Aquatic Bioremediation of Metals

Mona S. Zaki[1], Nadia El Battrawy[2] and Hammam A. M.[3], S. I. Shalaby[3].

[1] Department of Hydrobiology, Veterinary Division, National research Center
[2]Animal Reproduction Institute, Agriculture Research Centre, Ministry of Agriculture, Egypt
[3]Department of Animal Reproduction and A.I., Veterinary Division National Research Center, Egypt.
dr_mona_zaki@yahoo.co.uk

Abstract: Heavy metals have been used by humans for thousands of years. Although several adverse health effects of heavy metals have been known for a long time, exposure to heavy metals continues, and is even increasing in some parts of the world, in particular in less developed countries, though emissions have declined in most developed countries over the last 100 years. Excessive levels of heavy metals can be damaging to the organism. Some of them are dangerous to health or environment (e.g. mercury, cadmium, lead, chromium), some may cause corrosion (e.g. zinc, lead), some are harmful in other ways (e.g. arsenic may pollute catalysts). Treating the polluted environment with these bioremediators is the most efficient and least costly method. As far as health effects of metals on aquatic flora and fauna is concerned, there are two categories of metals; one, which are nutritionally important but exceeding concentrations tend to be toxic and other category of metals have no role in the physiology of body and are toxic even at low levels. Cu, Zn, Fe, Ni, Co, Se, Mo and Cr are the metals belonging to the first category of metals having biological roles,while Ag, Al, Cd, Pb, Hg, As, Sr, and U belong to the second category. There are other toxic metals too but these are the major elements which have aroused lot of public sentiments and have been extensively studied by the researchers. Maintaining the optimal levels of the elements mentioned by pumping and treating is not only expensive but also less effective. Therefore, bioremediation is a viable option but the toxicity of contaminants to microorganisms and plants to be used for such purpose have to be considered. Another factor to be considered while using biological agents for cleanup is the bioavailability of the metals. Water pH affects the speciation and bioavailability to a considerable level, for example, at pH 7, 6811M of cobalt is predicted to exist in the free ionic form while only 4.1 iiM of nickel remains in this form. Hence, using a buffering system to maintain pH or using lime to increase pH or alum to reduce pH is advisable.

[Mona S. Zaki, Nadia El Battrawy and Hammam A. M., S. I. Shalaby**. Aquatic Bioremediation of Metals.** *Life Sci J* 2014;11(4):66-72]. (ISSN:1097-8135). http://www.lifesciencesite.com. 7

Keyword: Heavy metals – corrosion – toxic- pH.

Introduction

Our environment, and especially the aquatic environment, has been under focus within the past decades because of the large amount of chemical substances released into it. Thousands of synthetic chemical compounds are currently registered for use in industry and agriculture, and thousands of tons of these are produced annually.. In addition, several tons of more unintended byproducts accompany these synthetic compounds. Regardless of the source or original intended use, substantial amounts of these chemicals end up in the aquatic environment due to physico-chemical, hydrologic and atmospheric processes. Organic micropollutants such as metals and pesticides will only cause detrimental effects to organisms if they are taken up by the organism and can reach a target site where they can do harm (**Escher & Hermens, 2004; Schwarzenbach *et al.,* 2006**). The processes of uptake, biotransformation, and elimination, also termed bioaccumulation or toxicokinetics, modify the concentration of organic chemicals in organisms, and kinetic rate constant models of these processes quantify and yield the time course of internal concentrations(**Landrum *et al.,* 1992; Mackay & Fraser, 2000; Hendriks *et al.,* 2001**). Bioaccumulation and biotransformation are key factors modifying toxicity (**McCarty &Mackay, 1993; Escher& Hermens, 2002; Meador *et al.,* 2008**) and bioaccumulation itself is one of the assessment end points in risk assessment of chemicals (**van Leeuwen *et al.,* 2007**). Bioaccumulation based on total radioactivity measurements of 14C-labeled compounds varies greatly among species (**Rubach *et al.,* 2010**), and compounds (**Ashauer *et al.,* 2010**), but the causes remain partially unresolved because the contribution of biotransformation cannot be quantified with these methods.

Biotransformation in freshwater arthropods has been shown to greatly modify internal concentrations of organic chemicals for various biological species and chemical compounds (**Akkanen& Kukkonen,2003; Nuutinen, *et al.,* 2003; Ikenaka *et al.,* 2006; Richter & Nagel, 2007**). Differentiation between parent and metabolites increased accuracy of bioaccumulation parameters compared to total 14C measurements. Biotransformation dominated toxicokinetics and strongly affected internal concentrations of parent compounds and metabolites. Many metabolites reached higher internal concentrations than their parents, characterized by large metabolite enrichment factors**.(Roman** ***et al.,*** **2012**).

Microbial Bioremediation of Metals

Living system requires special transport and handling mechanisms to keep them from toxic metals (**Rehman** ***et al.,*** **2008**). The toxicity occurs in humans due to environmental pollution via soil or water contamination or due to occupational exposure. Some of these metals are useful to us in low concentrations but are highly toxic in higher concentrations **(Ge** ***et al.,*** **2009).**

Bioremediation processes are very attractive in comparison with physicochemical methods such as electrochemical treatment, ion exchange, precipitation, reverse osmosis, evaporation, and sorption for heavy metal removal techniques because they can have lower cost and higher efficiency at low metal concentrations **(Bogdanova** ***et al.,*** **1992; Gadd and White,1993).**

There are a number of bio materials that can be use to remove metal from waste water, such molds, yeasts, bacteria, and seaweeds **(Vieira and Volesky, 2000; Waisberg** ***et al.,*****2003).** The ability of microbial stains to grow in the presence of heavy metals would be helpful in the waste water treatment where microorganisms are directly involved in the decomposition of organic matter in biological processes for waste water treatment **(Prasenjit and Sumathi, 2005; Munoz** ***et al.,*** **2006),** because often the inhibitory effect of heavy metals is a common phenomenon that occurs in the biological treatment of waste water and sewage **(Filali** ***et al.,*****2000)**. Mechanisms of metal resistance in microbes include precipitation of metals as phosphates, carbonates and/or sulfides; volatilization via methylation or ethylation; physical exclusion of electronegative components in membranes and extra cellular polymeric substances (EPS); energy-dependent metal efflux systems; and intra cellular sequestration with low molecular weight, cysteine-rich proteins (**Gadd, 1990; Silver, 1996**).

There are some yeast like *Rhodotorula mucilaginosa* which is efficient in lead bioadsorption (**Chatterjee** ***et al.,*****2011**). Hexavalent chromium (Cr (VI)) and trivalent chromium (Cr (III)) are the most prevalent species of chromium in the natural environment (**Chung** ***et al.,*****2006**).

These identified heavy metal resistant bacteria could be useful for the bioremediation of heavy metal contaminated sewage and waste water. Biotechnological approaches are recommended for extraction of metal forms can be grown in ponds where effluents (rich in heavy metals) are dis- charged. The microbes will extract the heavy metals and sequester them inside their cell membranes (**Sabyasachi** ***et al.,*** **2012**).

Organic compounds are detoxified or removed by the microbes by converting them into harmless water, carbon dioxide and other volatile gases but metals are just transformed by the microbes to less soluble or bioavailable form (**Lovley and Coates, 1997**). This generally is made possible by converting inorganic forms into organic forms by redox conversions and coupling in respiratory pathways (**Lovley and Coates, 1997; Tebo** ***et al.*** **1997**). Microbes have capabilities to immobilize metals by bioaccumulation and biosorption. The process of active uptake of metals by bacteria is termed as bioaccumulation while passive uptake is called biosorption (**Unz and Shuttleworth, 1996**).

Bioaccumulation is an interaction between the microorganism and the metal ion in relation to metabolic pathways. Metal ions required for biological functions are actively taken up by the microbes and converted into organic forms. Accumulation of radio nucleotides through the pathways of their stable isotopes or of chemical homologous elements can be considered as bioaccumulation. One such example is of accumulation of cesium by potassium channels (**Avery, 1995**).

Biosorption is simply a physiochemical process of accumulating metal species by sorption, surface complexion, ion exchange and entrapment (**Gadd, 2004; Le** Cloirec **and** Andre **A, 2005**). The biosorption qualities of Saccharomyces cerevisiae have a special mention. This is a by-product of fermentation and brewery industry and is hence quite cost effective to treat water bodies dissolving certain metals (**Unz and Shuttleworth, 1996; Lovley and Coates, 1997**). In fact, the dehydrated yeast *Candida utilis* demonstrated improved chromium sorption (**Simmons** ***et al.,*** **1995**). *Micrococcus luteus*, *Pseudomonas aeruginosa* and *Escherichia coli* have also been attributed with biosorption properties of metals like chromium, copper, nickel and cobalt (**Churchill and Churchill, 1995**).

Peptidoglycan carboxylic groups of the Gram-positive bacteria phosphate groups in gram-negative bacteria (**Beveridge and Doyle, 1989; Schultze-Lam** ***et al.*****, 1996; McLean,** ***et al.,*** **2002**), chitin in fungal cell walls, chitosan and other chitin derivatives (**Simmons** ***et al.,*** **1995**) have been attributed with metal adsorptive propertig. Fungal phenolic polymers and melanins possess many potential metal binding sites with oxygen-containing groups such as carboxyl, phenolic and alcoholic hydroxyl, carbonyl and methoxyl groups (**Gadd and White, 1993**). Due to its cost effectiveness and easy availability of raw material, this technology is being widely appreciated and accepted. This method not only remediates effluents and water in the water bodies but recovery of soluble metals is also possible (**Gavrilescu, 2004**). This technology is being used as immobilized living biomass mainly in the form of bacterial biofilms on inert supports in a variety of bioreactor configurations such as rotating biological contactors, fixed bed reactors, trickle filters, fluidized beds and air-lift bioreactors (**Macaskie and Dean, 1989; Gadd and White, 1993; Schiewer and Volesky, 2000; Gadd, 2001**).

Not only microorganisms but also other biosorbent substrates like tamaring shell, rice husk, cottonseed hull, corncobs, almond and peanut hulls have been shown to remove heavy metal ions (**Johnson *et al*. 2002; Shen and Duvnjak, 2005; Kumar and Bandyoadhyay, 2006; Rao Popuri *et al*., 2007**).

Bioremediation of certain metals by microbes can be affected by mobilization (**Gadd, 2004**). Microorganisms can affect dissolution of metals by leaching, chelation while they are metabolized by action of siderophores. Once leached or chelated, the metals become unavailable for biological functions in water. Processes such as methylation of certain metals can also volatilize them facilitating the removal from water. In general, mobilization is affected by various methods like chemoorganotrophic leaching, autotrophic leaching, siderophores, biomethylation and redox transformations.

Chemoorganotrophic Leaching (Heterotrophic)

Microorganisms maintain their charge balance through H+ efflux through H+-ATPase pumps so as to neutralize metabolic carbon dioxide. This proton efflux causes the microenvironment surrounding thebiofilm to get acidic and lead to metal release from the soil (**Gadd, 2004**). There is a dynamic equilibrium between the metals adsorbed in the soil and metal ions dissolved in water. Acidification of water shifts the equilibrium and causes the release of ions into water from soil. Microbes also release some organic acids that are formed during metabolic processes which supply water with protons and metal-complexing anions (**Burgstaller and Schinner, 1993; Gadd, 1999**). Citrate and oxalate ions have the ability to form complexes with a wide variety of elements (**Gadd, 2001**).

Metallocitrate ions are very stable and hard to break thereby removing many metals from water (**Francis, *et al*., 1992**). Oxalate forms stable complexes with Al, Li, Mn and Fe (**Strasser, *et al.,* 1994**). Acid producing fungi is a better appThach for bioremediation as they can tolerate a wider fluctuation in pH than bacteria (**Burgstaller and Schirmer, 1993**). Some of the acid producing fungi are Yarrowia lipolytica (citric), Mucor spp.(fumaric and gluconic), Rhizopus spp. (lactic, fumaric and gluconic), Aspergillus niger (citric, oxalic, gluconic), Aspergillus spp. (citric, tartaric, malic, a-ketoglutaric, itaconic, aconitic), Penicillium spp. (citric, tartaric, malic, α--ketoglutaric, gluconic) and Scliizophyllum coyqune (malic) (**Burgstaller and Schirmer, 1993**).

Autotrophic Leaching

Some bacteria oxidize ferfous ions or reduce sulphur so as to obtain energy. Such a chemical change results in solublization of metals as the end product is usually Fe(III) or H2SO4 which are soluble (**Rawlings, 1997; Schippers and Sand, 1999**). Such bacterial are called chemoautotcohic, chemolithotrophic and acidophilic bacteria which fix carbon by obtaining energy from such chemical reactions (**Gadd, 2001**). Organic acids act as carbon substrates which are oxidized completely to CO2 or to some other organic intermediates. The ATPs are produced through electron transport chain with sulphur as terminal electron acceptor which is reduced to sulphide (**Hansen, 1993; Peck Jr, 1993**). The sulphide so generated form metal sulphide and gets precipitated. Sulphur reducing bacteria are essentially anaerobic (**White, *et al.,* 1998**). Some of the bacterial species used in 13ioremediation are: sulphur oxidizing Thiobacillus thioxidans, Iron and sulphur oxidizing T. ferroxidans, Iron oxidizing Leptospirillum ferroxidans (**Ewart and Hughes, 1991; Bosecker, 2006**). Autotrophic reduction of sulphuric acid causes metag to soublize from sewage and sludge (**White *et al.,* 1998**). Both sulphate and iron reducing bacteria have been used to treat the mine waste water in artificial wet, lands (**Harnmack and Edenborn, 1992**).

Siderophores

Siderophores (from the Greek: "iron carriers") are defined as relatively low molecular weight, ferric ion specific chelating agents released by bacteria and fungi growing under low iron stress **(Neilands, 1995**). Bacteria producing siderophores have been used to treat metal contaminated sandy soils.

Alcaligenes eutrophus is used to solublize metal from contaminated soils which can be removed by biosorption techniques as mention earlier. This method has been used effectively for reduction of Cd, Zn.and Pb from contaminated soils **(Diels, *et al.,*1999).**

Biomethylation

Microbes can methylate metals so as to yield volatile derivatives such as dimethylselenide and trimethylarsine (**Brady, *et al*., 1996; Dungan and Frankenberger, 1999; Gadd, 1993**). Selenium methylation has been widely discussed and the probable mechanism is by transfer of methyl group to selenium by S-adenosyl methionine system (**Gadd, 1993**). Mediation of Hg, As, Se, Sn, Te and Pb by bacteria has been discussed by **Gadd, (2004).**

Bioremediation of Petroleum Contaminants

Petroleum and its components drive the present civilization and are the major energy sources. But, where there is use there is a chance for abuse too. Hence, being the prime source of energy, petroleum is also a major environment pollutant. Since 1992, there have been 21 major oil spills causing huge economic and immeasurable non-economic losses (**Cedre, 2012. http:/www.endgame.org/oilspills.htm**). Petroleum contamination is quite harmful for the higher organisms (**Lyons, *et al.,* 1999; Janjua *et al*, 2006; Cheong *et al.,* 2011**) but it is fortunate that micf6 organisms can thrive on it and assimilate (**Atlas, 1995; de Oliveira *et al.,* 2012**). Soon after major oil spill incident is reported, the efforts are concentrated at physical removal of oil but they rarely achieve complete clean up. As per Office of Technology Assessment (OTA; USA), such mechanical methods are efficient at removing no more than 10-15 per cent of oil after a major spill. In such cases, bioremediation has a major role to play in neutralizing the harmful effects of oil in the open environment. The basic principle is to use organisms that can use petroleum as carbon source and hence, break them down to harmless end products.

Like any other technology that uses biological agents, success of bioremediation of petroleum contamination also depends on establishing and maintaining conditions that favour proliferation of petroleum scavenging microorganisms. Bioaugmentation and Biostimulation are the two main approaches followed in this regard. Bioaugmentation refers to inoculating the affected area with degrading microorganisms while biostimulation would require favouring growth of such microorganism through addition of nutrients or by providing other growth-limiting substrates (e.g. oxygen, surf washing etc.). As petroleum is hydrophobic in nature, its bioavailability becomes a major constraint in the process of bioremediation. Use of biosurfactants is a common approach to increase the bioavailability. Requirements of a successful bioremediation process of petroleum contamination are as follows:

The very first requirement is the availability of microorganisms that can utilize oil as a metabolic substrate. Finding and transplanting such an organism to the site of contamination would be the first approach. **Jones *et al.* (1983)** reported for the first time biodegraded petroleum byproducts in marine sediments (**Das and Chandran, 2010**). Enzymatic degradation of petroleum can be achieved by bacteria, algae or fungi. Different organisms have varied degradation capabilities and act on different substrates. As petroleum is an assortment of different components, it is advisable to use a cocktail of organisms to effect remediation. Bacteria are the most efficient of all organisms that can degrade hydrocarbons (**Rahman *et al.,* 2003; Brooijmans 2009. Floodgate, (1984)** mentioned 25 genera of hydrocarbon degrading bacteria" and 25 genera of hydrocarbon degrading fungi which were isolated from marine environment.

Some of the bacteria recognized as hydrocarbon degrading are *Arthrobacter, Burkholderia, Mycobacterium, Pseudomonas, Sphingomonas, Rhodococcus, Pseudomonas fluorescens, P. aeruginosa, Bacillus subtilis, Bacillus sp., Alcaligenes sp.,* Acinetobacter lwoffi, *Flavobacterium sp.,* Micrococcus roseus, and *Corynebacterium sp.* (**Jones *et al.,* 1983; Adebusoye *et al.,* 2007**). Some fungal genera utilized for this purpose are A-inorphoteca, Neosartorya, Tal aromyces, Graphium, Candida lipolytica, Yarrowia, Pichia, Aspergillus, Cephalosporium, Rhodotorula mucilaginosa, Geotrichum sp, Trichosporon mucoides and Pencillium (**Boguslawska-Was and Dabrowski, 2001; Chaillan *et al.,* 2004; Singh, 2006**). Alter the potential scavengers have been identified, the conditions for their survival and proliferation have to be ascertained.

Among the physical factors temperature is most important one determining the survival of microorganisms and composition of the hydrocarbons (**Das and Chandran, 2010**). At higher temperature some fraction may get evaporated and the oil would tend to spread while in low temperature the slick would be more viscous and retention of otherwise volatile fractions thereby delaying the bioremediation process. For freshwater bioremediation process 20-30°C is the ideal temperature while for marine 15-20°C is recommended. For high molecular weight polycyclic hydrocarbons, which are otherwise difficult to degrade, higher temperatures may be required (**Bartha and Bossert, 1984; Cooney, 1984**). As temperature has effect on enzymafic turnover rate "Q^{10}" hence, higher temperature would favour bioremediation. It was reported that the rate of hydrocarbon remediation was maximum in the range of 30-40°C in general and above this, the membrane toxicity effect of hydrocarbons was found to inhibit the survival of microorganisms (**Bartha and Bossert, 1984**). As there is a close relationship between temperature and oil bioremediation, it is easy to understand why an oil leak disaster would be dangerous in polar regions.

References:

1. Adebusoye, S.A., Ilori, M.O., Amund, 0.0., Teniola, 0.D., and Olatope, S. (2007). Microbial Degradation of Petroleum Hydrocarbons in a Polluted Tropical Stream. World Journal of Microbiology and Biotechnology, 23(8): 1149-1159.
2. Akkanen, J.; Kukkonen, J. V. K. Biotransformation and bioconcentration of pyrene in Daphnia magna. Aquat. Toxicol. 2003, 64 (1), 53−61.
3. Ashauer, R.; Caravatti, I.; Hintermeister, A.; Escher, B. I. Bioaccumulation kinetics of organic xenobiotic pollutants in the freshwater invertebrate Gammarus pulex modeled with prediction intervals. Environ. Toxicol. Chem. 2010, 29 (7), 1625−1636.
4. Atlas, R.M. (1995). Bioremediation of Petroleum Pollutants. International Biodeterioration and

Biodegradation, 35(1): 317-327.

5. Avery, S.V. (1995). Microbial Interactions with Caesium—Implications for Biotechnology. Journal of Chemical Technology and Biotechnology, 62(1): 3-16.
6. Bartha R. and Bossert I. (1984). The Treatment and Disposal of Petroleum Wastes. Petroleum Microbiology, R.M. Atlas, Ed., pp. 553-578, Macmillan, New York, NY, USA.
7. Beveridge, T.J., and Doyle, R.J. (1989). Metal Ions and Bacteria: Wiley-Interscience.
8. Bogdanova, E.S., Mindlin, S.Z., Pakrova, E., Kocur, M. and Rouch, D.A. (1992) Mercuric reductase in environ- mental Gram-positive bacteria sensitive to mercury. FEMS Microbiology Letters, 97, 95-100.
9. Boguslawska-Was, E., and Dabrowski, W. (2001). The Seasonal Variability of Yeasts and Yeast-like Organisms in Water and Bottom Sediment of the Szczecin Lagoon. International journal of hygiene and environmental health, 203(5): 451-458.
10. Bosecker, K. (2006). Bioleaching: Metal Solubilization by Microorganisms. FEMS Microbiology Reviews, 20(3 4): 591-604.
11. Brady, J.M., Tobin, J.M., and Gadd, G.M. (1996). Volatilization of Selenite in Aqueous Medium by a Penicillium Species. Mycological Research, 100(8): 955-961.
12. Brooijmans, R., Pastink, M., and Siezen, R. (2009). Hydrocarbon-degrading Bacteria: The Oil-spill Clean-up crew. Microbial Biotechnology, 2(6): 587.
13. Burgstaller, W., and Schirmer, F. (1993). Leaching of Metals with Fungi. 7ournal of Biotechnology, 27(2): 91-116.
14. Bury, N.R., Walker, P.A., and Glover, C.N. (2003). Nutritive Metal Uptake in Teleost Fish. Journal of Experimental Biology, 206(1): 11-23.
15. Chaillan, F., Le Fleche, A., Bury, E., Phantavong, Y.H., Grimont, P., Saliot, A., and Oudot, J. (2004). Identification and Biodegradation Potential of Tropical Aerobic Hydrocarbon-degrading Microorganisms. Research in Microbiology, 155(7): 587.
16. Chatterjee, S., Gupta, D., Roy, P., Chatterjee, N.C., Saha, P. and Dutta, S. (2011) Study of a lead tolerant yeast strain BUSCY1 (MTCC9315). African Journal of Micro- biology Research, 5, 5362-5372.
17. Cheong, H.K., Ha, M., Lee, J.S., Kwon, H., Ha, E.H., Hong, Y.C., Lee, S.M. (2011). Hebei Spirit Oil Spill Exposure and Subjective Symptoms in Residents Participating in Clean-up Activities. Environmental Health and Toxicology, 26.
18. Chung, J., Nerenberg, R. and Rittmann, B.E. (2006) Bio- reduction of soluble chromate using hydrogen based mem- brane bioflim reactor. Water Research, 40, 1634-1642.
19. Churchill, S., and Churchill, P. (1995). Sorption of Heavy Metals by Prepared Bacterial Cell Surfaces. Journal of Environmental Engineering, 121: 706.
20. Cooney J. J.(1984). The Fate of Petroleum Pollutants in Fresh Water Ecosystems. Petroleum Microbiology, R.M. Atlas, Ed., pp. 399-434, Macmillan, New York, NY, USA, 1984.
21. Das, N., and Chandran, P. (2010). Microbial Degradation of Petroleum Hydrocarbon Contaminants: An Overview. Biotechnology Research International, 2011.
22. De Oliveira, N. C., Rodrigues, A. A., Alves, M. I. R., Antoniosi Filho, N. R., Sadoyama, G., and Vieira, J. D. G. (2012). Endophytic Bacteria with Potential for Bioremediation of Petroleum Hydrocarbons and Derivatives. African Journal of Biotechnology, 11(12): 2977-2984.
23. Diels, L., De Smet, M., Hooyberghs, L., and Corbisier, P. (1999). Heavy Metals Bioremediation of soil. Molecular Biotechnology, 12(2): 149-158.
24. Dungan, R., and Frankenberger, W. (1999). Microbial Transformations of Selenium and the Bioremediation of Seleniferous Environments. Bioremediation Journal, 3(3): 171-188.
25. Escher, B. I.; Hermens, J. L. M. Internal exposure: Linking bioavailability to effects. Environ. Sci. Technol. 2004, 38 (23), 455A−462A.
26. Escher, B. I.; Hermens, J. L. M. Modes of action in ecotoxicology: Their role in body burdens, species sensitivity, QSARs, and mixture effects. Environ. Sci. Technol. 2002, 36 (20), 4201−4217.
27. Ewart, D.K., and Hughes, M. N. (1991). The Extraction of Metals from Ores Using Bacteria. Adv. Inorg. Chem, 36: 103-135.
28. Filali, B.K., Taoufik, J., Zeroual, Y., Dzairi, F.Z., Talbi, M. and Blaghen, M. (2000) Waste water bacteria resistant to heavy metals and antibiotics. Current Microbiology, 41, 151-156.
29. Floodgate G. (1984). The Fate of Petroleum in Marine Ecosystems in Petroleum Microbiology, R. M. Atlas, Ed., pp. 355-398, Macmillion, New York, NY, USA, 1984.
30. Francis, D. K., Dodge, C. and Gillow, J. (1992). Biodegredation of metal citrate complexes and implications for toxic-metal mobility. Nature, 356: 140-142.
31. Gadd, G.M. (1990) Heavy metal accumulation by bacte- ria and other microorganisms. Experientia, 46, 834-840.
32. Gadd, G.M. (2001). Accumulation and Transformation of Metals by Microorganisms. Biotechnology Set, 225-264
33. Gadd, G.M. (2004). Microbial Influence on Metal Mobility and Application for Bioremediation. Geoderma, 122: 109-119.
34. Gadd, G.M. and White, C. (1993) Microbial treatment of metal pollution—A working biotechnology. Trends Bio- technology, 11, 353-359.
35. Gadd, G.M., and White, C. (1993). Microbial Treatment of Metal Pollution-A Working Biotechnology? Trends in Biotechnology, 11(8): 353-359.

36. Garbisu and Alkorta(2003) Review Basic concepts on heavy metal soil bioremediation The European Journal of Mineral Processing and Environmental Protection.Vol.3, No.1, 1303-0868, 2003, pp. 58-66
37. Gavrilescu, M. (2004). Removal of Heavy Metals from the Environment by Biosorption. Engineering in Life 'Sciences, 4(3): 219-232.
38. Ge, H.W., Lian, M.F., Wen, F.Z., Yun, Y.F., Jian, F.Y. and Ming, T. (2009) Isolation and characterization of the heavy metal resistant bacteria CCNWRS33-2 isolated from root nodule of Lespedeza cuneata in gold mine tailings in China. Journal of Hazard Materials, 162, 50-56.
39. Hammack, R.W., and Edenborn, H.M. (1992). The Removal of Nickel from Mine Waters Using Bacterial Sulfate Reduction. Applied Microbiology and Biotechnology, 37(5): 674-678.
40. Hansen, T. (1993). Carbon Metabolism of Sulfate-reducing Bacteria. The Sulfate-reducing Bacteria: Contemporary Perspectives. Springer, New York Inc.: S, 21-40.
41. Harnmack, R. W. and. Edenbor H.M (1992). The removal of nickel from mine wastes using bacterial sulfate reduction. Applied Microbiology and Biotechnology, 37 (5): 674-678
42. Hendriks, A. J.; van der Linde, A.; Cornelissen, G.; Sijm, D. T. H. M. The power of size. 1. Rate constants and equilibrium ratios for accumulation of organic substances related to octanol-water partition ratio and species weight. Environ. Toxicol. Chem. 2001, 20 (7), 1399− 1420.
43. Ikenaka, Y.; Eun, H.; Ishizaka, M.; Miyabara, Y. Metabolism of pyrene by aquatic crustacean, Daphnia magna. Aquat. Toxicol. 2006, 80 (2), 158−165.
44. Janjua, N., Kasi, P., Nawaz, H., Farooqui, S., and Khuwaja, U. (2006). Acute Health Effects of the Tasman Spirit Oil Spill on Residents of Karachi, Pakistan. BMC Public Health, 6(1): 84.
45. Johnson, P., Watson, M., Brown, J., and Jefcoat, I. (2002). Peanut Hull Pellets as a Single Use Sorbent for the Capture of Cu (II) from Wastewater. Waste Management, 22(5): 471-480.
46. Jones D.M., Douglas A.G., Parkes R.J., Taylor J., Giger W., and Schaffner C. (1983). "The Recognition of Biodegraded Petroleum-derived Aromatic Hydrocarbons in Recent Marine Sediments," Marine Pollution Bulletin, 14(3): 103-108.
47. Kumar, U., and Bandyopadhyay, M. (2006). Sorption of Cadmium from Aqueous Solution Using Pretreated Rice Husk. Bioresource Technology, 97(1): 104-109.
48. Landrum, P.; Lee, H. II; Lydy, M. Toxicokinetics in aquatic systems: model comparison and use in hazard assessment. Environ.Toxicol. Chem. 1992, 11, 1709−1725.
49. Le Cloirec P, Andres Y. (2005). Bioremediation of Heavy Metals Using Microorganisms, In: Bioremediation of Aquatic and Terrestrial Ecosystems. Science Publishers, India, pp: 97-140.
50. Lovley, D.R., and Coates, J. D. (1997). Bioremediation of Metal Contamination. Current Opinion in Biotechnology, 8(3): 285-289.
51. Lyons, R.A., Temple, J., Evans, D., Fone, D.L., and Palmer, S. R. (1999). Acute Health Effects of the Sea Empress Oil Spill. Journal of Epidemiology and Community Health, 53(5): 306-310.
52. Macaskie, L., and Dean, A. (1989). Microbial Metabolism, Desolubilization, and Deposition of Heavy Metals: Metal Uptake by Immobilized Cells and Application to the Detoxification of Liquid Wastes. Advances in Biotechnological Processes, 12: 159.
53. Mackay, D.; Fraser, A. Bioaccumulation of persistent organic chemicals: mechanisms and models. Environ. Pollut. 2000, 110 (3),375−391.
54. McCarty, L. S.; Mackay, D. Enhancing ecotoxicological modelling and assessment: body residues and modes of toxic action. Environ. Sci. Technol. 1993, 27 (9), 1719−1728.
55. McLean, J. Lee, J. and Beveridge, T. (2002). In Interactions of Bacteria and Environmental Metal Development And Bioremediation Strategies. IUPAC Series on Analytical and Physical Chemistry Of Environmental System, 8:227-262.
56. Meador, J. P.; McCarty, L. S.; Escher, B. I.; Adams, W. J. 10th Anniversary Critical Review: The tissue-residue approach for toxicity assessment: Concepts, issues, application, and ecommendations. J. Environ. Monit. 2008, 10 (12), 1486−1498.
57. Munoz, R.A., Munoz, M.T., Terrazas, E., Guieysse, B. and Mattisasson, B. (2006) Sequential removal of heavy metals ions and organic pollutants using an algal-bacterial consortium. Chemosphere, 63, 903-991.
58. Neilands, J. (1995). Siderophores: Structure and Function of Microbial Iron Transport Compounds. Journal of Biological Chemistry, 270(45): 26723-26726.
59. NRC National Research Council, Polychlorinated Biphenyls, 1979.
60. Peck Jr, H. (1993). Bioenergetic Strategies of the Sulfate-reducing Bacteria. In: The Sulfate-reducing Bacteria: Contemporary Perspectives. Springer, New York Inc.: S, 41-76.
61. Prasenjit, B. and Sumathi, S. (2005) Uptake of chromium by Aspergillus foetidus. Journal of Material Cycles and Waste Management, 7, 88-92.
62. Rahman, K.S.M., Rahman, T.J., Banat, I.M., Lord, R. and Street, G. (2007). Bioremediation of Petroleum Sludge Using Bacterial Consortium with Biosurfactant, In: Environmental Bioremediation Technologies. Springer Berlin Heidelberg New York, pp: 391-408.
63. Rao Popuri, S., Jammala, A., Naga Suresh Reddy, K. V., and Abburi, K. (2007). Biosorption of Hexavalent Chromium Using Tamarind (Tamarindus

indica) Fruit Shell-a Comparative Study. Electronic Journal of Biotechnology, 10(3): 358-367.

64. Rawlings, D. (1997). Mesophilic, Autotrophic Bioleaching Bacteria: Description, Physiology and Role, DE Rawlings. In: Theory, Microbes and Industrial Processes Ed. Biomining: 229-245.
65. Rehman, A., Zahoor, A., Muneer, B. and Hasnain, S. (2008) Chromium tolerance and reduction potential of a Bacillus sp.ev3 isolated from metal contaminated wastewater. Bul- letin of Environmental and Contamination Toxicology, 81, 25-29.
66. Richter, S.; Nagel, R. Bioconcentration, biomagnification and metabolism of 14C-terbutryn and 14C-benzo[a]pyrene in Gammarus fossarum and Asellus aquaticus. Chemosphere 2007, 66 (4), 603−610.
67. Roman Ashauer,*,†Anita Hintermeister,†Isabel O'Connor,†,‡Maline Elumelu,†Juliane Hollender and Beate I. Escher(2012): Significance of Xenobiotic Metabolism for Bioaccumulation Kinetics of Organic Chemicals in Gammarus pulex. Environ. Sci. Technol. 2012, 46, 3498−3508
68. Sabyasachi Chatterjee, Anindita Mukherjee, Agniswar Sarkar, Pranab Roy,2012: Bioremediation of lead by lead-resistant microorganisms, isolated from industrial sample. Advances in Bioscience and Biotechnology, 2012, 3, 290-295
69. Sandarin T.R. and Hoffman D.R. (2007). Bioremediation of Organic and Metal Contaminants, In: Environmental Bioremediation Technologies. Springer Berlin Heidelberg New York, pp: 2-18.
70. Schiewer, S., and Volesky, B. (2000). Biosorption Processes for Heavy Metal Removal. Environmental Microbe-Metal Interactions. ASM Press, Washington, DC, USA, 329-362.
71. Schippers, A., and Sand, W. (1999). Bacterial Leaching of Metal Sulfides Proceeds by Two Indirect Mechanisms via Thiosulfate or via Polysulfides and Sulfur. Applied and Environmental Microbiology, 65(1): 319-321.
72. Schultze-Lam, S., Fortin, D., Davis, B., and Beveridge, T. (1996). Mineralization of Bacterial Surfaces. Chemical Geology, 132(1): 171-181
73. Schwarzenbach, R. P.; Escher, B. I.; Fenner, K.; Hofstetter, T. B.; Johnson, C. A.; von Gunten, U.; Wehrli, B. The challenge of micropollutants in aquatic systems. Science 2006, 313 (5790), 1072−1077.
74. Shen, J., and Duvnjak, Z. (2005). Adsorption Kinetics of Cupric and Cadmium Ions on Corncob Particles. Process Biochemistry, 40(11): 3446-3454.
75. Silver, S. (1996) Bacterial resistances to toxic metals—A review. Gene, 179, 9-19.
76. Silver, S. and Misra, T.K. (1988) Plasmid mediated metal resistance. Annual Review of Microbiology, 42, 717-743.
77. Simmons, P., Tobin, J. M., and Singleton, I. (1995). Considerations on the Use of Commercially Available Yeast Biomass for the Treatment of Metal-containing Effluents. Journal of Industrial Microbiology and Biotechnology, 14(3): 240-246.
78. Singh, H. (2006). Mycoremediation: Fungal Bioremediation: John Wiley and Sons.
79. Siron R, Pelletier E and Brochu H. (1995). Environmental Factors Influencing the Biodegradation of Petroleum Hydrocarbons in Cold Seawater. Arch Environ Cort1am Toxicol 28: 406-416.
80. Smith, D., Alvey, S., and Crowley, D.E. (2005). Cooperative Catabolic Pathways within an Atrazine Degrading Enrichment Culture Isolated from Soil. FEMS Microbiol. Ecol., 53: 265-273.
81. Sreekrishnan, T., and Tyagi, R. (1994). Heavy Metal Leaching from Sewage Sludges: A Techno Economic Evaluation of the Process Options. Environmental Technology, 15(6): 531-543.
82. Strasser, H., Burgstaller, W., and Schinner, F. (1994). High-yield Production of Oxalic Acid for Metal Leaching Processes by Aspergillus Niger. FEMS Microbiology Letters, 119(3): 365-370.
83. Sutherland, T.D., Horne, I., Harcourt, R.L., Russell, R.J., and Oakeshott, J.G. (2002). Isolation and Characterization of a Mycobacterium Strain that Metabolizes the Insecticide Endosulfan. J. Appl. Microbiol., 93: 380-389.
84. Tebo, B.M., Ghiorse, W.C., van Waasbergen, L.G., Siering, P.L., and Caspi, R. (1997). Bacterially Mediated Mineral Formation; Insights into Manganese (II) Oxidation from Molecular Genetics and Biochemical Studies. Reviews in Mineralogy and Geochemistry, 35(1): 225-266.
85. Unz, R.F., and Shuttleworth, K.L. (1996). Microbial Mobilization and Immobilization of Heavy Metals. Current Opinion in Biotechnology, 7(3): 307-310.
86. van Leeuwen, C. J.; Vermeire, T. G. Risk assessment of chemicals - an introduction, 2nd ed.; Springer: Dordrecht, The Netherlands, 2007; p 686.
87. Vikas Phulia, India; Ankur Jamwal, India, Neha Saxena, India, N.K. Chadha, India; A.P. Muralidhar, India;. Technologies in Aquatic Bioremediation.
88. White, C., Shaman, A.K., and Gadd, G.M. (1998). An Integrated Microbial Process for the Bioremediation of Soil Contaminated with Toxic Metals. Nature Biotechnology, 16(6): 572-575.

2/19/2014