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REVIEW ARTICLE

Phytoremediation - A sustainable approach for contaminant remediation in arid and semi-arid regions – a review

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Abstract

Existing information relating to the application of phytoremediation in arid regions, for mitigating the toxicity of organic and inorganic contaminants is summarized, emphasizing the comparative merits of different phyto-strategies. Adverse climatic conditions in arid and semi-arid environments along with the intrinsic abiotic stresses need specific considerations, which are discussed here. The current "state of art" for petrochemical and metal phytoremediation, as well as phytodesalination is presented, making it possible to choose the very best decision, when the technology is applied for various contaminant scenarios. Information is also provided on contaminants in arid regions, remediation approaches and different phytoremediation strategies to be adopted, depending on the nature of contaminants and the site situations. Furthermore, phytodesalination may well occur in parallel with phytoremediation of heavy metal polluted soils in arid regions, enhancing the potential of this process. This has drawn a great deal of interest during recent years and is reviewed here. Finally, the lacunae in the current knowledge are identified, which has to be addressed to improve the effectiveness of phytoremediation under arid conditions.

Key words: Contaminants, Pollution, Arid soils, Phytoremediation, Phytodesalination

Abbreviations: BCF – Bioconcentration factor, EC - Enrichment Coefficient, ECR – Enrichment Coefficient (Root), ECS - Enrichment Coefficient (Shoot), EPA - Environmental Protection Agency, TF - Translocation Factor, TPH – Total Petroleum Hydrocarbons, UNEP – United Nations Environment Program, PCS – Petroleum Contaminated Soil

1. Introduction

Arid environments are really different in terms of their land forms, soils, fauna, flora, water balance, and human activities. Arid and semi-arid regions cover fairly huge areas of our planet, representing about one third to one fourth of the total land mass of earth (Dan, 1973). The soils are often saline, as evaporation rates exceed rainfall and natural salts derive from saline rainfall, unweathered minerals, and fossil salts (Mendez and Maier, 2008). They have low contents of organic matter and moisture, and are usually subjected to rather harsh environmental conditions, e.g., extreme temperatures and irradiance (Radwan, 2009). Arid zones are classified as desert (< 100 mm annual rainfall), semi-desert (100 to 300 mm annual rainfall), low rainfall woodland savanna (300 to 600 mm annual rainfall), and evergreen scrub (> 500 mm annual rainfall) (Verheye, 2009). The arid climate in Middle East region is characterized by constant hot prevailing winds with low precipitation. In arid and semiarid regions, plant establishment is restricted by a number of physicochemical factors including extreme temperature, low precipitation, and high velocity winds. These factors contribute to the development of extremely high salt concentrations, up to 22 dS m^{-1} due to high evaporation and low water infiltration (Munshower, 1994). Vegetation in arid zones comprises of ephemeral annuals (growth restricted to short wet periods), succulent perennials (store water for drought), and non-succulent perennials (withstand the stress of arid environment) (Virheye, 2009).

Land and water contamination is a relevant

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problem, observed in arid region habitats (Virheye, 2009). Along with drought and salinity, organic and inorganic contaminants pose huge threats to the environment. There are several remediation approaches to prevent the contaminants from polluting the environment (Frick et al., 1999). Phytoremediation is a proven technology to clean up metals, pesticides, solvents, explosives, crude oil, polyaromatic hydro-carbons, and landfill leachates (Hughes et al., 1997). Phytoremediation can be used along with other cleanup approaches as a 'finishing' or 'polishing' step. Generally, the use of phytoremediation is limited to sites with low to medium contaminant concentrations, and contamination in shallow soils, where phytotoxicity does not occur and the roots of plants can easily access the contaminants (Pivetz, 2001). Grasses, shrubs as well as trees can be used for phytoremediation. Grasses provide a ground cover and limit wind dispersion of tailings, whereas shrubs and trees provide an extensive canopy and establish a deep root network to prevent erosion (Williams and Currey, 2002).

Although phytoremediation of contaminated sites in arid and semiarid regions has been attempted by many organizations, the remediation technologies are not properly documented and occasionally appear in published literature. In this review, the current knowledge of phytoremediation for organic and inorganic contaminants in arid and semiarid environments as well as the potential problems that have an impact on the long-term success of this technology is discussed. .

2. Contaminants in arid regions

"Contaminated land" is a special designation assigned to a land site where a significant level of ground (soil and/or water) pollution has been detected. Soil, surface and groundwater contamination is the result of sustained accumulation of toxic compounds above permissible levels, due to the release of organic and inorganic compounds into the environment. Releases are deliberate and well regulated in some cases (e.g., industrial emissions) while in other cases, they are accidental and largely unavoidable (e.g., oil/chemical spills). These contaminants become pollutants when their concentrations exceed certain threshold limits to have an impact on the environment. This causes serious threat to the environment and human health. When it happens under arid conditions, the problems associated with aridity such as salinity, drought etc. make them more threatening.

The contamination by petroleum hydrocarbons (crude oil) is a major problem observed in arid region soils, especially in the Middle East. Petroleum hydrocarbons are naturally occurring chemicals used by humans for a variety of activities, including the fueling of vehicles and heating of homes (Frick et al., 1999). Due to the extensive production and use of crude oil, their products and derivatives as energy sources, they have become major environmental pollutants in the Middle East (Radwan, 2009). This could be due to oil tanker accidents, tank ruptures, process leaks, or drilling activities, resulting in marine and terrestrial spills. Moreover, petroleum was impregnated to soil during the exploration, translocation, and processing, causing significant environmental pollution (Banks et al., 2000). When the soil is contaminated with oil there is an imbalance in the carbon-nitrogen ratio at the fall site, because crude oil is a blend of carbon and hydrogen. This causes nitrogen deficiency, which retards the growth of bacteria and the utilization of carbon sources. Moreover, large concentrations of biodegradable organics in the top layer exhaust oxygen reserves in the soil, decelerating the rate of oxygen diffusion into deeper layers. When a hydrocarbon spill occurs, in most cases, salt water is also involved. Thus, the impact from both sodium chloride and hydrocarbons will affect soil structure and plant growth.

Large quantities of oil production waters (OPWs) are a byproduct from oil fields and they reach to a total volume of one million m^3 day^{-1} in Oman (Mahruki et al., 2006). These OPWs are contaminated with 10-800 mg L^{-1} petroleum hydrocarbons and a variety of metals at reasonably low concentrations. With a typical electrical conductivity (EC) of 12 dS m^{-1}, they are quite saline and contain organic and inorganic suspended particles. Regardless of environmental concerns, re-injection into deep or shallow aquifers is the only alternative for its disposal (Mahruki et al., 2006). There are different types of petroleum hydrocarbons such as natural gas, crude oil, tars and asphalts. They are made up of various proportions of alkanes (*e.g.*, methane, ethane, propane), aromatics (*e.g.*, benzene, toluene, ethylbenzene, and xylene, collectively known as BTEX), and polycyclic aromatic hydrocarbons (PAHs; *e.g.*, naphthalene, phenanthrene, anthracene, benzopyrene) (Mackay, 1991, Committee on In Situ Bioremediation et al., 1993, Lyons, 1996). Industrialization has caused the contamination of a significant number of sites with petroleum and petroleum byproducts (Bauman, 1991). Crude oil is composed of four major constituents: saturated hydrocarbons, aromatic hydrocarbons, asphaltenes and resins (Leahy and Colwell, 1990). Among the alkanes, higher straight chain alkanes and polycyclic aromatic compounds do not usually degrade by traditional methods (Abraham, 2011). The different types of organic contaminants are given in Table 1.

Soil pollution with crude oil and its products may affect the plants growing there. The contact toxicity arises from low boiling point hydrocarbons which may dissolve and harm cell membranes of fragile portions of plant roots and shoots (McGill et al., 1981). Inadvertent harmful effects include oxygen denial of plant roots as a result of oxygen exhaustion by the rhizospheric microflora, particularly the hydrocarbon-utilizing microorganisms (Bossert and Bartha, 1984). Transitional products arising from microbial hydrocarbon degradation may also exhibit phytotoxicity, *e.g.*, fatty alcohols, fatty aldehydes, fatty acids, terpenoids and others (Stevenson, 1966).

The major inorganic contaminants in arid region soils comprise of metals: silver (Ag), mercury (Hg), cadmium (Cd), zinc (Zn), copper (Cu), lead (Pb), chromium (Cr), arsenic (As), etc., major ions and nutrients: chloride (Cl), nitrate (NO_3), sulphate (SO_4), bicarbonate (HCO_3), ammonia (NH_3), phosphate (PO_4), sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), etc. The main sources of heavy metal contaminants in soils are metalliferous mining and smelting sites, metallurgical industries, sewage sludge treatment, warfare and military training, waste disposal sites, agricultural fertilizers and electronic industries (Alloway, 1995). Mine tailings rich in sulphide minerals may form acid mine drainage (AMD), containing very high concentration of metals that could be harmful to animals and plants (Stoltz, 2004). Vehicular traffic also causes metal contamination (Padmavathiamma and Li, 2008).

Heavy metal contaminants cause DNA damage, and their carcinogenic effects in animals and humans are possibly caused by their mutagenic ability (Knasmuller et al., 1998; Baudouin et al., 2002). In fact, exposure to high levels of these metals has been connected to undesirable effects on human health and wildlife. Lead poisoning in children causes neurological damage leading to reduced intelligence, loss of short term memory, learning disabilities and coordination problems.

High anthropogenic contamination of groundwater with nitrate in an arid region of Algeria (Southern Hodna) was revealed in a case study by Abdesselam et al. (2013). Efficient irrigation techniques, localized irrigation as well as adaptation of cropping systems and fertilizer inputs were suggested to prevent nitrate leaching in arid conditions. Nonetheless, insignificant concentrations of Cu, Ni, Pb and Zn were observed in soil and water samples collected from different sites of Oman (Abdelrahman and Al-Ajmial, 1994).

Table 1. Organic Contaminants.

Petroleum hydrocarbons	Gasoline (C6 to C12 hydrocarbons), Diesel (C12 to C24 hydrocarbons), Motor oil (C20 and larger hydrocarbons), Bunker C (C20 and larger hydrocarbons).
Poly-nuclear Aromatic Hydrocarbons (PAHs)	Napthalene, Fluorene, Pyrene, Benzo(a)pyrene and Anthracene.
Phenols	Pentachlorophenol (PCP), Tetrachlorophenol
Chlorinated solvents	Trichloroethene (TCE), 1,1,1-Trichloroethane (1,1,1-TCA), Tetra or perchloroethylene (PCE), Methylene chloride, Chlorobenzenes, Freons
Polychlorinated biphenyls (PCBs), pesticides	DDT, Chlordane, 2-4-D, toxaphene, Lindane, Ethylene dibromide, 1.2-dichloropropane

Large concentrations of nitrate in desert soils, within a few meters of land surface and below the biologically active root zone, cause a great threat to the environment (Walvoord et al., 2003). Apart from the organic and inorganic contaminants discussed above, the most important contaminant factor in arid and semi-arid regions is salinity, which affects fresh water and soil. Irrigation has resulted in the buildup of salts to above normal concentrations in the rooting zone of arable land, as high rates of evaporation and transpiration draw soluble salts from deep layers of the soil profile under arid conditions (Rozena and Flowers, 2008). The mobility of heavy metals, such as As, Cu and Zn, is facilitated by the chemical properties of soil and aridity of climate in the Kyzykum deserts, which can create a serious environmental impact (Ozturh et al., 2010).

3. Remediation approaches

Because of the serious environmental and human health problems caused by the increased accumulation of organic and inorganic contaminants in soils and water, there is a pressing need for a cost-effective, and an environment-friendly technology for the remediation of these contaminants. Today, environmental management can gain from a variety of approaches to remediate metal and petroleum-contaminated soil and groundwater. These approaches vary from intensive engineering techniques to natural attenuation, an approach relying entirely on natural processes to remediate sites with no human involvement. Physical, chemical and biological remediation methods are recognized. Physical and chemical methods are expensive and make the soil useless as a medium for plant and microbial growth after remediation. Hence, a method that can maintain the functional and biological integrity of soil after remediation is obligatory. Bioremediation, the containment or removal of contaminants by microorganisms could be an ecologically safe and economically feasible method of remediation. It can be used along with other physical and chemical technologies, which would reduce the surface tension phenomenon normally linked with hydrocarbon spillage on substrates like soil and water (Abraham, 2011). There is a bunch of literature on the biodegradation of pesticides in the rhizosphere of many plant species (Anderson et al., 1993; Atlas and Bartha, 1998). Jamrah et al. (2007) studied the leaching characteristics of petroleum contaminated soil (PCS), and their application in hot mix asphalt concrete. The total petroleum hydrocarbons (TPH) present in the PCS before and after bioremediation treatment was found to be 6.8% and 5.3% by dry weight, signifying a reduction of 1% in the TPH of PCS due to the bioremediation treatment.

Enhanced biodegradation of the contaminants in the rhizosphere was attributed to higher microbial activities compared to those in the unvegetated soil (Radwan, 2009). As stated earlier ,the typical remediation methods for petroleum- and metal-contaminated soil involve excavating the soil and relocating it for treatment using physical or chemical methods (Hans-Holgar and Alexander, 2000; Juck et al., 2000). Nevertheless, these treatments, are expensive and involve extensive site disturbance. Hence, a financially acceptable and ecologically safe option is a biological technique such as phytoremediation, which uses living green plants *in situ* to ‘‘clean-up’’ contaminated lands.

4. Phytoremediation

Phytoremediation is a sustainable, cost effective, environment friendly technique for contaminant remediation in soil, water and sediments. It involves the use of plants to remove, transfer, stabilize and/or degrade contaminants in soil, sediment and water (Hughes et al., 1997). It is a low input approach depending on natural attenuation by biodegradation and physiochemical mechanisms that decrease the pollutant concentration (Schwab and Banks, 1994; Parrish et al., 2005).

The implementation of phytoremediation in arid regions requires special plant selection and is anticipated to be less feasible than in humid regions with more favorable climate for plant growth. The arid climate, characterized by low annual rain fall and high wind make the phytoremediation research challenging in the Middle East. Phytoremediation in arid and semiarid environments necessitates setting up a varied plant community, including drought-, metal-, and salt-tolerant plants that can accumulate, stabilize or degrade contaminants. The plants for phytoremediation should be preferably indigenous to the area in which the contaminants are found, as they have developed adaptation and survival mechanisms suitable to the harsh climate of arid and semiarid environments (Piha et al., 1995). There is a great deal of environmental concern about the use of exotic species and their threat to indigenous plant communities. Hence, attention should be given to the use of exotic species before efforts are made to develop these plants for phytoremediation. This should include discussions with concerned regulatory agencies and public organizations about the suitability of the plant species as well. However, non-native species may be an acceptable option, provided the climatic conditions are the same and the introduced species do not build a new ecological risk (Radwan, 2009). Till date, many trials have not taken advantage of indigenous plant diversity, resulting in poor plant colonization under arid conditions.

Phytoremediation, which involves the growth of plants, have chemical and biological impacts on the soil under arid conditions. The breaking up of soil clods is a physical effect of root tips pushing through the soil as the root tips grow. Growth of roots can form macropores in the soil, which can contribute to soil aeration, water holding capacity as well as the transport of contaminants in the soil. The increase in the organic matter content of soil by the growth of plants improves the structure and ‘workability’ of soil in aridisols. Root exudates such as organic acids, phenolics, sugars, polysaccharides etc can change the metal speciation (*i.e.*, form of the metal), and the uptake of metal ions and simultaneous release of protons. This acidifies the soil and promotes the metal transport and bioavailability (Ernst, 1996). In some cases, the changed metal speciation can lead to increased precipitation and immobility of the metals, reducing the environmental impact (Padmavathiamma and Li, 2008). The organic compounds in the root exudates can encourage microbial growth in the rhizosphere (the region immediately surrounding plant roots). Mycorrhizae associated with some plant roots can also influence the soil microclimate, complementing phytoremediation. The organic matter content of the soil contributed by decaying roots as well as plant remains changes the pedogenic properties, leading to humification and increased sorption of contaminants (Ernst, 1996). Phytoremediation can restore the balance in a stressed environment by the natural, synergistic relationships among plants, microorganisms and the environment. Thus, phytoremediation is a continuum of different processes, occurring to differing degrees for different conditions, media, contaminants, and plants (Padmavathiamma and Li, 2007). For establishing an appropriate plant-microbe community, human involvement is necessary at the site. Suitable agronomic techniques such as tillage and fertilizer application have to be applied as well, to enhance natural degradation or containment processes (Cunningham and Ow, 1996). There is an extensive body of research during the past decade, on the suitability of phytoremediation for organic and inorganic contaminants in soil and water (Singer et al., 2003; Pilon-Smiths, 2005, Padmavathiamma and Li, 2007; Campos et al., 2008; Lee, 2013). The different phyto-strategies that can lead to contaminant degradation, removal (through accumulation or dissipation) or immobilization are given in Table 2.

It is necessary to make sure that unnecessary transport of contaminants to other media does not occur with any phytoremediation strategy. This is applicable to all contaminants, such as petroleum hydrocarbons, chlorinated solvents, metals, radionuclides, nutrients, pentachlorophenol (PCP), and polycyclic aromatic hydrocarbons (PAHs). Various plants, including canola (*Brassica napus* L.), oat (*Avena sativa*), and barley (*Hordeum vulgare*), tolerate and accumulate metals such as Se, Cu, Cd and Zn (Ebbs et al., 1997). Contaminants move through apoplastic or symplastic pathways, in the epidermis and through the casparian strip, go into the endodermis, where they can be sorbed, bound, or metabolized. Metabolites from the endodermis reach the xylem and are then transported in the transpiration stream or sap. These compounds may be sequestered in plant tissues, metabolized or released to the atmosphere through stomatal pores (Paterson et al., 1990; Shimp et al., 1993). Reboredo (2012) observed that carbohydrates of cell walls and proteins were the preferential binding sites of Zn in the halophyte *Halimione portulacoides*.

There is no evidence that plant roots can absorb the water insoluble oil and oil derivatives. Thus it can be presumed that phytoremediation for oily soils make use of the microbial activities in the rhizosphere soil rather than those of the plant itself. Therefore, plants have an inadvertent role in the phytoremediation of oily soils by stimulating the rhizospheric microflora (Radwan et al., 2006; Radwan, 2009).

For phytoremediation, both direct seeding and use of transplants are recommended. If the seeds are directly sown in the contaminated soil, it gives an inconsistent plant growth, compared to transplanting the seedlings. Thus, the use of transplants gives better results, though more labor intensive (Mendez and Maeir, 2008).

The phytoremediation of organic and inorganic contaminants are discussed separately in sub-sections below.

4.1. Petrochemical Phytoremediation

The phytoremediation of hydrocarbon contaminated soils is a steadily emerging and promising technology that could be low-cost alternative to most engineering techniques and traditional bioremediation methods. Very few studies have been conducted on the phytoremediation of petroleum hydrocarbons in the Middle East. This underscores the need for new research initiatives to assess the potential of phytoremediation in petrochemical contaminated sites. There are three main mechanisms by which plants and microorganisms remediate petroleum-contaminated soil and groundwater. They are degradation, containment, and transfer of contaminants from the soil to the atmosphere (Cunningham et al., 1997; Siciliano and Germida, 1998). Containment involves using plants to stabilise or immobilise the contaminants, thereby reducing their availability to other biota. The mechanisms of containment by plants comprise the accretion of petroleum hydrocarbons within the plants and adsorption of the contaminants on the root surface. Another mechanism involves the use of plants as organic pumps to isolate the contaminant within the root zone, thus avoiding the contaminant from spreading (Siciliano and Germida, 1998).

Table 2. Categories of phytoremediation (sources: Pivetz, 2001; Prasad and Freitas, 2003; Padmavathiamma and Li, 2007).

	Strategy	Method	Mechanism	Type of contaminants
1.	Degradation		Destruction or alteration of contaminants	Organic contaminants
(a)		Rhizodegradation	Biodegradation in the below-ground root zone by microorganisms	Organic contaminants
(b)		Phytodegradation	Contaminant uptake and metabolism above or below ground, within the root, stem, or leaves.	Organic contaminants
2.	Accumulation		Removal of contaminants	Organic and Metal contaminants
(a)		Phytoextraction	Contaminant uptake and accumulation for removal	Organic and Metal contaminants
(b)		Rhizofiltration	Contaminant adsorption on roots for containment and/or removal	Organic and Metal contaminants
3.	Dissipation		Removal of contaminants into the atmosphere	Organic and/or Inorganic contaminants
(a)		Phytovolatilisation	Contaminant uptake and volatilization	Organic and/or Inorganic contaminants
4.	Immobilisation		For containment of contaminants	Organic and/or Inorganic contaminants
(a)		Hydraulic Control	Control of ground-water flow by plant uptake of water	Organic and/or Inorganic contaminants
(b)		Phytostabilisation	Contaminant immobilization in the soil.	Organic and/or Inorganic contaminants

The root exudates of plants increase the density, diversity, and activity of specific microorganisms in the rhizosphere, which in turn degrade the hydrocarbons (Siciliano and Germida, 1998; White et al., 2006). Thus, the microorganisms associated with the plants have been found to increase the removal of petroleum hydrocarbons from contaminated soil (Qiu et al., 1997; Pradhan et al., 1998). Some studies (Liu et al., 2012; Cui et al., 2013) have examined the possibility of using ornamental plants for phytoremediation of petroleum-contaminated soils. This has an advantage of beautifying the neighbouring environment. Moreover, phytoremediation using ornamental plants can avoid contaminants from entering the food chain and causing human health risks.

It is recommended to apply phytoremediation at moderate contamination levels or as a polishing step after the application of other remediation measures (Vangronsveld et al., 2009). The degradation of total petroleum hydrocarbons (TPH) in the rhizosphere and non-rhizosphere soil of three plants namely, alfalfa (*Medicago sativa*), broad bean (*Vicia faba*) and ryegrass (*Lolium perenne*) was examined by Yateem et al. (2000). All the three plants exhibited normal growth in the presence of 1% TPH. However, the degradation was more significant in the case of leguminous plants. They found that in the soil cultivated with broad bean and alfalfa, the degradation reached 36.6% and 35.8% respectively, compared to 24% for ryegrass. In another study, Adams and Duncan (2003) observed that *Vicia sativa* was able to grow well in a diesel contaminated soil, and the total number of nodules was significantly reduced, but more developed when compared to control plants.

The phytoremediation performance of hydrocarbons using bermuda grass (*Cynodon dactylon*), fescue (*Festuca rubra*), reed grass (*Phragmites australis*), and *Thespesia lampas* trees was assessed under arid conditions of Saudi Arabia (Envirorisk, 2002). It was reported that most of the n-alkane compounds were degraded by the growth of bermuda grass and the concentration levels were significantly lowered by seven months. The relative evaluation showed higher remediation efficiency by the reed grass and fescue in degrading n-C16 to n-C40 than by the *Thespesia lampas* trees (Envirorisk, 2002). Furthermore, there was > 90% reduction in the volatile and light hydrocarbons; 75% reduction in the mid-range hydrocarbon fraction, and about 45 to 50% reduction in the heavy oil constituents over the full test period of seven months. Only 12% reduction in volatile organic compounds was noticed in the control cell, which concluded that most of the reduction was due to phytoremediation rather than volatilization.

A study was conducted to stimulate the microbial degradation of soil pollutants in a desert soil, contaminated with 2.5-2.6% crude petroleum oil, using *Prosopis cineraria* (L.) Druce, *Acacia senegal* (L.) Willd. and *Acacia nilotica* (L.) Willd (Mathur et al., 2010). The rhizosphere of these plants was tested for their abilities to degrade the pollutants. The results showed that a highert reduction (26%) of total petroleum hydrocarbons (TPHs) was observed in the rhizosphere soil of *P. cineraria* as compared to 15.6 % and 12.8 % reduction in the rhizosphere soil of *A. senegal* and *A. nilotica* respectively. In the polluted non-cultivated soil, the TPHs were reduced by 8.2-10.5 % as a result of biostimulation process (addition of nutrients). The results clearly revealed the efficiency of *P. cineraria* for phytoremediation of TPHs in a contaminated desert soil when compared to the other two legume trees (Mathur et al., 2010).

Alternatively, an innovative reed bed technology, using reeds (*Phragmites australis*) was evaluated at field scale to treat 3000 m^3 day^{-1} of oil production waters (OPWs) in Oman. A significant reduction of the concentration of toxic heavy metals (80%) and total hydrocarbons (96%) proved the effectiveness of the treatment. The quality of the treated water was in conformity with Omani wastewater standards for agricultural reuse. This was accomplished by a combination of biological, chemical and physical processes in the substrate, the plant and the microflora associated with the roots (Mahruki et al., 2006).

Chlorinated benzoic acids that arise out of the degradation of polychlorinated biphenyls (PCBs) and chlorinated herbicides are found to be degraded by the growth of forage grasses inoculated with bacteria (Siciliano and Germida, 1998). The uptake and translocation of organic compounds is dependent on their hydrophobicity (lipophilicity), solubility, polarity, and molecular weight (Briggs et al., 1982; Schnoor et al., 1995). For intermediate polarity compounds that were moderately hydrophobic, the translocation of non-ionized compounds to shoots was higher when compared to high polarity compounds (Briggs et al., 1982). Organic compounds with high hydrophobicity are strongly bound to root surfaces or partition into root solids, resulting in less translocation within the plant (Briggs et al., 1982; Schnoor et al., 1995). Organic compounds with high solubility (low sorption) will not be sorbed onto roots as much as low solubility compounds, and translocated within the plant (Schnoor et al., 1995). Plant uptake of organic compounds is also dependent on the type of plant, age of the contaminant, and many other physical and chemical characteristics of the soil. Parameters such as organic carbon, pH, solubility of inorganic constituents and others are significantly altered in the rhizosphere, triggering the soil biology when compared to the bulk soil (Reilley et al., 1996). Paterson et al., 1994 reported that more than 70 organic chemicals were found to be taken up and accumulated by 88 species of plants and trees. When pentachlorophenol (PCP) was spiked into soil, 21% was found in roots and 15% in shoots after 155 days in the presence of grass (Qiu et al., 1997), whereas in other studies, minimal uptake of PCP by several plants was reported. Hybrid poplar trees (*e.g.*, *Populus deltoides* x nigra) reduced the concentration of nitrate in surficial groundwater (Gatliff, 1994; Schnoor, 2000) and degraded the herbicide atrazine from contaminated soils (Burken and Schnoor, 1997). Additional literature on phytoremediation of organic contaminants is given in Table 3.

4.2. Phytoremediation of metal-contaminants

The four different phytoremediation strategies, each having a different mechanism of action for remediating metal-polluted soil, sediment, or water are (1) phytostabilization, where plants immobilize contaminants in soil, through absorption and accumulation by roots, adsorption onto roots or precipitation within the root zone and physical stabilization of soils (Padmavathiamma and Li, 2007); (2) phytofiltration, use of plant roots (rhizofiltration) or seedlings (blastofiltration) to absorb or adsorb pollutants, mainly metals, from water and aqueous waste streams (Prasad and Freitas, 2003); (3) phytovolatilization, utilizing plants to absorb elemental forms of these metals from the soil, biologically converting them to gaseous species within the plant, and releasing them into the atmosphere (Thangavel and Subhuram, 2004); and (4) phytoextraction, in which plants absorb metals from soil and translocate them to harvestable shoots where they accumulate (Padmavathiamma and Li, 2007). Metal availability or toxicity in soil depends on the fraction to which it is bound in the soil. The solubility decreases in the order exchangeable > carbonate bound > oxide bound > organic bound > residual (Padmavathiamma and Li, 2007). Metal toxicity decreases as plants make possible the precipitation of metals to less soluble forms, such as, metal sulfides, metal carbonates, and organic metal complexes or sorb metals onto root surfaces (Cunningham et al., 1997).

Table 3. Phytoremediation of organic contaminants.

Plant species	Contaminant	Mechanism	Results	Reference
Canola, wheat	oil- and creosote-contaminated	Tolerance		Bailey and McGill, 1999
Ryegrass	hydrocarbon mixture – *n* alkanes as well as pristane, hexadecane, phenanthrene, anthracene, fluoranthene, and pyrene	Degradation	After 22 weeks, there was 97% reduction in hydrocarbon concentration in planted soils, but only 82% reduction in unplanted soil	Gunther et al., 1996
grasses and legumes (legume alfalfa and three grasses: tall fescue, sudangrass, and switchgrass)	PAHs (Pyrene and anthracene)	Removal, primary mechanism of dissipation	30 to 40% more degradation in the planted soils than unplanted soils	Reilley et al., 1996
red fescue and annual ryegrass	crude oil or diesel.		In crude oil contaminated soil, after 640 days, 77% reduction of TPH in planted soil compared to 60 % in unplanted controls. In diesel contaminated soil, 92% reduction in TPH in planted soils compared to 74% in unplanted controls	Reynolds and Wolf, 1999
alfalfa, switchgrass, and little bluestem	Soil contaminated at a gas plant	Degradation	After 6 months, the concentration in the unplanted control soil was 135.9 ± 25.5 mg kg^{-1}, Planted treatments were much lower (switchgrass = 79.5 ± 3.7 mg kg^{-1}; alfalfa = 80.2 ± 8.9 mg kg^{-1}; little bluestem = 97.1 ± 18.7 mg kg^{-1}).	Pradhan et al., 1998
Sorghum, bermuda grass, or alfalfa	Phenanthrene	Mineralization of [14C]phenanthrene	sorghum (0.46% of recovered 14C) and bermuda grass (0.31%) – compared to a sterile, unplanted control (0.11%), alfalfa (0.09%)	Schwab et al., 1994
tall fescue	[14C]benzo[a]pyrene	Mineralization	Significant reduction in soil planted to tall fescue compared to unplanted soil.	Epuri and Sorensen, 1997
poplar trees	Benzene, toluene, and xylene	Degradation	Microorganisms capable of degrading benzene, toluene, and xylene were five times more in the rhizosphere of poplar trees compared to bulk soil	Jordahl et al., 1997
Senecio glaucus, Cyperus conglomeratus, Launaea mucronata, Picris babylonica and Salsola imbricate from Kuwaiti desert	Hydro carbons	Degradation	Rhizosphere had high concentration of hydrocarbon-utilizing bacteria and high degradation of hydrocarbons than bulk soils	Radwan et al., 1998

Like organic contaminants, very few studies have been carried out on the phytoremediation of metal contaminants in the Middle East. Soil pollution by metals differs from air or water pollution, because heavy metals persist in soil much longer than in other compartments of the biosphere (Lasat, 2002). Chemical pollutants such as toxic metals may remain in the environment for a long period and can eventually accumulate to levels that could harm humans (Padmavathiamma and Li, 2007). High levels of As, observed in the northern arid and semi-arid regions of Mexico were remediated by a native plant, *Eleochari* sp. (Cyperaceae), Flores-Tavizón et al. (2003). It was found to contain an As concentration of 301 $\mu g\ g^{-1}$. The bioconcentration factor (BCF) and translocation factor (TF) for arsenic exceeded 1 (5.22 and 7.37, respectively) in this plant, which classifies it as an arsenic-tolerant plant with potential use in As phytoextraction. The TF of *Brickellia veronicaefolia, Nicotiana glauca* and *Baccharis salicifoli* were above one, but they had very low BCF, which limited their potential to be considered for phytoextraction of As. *Stanleya pinnata* was found to be a useful species for phytoremediation of Mn and Se due to its broad adaptation to arid and semi-arid environments, its uptake, metabolism and volatilization of Se (Parker et al., 2003).

Typha domingensis, a wet land species in Egypt was reported to be promising for phytoextraction of Al, Zn, Fe and Pb, preferentially from waste water than from sediments. Rhizofiltration was found to be the best mechanism to explain the phytoremediation potential of Typha *domingensis* (Hegazy et al., 2011). The creosote bush (*Larrea tridentate)*, found primarily in the arid southwestern regions of the United States, have potential for the phytoremediation of metals. This creosote bush requires very little water, has antiherbivore compounds that make it inedible to animals, thus minimizing the risk of contaminant transfer to the ecological environment. Moreover, creosote bush has been found growing in soils highly contaminated with metals and studies have shown that it is capable of sequestering metal ions (Gardea-Torresdey et al., 2001).

Another, study conducted in Saudi Arabia to assess the performance of phytoremediation for removal of Pb, Ni and Va with hydrocarbons from soil in a hot and arid environment revealed some interesting results (Enviro Risk, 2002). Black mustard and fescue were found to be effective for the removal of Pb whereas, sunflower and fescue were found to be effective for the removal of Ni and Va from the soil. The study also shows that the fescue roots have a higher affinity for Va than sunflower.

Grass pea (*Lathyrus sativus* L.), a ubiquitous annual leguminous crop, which can thrive in poor soils, and in very arid environments was observed to accumulate Pb in its root tissues, with impact on the mineral homeostasis for Ca, Cu and Zn, though (Brunet et al., 2009**)**. The phytoremediation potential of seven plants, *Calotropis procera, Citrullus, colocynthis, Rhazya stricta, Cassia italic, Phragmites australis, Cyperus laevigatus* and *Argemone Mexicana* was assessed in heavy metal polluted soil (Cd, Cr, Co, Cu, Fe, Ni, Pb and Zn) of Riyadh, Saudi Arabia (Badr et al., 2012). They found that *Phragmites australis* and *Cyperus laevigatus* were found to be the best candidates for biomonitoring and phytoremediation programs of metal-polluted soils (Badr et al., 2012). Another recent study conducted in Saudi Arabia to evaluate the phytoremediation potential of six wild plants for metals, exposed the phytoextraction potential of *Phragmites australis and Lycium shawii* for Cd and Pb, whereas, *Datura stramonium and Citrullus colocynthis* were found to be suitable for phytostabilisation of Ni and Cu (Ibrahim et al., 2013).

Studies have been conducted on the potential of phytoremediation for removing radionuclides in arid soils. Both green house and field trials have been conducted to assess the phytoremediation effectiveness in removing radionuclides from contaminated soils (Dushenkov, 2003). The efficiencies of four grasses; *Agropyron spicatum* (Pursh) Scribn & Smith, *Leymus cinereus* Scribn &Merr., *Agropyron cristatum* (L.) Gaertn and *Bromus tectorum* L. for phytoremediation of caesium (Cs) in arid soils was evaluated by Cook et al., 2009. In all the four grasses, Cs transfer factor was approximately 1.0, indicating no Cs accumulation in shoots, making them unsuitable as phytoremediation agents. Entry and Watrud (1998) observed that Alamo switchgrass (*Panicum virginatum*) accumulated the radionuclides Cesium-137 (^{137}Cs) and Strontium-90 (^{90}Sr), compounds present in nuclear fallout from weapons testing and reactor accidents, revealing its suitability as a phytoremediation agent for radionuclides.

Desert plants serve an important role in the detection and potential remediation of subsurface tritium contamination (Andraski, 2013). A study conducted on the application of a plant-based method for ^{3}H at Armargosa Desert Research Site (ADRS), Nevada revealed that the remedial effect of vegetation was extended well beneath the root zone. Native desert plants, grown on metalliferous and salinized soils tend to accumulate high ion concentrations in epidermal and sub-epidermal tissues, as well as in water bearing parenchyma, including various glandular structures of bracts/bracteoles and perianth segments.

Mine tailings disposal sites from either inactive or abandoned mine sites are prevalent in arid and semiarid regions throughout the world. Tailings are characterized by elevated concentrations of metals such as As, Cd, Cu, Mn, Pb, and Zn (1–50 g/kg) (Boulet and Larocque, 1998)., Plant establishment on mine tailings in arid and semiarid regions is influenced by a number of limiting physicochemical factors such as extreme temperatures especially at the tailings surface, low precipitation, and high winds. These factors contribute to the development of extremely high salt concentrations ranging up to 22 dSm^{-1} due to high evaporation and low water infiltration (Munshower, 1994). The long-term stabilization and containment of the tailings can be achieved by phytostabilisation. Eolian dispersion is reduced by the plant canopy whereas plant roots prevent water erosion, immobilize metals by adsorption or accumulation, and provide a rhizosphere wherein metals precipitate and stabilize (Mendez and Maier, 2008).

The distribution of metal fractions governs the mobility/immobility of metals. This controls the off-site migration of the soluble/mobile fraction either to surface water or ground water, where they contaminate drinking water resources and enter the food chain. Phytostabilisation is more feasible under arid conditions since it reduces the environmental impact by holding the metal-pollutants at the source location in immobile forms so that they do not interfere with the normal biological processes.

The efficiency of plants for phytoextraction/ phytostabilisation is governed by the accumulation characteristics and translocation properties of phytoremediating plants. To assess the accumulation characteristics and translocation properties of metals in plants, bioconcentration factor (BCF) or enrichment coefficient (EC) and translocation factor (TF) were determined (Padmavathiamma and Li, 2012). EC of root (ECR) is the ratio of root to soil metal concentration (C_{roots}/C_{soil}), EC of shoot (ECS) is the ratio of shoot to soil metal concentration (C_{roots}/C_{soil}) and translocation factor (TF) is the ratio of shoot to root metal concentration (C_{roots}/C_{soil}), Kumar et al., 1995.

5. Phytodesalination approach

Phytodesalination is a new approach of phytoremediation that has attracted a great deal of interest during the past few years for the reclamation of salt-affected soils. Halophytes (salt-tolerant plants) have been suggested to be naturally better adapted to cope up with environmental stresses, such as heavy metals and other organic contaminants, compared to salt-sensitive plants commonly chosen for phytoremediation purposes (Ghnaya et al., 2007). This has high implication in salt affected arid region soils, since halophytes could be used for desalination as well as the remediation of both organic and inorganic contaminants (Rozena and Flowers, 2008). The tolerance of halophytes to the stresses is correlated with a more efficient antioxidant system than common plants (Zhu et al., 2004). Research findings suggest that halophytes are ideal candidates for phytoextraction and phytostabilization in metal polluted saline and non-saline soils, apart from soil desalination in arid and semiarid regions (Ghnaya et al., 2007; Nedjimi and Daoud, 2009; Manousaki and Kalogerakis, 2011).

Members of the Chenopodiaceae family, specifically *Atriplex* spp., are highly salt tolerant, being used as pioneer species in semiarid Western Australia and re-vegetation in the Western United States (Glenn et al., 1999). Other halophytic shrubs recommended in the arid Western United States are creosote bush (*Larrea tridentate* DC, Zygophyllaceae) and desert broom (*Baccharis sarothroides* Gray, Asteraceae). Also, leguminous trees that serve for nitrogen supply such as *Acacia* spp. and *Prosopis* spp. have been reported as successful in the Western United States (Glenn et al., 1999).

In the United Arab Emirates (UAE), a study has been carried out examining the growth characteristics and performance of mangroves, halophytes and other plants in soil irrigated with saline water (UNEP, 2012). The study showed that the tested plants have the necessary physiological mechanisms and capability to accumulate significant concentrations of Fe, Mn, as well as Mg, Ca Na and Cl ions, thereby reducing the overall salinity and metal concentration of the soil system. Thus it has been suggested that higher agricultural production levels in arid regions can be achieved by introducing highly salt-tolerant species (*i.e., Conocarpus erectus*, *Atriplex lentiformis*, etc.) that can be irrigated with saline water, (UNEP, 2012).

The capacity of salt-tolerant plants to accumulate metals has also been reported by Przymusiński et al., 2004 and this offers a great potential for phytoremediation research in arid region soils.

The ability of halophytes to synthesize osmoprotectants in order to maintain a favorable water potential gradient make them tolerant to ionic and osmotic components of salt stress (Lefèvre et al., 2009). Proline is one of these osmoprotectants which plays a significant role under metal stress by three major actions, namely metal binding, antioxidant defense, and signaling. Proline accumulates in plants in response to Cd, Cu, and other heavy metals (Nedjimi and Daoud, 2009). It was found that Cd may trigger glycinebetaine oversynthesis, which is considered the most efficient osmoprotectant synthesized by Chenopodiaceae (Lefèvre et al., 2009). Since salinity and heavy metals may induce in plants secondary stresses as drought (Nedjimi and Daoud, 2009) and oxidative stress (Verma and Dubey, 2003), the capability of halophytic plants to synthesize those organic compatible solutes may be involved in their ability to cope up with heavy metals (Lefèvre et al., 2009). In fact, the presence of several physiological mechanisms, related to the tolerance to a wide range of abiotic factors, has been reported in halophytes (Shevyakova et al., 2003).

The metal speciation as well as the bioavailability is affected by soil salinity. This is more pronounced for metals with high mobility like Cd, due to the displacement of metals from binding sites in the soil matrix by salt cations and formation of soluble chloro-complexes of Cd which tend to shift Cd from solid to solution phase (Wahla and Kirkham, 2008; Manousaki and Kalogerakis, 2009;). Salt glands of *Tamarix smyrnensis* Bunge accumulate and excrete Cd and Pb using its salt excretion mechanism, which is a detoxification strategy for metals by the plant (Kadukova et al., 2008; Manousaki and Kalogerakis, 2009). Another halophyte, *Halimione portulacoides* regulates its Cd intracellular levels through salt excretion (Reboredo, 2001).

The term "phytoexcretion" indicates a novel phytoremediation process, which entails the idea of using plants as biological pumps for heavy metals in sites contaminated with metals. The excreted metals can be collected before they go back to the soil and the major problem of managing the disposal of contaminated plant parts is reduced (Kadukova et al., 2008; Manousaki et al., 2009). It is observed that 50% or more of the salt entering the leaf of a salt-excreting halophyte can be excreted (Glenn et al., 1999), and hence, this novel approach of phytoremediation could be used for the remediation of salt-affected as well as metal-contaminated soils in arid region soils.

6. Conclusions

Phytoremediation technologies have been used to clean up metals, pesticides, solvents, explosives, crude oil, polyaromatic hydro-carbons and landfill leachates. It was found to be a promising technology for oil-contaminated sites in arid regions and its effect has exceeded the performance of landfarming. The establishment of appropriate species of plants and microorganisms at the contaminated site is required for successful phytoremediation. Factors that need consideration for the successful implementation of the technology are (i) the effect of contaminants on germination of plants or survival of transplanted vegetation, (ii) the effectiveness of inoculating contaminated soils with microorganisms and (iii) the use of local versus exotic plants and microorganisms to phytoremediate the site. Existing phytoremediation studies in arid and semiarid environments are inadequate and have not yet addressed effectively several relevant issues. There are a number of areas where research is required to optimize the phytoremediation efficiency in arid habitats. Plant physiological and root growth expansion studies are needed to optimize plant uptake of contaminants and to maximize process output performance. The effects of bioaccumulation and biomagnification in the food chain that could occur if insects and small rodents eat the plants that accumulate contaminants need further research. Contaminant migration by leaching during phytoremediation under field conditions is an important aspect as well, that needs further investigations. Moreover, the expansion and use of phytoremediation as an environmentally sound technology entails a number of challenges, together with the development of local capacity to understand and apply phytoremediation technologies, and the establishment of an effective regulatory framework. Supplementary research is needed to orchestrate appropriate phytoremediation technologies and techniques applicable to arid conditions, where there is an interactive effect of several abiotic stress factors, such as drought, salinity and multiple contaminations.

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