition to plant selection, site-specific issues such as soil characteristics and proper management of fertilization and irrigation are important in maintaining an efficient phytoremediation process.

5. Conclusion

Rhizosphere bioremediation or rhizodegradation is the enhanced biodegradation of recalcitrant organic pollutants by root-associated bacteria and fungi under the influence of select plant species. In addition, some root-released compounds have the capability to induce genes for enzymes responsible for microbial metabolism of recalcitrant organic pollutants. From the successive use of select vegetation and sound plant management practices, the total proportion of pollutant degraders will increase in numbers and activity in the rhizosphere, leading to enhanced rhizodegradation of recalcitrant organic pollutants and faster site recovery. Thus, the application of fundamental ecological principles to rhizo-sphere bioremediation designs is critical for success. Phytoremediation is evolving into a cost-effective means of managing wastes, especially excess petroleum hydrocarbons, polycyclic aromatic hydrocarbon, explosives, organic matter, and nutrients. Applications are being tested for cleaning up contaminated soil, water, and air. A number of important botanical processes have been discovered, including phytoextraction and hyperaccumulation from soil, plant-assisted microbial degradation of hydrocarbons in soil, use of specific enzymatic processes involved in created wetland treatment, and several other means of transforming and sequestering organic pollutants. The proven uptake and complete removal of low levels of explosives in aqueous plant systems suggest that plants show promise in the field for remediation of TNT.

References

[1] Abdel Ghany T. M.; Alawlaqi M. M. and Al Abboud M. A. (2013) Role of biofertilizers in agriculture: a brief review Mycopath, 11(2): 95-101.

[2] Abdel Ghany T. M. (2014) Eco-friendly and Safe Role of *Juniperus procera* in Controlling of Fungal Growth and Secondary Metabolites. J. Plant Pathol Microbiol 5(3): 1-9.

[3] Alexander, M. (1977) Introduction to Soil Microbiology. 2nd ed. John Wiley, New York, pp. 423-437.

[4] Anderson T (1997) Development of a phytoremediation handbook: consideration for enhancing microbial degradation in the rhizosphere. http://es.epa.gov/ncerga/ru/index.html.

[5] Anderson, T. A., E. A. Guthrie, and B.T. Walton (1993) "Bioremediation," Environmental Science and Technology. 27(13): 2630-2636.

[6] Aprill, W. and R.C. Sims (1990) Evaluation of the use of prairie grasses for stimulating polycyclic aromatic hydrocarbon treatment in soils. *Chemosphere* 20: 253-265.

[7] Barber, D. A. and J. K. Martin (1976) The release of organic substances by cereal roots into soil. *New Phytol.* 76: 68.

[8] Barber, S. A. (1984) *Soil Nutrient Bioavailability.* Wiley-Interscience, New York.

[9] Bhadra, R., D. G. Wayment, J. B. Hughes, and J. V. Shanks (1999b) Confirmation of conjugation processes during TNT metabolism by axenic roots. *Environ. Sci. Technol.* 33: 446-452.

[10] Bhadra, R., R.J. Spanggord, D.G. Wayment, J.B. Hughes, and J.V. Shanks (1999a) Characterization of Oxidation products of TNT metabolism in aquatic phytoremediation systems of *Myriophyllum aquaticum. Environ. Sci. Technol.* 33: 3354-3361.

[11] Brazil GM, Kenefick L., Callanan M., Haro A., de Lorenzo V., Dowling DN. Construction of a rhizosphere pseudomonad with potential to degrade polychlorinated biphenyls and detection of bph gene expression in the rhizosphere. Appl Environ Microbiol. 1995; 61:1946–52.

[12] Burken, J. G., J. V. Shanks, and P. L. Thompson (2000) Phytoremediation and plant metabolism of explosives and nitroaromatic compounds. In: *Biodegradation of Nitroaromatic Compounds and Explosives.* J. C. Spain, J. B. Hughes, and H. J. Knackmuss, eds. Lewis Publishers, Boca Raton, Florida, pp. 239-275.

[13] Chowdhury A. S. M. H. K, Das P., Sarkar I., Islam R., Aksharin L., Parvin F., Islam Z., Faris M. and Shaekh M. P. E. (2015). Phytoremediation of Heavy Metals (Ar, Cd, Pb) Using Transgenic Rice Plants - an Overview; international Journal of Scientific & Engineering Research, 6,1, 878-883.

[14] Detling, J. K. (1979) Processes controlling blue grama production on the shortgrass prairie. In: *Perspectives in grassland ecology.* N. French, ed. Springer-Verlag, New York, p. 25.

[15] Dhanker, O., J. Tucker, V. Nzengung, and N. Wolfe (1999) “Isolation, Purification and Partial Characterization of Plant Dehalogenase-like Activity from Waterweed (Elodea Canadensis),” In Phytoremediation and innovative strategies for specialized remedial applications 5th International Symposium In-Situ and On-Site Bioremediation. Phytoremediation, Eds: Andrea Leeson and Bruce C. Alleman. Batelle Press, Columbus. OH pp. 145-150.

[16] Eapen S, Suseelan KN, Tivarekar S, Kotwal SA, Mitra R. (2003) Potential for rhizofiltration of uranium using hairy root cultures of Brassica juncea and Chenopodium amaranticolor. Environ Res., 91:127–33.

[17] EPA (2000). A Citizen’s Guide to Phytoremediation. EPA 542-F-98-011. United States Environmental Protection Agency, p. 6. Available at: http//www.bugsatwork.com/ XYCLONYX/EPA_GUIDES /PHYTO.PDF.

[18] Evans, G. M. and J. C. Furlong. (2003) Environmental Biotechnology: theory and applications. (West Sussex, UK, John Wiley and Sons.

[19] French, C. E., S. J. Rosser, et al. (1999) Biodegradation of explosives by transgenic plants expressing pentaerythritol tetranitrate reductase. Nat. Biotechnol. 17, 491-4.

[20] Gordon M, Choe N, Duffy J, Ekuan G, Heilman P, Muiznieks I, Ruszaj M, Shurtleff BB, Strand S, Wilmoth J, Newman LA. (1998) Phytoremediation of trichloroethylene with hybrid poplars. Environ Health Perspect. 106, 1001-4.

[21] Gunther T., U. Dornberger, and W. Fritsche (1996). Effects of ryegrass on biodegradation of hydrocarbons in soil. *Chemosphere* 33: 203-215.

[22] Hannink, N., S. J. Rosser, et al. (2001). Phytodetoxification of TNT by transgenic plants expressing a bacterial nitroreductase. Nat. Biotechnol. 19, 1168-72.

[23] Hatzinger, P.B. and M. Alexander (1995). Effect of aging of chemicals in soil on their biodegradability and extractability. *Environ. Sci. Technol.* 29(12): 537-545.

[24] Huang XD, El-Alawi Y, Gurska J, Glick BR, Greenberg BM. (2005). A multi-process phytoremediation system for decontamination of persistent total petroleum hydrocarbons (TPHs) from soils. Microchem J., 81:139–47.

[25] Huang XD, El-Alawi Y, Penrose DM, Glick BR, Greenberg BM. (2004) A multiprocess phytoremediation system for removal of polycyclic aromatic hydrocarbons from contaminated soils. Environ Pollut., 130:465–76.

[26] Chris O. Nwoko (2010) Trends in phytoremediation of toxic elemental and organic pollutants. African Journal of Biotechnology Vol. 9 (37), pp. 6010-6016.

[27] January MC, Cutright TJ, Van Keulen H, Wei R. (2008) Hydroponic phytoremediation of Cd, Cr, Ni, As, and Fe: can Helianthus annuus hyperaccumulate multiple heavy metals? Chemosphere. 2008; 70:531–7.

[28] Kabata-Pendias A, Pendias H. Trace Elements in the Soil and Plants. Boca Raton, FL: CRC Press; 1989.

[29] Kassenga, G. (2003) “Treatment of Chlorinated Volatile Organic Compounds Using Wetland Systems,” PhD Dissertation Louisiana State University, The Department of Civil and Environmental Engineering.

[30] Kozlowski, T., and S. Pallardy (1997) “Physiology of Woody Plants,” Second Edition. Academic Press, San Diego.

[31] Larson, S.L. (1997). Fate of explosive contaminants in plants. In: *Bioremediation of Surface and Subsurface Contamination.* R.K. Bajpai and M.E. Zappi, eds. *Ann. New York Acad. Sci.,* New York, 829: 195-201.

[32] Larson, S.L., C.A. Weiss, L.B. Escalon, and D.B. Parker (1999b). Increased extraction efficiency of acetonitrile/water mixtures for explosive determination in plant tissues. *Chemosphere* 38(9): 2153-2162.

[33] Larson, S. L., R. P. Jones, L. Escalon, and D. Parker (1999a). Classification of explosives transformation products in plant tissue. *Environ. Toxicol. Chem.* 18(6): 1270-1276.

[34] Lee, E. (1996). The fate of polycyclic aromatic hydrocarbons in the rhizosphere of *Festuca arundinacea.* Ph.D. dissertation, Dept. of Civil Engineering, Kansas State University, Manhattan.

[35] Lynch JM. 1990The rhizosphere. New York: John Wiley and Sons.

[36] Macek, T., M. Mackova, and J. Kas (2000). Exploitation of plants for the removal of organics in environmental remediation. *Biotechnol. Adv.* 18: 23-34.

[37] Mahro, B., G. Schaefer, and M. Kastner (1994). Pathways of microbial degradation of polycyclic aromatic hydrocarbons in soil. In: *Bioremediation of Chlorinated and Aromatic Hydrocarbon Compounds.* R.E. Hinchee, A. Leeson, L. Semprini, and S.K. Ong, eds. Lewis Publishers, Boca Raton, Florida, pp. 203-217.

[38] Marschner P., Crowley D., Yang C.H. (2004) Development of specific rhizosphere bacterial communities in relation to plant species, nutrition and soil type. Plant Soil. , 261: 199–208.

[39] McCutcheon, S. and J. Schnoor (eds.) (2003) Phytoremediation Transformation and Control of Contaminants. John Wiley & Sons, Inc., Hoboken, New Jersey.

[40] Narayanan, M., L. C. Davis, and L.E. Erickson (1995) “Fate of Volatile Chlorinated Organic Compounds in a Laboratory Chamber with Alfalfa Plants,” Environmental Science and Technology. 29(9): 2437-2444.

[41] Newman LA, Reynolds CM. 2004. Phytodegradation of organic compounds. Curr Opin Biotechnol.; 15:225–30.

[42] Nichols, T. D., D. C. Wolf, H.B. Rogers, C. A. Beyrouty, and CM. Reynolds (1997). Rhizosphere microbial populations in contaminated soils. *Water, Air Soil Pollut.* 95: 165-178.

[43] Normander B, Hendriksen NB, Nybroe O. 1999. Green fluorescent protein-marked Pseudomonas fluorescens: localization, viability, and activity in the natural barley rhizosphere. Appl Environ Microbiol. ; 65:4646–51.

[44] Nzengung, V., N. Wolfe, D. Rennels, and S. McCutcheon (1999). “Use of Aquatic Plants and Algae for Decontamination of Waters Polluted with Chlorinated Alkanes,” International Journal of Phytoremediation. 1(3): 203-226.

[45] Palazzo, A. J. and D. C. Leggett (1986) Effect and disposition of TNT in terrestrial plants. *J. Environ. Qual.* 15(1): 49-52.

[46] Paul, E. A. and F. E. Clark (1989) Soil Microbiology and Biochemistry. Academic Press, San Diego, California, pp. 81-84.

[47] Pavlostathis, S.G., K.K. Comstock, M.E. Jacobson, and M.F. Saunders (1998). Transformation of 2,4,6-trinitrotoluene by the aquatic plant *Myriophyllum spicaticum. Environ. Toxicol. Chem.* 17(11): 2266-2273.

[48] Pradhan, S.P., J.R. Conrad, J.R. Paterek, and V.J. Srivastava (1998). Potential of phytoremediation for treatment of PAHs in soil at MGP sites. *J. Soil Contam.* 7: 467-480.

[49] Qui, X,, S.I. Shah, E.W. Kendall, D.L. Sorenson, R.C. Sims, and M.C. Engelke (1994) Grass-enhanced bioremediation for clay soils contaminated with polynuclear aromatic hydrocarbons. In: *Bioremediation through Rhizosphere Technology.* ACS Symposium Series No. 563. T.A. Anderson and J.R. Coats, eds. American Chemical Society, Washington, D.C, pp. 142-157.

[50] Quinn, J., M. Negri, R. Hinchman, L. Moos, J. Woznaik, E. Gatliff (2001) “Predicting the Effect of Deep-rooted Hybrid Poplars on the Groundwater Flow System at a Large-scale Phytoremediation Site,” International Journal of Phytoremediation. 2(3): 193-211.

[51] Radwan S. S., H. Al-Awadhi, N. A. Sorkhoh, and I. M. El-Nemr (1998) Rhizospheric hydrocarbon-utilizing microorganisms as potential contributors to phytoremediation for the oily Kuwaiti desert. *Microbiol. Res.* 153: 247-251.

[52] Raskin, I., and Ensley, B. D. (2000) Recent developments for in situ treatment of metal contaminated soils. In: Phytoremediation of Toxic Metals: Using Plants to Clean Up the Environment. John Wiley & Sons Inc., New York. Available at: http//clu-n.org/techfocus.

[53] Reilley, K., M. K. Banks, and A. P. Schwab (1996) Dissipation of polynuclear aromatic hydrocarbons in the rhizosphere. *J. Environ. Qual.* 25: 212-219.

[54] Rieger, P.-G. and H.-J. Knackmuss (1995) Basic knowledge and perspectives on bio-degradation of 2,4,6-trinitrotoluene and related nitroaromatic compounds in contaminated soil. In: *Biodegradation of Nitroaromatic Compounds.* J.C. Spain, ed. Plenum Press, New York, pp. 1-18.

[55] Rivera, R., V. F. Medina, S. L. Larson, and S. C. McCutcheon (1998) Phytotreatment of TNT-contaminated groundwater. *Soil Contam.* 7(4): 511-529.

[56] Rovira, A. D. and CB. Davey (1974) Biology of the rhizosphere. In: *The Plant Root and its Environment.* E. W. Carson, ed., University Press of Virginia, Charlottesville, pp. 153-204.

[57] Ryan, J. A., R. M. Bell, J. M. Davidson, and G. A. O'Connor (1988). “Plant Uptake of Nonionic Organic Chemicals from Spills,” Chemosphere. 17: 2299-2323.

[58] Saleh S, Huang XD, Greenberg BM, Glick BR. (2004) Phytoremediation of persistent organic contaminants in the environment. In: Singh A,Ward O, editors. Soil Biology: vol. 1. Applied Bioremediation and Phytoremediation. Berlin: Springer-Verlag, p. 115–34.

[59] Salt DE, Smith RD, Raskin I (1998) Phytoremediation. Annu Rev Plant Physiol Mol Biol 49:643–668.

[60] Salt, D.E., R.D. Smith, and I. Raskin (1998) Phytoremediation. In: *Annual Review of Plant Physiology and Plant Molecular Biology*. Annual Reviews, Palo Alto, California: 49: 643-648.

[61] Scheidemann, P., A. Klunk, C. Sens, and D. Werner (1998) Species dependent uptake and tolerance of nitroaromatic compounds by higher plants. *J. Plant Physiol.* 152(2-3): 242-247.

[62] Schnoor, J. L., L. A. Licht, S.C. McCutcheon, N. L. Wolfe, and L. H. Carreira (1995) Phytoremediation of organic and nutrient contaminants. *Environ. Sci. Technol.* 29: 318A-323A.

[63] Schwab, A. P. and M.K. Banks (1994) Biologically mediated dissipation of polyaro-matic hydrocarbons in the root zone. In: *Bioremediation through Rhizosphere Technology*. ACS Symposium Series No. 563. T.A. Anderson and J. R. Coats, eds. American Chemical Society, Washington, D. C., pp. 132-141.

[64] Schwab, A. P., M. K. Banks, and M. Arunuchalam (1995) Biodegradation of polycyclic aromatic hydrocarbons in rhizosphere soil. In: *Bioremediation of Recalcitrant Organics*. R. E. Hinchee, R. H. Hoeppel, and D.B. Anderson, eds. Battelle Press, Columbus, Ohio, pp. 23-29.

[65] Schwarzenbach, R. P., P. M. Gschwend, and D. M. Imboden (1993) *Environmental Organic Chemistry*. John Wiley, New York, pp. 682.

[66] Tate, R. L. (1995) *Soil Microbiology*. John Wiley, New York. p. 107.

[67] Teng Y, Luo Y, Ma W, Zhu L, Ren W, Luo Y, Christie P and Li Z (2015) *Trichoderma reesei* FS10-C enhances phytoremediation of Cd-contaminated soil by *Sedum plumbizincicola* and associated soil microbial activities. *Front. Plant Sci.* 6:438. doi: 10.3389/fpls.2015.00438

[68] Thomas, P. and J. Krueger (1999). “Salt Tolerance of Woody Phreatophytes for Phytoremediation Applications,” In Phytoremediation and Innovative Strategies for Specialized Remedial Applications, Editors, Andrea Leeson and Bruce C. Alleman, Battelle Press.

[69] Tinker PB. 1984. The role of microorganisms in mediating and facilitating the uptake of plant nutrients from soil. Plant Soil. 1984; 76:77–91.

[70] Trapp, S. and C. McFarlane (1995) Plant Contamination: Modeling and Simulation of Organic Processes. Lewis Publishers, Boca Raton, Florida, 254 pp.

[71] USEPA (United States Environmental Protection Agency) (2000) Introduction to Phytoremediation. EPA 600/R-99/107, U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH.

[72] van der Lelie D, Corbisier P, Diels L, Gilis A, Lodewyckx C, Mergeay M, Taghavi S, Spelmans N, Vangronsveld J (1999) The role of bacteria in the phytoremediation of heavy metals. In: Terry N, Banuelos G (eds) Phytoremediation of contaminated soils and wate. CRC, Boca Raton, pp 265-281. ISBN ISBN 1-56670- 450-2.

[73] Vanek T. , Ales Nepovim , Radka Podlipna , Anja Hebner , Zuzana Vavrikova , Andre Gerth , Hardmuth Thomas and Stanislav Smrcek 2006. Phytoremediation of explosives in toxic wastes .Phytoremediation of Explosives in Toxic Wastes. 455- 465.

[74] Vargas JP, Esquivel GG, García FE. (2002) Papel ecológico de la flora rizosférica en fitorremediación. Av Perspect. , 21:297–300.

[75] Wildung, R. E., T. R. Garland, and R. L. Buschbom (1975) The interdependent effects of soil temperature and water content on soil respiration rate and plant root decomposition in arid grassland soils. *Soil Biol. Biochem.* 7: 373-378.

[76] Wilson, J. M. and D. M. Griffin (1975) Water potential and the respiration of microorganisms in the soil. *Soil Biol. Biochem.* 7: 199-204.

[77] Wolfe, N. L., T. Y. Ou, L. Camera, and D. Gunnison (1994) Alternative methods for biological destruction of TNT: a preliminary feasibility assessment of enzymatic degradation. U.S. Army Corps of Engineers Waterways Technical Report IRRP-94-3, Vicksburg, Mississippi.

[78] Yang J, Kloepper JW, Ryu C-M. (2009) Rhizosphere bacteria help plants tolerate abiotic stress. Trends Plant Sci.;14:1–4.

[79] Yasin, M., El-Mehdawi, A. F., Jahn, C. E., Anwar, A, Turner, M. F. S., Faisal, M., et al. (2015) Seleniferous soils as a source for production of selenium-enriched foods and potential of bacteria to enhance plant selenium uptake. Plant Soil 386, 385–394. doi: 10.1007/s11104-014-2270-y.