How to Cite: Mukhtar B, Malik MF, Shah SH, Azzam A, Slahuddin, Liaqat I. 2017. Heavy Metal Bioremediation in Soil: Key Species and Strategies involved in the Process. International Journal of Applied Biology and Forensics 1(2): 38-48

REVIEW ARTICLE

Heavy Metal Bioremediation in Soil: Key Species and Strategies involved in the Process

*Bilal Mukhtar[1], Muhammad Faheem Malik[2], Suleman Hussain Shah[3], Abdullah Azzam[4], Slahuddin[5] and Ihtisham Liaqat[6]

[1, 2, 3, 4, 5, 6] Department of Zoology, University of Gujrat, Hafiz Hayat Campus, Gujrat, Pakistan
Correspondence: *bilalmukhtar457@gmail.com*

Abstract
Soil serves as one of the basic medium of life. However, the human activities are polluting the soil unintentionally. Consequently, a wide range of contaminants enter the soil. However, heavy metals are the most toxic of all these pollutants. Among these, lead, cadmium, chromium, mercury and arsenic are the most toxic and can cause multiple organ damages even when present in small quantities. Although, these elements are necessary for soil organisms in extremely low quantities. However, anthropogenic activities like mining, smelting, fuel burning etc. have disturbed the natural geochemical cycles of heavy metals which raises concern over their management and control. Physiochemical techniques have traditionally been suggested for the removal of heavy metals from the environment. However, there are many limitations regarding the use of these conventional approaches such as higher operating costs, potential side effects, relatively inefficient process, confined to temporary treatment and the harmful intermediate by products. Conversely, bioremediation overcome these limitations. It involves biological agents such as microorganisms (indigenous and extraneous) and plants to control heavy metal pollution. This is an emerging technology, which is comparatively efficient, economical and environmentally safe process, therefore its use should be encouraged for large scale cleanup of soil contaminated with heavy metals. However, there are certain barriers regarding the introduction, uniform distribution and adaptation of exogenous microbes into foreign and compact soil which need immediate attention and possible solution.

Keywords: Bioremediation, Soil, Heavy metals, Soil Pollution, Contaminants.

Introduction

The term heavy metal is applied to a particular group of natural elements with higher atomic weights and a density five times greater than that of water (Morris, 1992; Nies, 1999; Kulshreshtha et al, 2014; Tchounwou et al, 2014). Heavy metals include certain metals and metalloids (Kulshreshtha et al, 2014) with the atomic weight ranges between 63.546 and 200.590 (Kennish, 1992).

Lithosphere acts as a spirit for various life forms. However, the industrial revolution and urbanization has resulted in a day by day increase in its contamination with a wide range of pollutants (Meenambigai et al, 2016). Of these, heavy metals are natural components of our environment, but anthropogenic activities have disturbed their natural geochemical cycles, which in turn, lead to their abundant discharge and subsequently accumulation into soil and water. Accordingly, their adverse effects on human health and the environment are increasing dramatically (Dixit et al, 2015).

Although, there is a variety of pollutants in the soil and their effects are determined by their persistence, concentration and types. But some are playing havoc to every life form while the others have negligible effects. Among these, heavy metals are the contaminants which are harmful even when present in traces (Shazia et al, 2013; Jayanthi et al, 2016).

Heavy metals are the most toxic of the all inorganic pollutants present in soil. These may either be present naturally or injected through human activities. The soil properties including pH, soil organic matter and clay content determine the bioavailability of heavy metals in soil (Annu et al, 2016).

Rhodobacter sphaeroids is a photosynthetic, gram-positive bacterium and it has been used extensively to treat soil contaminated with various pollutant types including heavy metals such as Cd and Pb, due to its resistance to different factors that affect bacterial growth and activity. These factors include carbon starvation, herbicides, varied amounts of salt, organic matter and heavy metals. *R. sphaeroids* minimizes the effects of lead and cadmium by reducing their bioavailability to plants (Li et al, 2016).

Table 1: Sources of Heavy Metals.

Heavy Metals	Sources	References
As	Mining, smelting, pesticides, wood preservatives, bio-solids, semiconductors, petroleum refining processes, food additives, coal-based power plants, volcanic eruptions.	(walsh et al, 1979; Nriagu, 1994; Dixit et al, 2015).
Hg	Volcanic activities, forest fires, waste emissions from caustic soda industries, Gold-Silver mining, medical waste, peat, burning of wood and coal.	(Lindqvist, 1991; Dixit et al, 2015).
Pb	Petroleum derivatives, mining, smelting, paints. Lead laden industrial wastes and municipal sewage, Pb containing fuel oil combustion, Pesticides and Wastes from batteries.	(Seaward and Richardson, 1990; Gisbert, et al, 2003; Dixit et al, 2015; Meenambigai et al, 2016).
Cd	Anthropogenic activities, smelting and refining of metals, combustion of fossil fuels, phosphate fertilizers, improper disposal of sewage sludge, Paint, Pigments, Plastic stabilizers, Electroplating.	(Nriagu and Pacyna, 1988; Alloway, 1995; Kabata-Pendias, 2001; Dixit et al, 2015).
Cr	Electroplating, sludge, solid wastes, fly ash, tanning, textile, steel and pulp processing industries.	(Knox et al, 1999; Dixit et al, 2015; Meenambigai et al, 2016).

U.S Environmental Protection Agency and International Agency for Research on Cancer declared certain heavy metals including Pb, Cd, Hg, As and Cr as most toxic of all the pollutants and termed them carcinogens due to their potential harms to human health (Tchounwou et al, 2014).

Subsequently, it is the need of hour to develop useful techniques to get rid of these toxic heavy metals. Among these, Bioremediation is one of the most familiar and reliable method for degradation and elimination of heavy metals. Bioremediation involves variety of living organisms including bacteria, fungi and algae for the removal and degradation of these contaminants from the environment (Li et al, 2016).

Microbial communities are either naturally present in the soil or suitable species are injected, but it is to determine whether these naturally existing microorganisms are capable of potentially degrading the specific required pollutants or not (Kuppusamy et al, 2016).

In addition, it is necessary to isolate, develop, transform and characterize such microbial strains that are resistant to elevated levels of heavy metals and are either capable of eliminating them completely or reduce their concentrations to tolerable levels (Kang et al, 2016).

The phylum Actinobacteria includes facultative, gram positive anaerobic microorganisms which have the ability to stabilize or transform Cd, Cr, As, Hg and Pb to less toxic forms, thus making them less bioavailable to plants (Alvarez et al, 2016).

Sources of Heavy Metals

Heavy metals may either be present naturally in the environment or they are anthropogenic in origin. The most distinct natural sources include soil erosion, chemical weathering, volcanoes, forest fires and biogenic sources. The anthropogenic sources rely entirely on human activities such as smelting, electroplating, mining, use of fertilizers and pesticides, manures, composts, atmospheric deposition and municipal sewage (Sumner, 2000; Modaihsh et al, 2004; Chehregani and Malayeri, 2007; Fulekar et al, 2009; Sabiha-Javied et al, 2009; Wuana and Okieimen, 2011).

Human activities have resulted in significant changes in heavy metal's natural geochemical cycles, which in turn, pose an extreme risk to every life form i.e. animals including humans, plants and aquatic organisms (D'Amore et al, 2005).

Table 2: Harmful Effects of Heavy Metals.

Metal species	Harmful effects	References
As	It interferes with some cellular processes like synthesis of ATP.	(Tripathi et al, 2007).
Hg	It causes autoimmune diseases, depression, condition of drowsiness, severe fatigue, loss of hair, insomnia, disturbed vision, memory loss, tremors, loss of temper, damage to lungs, kidney failure, brain damage and restlessness.	(Neustadt and Pieczenik, 2007; Gulati et al, 2010).
Pb	Affects and damages our central nervous system, reproductive system, kidneys, process of circulation. In children, it causes impaired development, lower the intelligence, short-term loss of memory, decreases learning abilities and acts as a cardiovascular risk factor as well.	(Salem et al, 2000; Wuana and Okieimen, 2011; Padmavathiamma and Li, 2007; Meenambigai et al, 2016).
Cd	It causes cancer, mutations, disrupts endocrine functions, causes damage to lungs, weaken the bones and interferes with the regulation of Ca- ions within the biological systems.	(Salem et al, 2000; Degraeve et al, 1981).
Cr	Carcinogenic, short time exposure results in irritation, sickness, ulceration where as long term exposure can affect nervous system, circulatory system, liver and kidney. It causes hair loss as well.	(Salem et al, 2000; Meenambigai et al, 2016).

Heavy Metal Toxicity and Human Health

In highly congested areas, industrial revolution has led to waste emissions in huge quantities, which resulted in an increase in heavy metal discharge and their subsequent accumulation into soil. Accordingly, their indiscriminate discharge into soil is a serious global health concern, because these cannot be degraded into non-toxic compounds, therefore, heavy metals have persist effects on the environment. Several heavy metals like arsenic, cadmium, chromium, lead, mercury, copper, nickel, selenium, silver, zinc are toxic whether they are present in minute quantities and exhibit cytotoxic, mutagenic and carcinogenic effects (Salem et al, 2000).

Conventional Techniques for Remediation

Physiochemical techniques have tradition-nally been suggested for the removal of heavy metals from the environment. These approaches are applicable for the temporary control of metal contamination, but are not able to remediate heavy metals on permanent basis, so cannot be applied for long run (Akshata et al, 2014). Physiochemical methods include fixation (chemical immobilization of metals), excavation, soil burial, acidic metal leaching (Salt et al, 1995) microfiltration, flocculation, ion exchange and reverse osmosis (Raskin et al, 1996).

However, there are many limitations regarding use of these conventional approaches such as higher operating costs, potential side effects, relatively inefficient process, confined to temporary treatment and the harmful intermediate by products (Raskin et al, 1997; McGrath et al, 2001; Akshata et al, 2014).

Bioremediation

The term bioremediation is attributed to a natural process which involve biological agents, predominantly microorganisms (bacteria, yeast, fungi), algae and plants to decrease metal contamination, for the elimination of toxic wastes and to reduce environmental pollution (Kumar et al, 2011; Asha and Sandeep, 2013; Li et al, 2016).

Bioremediation is a promising and sustainable technology which provides possible solution for clean-up of soil and water contaminated with heavy metals (Doelman et al, 1994; Gadd, 2000). Various microbes respond differently to heavy metals depending upon factors like microbial species, nature of medium and type, concentration or availability of heavy metals (Goblenz et al, 1994).

The microorganisms are either naturally present in the contaminated site or these are extraneous which are first isolated from elsewhere and then injected to the contaminated area (Kumar et al, 2011). To achieve effective remediation it is however necessary for biological agents to degrade the contaminants enzymatically and transform them into less toxic substances (Asha and Sandeep, 2013).

Although, the process of biological remediation can be performed under aerobic or anaerobic conditions but the aerobic process is more effective and provide rapid results (Akshata et al, 2014). Most significant factors that measure the rate of bioremediation include type, concentration or availability of contaminants (Goblenz et al, 1994), soil structure and texture, temperature, pH, moisture, nutrient availability for biological agents and diversity of indigenous microbes (Asha and Sandeep, 2013).

Kang et al, 2016).

The phylum *Actinobacteria* being facultative, anaerobic microorganisms were found to be more effective in this experiment due to their ability to stabilize or transform Cd, Cr, As, Hg and Pb to less toxic forms (Alvarez et al, 2016).

Biological Agents

The fundamental agents used in bio-remediation are natural organisms, which may either be indigenous or introduced. The choice of selection of agents depends directly on the type and nature of contaminants because living organisms can only tolerate a confined range of pollutants. For example, a strain of *Pseudomonas putida*, that is associated with petroleum degradation was first to be registered in 1974 (Asha and Sandeep, 2013).

Bacteria

There is a variety of bacteria e.g. *Pseudomonas*, *Alcaligenes*, *Sphingomonas*, *Rhodococcus*, and *Mycobacterium* that are capable of potentially degrading heavy metals. Moreover, these can also degrade pesticides and hydrocarbons. Furthermore, these bacteria utilize the pollutants as their sole source of carbon and energy (Kumar et al, 2011).

Table 3: Streptomyces Strains and Heavy Metal Bioremediation.

Heavy Metal	Strain	Isolation Sample	Reference
Arsenic	VITDDK-3	Marine soil	Deepika and Kannabiran, 2010.
Cromium (III)	VITSVK-9	Marine sediment	Saurav and Kannabiran, 2011.
Cromium (VI)	RSF 17	Saline farmlands, Punjab, Pakistan.	Javaid and Sultan, 2013.
Mercury	CHR 28	Harbour, USA	Ozturk et al, 2002.
Cadmium	F-4	Uranium mine	Sineriz et al, 2009.
Lead	*S. rimosus*	Biomass produced during oxytetracycline production and collected after fermentation.	Selatnia et al, 2004.

Although, microbes required a very small amount of heavy metals for the maintenance of their growth, but discharge of extra amount into soil will cause certain changes within the microbial cell (Doelman et al, 1994). These changes will lead to inhibition of specific pathways such as displacement of important metal component, functional group blockage and conformational modifications (Wood and Wang, 1983; Li and Tan, 1994).

To overcome these modifications, there is a need to identify and isolate the heavy metal resistant microbes, then isolate, characterize, modify their heavy metal resistant genes, which are ultimately transformed into indigenous as well as extraneous microbes to increase their survival and adaptability under higher metal concentrations. Consequently, this will aid in improving the efficiency of bioremediation (Akshata et al, 2014;

Fungi

Various fungal species have also been found to be involved in remediation of toxic environmental contaminants. Among these, ligninolytic fungi are most familiar for their degradative capabilities. For instance, the white rot fungus *Phanaerochaete chrysosporium* utilize various substrates such as straw, saw dust, or corn cobs as energy source to act on a wide range of pollutants (Akshata et al, 2014).

Table 4: Heavy Metal Bioremediation with Bacteria.

Heavy metal	Natural Bacterial species	Genetically modified bacteria
Hg	*Pseudomonas spp.*	*Ralstonia eutropha* CH34, *Deinococcus radiodurans*, *E. coli* strain, *E. coli* JM109, *Pseudomonas* K-62, *Achromobacter sp.* AO22
Pb	*Citrobacter spp., Bacillus sp. and P. aeruginosa*	
Cd	*Alcaligenes spp., Pseudomonas spp., Moraxella spp., Citrobacter spp., Zooglea spp.*	*Ralstonia eutropha* CH34, *Deinococcus radiodurans*, *E .coli* strain
Cr	*Pseudomonas aeruginosa, Bacillus subtilis*	*Methylococcus capsulatus, P. putida* strain
As	*E. coli*	*E .coli* strain

(Akhtar et al, 2013; Akshata et al, 2014; Dixit et al, 2015)

Table 5: Fungi Involved in Heavy Metal Bioremediation.

Fungal species	References
Penicillium chrysogenum	(Malik, 2004).
Aspergillus tereus	(Kumari and flores, 2014).
Candida utilis	(Laddaga and Silver, 1985).
Hansenula anomala	(Goyal et al, 2003).
Rhodotorula mucilaginosa	(Malik, 2004).
Rhodotorula rubra GVa5	(Roane and Pepper, 2001).
Saccharomyces cerevisiae	(Kim et al, 2007; Roane and Pepper, 2001; Malik, 2004).

Table 6: Our Target Heavy Metal Bioremediation with Fungi.

Heavy metal	Fungal species
Cd	*Aspergillus niger, Stereum hirsutum, Ganoderma appla, Pleurotus ostreatus*
Cr	*Saccharomyces cerevisiae*
Pb	*Penicillium chrysogenum, Stereum hirsutum, Ganoderma appla, Volvariella volvacea*
Hg	*Penicillium chrysogenum, Rhizopus arrhizus, Volvariella volvacea*

(Akshata et al, 2014; Meenambigai et al, 2016).

Table 7: Heavy Metal Bioremediation With Plant and Algae.

Heavy metal	Algal species	Plant species
Pb	*Chlorella vulgaris*	*Zea mays L, B. campetris L, Viola, Baoshanensis, Sediumalfredii, Rum excrispus, Helianthus annus, B. juncea, Anthyllis, Vulneraria, Festuca, Koeleria, Vallesiana, Salix spp., Populus spp., Jatropha, Vetiveria zizanioides, Cardaminopsis halleri, Arvernensis*
Cd	*Phormidium valderium*	*Viola, Baoshanensis, Sediumalfredii, Rum excrispus, Helianthus annus, B.juncea, Anthyllis, Vulneraria, Arvernensis, Koeleria, Vallesiana, Salix spp., Ricinus communis, Zea mays, Populus spp., Jatropha, Festuca*
Cr		*B.juncea, Anthyllis, Vulneraria, Festuca, Arvernensis, Koeleria, Vallesiana*
As		*Viola, Baoshanensis, Sediumalfredii, Rum excrispus, Helianthus annus, B.juncea, Anthyllis, Vulneraria, Arvernensis, Festuca, Koeleria, Vallesiana, Fern*
Hg	*Chlorella vulgaris*	*Populus deltoids, Arabidopsis thaliana*

(Yao et al, 2012; Akhtar et al, 2013; Akshata et al, 2014; Dixit et al, 2015)

Plants

Phytoremediation is an emerging technology and a sub-type of bioremediation which is strictly applied to the use of green plants for the remediation of organic as well as inorganic contaminants from polluted soil, water or air (Salt et al, 1998), therefore, it is also known as botanical bioremediation (Chaney et al, 1997). In addition, this technology is reliable and cost effective method of choice for reclamation and clean-up of contaminated sites. (Garbisu and Alkorta, 2001; McGrath et al, 2001; Raskin et al, 1997).

Types of Bioremediation

There are two main types of biological remediation i.e. microbial bioremediation and phytoremediation (Yao et al, 2012).

i. Microbial Bioremediation

It refers to the use of microorganisms (bacteria, fungi, yeast) to reduce heavy metal pollution (Kumar et al, 2011).

Bio-Stimulation

Bio-stimulation is the natural type of bioremediation which can enhance the degradation of contaminants by maintaining various factors, including nutrient addition, soil aeration, maintenance of temperature and pH (Margesin, et al, 2001). This involves the addition of organic and inorganic nutrients to increase activity of microbes. Bio-stimulation is mainly associated with treatment of contaminated soil (Sang-Hwan et al, 2007).

It can also be defined as a process of bioremediation in which we trigger the growth of indigenous microbes by changing the various conditions in their surroundings. It is reported that supplementation of nutrients and electron acceptors like carbon, oxygen, nitrogen and phosphorus is necessary because they occur in too low quantity in the soil to sustain the microbial growth and activity (Elektorowicz, 1994; Piehler et al, 1999; Rhykerd et al, 1999). For instance, it was described that the addition of carbon source in the form of pyruvic acid not only enhance the microbial growth but it was also found to involved in PAH degradation (Lee et al, 2003).

Bio-stimulation is advantageous, on one hand, with respect to the fact that microbes are present naturally and are well adapted and uniformly distributed in the target substrates as well as there is no need to add extraneous microbes. On the other hand, it exhibits a tough challenge for the introduction and uniform distribution of nutrient additives in a manner to make them available to all microbes. It depends on the local geology of land e.g. tight and impermeable soil sub-surface prevents equal distribution as well as fractures in the substrate will allow flow of nutrients in certain preferential pathways (Margesin, et al, 2001).

Furthermore, nutrients may also stimulate the growth of microbes that do not participate in contaminate degradation. Consequently, these will decrease the effectiveness of the process competing with pollutant degrading microbes (Adams, 2014).

Bio-Augmentation

Bio-augmentation involves the inoculation of either naturally occurring bacteria or genetically modified microbes, which have the potential for the remediation of contaminated site. (Akshata et al, 2014). These exogenously added microbes tend to aid the local microorganisms, thereby, improving the efficiency of the process. Genetically modified microbes are mainly concerned with heavy metal degradation. The introduction of effective bacterial mixtures indicated that bio-augmentation is a reliable and economical technology (Gentry et al, 2004).

However, the physical, chemical and biological properties of soil tend to affect the degrading capabilities of extraneously administered microbes. Moreover, the exogenous bacterial strains are comparatively less effective in terms of growth and adaptability than local microbes (Thieman and Pallandino, 2009).

Certain factors must take into consideration before application like contaminant concentration, contaminant structure, nature of physical environment, pollutant's availability to microbes, the number and type of microbial strains added as well as indigenous microbes. For the process to be effective, it is essential for the extraneously introduced microbes to adapt and survive under foreign challenging conditions, remain genetically stable and viable, capable of potentially degrading target substrates, possess the ability to pass through the soil to reach the pollutants, grow rapidly to outcompete the local microbes (Atlas, 1984; Goldstein et al, 1985).

ii. Phytoremediation

Phytoremediation is an emerging technology and a sub-type of bioremediation which is strictly applied to the use of green plants for the remediation of organic as well as inorganic contaminants from polluted soil, water or air (Salt et al, 1998), therefore, it is also known as botanical bioremediation (Chaney et al, 1997). In addition, this technology is reliable and cost effective method of choice for reclamation and clean-up of contaminated sites (Raskin et al, 1997; Garbisu and Alkorta, 2001; McGrath et al, 2001).

Phyto-Volatilization

Phyto-volatilization involves the uptake of pollutants from soil into plant body (Akhtar et al, 2013), then transform them into low boiling (Dixit et al, 2015), less harmful compounds (Heaton et al, 1998) and consequently, discharge them into air (Heaton et al, 1998; Dixit et al, 2015) through plant leaves or shoots (Akshata et al, 2014) with the aid of process of transpiration. The process is preferably applicable for remediation of soil polluted with mercury (Akhtar et al, 2013). For instance, Hg is present in soil in combination with methyl group which makes it extremely toxic, nevertheless, modified tobacco plants are capable to uptake and transform methyl mercury into less toxic molecular form and ultimately release it into the atmosphere (Akshata et al, 2014).

Phyto-Extraction

Phyto-extraction refers to the use of hyper-accumulator plants (Matheickal et al, 1999) that are adapted to uptake large quantities of heavy metals from soil through their roots (Brennan and Shelley, 1999) and subsequently, migrate them to the above ground portions (Akshata et al, 2014) where these can be stored (Dixit et al, 2015) in large concentrations. As a result the plant biomass is increased (Brennan and Shelley, 1999), which is then harvested (Meenambigai et al, 2016). The process is predominantly applicable for the clean-up of polluted soils (Akhtar et al, 2013). Plants can readily extract those pollutants that can dissolve in water (Akshata et al, 2014). For the process to be efficient, plant should be able to tolerate high metal concentrations (Matheickal et al, 1999).

Phyto-Stabilization

Phyto-stabilization refers to grow plants in the soil (Latha et al, 2004) contaminated with heavy metal with the purpose to limit the mobility (Akshata et al, 2014) and bioavailability of these contaminants (Latha et al, 2004) by the plant roots (Akhtar et al, 2013). In addition, it reduces soil erosion and heavy metal migration to distant sites, therefore, it is a useful strategy for clean-up of soil (Raskin and Ensley, 2000). Moreover, it is predominantly applicable for remediation of heavy metals including Ar, Cr, Cd, Zn and Cu (Kunito et al, 2001). For the effective stabilization, plant should be resistant to heavy metals (Latha et al, 2004).

Rhizo-Filtration

Rhizo-filtration in this method, plant roots are used either to adsorb heavy metals on roots (Latha et al, 2004) or to accumulate them in the root zone (Akshata et al, 2014) or to transform them by the microbes present in the root zone (Dixit et al, 2015). This process is predominantly useful for the treatment of surface water, extracted ground water and less contaminated waste water (Akhtar et al, 2013). Land plants with dense and hairy roots are greatly suitable for this purpose (Camargo et al, 2003). Large concentrations of Pb and Cr can be treated with this method (Akshata et al, 2014). Although various plants (sunflower, Indian mustard, tobacco, rye, spinach, corn) are capable of removing lead from soil and water but sunflower has been found to remove large amount of lead after one hour of exposure (Camargo et al, 2003).

Phytodegradation

In this technique, heavy metals are either broken down enzymatically or converted to less toxic forms with the aid of enzymes present in plant tissues (Dixit et al, 2015). After uptake of heavy metals, they are subjected to various catalytical reactions by entering the natural processes taking place within the living tissues of the plant. The effectiveness of the process relies exclusively on the nature of soil, plant type and the quantity and type of pollutant to be treated (Akshata et al, 2014).

Advantages of Bioremediation over conventional technologies

The use of conventional technologies is limited by their above mentioned drawbacks. Conversely, bioremediation is a natural technique, which overcome these limitations. Bioremediation is a reliable and promising technology as it degrades or transforms the pollutants specifically. In addition, the process is cost effective because the microorganisms utilize the contaminants as energy or carbon source. Moreover, it does not produce toxic intermediates which makes it ecologically as well as environmentally safe. Furthermore, it has also been reported that this approach is comparatively more efficient and effective process as it rapidly remediates the toxicants (Doelman et al, 1994; Gadd, 2000; Akshata et al, 2014).

Conclusion and Recommendations

Through this review it is concluded that there is a wide range of biological agents (bacteria, fungi, algae, plants) that specifically degrade and transform heavy metals. It is also indicated that bioremediation is an efficient, cost effective and ecologically sound technology for clean-up of contaminated soil. It is recommended that its use should be encouraged for large scale clean-up of contaminated soil. In our opinion, bioremediation is the best available tool to treat soil contaminated with heavy metals. However, in case of microbial bioremediation, there are certain barriers regarding the introduction, uniform distribution and adaptation of exogenous microbes into foreign and compact soil which need immediate attention and possible solution. Conversely, phytoremediation does not offer such barriers but it is a relatively slow process.

References

Adams GO, Tawari-Fufeyin P, Igelenyah E. 2014. Bioremediation of spent oil contaminated soils using poultry litter. Research Journal in Engineering and Applied Sciences 3:124-130.

Akhtar MK, Turner NJ, Jones PR. 2013. Carboxylic acid reductase is a versatile enzyme for the conversion of fatty acids into fuels and chemical commodities. PNAS 110:87-92

Akshata JN, Udayashankara TH, Lokesh KS. 2014. Review on bioremediation of heavy metals with microbial isolates and amendments on soil residue. International Journal of Science and Research 3:118-123.

Alloway BJ. 1995. Heavy Metals in Soils. Blackie Academic & Professional, London.

Alvarez A, Saez JM, Costa JSD, Colin VL, Fuentes MS, Cuozzo SA, Benimeli CS, Polti MA, Amoroso MJ. 2016. Actinobacteria: Current research and perspectives for bioremediation of pesticides and heavy metals. J. of Chemosphere 166:41-62.

Annu, Garg A, Urmila. 2016. Level of Cd in different types of soil of Rhotak district and its bioremediation. Journal of Environmental Chemical Engineering 4:3797-3802.

Asha LP, Sandeep RS. 2013. Review on bioremediation-potential tool for removing environmental pollution. International Journal of Basic and Applied Chemical Sciences 3:21-33.

Atlas RM. 1984. Petroleum Microbiology. Macmillan Publishing Company, New York.

Brennan MA, Shelley ML. 1999. A model of the up takes translocation and accumulation of lead (Pb) by maize for the purpose of phyto-extraction. Ecological Engineering 12:271-297.

Camargo FA, Okeke BC, Bento FM, Frankenberger WT. 2003. In-vitro reduction of hexavalent chromium by a cell-free extract of *Bacillus sp*. ES 29 stimulated by Cu^{2+}. Applied Microbiology and Biotechnology 62:569-573.

Chaney RL, Malik M, Li YM, Brown SL, Brewer EP, Scott-Angle J, Baker AJM. 1997. Phytoremediation of soil metals. Curr. Opin. Biotechnol 8:279-284.

Chehregani A, Malayeri BE. 2007. Removal of heavy metals by native accumulator plants. Int. J. Agric. Biol 9:462-465

D'Amore JJ, Al-Abed SR, Scheckel KG, Ryan JA. 2005. Methods for speciation of metals in soils: A review. J. Environ. Qual 34:1707-1745

Deepika L, Kannabiran K. 2010. Antagonistic Activity Of *Streptomyces* VITDDK1 Spp. (Gu223091) Isolated From The Coastal Region of Tamil Nadu, India. Pharmacologyoline 1:17-29.

Degraeve N. 1981. Carcinogenic, teratogenic and mutagenic effects of cadmium. Mutat. Res 86:115-135.

Dixit R, Wasiullah, Malaviya D, Pandiyan K, Singh UB, Sahu A, Shukla R, Singh BP, Rai JP, Sharma PK, Lade H, Paul D. 2015. Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability 7:2189-2212.

Doelman P, Jansen E, Michels M, Van-Til M. 1994. Effects of heavy metals in soil on microbial diversity and activity as shown by the sensitivity-resistance index, an ecologically relevant parameter. Biol. Fertil. Soils 17:177-178

Elektorowicz M. 1994. Bioremediation of petroleum contaminated clayey soil with pretreatment. Environ. Technol 15:373-380.

Fulekar M, Singh A, Bhaduri AM. 2009. Genetic engineering strategies for enhancing phytoremediation of heavy metals. Afr. J. Biotechnol 8:529-535.

Gadd GM. 2000. Bioremedial potential of microbial mechanisms of metal mobilization and immobilization. Curr. Opin. Biotechnol 11:271-279.

Garbisu C, Alkorta I. 2001. Phytoextraction: A cost effective plant based technology for the removal of metals from the environment. Biores. Technol 77:229-236.

Gentry TJ, Rensing C, Pepper IL. 2004. New approaches for bioaugmentation as a remediation technology. Critical Rev. Environ. Sci. Technol 34:447- 494.

Gisbert C, Ros R, de Haro A, Walker DJ, Pilar-Bernal M, Serrano R, Avino JN. 2003. A plant genetically modified that accumulates Pb is especially promising for phytoremediation. Biochem. Biophys. Res. Commun 303:440-445.

Goblenz A, Wolf K, Bauda P. 1994. The role of glutathione biosynthesis in heavy metal resistance in the fission yeast *Schizosaccharomyces pombe*. FEMS Microbiol. Rev 14:303-308.

Goldstein RM, Mallory LM, Alexander M. 1985. Reasons for possible failure inoculation to enhance biodegradation. Applied and Environmental Microbiology 50:977-983.

Goyal N, Jain SC, Banerjee UC. 2003. Comparative studies on the microbial adsorption of heavy metals. Advances in environmental Research 7:311-319.

Gulati K, Banerjee B, Bala LS, Ray A. 2010. Effects of diesel exhaust, heavy metals and pesticides on various organ systems: Possible mechanisms and strategies for prevention and treatment. Indian J. Exp. Biol 48:710-721.

Heaton ACP, Rugh CL, Wang N, Meagher RB. 1998. Phytoremediation of mercury and methyl mercury polluted soils using genetically engineered plants. Journal of Soil Contamination 7:497-510.

Javaid M, Sultan S. 2013. Plant growth promotion traits and Cr (VI) reduction potentials of Cr (VI) resistant Streptomyces strains. J Basic Microbiol 53:420-8.

Jayanthi B, Emenike CU, Agamuthu P, Simarani K, Mohamad S, Fauziah SH. 2016. Selected microbial diversity of contaminated landfill soil of Peninsular Malaysia and the behaviour towards heavy metal exposure. J. of Catena 147:25-31.

Kabata-Pendias A. 2001. Trace Elements in Soils and Plants, 3rd Ed. CRC Press, Boca Raton, Florida.

Kang CH, Kwon YJ, So JS. 2016. Bioremediation of heavy metals using bacterial mixtures. J. of Ecological Engineering 89:64-69.

Kennish M. 1992. Ecology of estuarines: anthropogenic effects. CRC Press, Boca Raton, Florida.

Kim SU, Cheong YH, Seo DC, Hur JS, Heo JS. 2007. Characterisation of heavy metal tolerance and bio absorption capacity of bacterium strain CPB4 (*Bacillus spp.*). Water Sci. Technol 55:105-111.

Knox AS, Gamerdinger AP, Adriano DC, Kolka RK, Kaplan DI. 1999. Sources and Practices Contributing to Soil Contamination. In: Adriano, D.C., Bollag, J.M., Frankenberg, W.T. (Jr), Sims, R.C. (Eds.), Bioremediation of the Contaminated Soils. Agronomy Series No. 37, ASA, CSSA, SSSA, Madison, Wisconson, USA. 53-87.

Kulshreshtha A, Agrawal R, Barar M, Saxena S. 2014. A Review on Bioremediation of Heavy Metals in Contaminated Water. IOSR Journal of Environmental Science, Toxicology and Food Technology 8:44-50.

Kumar A, Bisht BS, Joshi VD, Dhewa T. 2011. Review on bioremediation of polluted environment: a management tool. International Journal of Environmental Sciences 1:1079.

Kumari S, Flores LC. 2014. Plant mediated detoxification of mercury and lead. Arabian Journal of Chemistry. In Press.

Kunito T, Saeki K, Oyaizu K, Mutsumoto S. 2001. Characterization of copper resistant bacterial communities in copper contaminated soils. European Journal of Soil Biology 37:95-102.

Kuppusamy S, Thavamani P, Megharaj M, Venkateswarlu K, Lee YB, Naidu R. 2016. Pyrosequencing analysis of bacterial diversity in soil contaminated long term with PAHs and heavy metals: Implications to bioremediation. J. of Hazardous Materials 317:169-179.

Laddaga RA, Silver S. 1985. Cadmium uptake in Escherichia coli K-12. J. Bacteriol 162:1100-1105.

Latha MR, Indirani R, Kamaraj S. 2004. Bioremediation of polluted soil. Agri. Rev 25:252-266.

Lee K, Park JW, Ahn IS. 2003. Effect of additional carbon source on naphthalene biodegradation by *Pseudomonas putida* G7, J. Hazardous Materials 105:157-167.

Li F, Tan TC. 1994. Monitoring BOD in the presence of heavy metal ions using a poly (4-vinylpyridine) coated microbial sensor. Biosen. Bioelectron 9:445-455.

Li X, Peng W, Jia Y, Lu L, Fan W. 2016. Bioremediation of lead contaminated soil with *Rhodobacter sphaeroids*. J. of Chemosphere 156:228-235.

Lindqvist O. 1991. Mercury in the Swedish environment. Water Air Soil Bull 55:23-32.

Malik A. 2004. Metal bioremediation through growing cells. Environ. Int 30:261-278.

Margesin R, Schinner F. 2001. Bioremediation (natural attenuation and biostimulation) of diesel-oil contaminated soil in an alpine glacier skiing area. Appl. Environ. Microbiol 67:3127-3133.

Matheickal JT, Yu Q. 1999. Biosorption of lead (II) and copper (II) from aqueous solution by pre-treated biomass of Australian marine algae. Biores. Technol 69:223-229.

McGrath SP, Zhao FJ, Lombi E. 2001. Plant and rhizosphere process involved in phyto-remediation of metal contaminated soils. Plant Soil 232:207-214.

Meenambigai P, Vijayaraghavan R, Gowri RS, Rajarajeswari P, and Prabhavathi P. 2016. Biodegradation of Heavy Metals - A Review. Int. J. Curr. Microbiol. App. Sci 5:375-383.

Modaihsh A, Al-Swailem M, and Mahjoub M. 2004. Heavy metal contents of commercial inorganic fertilizer used in the Kingdom of Saudi Arabia. Agric. Mar. Sci 9:21-25.

Morris C. 1992. Dictionary of Science and Technology. Academic Press, San Diego.

Neustadt J, Pieczenik S. 2007. Toxic metal contamination: Mercury. Integr. Med 6:36-37.

Nies DH. 1999. Microbial heavy metal resistance. Appl. Microbiol. Biotechnol 51:730-750.

Nriagu JO, Pacyna JM. 1988. Quantitative assessment of worldwide contamination of air water and soils by trace metals. Nature. 333:134-139.

Nriagu JO. 1994. Arsenic in the Environment: Cycling and Characterization. John Wiley and Sons, New York.

Ozturk M, Guvensen A. 2002. Studies on the Halophytic Vegetation of Saline-Alkaline Habitats in West Anatolia Turkey. International Symposium on Optimum Resources Utilization in Salt-Effected Ecosystems in Arid and Semiarid Regions, 8-11 April, Cairo-Egypt

Padmavathiamma PK, Li LY. 2007. Phytoremediation technology: Hyper accumulation of metals in plants. Water Air Soil Poll 184:105-126.

Piehler MF, Swistak JG, Pinckney JL, Paerl HW. 1999. Stimulation of diesel fuel biodegradation by indigenous nitrogen fixing bacterial consortia. Microb. Ecol 38:69-78.

Raskin I, Ensley D. 2000. Phytoremediation of toxic metals: Using plants to clean up the environment. John Wiley and Sons, New York.

Raskin I, Gleba D, Smith R. 1996. Using plant seedlings to remove heavy metals from water. Plant Physiol. 111:552-552.

Raskin I, Smith RD, Salt DE. 1997. Phytoremediation of metals: Using plants to remove pollutants from the environment. Curr. Opin. Biotechnol 8:221-226.

Rhykerd RL, Crews B, McInnes KJ, Weaver RW. 1999. Impact of bulking agents, forced aeration and tillage on remediation of oil contaminated soil. Bioresour. Technol 67: 279-285.

Roane TM, Pepper IL. 2001. Environmental microbiology. Academic Press 17:403-423.

Sabiha-Javied, Mehmood T, Chaudhry MM, Tufai M, Irfan N. 2009. Heavy metal pollution from phosphate rock used for the production of fertilizer in Pakistan. Microchem J. 91:94-99.

Salem HM, Eweida EA, Farag A. 2000. Heavy metals in drinking water and their environmental impact on human health. In ICEHM 2000: Cairo University: Giza, Egypt. 542-556.

Salt DE, Blaylock M, Kumar PBAN, Dushenkov V, Ensley BD, Chet L, Raskin L. 1995. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. Biotechnology 13:468-474.

Salt DE, Smith RD, Raskin L. 1998. Phytoremediation. Ann. Rev. Plant Phys. Plant Mol. Biol 49:643-668.

Sang-Hwan L, Seokho L, Dae-Yeon K. 2007. Degradation characteristics of waste lubricants under different nutrient conditions. J. Hazardous Materials 143:65-72.

Saurav K Kannabiran K. 2012. Cytotoxicity and antioxidant activity of 5-(2, 4-dimethylbenzyl) pyrrolidin-2-one extracted from marine *Streptomyces* VITSVK5 spp. Saudi J Biol Sci 19:81-86.

Seaward MRD, Richardson DHS. 1990. Atmospheric Sources of Metal Pollution and Effects on Vegetation. In: Shaw AJ, editor. Heavy Metal Tolerance in Plants: Evolutionary Aspects. Florida: CRC Press 75-92.

Selatnia A, Boukazoula A, Kechid N, Bakhti MZ, Chergui A, Kerchich Y. 2004. Biosorption of lead (II) from aqueous solution by a bacterial dead *Streptomyces rimosus* biomass. Biochemical. Engineering Journal 19:127

Shazia I, Uzma, Sadia GR, Talat A. 2013. Bioremediation of heavy metals using isolates of filamentous fungus *Aspergillus fumigatus* collected from polluted soil of Kasur, Pakistan. International Research Journal of Biological Sciences 2:66-73.

Sineriz ML, Kothe E, Abate CM. 2009. Cadmium biosorption by Streptomyces sp. F4 isolated from former uranium mine. J Basic Microbiol 49:S55-S62.

Sumner ME. 2000. Beneficial use of effluents, wastes, and biosolids. Commun. Soil Sci. Plant Anal 31:1701-1715.

Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. 2014. Heavy metal toxicity and the environment. PMC 101:133-164.

Thieman WJ, Palladino MA. 2009. Introduction to biotechnology, 2nd edition. Pearson, New York. 209-222.

Tripathi RD, Srivastava S, Mishra S, Singh N, Tuli, Gupta DK, Maathuis FJM. 2007. Arsenic hazards: Strategies for tolerance and remediation by plants. Trends Biotech. 25: 158-165.

Walsh PR, Duce RA, Finishing JI. 1979. Consideration of the enrichment, sources, and flux of arsenic in the troposphere. J. Geophysical. Res 84:1719-1726.

Wood JM, Wang HK.1983. Microbial resistance to heavy metals. Environ. Sci. Technol 17:582-590.

Wuana RA, Okieimen FE. 2011. Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecol. Article 20.

Yao Z, Li J, Xi H, Yu C. 2012. Review on remediation technologies of soil contaminated by heavy metals. Procedia Environmental Sciences. 16: 722-729