Journal of Bio-Molecular Sciences (JBMS) (2020) 7: 10-43.

Journal of Bio-Molecular Sciences (JBMS)
ISSN: 2311-4630
www.directsciences.com/jbms

Bacteria; An Efficient Bioremediator of Heavy Metals

Mehvish Riaz Khattak[1], Muhammad Fayyaz[1], Sadaf Masood[1], Maha Rehman[1], M. Shadab Khan[1], Iftikhar Ahmed[2], and Muhammad Jamil[1]*

[1]Department of Biotechnology and Genetic Engineering, Kohat University of Science and Technology, Kohat 26000, Pakistan
[2]Bio Resources Conservation Institute, National Agricultural Research Center (NARC), Islamabad, Pakistan

Received 25 April, 2020; Accepted 14 Nov,. 2020; Available online 25 Dec., 2020

Abstract: Commercialization and Indiscriminate growth of industrial sector has led down great impact not only on our living standard but also on environment. Indiscriminate release of heavy metals as industrial pollutant has been tremendously increased. The bio-availability of toxic heavy metals ions directs biomagnification that resulted in severe health hazards. Microorganism can offers attractive, eco-friendly and possible solution to this concern. Bacteria combat metal toxicity through adapted resistance mechanisms that can be exploited to minimize the alarming effects of heavy metals. Bioremediation through resistant bacteria serve as great temptation in modern research due to its promising results. This technology still needs more exploration in order to yield maximal results. Further research on different parameters of research design for bioremediation of heavy metals can led to innovation and even more sustainable model of pollution control. This review comprehensively highlights the sources, importance, consequences of heavy metals pollution. This review also described the underlying mechanisms of metal resistance by bacterial species to combat their devastating effects in terms of environmental pollution.

Key words: Heavy metals, Pollution, Resistance mechanism, health hazards, Bioremediation, Regulatory standards

Introduction

Environmental pollution has been emerged as global concern due to rapid industrialization, massive population growth, enhanced metropolitan living standards, addiction to electronics and establishment of modern agricultural practices and plenty of other modern regimes. All these aforementioned advancements have not only created million of benefits and luxuries to mankind on one side but also created potent challenges on other hand. The biggest challenge that needs to be addressed seriously is deterioration of environment which serves as basic medium of living to all forms of flora and fauna.

The rapid discharge of industrial wastes comprising of effluents, emissions, sewage sludge results in accumulation of

*Correspondence to: Muhammad Jamil, Department of Biotechnology and G. E., Kohat University of Science and Technology, Kohat, Pakistan, E-mail; dr.jamil@kust.edu.pk

toxic pollutants including heavy metals into soil, air and water (Martinez et al. 2014). The contamination of 1.8 million cubic meter (m^3) of water resources and about 75 million m^3 of soil have been reported in USA, because of enhanced use of nuclear weapons and maximal anthropogenic activities (DOE, 1997). About one third of water resources have been polluted in India due to inappropriate waste disposal, sewage and release of effluents (Deepali, 2012). Industries dealing with manufacture of paper products, paints, dyes, rubbers, plastics, detergents, herbicides, pesticides, insecticides, detergents, organic solvents and chemicals, rubber, fuels additives and pharmaceuticals serves as major heavy metals utilization units (Garbisu and Alkorta 1997; Iwamoto and Nasu 2001). Approximately 1 million metric tons of metals incorporated wastes is generated and inadvertently released by these industries, every year all across the world (Morris et al., 2003).

Heavy metals are regarded as potential contaminants due to their mobile, stable, persistent, recalcitrant and toxic chemical nature (Dhankhar and Guriyan, 2011). Metals having specific gravity > $5g/cm^3$ are termed as heavy metals (Ali and Khan, 2018). Heavy metals represent three main subgroups; toxic metals, radionuclides and precious metals (Appenroth, 2010). Toxic metals group comprise of Lead (Pb), Cadmium (Cd), Mercury (Hg), Arsenic (As), Chromium (Cr), Cobalt (Co) and Zinc (Zn). Radionuclides constitute Uranium (U), Tellerium (Te) and Radium (Ra). Precious metals group includes Gold (Au), Silver (Ag), Plantinum (Pt) and Palladium (Pd) etc. (Bishop, 2002; Nies, 1999).

Heavy metals occur in two distinct chemical forms in the environment, bioavailable and non bioavailable. The bioavailable state is characterized to be readily soluble, more toxic, mobile and unprecipitated. However the non bioavailable form of existence is tends to be in compound form, precipitated, immobile and less chemically interfering (Roane et al., 2001). Heavy metals have been emerged as potential toxicological agents due their bio availability and toxic effects on health and thus included in United States environmental protection agency USEPA list of priority pollutants. Arsenic, Lead, Mercury, Cadmium, Chromium (VI), Cobalt are ranked as "Top- 20" in list priority substances (Ahmad et al., 2009; Cameron, 1992).

Heavy metals pollution is one of serious environmental concern based upon its potential risks and health hazards to different forms of life (Siddiquee et al., 2015; Igiri et al., 2018). Bacteria inhabiting the contaminated environment have potential role in biogeochemical cycling of metals ions from toxic into less toxic state. Based upon its unique properties of metals tolerance, resistance and transformation along with its cultural and physiochemical requirements makes bacteria as suitable candidate and efficient vehicle for remediation of heavy metal contaminated sites in comparison to any other approach.

This review briefly evaluates the mode of production of toxic heavy metals, importance and toxicity to the biotic (mainly plants & humans) elements of ecosystem, the underlying mechanisms of metal resistance by bacterial species; adapted against to combat their devastating effects in terms of environmental pollution.

Sources of Heavy metals

Heavy metals are released into environment through three major reservoirs broadly classified as natural, industrial and agricultural practices. Volcanic explosions, burning of fossils, weathering of rocks and minerals followed by soil erosions together constitutes the natural sources of heavy metals contamination into environment (Modaihsh et al., 2004). Industries involving the production of electronics, ceramics, leather, dyes, paints, batteries, building materials are known to be major heavy metals generating waste units (Wang and Chen, 2006). Besides the manufacturing units some the important industrial processes such as electrolysis, electroplating, smelting and mining also serve as main contributors of heavy metals discharge into environment (Kotrba et al., 2009). Modern agricultural practices employing the use of pesticides, fungicides, insecticides, metals incorporated agrochemical along with extensive use of animal manures, sewage sludge and wastewater treatment composes the non point sources of heavy metals contamination (Khan et al., 2008; Zhang et al., 2010). Traffic exhaust, petrochemicals, atomic energy power plants, massive use of weapons in military operations and nuclear testing also contributes to heavy metals pollution (Wang and Chen, 2006; Zhang et al., 2010) (Table 1).

Importance of heavy metals

The pros and cons of heavy metals highly depend upon its available concentration. Heavy metals are required in trace amount for normal biological functioning of microbes, plants and humans (Adriano, 2001). The minute quantities of heavy metal ions perform vital functions in different metabolic activities of cell. Heavy metals serve as cofactors for enzymes and important constituent of protein structure such as Iron is central element of ferrodoxin, cytochromes, catalase and other haem proteins (Cefalu and Hu, 2004). Lead, mercury, arsenic and cadmium has no biological role in normal functioning of plants and humans. Besides chromium, manganese, copper, zinc and nickel has got important functions in the normal physiological, biochemical and metabolic profiles of both plants and humans but in specific concentration. The concentrations of biologically important heavy metals are controlled within narrow limits by setting up specific threshold limit for each individual metal. When their concentration exceeds the threshold limits it can pose toxicity to all forms of life (Table 2).

The toxicity is inferred by disturbance in normal functioning, disruption in protein and nucleic acid structure and inhibition of enzymatic activities (Bruins et al., 2000). Growth rate is reduced due to interference in important cellular processes such as photosynthesis and respiration (Vangronsveld and Clijsters, 1994). Free radicals are produced due to induction of oxidative stress (Seth et al., 2008; Liu et al., 2008). In case of plants; Germination rate is decreased, chlorosis, senescence, stunted growth ultimately leads to death of plants and lessen crop yield (Vangronsveld and Clijsters, 1994; Mohanty et al., 2012). Skin allergies, kidneys malfunctioning, liver disorders, hormonal imbalance, are mainly reported due to heavy metals exposure. Heavy metals such as arsenic, mercury, cadmium, lead, chromium are extremely toxic and pose mutagenic and carcinogenic effects even in minute concentration (Salem et al., 2000) (Table 2).

Soil, Water and Air pollution

Soil, air and water act as main medium for all kind of anthropogenic activities along with co-occurring natural phenomenon. Rapid onset of industries resulted in inappropriate discharge of wastes, effluents and emissions resulting in deterioration of soil, air and water. Inadequate management of waste, frequent spills, improper enforcement of environmental protection laws and lack of industrial waste monitoring has contributed to pollution of these three basic mediums of life (Cefalu and Hu, 2004; Kim and Vipulanandan, 2006) which eventually consumed by human being (Figure 1).

Table 1. Different sources of heavy metals contamination.

S. No	Heavy Metals	Sources	References
1	Lead (Pb)	Batteries, Paints, Plastics, Cables, Varnishes, Dyes,, Plumbing, Pigments, Traffic Exhaust	(Manahan, 2003)
2	Chromium (Cr)	Leather Industry, Dyes, Paints, Pigments, Steel And Metal Plating Industry, Woods Preservatives, Petroleum Refining, Making Of Paper Pulp, Industrial Water Cooling Operations and Nuclear Power Plants.	(Baladi et al. 1990; McGrath and Smith 1990)
3	Copper (Cu)	Building Material, Alloys, Electrical Conductors and Additive in Fertilizers	(Noyce et al. 2006; Singh et al., 2010).
4	Cadmium (Cd)	Batteries, Pvc Plastics, Pigments, Alloys, Electronic Equipments , Minute Amount in Detergents, Fertilizers and Petroleum Products	(Campbell 2006)
5	Mercury (Hg)	Combustion of Coal and Petrochemicals, Volcanic Eruptions, Manufacturing of Lamps, Caustic Soda and Peat	(Lone et al. 2008)
6	Arsenic (As)	Refining of Petroleum, Wood Preservatives, Herbicides and Coal Plants. Smelting, Mining and Volcanic Eruptions	(Lone et al. 2008)
7	Zinc (Zn)	Mining, Electroplating and Metallurgy Alloys, Textiles, Paints, Fertilizers, Batteries, Rubber and Wood Preservatives	(Abdelwaha et al. 2013; Arshad et al. 2008; Lee et al. 2004; Baig et al. 2009)
8	Nickel (Ni)	Steel, Electroplating and Metal Plating Manufacturing Units, Power Stations and Fossil Fuels Incineration	(Khodaddoust et al. 2004)
9	Cobalt (Co)	Magnets, Ceramics, Paints and Cutting Tools and In Military as Aircraft Engines Industries.	(ATSDR 2004)
10	Manganese (Mn)	Steel, Glass, Battery Cells, Fireworks, Bleaching Agents, Matches and Leather Tanning, Fuel Additives, Fungicides	(Pennington et al. 1986; ASTDR 2000)

Table 2. Effect of heavy metals toxicity on plants, human and animals.

S. No	Heavy Metals	Effects on Plants	References
1	Lead (Pb)	Disturbs the normal metabolism, Nutrient uptake and growth , Induces oxidative stress	(Stohs and Bagchi, 1995; Bouton et al ., 2001)
2	Chromium (Cr)	Inhibits seed germination and seedling growth, Oxidative stress, Disturbs metabolic processes, Lower biomass, Ionic imbalances, Stunting, Chlorosis	(Dixit et al., 2002)
3	Copper (Cu)	Interacts with free radicals in cell such as molecular oxygen yielding hydroperoxide radical which is toxic in nature, Stunted roots growth, Chlorosis of leaf veins	(Montelongo et al., 1993; Martinez and Motto, 2000)
4	Cadmium (Cd)	Affects minerals uptake, Photosynthesis, Stomatal clos, Leaf rolling and openings, Stunted growth and chlorosis	(Moreno et al., 1999; Sanita et al., 1999)
5	Mercury (Hg)	Effects antixoidant system, Reduced photsosynthetic rate, Biosynthesis of chlorophyll , Uptake of water by plants and rate of transpiration	(Boening, 2004)
6	Arsenic (As)	Stimulate sequence of events that results in reduced plant growth, Triggers the production of secondary metabolites, and Effects the plants respiratory and photosynthetic machinery	(Garg and Singla, 2011)
7	Zinc (Zn)	Wilting, necrosis, Phtobiomass reduction, Inhibition of cell division and elongation	(Soares et al., 2001)
8	Nickel (Ni)	infers with processes linked to its growth and development and results in wilting, chlorosis and necrosis.	(Rao and Sresty, 2000)
9	Cobalt (Co)	Inhibits active transports, Tetrapyrrole biosynthesis, Alter plastids morphology and chlorophyll content, Inhibits the development of strach grain	(Palit et al., 1994)
10	Manganese (Mn)	Browning and crack in leaves, Stems and roots and chlorosis of young leaves	(Wu, 1994)
		Effects on Humans	
1	Lead (Pb)	Carcinogenic and mutagenic, Accumulates in brain resulting in poisoning (plumbism) , Effects CNS central nervous system, Gastrointestinal tract and kidneys, Developmental defects and miscarriage of fetus	(NSC, 2009; Bellinger, 2005)
2	Chromium (Cr)	Allergies and irritations in skins and respiratory tract infections, Damages lungs, Carcinogenic	(Gibb et al., 2000)
3	Copper (Cu)	Affects kidneys, stomach and liver. Vomiting, Nausea dizziness, Headaches	(Flemming and Trevors, 1989)

4	Cadmium (Cd)	Acute and chronic toxicity levels in human , kidneys damage, Reproductive organs and bones, Can leads to cancer , Effects nutrients reabsorption in kidneys	(Barbier et al., 2005; Frery et al., 1993)
5	Mercury (Hg)	Effects nervous system by interfering with production of neurotransmitters, Lowers the production of hormones such as testosterone and thyroid hormones, Leads to autoimmune diseases such as hypertension, insomnia, memory loss, drowsiness, Tremors and brain, Lungs and kidney damages	(Neustadt and Pieczenik, 2007; Gulati et al., 2010)
6	Arsenic (As)	Decreased production of blood cells, “needles & pins” sensation in fingers and toes , Hyperkeratosis, Leuko-melanosis, Melanosis, Neuropathy, Black foot disease and cancer	(Abernathy, 2003; Caussy, 2005)
7	Zinc (Zn)	Disturbance in nervous, renal and circulatory systems. The common responses to elevated zinc concentration are cholestatic jaundices, Lethargy, Pancreatitis, thrombocytopenia in human	(Klein, 2000; Marin et al., 2009)
8	Nickel (Ni)	Contact dermatitis, Lungs cancer, Heart diseases, Kidney malfunction, Nervous system disorders, Induces genotoxic effects such as infertility, Hair loss and chromosomal aberrations, Digestive system disorders such as peptic ulcer and gastritis	(Salem et al., 2000; Khan et al., 2007; Dudachodak and Baszczyk, 2008)
9	Cobalt (Co)	Infection in lungs , Pneumonia, Asthma and wheezing	(ATSDR, 2004; Schmidt and Schlegel, 1994)
10	Manganese (Mn)	Nervous system malfunctioning, Potential neurotoxin, collection of ailments ‘manganese crusher disease’ (manganism), cauative agent for Parkinson’s disease	(Mergler et al., 1999; Inoue and Makita, 1996)
		Effects on Animals	
1	Lead (Pb)	Acute effects are damage to kidneys, liver necrosis, Decline in erythocytes aminolaevulinic acid results in anemia, Osteoporosis, Hydronephrosis, osteodystrophy, Inappetance and appearance of lead lines in teeth associated gingiva are reported in Lambs	(Butler et al., 1957; Quarterman et al., 1977)
2	Chromium (Cr)	Affects respiratory system, mutagenic in nature, Chromosomal aberrations in mammalian cells, Adverse effects in developmental stages such as increased embroyonic mortality rate, Reduced osteogenesis, Lower fetal body weight	(Henderson, Rebar et al., 1979; Kargacin et al., 1993; Meditext, 2005)
3	Copper (Cu)	Liver damage in sheep, Hepatotoxicity, effects gastrointestinal tract, kidneys, Hyperlpasia in stomach in rats	(King and Bremner, 1979; NTP, 1993)
4	Cadmium (Cd)	Cadmium toxicity in avian species causes damage to kidneys and to male reproductive organs resulting in late maturation. Egg production is decreased	(Scheuhammer , 1987; Sell,

		in hens, chronic exposure results in nephrotoxicity, anemia and bones mineralization	1975)
5	Mercury (Hg)	Farm animals exposure to mercury results in ataxia, Anorexia, blindness, hypersensitivity to people, Abrupt movements, Difficulty in drinking. Weakness in muscles and wings, Inappetance are reported in chickens.	(Scheuhammer , 1987)
6	Arsenic (As)	Acute arsenic toxicity in sheeps results in gastoentritis, Blood pressure fall, convulsions along with muscular twitching, Haemorrhage, Chronic toxicity leds to neurological ailments, Loss of coordination , Ataxia and swaying	(McCaughey, 2007; Kennedy et al., 1986)
7	Zinc (Zn)	Loss of appetite, subcutaneous oedema, Lesions formation in kidneys, abomasum along with pathological changes in liver, Adrenal glands, Rumen and pancreas	(Allen et al., 1983)
8	Nickel (Ni)	Nickel inhalation leads to lungs tumors, Reproductive organs can be affected causing abnormalities in sperm production, Defects in developments, Fetal mortality.	(USA EPA, 1999; ATSDR, 1997)
9	Cobalt (Co)	Elevated cobalt concentration in pigs results in muscular stiffness that leads to tremors,loss of balance and anorexia, Highest intake in chicks can cause hepatic necrosis, Pancreatic fibrosis and lesions in muscles	(Huck and Clawson, 1976; Diaz et al., 1994)
10	Mangane se (Mn)	Severe corony effects in pigs, Inflammatory response in lungs due to MnO_2, MnO_4	(Camner et al., 1985)

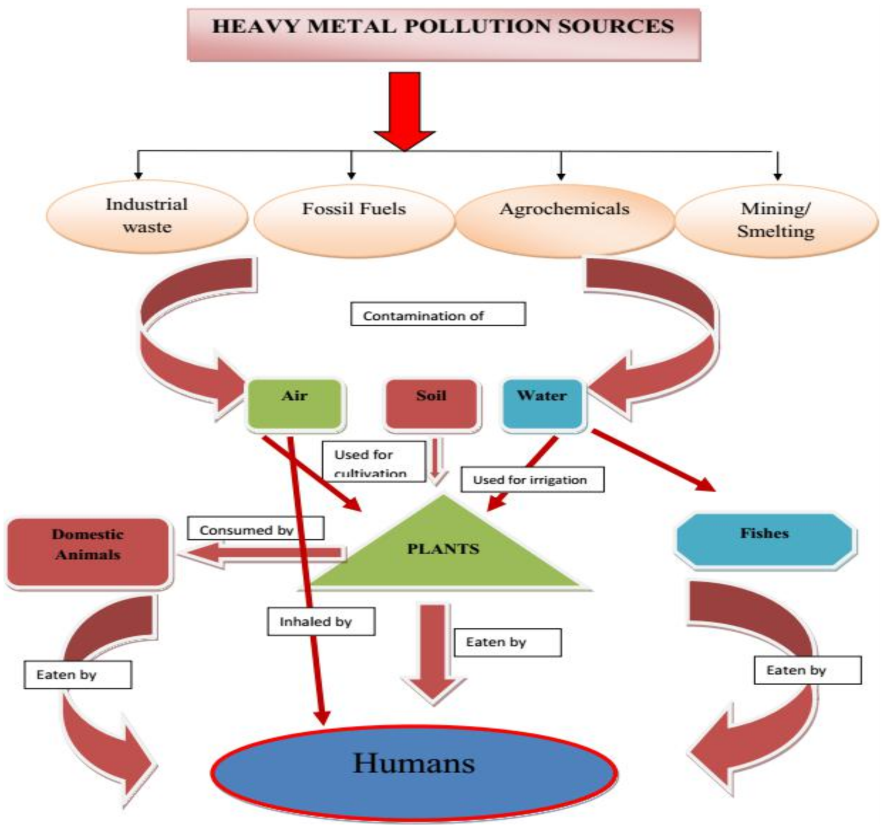

Figure 1. Sources of heavy metal contamination and how heavy metal enters human body through air, soil and water.

Heavy metals emerged as major environmental concern due to its reluctant chemical nature and severe toxic effects. Their high content in soil can lead to contamination of groundwater along with agricultural land. Food quality can be reduced due to phytotoxicity and as result agricultural productivity can be decreased leading to food insecurity and lower capital generation (McLaughlin et al., 2000; Ling, 2007). Wastewater samples collected from chromate mines Sukindia, India exhibited high heavy metals content within trend of Cr>Fe>Zn>Ni> Co>Mn and lesser microbial count. However, the isolated bacteria were observed to have antibiotic and heavy metal resistance (Das et al., 2013). Bangash et al., (2006) assessed the heavy metal content and physiochemical prosperities of wastewater samples from different industries of Hayatabad industrial estate, Peshawar in accordance to NEQS, Pakistan. Heavy metals (Pb, Cu, Zn, Ni, Co) analysis of soil, roots and shoots of 16 different plant species from industrial locality of Islamabad demonstrated high Cu accumulation in both roots and shoots and high Zn content in grasses. The study suggested high potential for phytoextraction and phytostabilization of different heavy metals by the selected plant *spp.* (Malik et al., 2010). Oti Wilberforce et al., (2012) investigated heavy metals concentration in top and sub soil of Abakaliki and Enyigba areas of Nigeria through Pixe spectroscopy and results suggested high concentration of Pb, Cd and Ni in comparison to regulatory standards of USEPA, indicating higher degree of contamination. The pollution load index for soil and food crops irrigated with industrial wastewater in Beijing, China indicated moderate enrichment with Cr, Cu, Pb, Ni and Zn and highly enriched with Cd, consequently surpassed the regulatory limits for vegetables established by SEPA (State environmental protection agency), China (Khan et al., 2008). Similarly, the examination of heavy metals content in soil and wastewater irrigated food crops of Sialkot and Wazirabad, Pakistan showed Cd, Pb, Cr, Mn contents above the standard limits. The Health Risk Index was recorded to be >1 for lead and cadmium in all the food crops and vegetables under investigation (Khan et al., 2013). he use of wastewater for irrigation purpose is one major source of heavy metal contamination of agricultural land. The evaluation of heavy metals in contaminated soil samples in Rawalpindi, Pakistan showed higher metal content with Cd and Cr exceeding the critical limits set by regulatory authorities (Mushtaq and Khan, 2010). Nasrullah et al., (2006) reported that heavy metals (Ni, Pb, Zn, Cr, Mn, Fe, Cu) in effluents samples of 8 different manufacturing units of Gadoon industrial estate, Sawabi were in accordance to regulatory standards set by EPA (environmental protection agency), Pakistan. The water samples collected from downstream of municipal plant in Tanzania exhibited high Cd, Pb, Cr concentration in reference to permissible limits of regulatory authorities. Similarly the heavy metals analysis of sediments indicated elevated level Zn, Cr, Pb (Kihampa, 2013). Findings of Amin et al., (2014) suggested that soil contaminated with industrial effluents of Gadoon industrial estate, Sawabi has higher heavy metals (Zn, Cu, Co, Ni, Pb, Cr, Mn) content in comparison to reference soil sample but concentration for all metals except manganese lies within regulatory limits. Heavy metals profile of agricultural land of Amritsar, India indicated concentration trends as Fe>Zn>Mn>Pb>Cu>Cd. The soil samples significantly induce genotoxicity in *Allium cepa* under experimental condition indicating probable alert for consumer's health (Vanita et al., 2014).

The atmosphere of metropolitan and industrial cities is densely polluted with high concentration of particulate matter (PM) all over the world. PM (size less than 10 µm) exhibits large surface and has tendency to collect variety of chemical compounds (including heavy metals) that can penetrate into deep inside the respiratory system (Siddiqui et al., 2006). United States environmental protection agency (US-EPA, 1979) and World Health Organization (WHO, 2006) has promulgated the quality standards for the concentration of fine particles in ambient air. Pal et al., (2014) reported the PM concentration (63-223 $\mu g/m^3$) and heavy metal concentration (Zn > Fe > Cu > Pb > C r > Cd > Ni) in ambient air samples collected from industrial zone in Moradabad India. The PM concentration in Moradabad, India was found higher than regulatory limits set by National Ambient Air Quality standards. Contamination of heavy metals in ambient air of Nagpur, India was evaluated in 2001 and 2006. Results indicated that concentration of Pb, Zn and Ni were increased subsequently (Chaudhri et al., 2012). The concentration of heavy metals (Cr, Ni, Pb, Cd and Zn) in particulate air matter of Isfahan, Iran was determined through atomic absorption spectroscopy and data indicated increase in their trends in comparison to other cities, to rapid industrial discharge of effluents containing metals into environment (Taleb and Ghinani, 2008).

Remediation strategies

Heavy metals contamination into environment can be countered through different remediation approaches including both physiochemical methods and biological procedures. Each remediation strategy has its own distinct requirements, installation cost, specific procedure, limitations and some drawbacks. The basic objective of each method is to reduce the toxicity level of contaminants. The physiochemical method for heavy metals remediation is based on principle of extraction, desorption, immobilization and leaching (Salt et al., 1998). Both the *in situ* and *ex situ* treatment strategies have been practiced for decontamination of heavy metals. Soil dilution, washing through organic acids, electrokinetics and immobilization are also some reported processes for control of heavy metals pollution (Fawzy, 2008; Kord et al., 2010). All physiochemical remediation methods are designed in way to diminish the solubility, bioavailability and mobility of metal ions by employing certain chemical chelators such as EDTA (Ethylene diamine tetraacetic acid) (Wenzel, 2003). The application of physical and chemical procedures such as Chelate extraction, reduction, leaching, absorbent fixation are limited due to their operational cost, high maintenance, lower efficiency, generation of toxic by product and contamination of ground and drinking water resources (Nouri et al. 2008). Fu and Wang, (2011) analyze eight different reported techniques such as floatation, electrochemical treatment, and coagulation for remediation of heavy metals in wastewater. Membrane filtration, ion exchange resins and adsorption matrices are most extensively methods for heavy metals pollution control.

Bioremediation

The limitations, concerns and drawbacks of physiochemical methods for heavy metals remediation can be resolved through alternative strategy having minor complications, lesser cost and more reliable results. This strategy is known to be biological treatment technology termed as bioremediation (Kratochvil and Volesky, 1998). Bioremediation exploits the natural tendency of biological agents such as microbes, enzymes, plants and nutrients to decontaminate the polluted sites by reducing either the concentration of pollutant or counteract its toxic nature (Dillewijn et al., 2007; Kratochvil and Volesky, 1998). Bioremediation deals with pollutants in order to lessen its harmful effects and to manage its level to the permissible limits established by regulatory authorities of environmental protection (Mueller, 1996). The enzymatic machinery of microbes especially bacteria is utilized either to degrade the pollutant or convert it into less toxic state through series of redox reactions (Vidali, 2001).

Role of bacteria in bioremediation

Bacteria have been emerged as strong contender for environmental pollutants more specifically heavy metals due to their dynamic structural features, growth pattern, biochemical profiles and genetics (Murugesan and Maheshwari, 2007). Bacteria serve as important agents in bioremediation research due to adaptation of different resistance mechanisms to combat the toxic effects of pollutants such as heavy metals (Ahirwar et al., 2016). The main listed heavy metals resistance mechanisms are known to be efflux (outflow of ions through transporters), bioaccumulation (accumulation at cell surface), aggregation (complexation of metal ions with cellular proteins) and biotransformation (conversion into less toxic form) (Lloyd and Lovely, 2001) (Figure 2). All these underlying resistance mechanisms utilize the enzymatic system for oxidation/reduction, cell surface compounds/proteins for entrapment, and protein pumps for ion efflux (Nies, 1999) (Figure 2).

Bioleaching is one of reported strategy for heavy metals remediation through bacteria. The mobility of heavy metals ions is targeted through different metabolic compounds produced by bacterial cells. The interaction between toxic ions and bacterial metabolic intermediates results in increased solubilization of metals. *Sulfobacillus*, *Ferromicrobium*, *Acidiphilum* and *Acidithiobacillus* are well known bacterial genera having role in bioleaching of heavy metals ions (Rohwerder et al., 2003). The treatment of wastewater with bacterial *spp*. is a new and reliable biological treatment method to reduce the metal content and minimize its toxicity. Biosorption is one of bioremediation technique through which metal ions concentration in wastewater is decreased due to stimulation of certain chemical and physical processes by bacterial cells such as diffusion, adsorption, complexation and chelation (Blancho, 2000; Xiong and Lu, 2002). Naz et al., (2015) demonstrated that *Pseudomonas spp.* obtained from sugar industry waste significantly reduced Pb (37 %), Ni (32 %), Cu (29 %) and Cr (32 %) contents in industrial wastewater samples. *Salmonella typhi*, *Escherichia Coli*, *Pseudomonas fluorescene* and *Bacillus licheniformis* isolated from effluents of textile industry of Tamilnadu, India decreased Cd (98.34 %), Pb (94.83 %) and Zn (96.14 %) upon subsequent treatment of textile dye effluents (Baha and Rajaganesh, 2014). Nanda et al., (2011) reported significant decrease in heavy metal (Hg, Cu, Cd, As, Co) contents in industrial effluent upon inoculation of heavy metal resistant bacteria such as *Bacillus*, *Pseudomonas* and *Staphylococcus*. Biotreatment with *Bacillus* demonstrated reduction in Hg (45%), Cu (62%), *Pseudomonas* exhibited decrease in Cd (56 %), As (34 %), Co (53 %) and *Staphylococcus* reduced Cd (44 %) and Cu (34 %) contents.

Valence transformation of metal ions through enzyme catalysed reaction is also effective strategy to reduce the toxicity of heavy metals. Heavy metals resistant bacteria play vital role in biotransformation of metal ions through series of oxidation reduction reaction. Oxidation of organic compounds is closely linked to reduction of Fe and Mn in certain bacterial *spp*. (Lovley, 1993). The reduction of hexavalent Cr^{+6} to trivalent Cr^{+3}, Mercuric Hg^{+2} into volatile Hg^{0}, Arsenate As^{+5} to Arsenite As^{+3} , Selinate Se^{+6} to Selinite Se^{+4} are most exploited chemical transformation reaction in bioremediation of metal ions (Garbisu et al., 1995a; Batool et al., 2014;

Misra, 1992; Huyusmans and Frankenberger, 1991). Biomethylation of metals ions such lead to trimethyl and tetramethyl lead, selenium to dimethylselenide and trimethylselenide, arsenic to dimethyl arsenic acid and dimethylarsinous acid is effective strategy to yield volatile metal compound and reduce the contaminant concentration (Walton et al 1988; White et al., 1997).

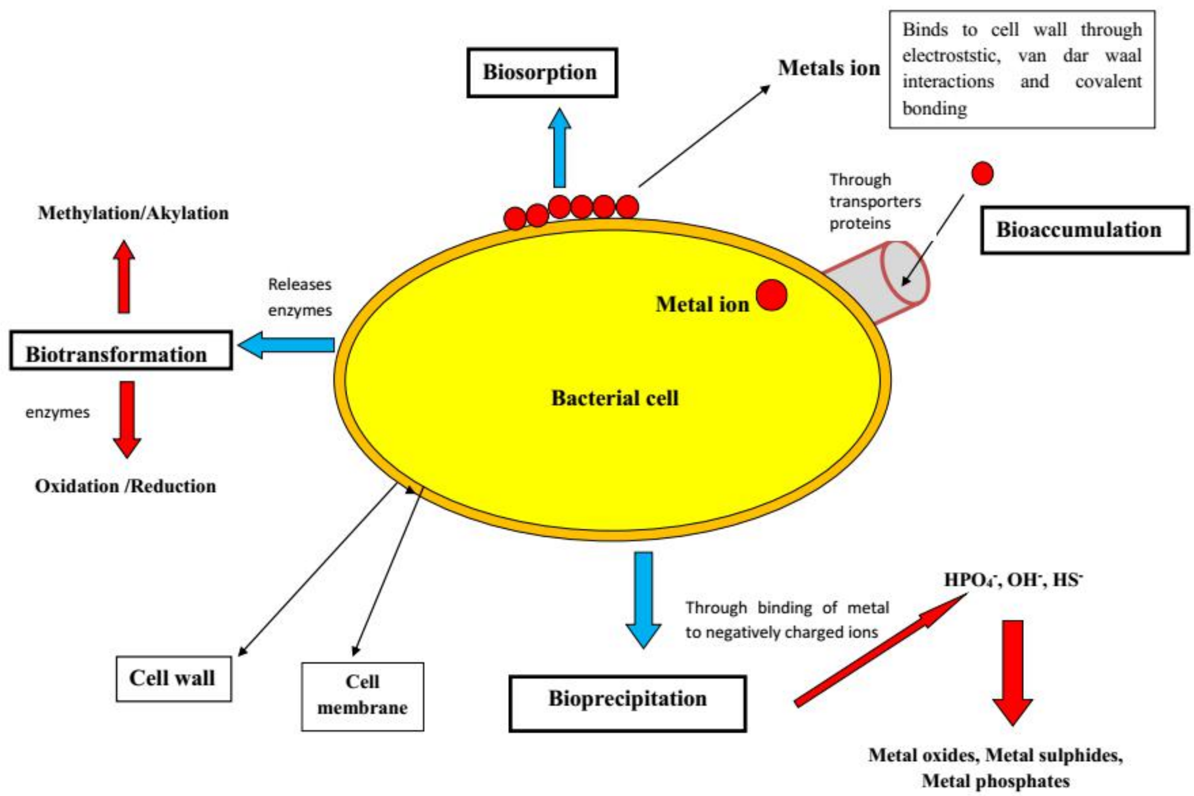

Figure 2. Heavy metal microbe interaction for heavy metal remediation.

Bacterial system employs different types of resistance mechanism to remediate heavy metals from the environment (Figure 3). The importance of some of toxic heavy metals and their possible bioremediation mechanisms are discussed below.

Lead (Pb)

Lead occurs naturally in trace amount in soil, water and earth crust (Raviraja et al., 2008). Lead (II) is reported to be the most reactive and frequently occurring form of lead. Lead is regarded as one of major environmental pollutant; falls on second in US-EPA and ATSDR "list of priority substance" (Sparks, 2005). Lead is fifth major metal produced from anthropogenic sources. The principal lead producing industries includes batteries, pigments, dyes, paints, varnishes, plumbing, cables, alloys, ammunition, fuels additives, plastics, crystals glass, X-rays and pesticides (Manahan, 2003). Lead has no biological role in both plants and human. However its toxicity can induce serious effects on normal functioning by altering proteins and nucleic acids conformation, osmotic imbalance, persuades oxidative stress, and disrupts membranes (Stohs and Bagchi, 1995; Bouton et al., 2001). Pb(II) can displace calcium and zinc ions in proteins and bears higher affinity to oxygen and thiol group (Bruins et al., 2000). Central nervous system (CNS), Brain, kidneys, blood cells and gastrointestinal tract are the major target of lead in human. Lead has mutagenic and carcinogenic nature and its accumulation can results in lead poisoning such as plumbism in brain (NSC, 2009). Lead is also listed as potential teratogens; minute concentration can lead to congenital defects and even miscarriage at fetal stage (Bellinger, 2005).

Bacteria overcome lead toxicity through several resistance mechanisms such as efflux due to p type ATpases pump and CadA- p type ATPase (Rensing et al., 1998). Precipitation of lead in form extracellular salts, such as $PbHPO_4$ in *Citrobacter freundi*, $Pb(PO_4)_2$ in *Staphylococus aureus*, $Pb9(PO_4)_2$ in *Vibrio harveyi* is also reported mechanism (Levinson et al., 1996; Levinso and Mahler, 1998; Mire et al., 2004). Bio methylation of lead yields volatile compounds, trimethyl lead (Me_3Pb) and tetramethyl lead (Me_3Pb); these reactions are reported to be catalyzed by *Pseudomonas spp.*, *Aeromonas spp.* and *Bacillus spp.* (Walton et al., 1988 Silverberg et al., 1976). Lead (II) also induced *smt* and *bmtA* genes encoding metallothionein in *B. cereus* and *Pseudomonas spp.* The produced metallothioneins thus binds lead ions and reduce its toxicity (Naik et al., 2012).

Staphylococcus aureus isolates from heavy metals contaminated soil of Baghdad displayed multi metal resistance against (Pb^{+2}, Zn^{+2}, Al^{+2}, Fe^{+2}, Hg^{+2}) with MIC ranging 300-1000 µg/ml and subsequent metal reduction capacity of 7 % and 43 % of Pb and Zn at varying temperature and pH (Radhi, 2012). *Bacillus spp.* isolates from sewage sludge of petrol pumps, garages and industrial effluent of Assam, India indicated 1200 µg/ml resistance level against Pb^{+2} and 1800 µg/ml against Cd^{+2} ions in media (Nath et al., 2012). The Pb remediation ability of *Bacillus pumilus* and *Pseudomonas spp.* was evaluated in cabbage grown soil under green house conditions. The bacterial inoculation improved soil urease, invertase and catalase content and decreased the lead concentration within range of 15-42 mg/kg with maximal remediation activity of *Pseudomonas spp.* (Chen et al. 2011). Ilhan et al., (2004) reported that *Staphylococcus saprophyticus* isolated from the polluted soil has 100% biosorption activity against Pb^{+2} ions (initial conc. 100 mg/l) at optimum pH of 4.5. Dry biomass of *Delftia tsuruhatensis* isolated from mine tailing exhibited 0.216 $mmol.g^{-1}$ absorption of Pb from metallic solution (Hernandez et al., 2012).

Cadmium (Cd)

Cadmium serves as one of key element involved in industrial preparation of batteries, paints and pigments, PVC plastics, alloys and surface coating of aerospace vehicles. Cadmium is also added in minute quantity in commercial synthesis of fertilizers, insecticides, fungicides, detergents and petrochemicals (Campbell, 2006). Cadmium appears as by-product in refining of lead and zinc. Cadmium is listed as priority pollutant by USEPA and also ranked on 7th in ATSDR "list of priority substances" (Campbell, 2006; Cameron, 1992). Cadmium has no reported role in normal biological functions of humans. Cadmium is closely linked to acute and chronic ailments in humans and its target organs are kidneys, bone skeleton, lungs, liver and reproductive system (Barbier et al., 2005; Frery et al., 1993). The major property that contributes to toxicity of Cadmium is its persistency over long duration. Cadmium alters the activity of enzymes such as δ-aminolevunilic acid synthetase, lipoamide dehydrogenase, pyruvate decarboxylase, arylsulfatase, pyruvate dehydrogenase (Manahan, 2003). The consumption of rice irrigated with polluted water of mines in Jinstu River valley of Japan, resulted in cadmium poisoning termed as *itai itai* disease in local language. *Itai itai* is characterized by kidneys dysfunction along with severe osteomalcia (Manahan, 2003). Cadmium toxicity is linked with disruption of membrane, protein denaturation due to attachment to thoil (~ SH) group and interference in metabolism of Zn^{+2} and Ca^{+2}(Rensing et al., 1997a). Bacteria combat cadmium toxicity through underlying resistance in form of efflux transporters such as RND mediated system like Ncc (Schmidt and Schlegel., 1994), CBA transporter *czc* (Nies, 1995) and p_{12}- type ATpases (Arguello 2003) such as CadA protein (Liu et al. 1997; Silver et al., 1989). Cd induces the expression of *Smt* gene that is involved in production of cysteine loaded proteins known as metallothioneins. These metallothoneins can thus binds the cytoplasmic free Cd^{+2} ions and leading to decrease in free metal concentration (Olafson et al., 1988). The first reported bacterial metallothionein, *SmtA* functions in detoxification of both zinc and cadmium ions (Turner et al., 1993).

Pseudomonas aeruginosa, *Proteus vulgaris*, *Actinobacter radioresistens* strains isolated from the wastewater sample of Madurai, India exhibited resistance level of 4-7 mM against cadmium ions in media (Raja et al. 2009). *Pseudomonas aeruginosa* strain JN102340 obtained from Electronic waste recycling unit can withstand 600 mg/L Cd ion concentration with spectacular biosorption rate of 92 % at optimum pH of 6.0 (Kumar, 2014). Jain and Bhatt, (2014) evaluated the cadmium resistance and remediation pattern in *Pseudomonas montelli* SB35 and *Pseudomonas putida* SB32 by amplifying the *czc* gene on plasmid DNA; czc gene functions as efflux transporter for Cd. Furthermore the inoculation of both the strains improves the agronomic traits of soyabean plants grown under Cd stress (Jain and Bhatt, 2014). *Actinomycetes*, *Bacillus* and *Streptomycetes* isolated from agricultural soil amended with sewage sludge in Iran, showed resistance against cadmium with MIC ranging in between 300-400 µg/mL and nickel ions with MIC of 350-500 µg/mL (Karakagh et al., 2012). Mutation study of *Pseudomonas aeruginosa* obtained from sewage sludge of food factory in Iran improved the resistance pattern uptill 7 mM against Cd and subsequently bioremoval ability upto 94.7 % within 1hour of incubation from Cd solution (30 mg/L) (Kermani et al., 2010). Samanta et al., (2012) reported that *Bacillus* isolated from municipal waste site in India showed co-resistance to both antibiotics and heavy metals (Cd, Ni, Co, Cr) with maximum resistance of 1 mg/mL against Cd^{+2}.

Copper (Cu)

Copper is ranked on 3rd as most frequently used metal all around the globe (Noyce et al., 2006). Copper is commonly utilized in firework industry, alloys, underground water pipes, building materials and synthesis of electrical conductors (Noyce et al., 2006). Copper has extensive application in agriculture as additive in fertilizers and in mining (Singh et al., 2010). In minute concentration Copper serves as cofactor for important bacterial enzymes; superoxide dismutase and cytochrome C oxidase. Copper acts as micronutrient for plants and function in regulation of osmotic balance, resistance against diseases and seed production. In human copper is essential for regulation of blood hemoglobin (Martinez and Motto, 2000). Copper pose toxicity to biological system when its concentration increased beyond threshold limits and becomes attached to organic compounds. This binding can result in denaturation of protein structure and inhibition of enzymatic activities (Hoekman et al., 1995). Toxic nature of copper is further characterized by hydroperoxide radical which is produced by reaction of copper with free cell radicals such as molecular oxygen (Montelongo et al., 1993). Chlorosis of leaves and reduced root growth are common signs of Cu toxicity in plants. Stomach, kidneys, liver and intestines are major target for copper in human (Martinez and Motto, 2000). Accidental exposure and intake can result in severe headaches, nausea, dizziness, stomach cramps, diarrhea and vomiting (Flemming and Trevors, 1989).

Copper toxicity is countered by bacteria through efflux by proteins encoded by *pco* gene located on plasmid DNA and chromosomal DNA *cut* genes (Gupta et al., 1995) and P- type ATpases efflux transporters (Kamanu et al., 1995; Phung et al., 1994). Two *cut* genes; *Cut*C and *cut*F gene has been characterized and encode proteins that can interact with Cu as well as outermembrane lipoprotein(Gupta et al., 1995). Aggregation of Cu is also one of resistance strategy reported in *Pseudomonas syringae*. Complexation of Cu is regulated through four protein encoded by *cop* operon located on plasmid DNA. Cop A, Cop B, Cop C and Cop D proteins work together in coordinated fashion at their distinct sites such as outer membrane, inner membrane and periplasm and bound Cu^{+2} from interference in cellular functions (Cooksey, 1994).Gupta and Kumar, (2012) reported *Pseudomonas* isolates from sewage sludge of lock industry in India can tolerate Cu^{+2} toxicity in media up till 2000 µg/ml. *Bacillus spp.* from Firework industrial waste exhibited tolerance to copper with resistant level of 300 mg/L and also served as efficient biosorbent by removing 88 % of Cu^{+2} from 100 mg/L aqueous solution (Kumar and Kartic, 2011). The immobilized cells of *Bacillus*, *Micrococcus* and *Pseudomonas* obtained from electroplating wastes has 63.9 % Cu^{+2} biosorption activity in comparison to 44.73 % by dried biomass of isolates (Rani et al., 2010). Ahemad and Malik, (2011) reported that multi metal resistant *Pseudomonas* isolates from farming soil irrigated with wastewater demonstrated bioaccumulation of Cu^{+2} at range of 20-25 mg/g .dry wt from 2.92 mM copper solution. *Pseudomonas* isolated from municipal treatment plant exhibited MIC of 300 µg/ml of copper resistance along with co resistance up to 150 µg/ml and 120µg/ml against Co and Cd respectively (Rajbanshi, 2008).

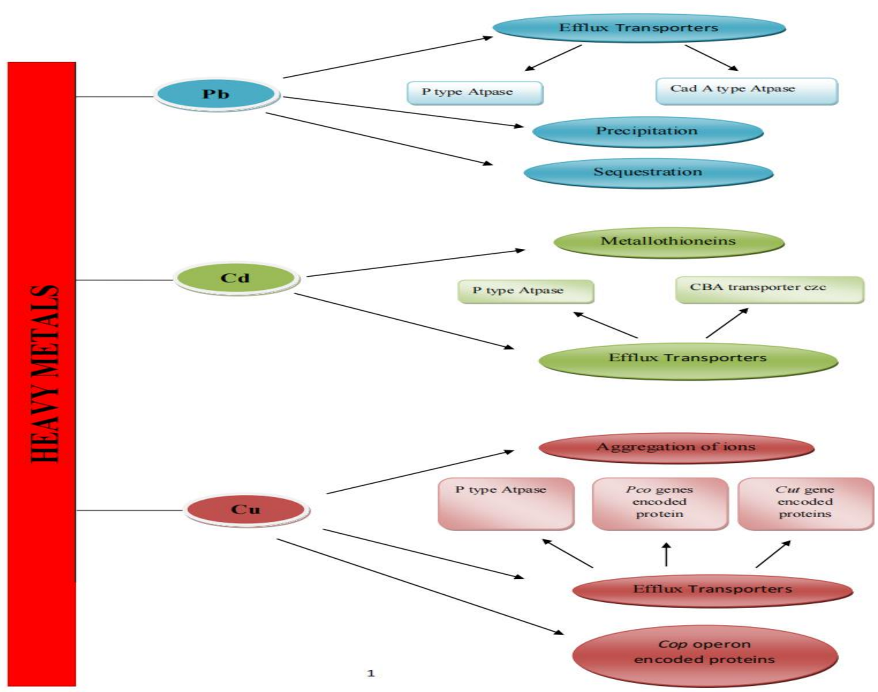

Figure 3. Different types of resistance mechanism employed by bacteria to remediate Lead (Pb), Cadmium (Cd) and Copper (Cu) from the environment.

Manganese (Mn)

Manganese is twelfth most abundant element in earth crust and also one of vital element that appears in water, soil and rocks in small amount. It is utilized as trace nutrient by all forms of life; plants, animals and microbes for normal physiological functions (Emsley, 2003). Manganese is 4th most extensively utilized metals in industrial preparation of glass, battery cells, leather, matches, firework materials, steel, iron, welding rods, fungicides, and medical equipment such as magnetic resonance imaging (MRI) (Pennington et al., 1986). Organic compounds of manganese like methlycyclopentadienyl manganese tricarbonyl (MMT) serves as additive compound in fuels (Pennington et al., 1986). Bacteria utilize manganese as primary electron acceptor during anaerobic respiration. Mn is the main component of photosystem II and associated with lysis of H_2O during photosynthesis (ASTDR, 2000). Chlorosis, browning and cracks in different parts of plants are the symbolic indication of excessive Mn (Wu, 1994). Manganese is involved in blood clotting mechanisms, skeletal development, metabolic, hormonal and enzymatic activities (Yachandra et al., 1993). Mn acts as cofactor for superoxide dismutase and neurotransmitters biosynthesis enzymes (Erikson and Aschner, 2003). Over dose of Mn acts as neurotoxin can lead to nervous malfunction (Aschner et al., 2007). Manganese crusher disease 'manganism' is set of ailments reported in France, caused due to accidental Mn exposure at workplace (Mergler et al., 1999). The major target of manganese poisoning is brain and its adverse effects include hallucinations, memory loss, collapse of nervous system, and even worse such as Parkinson's disease (Inoue and Makita, 1996). The accumulation of manganese ions inside the bacteria like *Ralstonia sp*. and *Salmonella typhimurium* is reported through magnesium uptake system. ABC (ATP binding cassette) transporters also plays vital role in Mn^{+2} uptakes under stress conditions (Nies, 1999).

The concentration of manganese was noted to be higher than regulatory limits in wastewater samples collected from mining region (Kamika and Momba, 2013). The live biomass and dead cells biomass of three bacterial strains; *Bacillus licheniformis*, *Pseudomonas putida* and *Peranema sp*. were analyzed for metals reduction in wastewater samples. The live cellular biomass of *Pseudomonas* exhibited 45 % reduction of Mn^{+2} content in comparison to dead biomass <25 % activity (Kamika and Momba, 2013).

Chromium (Cr)

Chromium has widespread application in industrial processing of leathers, steels, paints, pigments, dyes, paper pulp, wood preservatives, alloys, petroleum refining and electroplating (Baladi et al., 1990; McGrath and Smith, 1990). Chromium normally exists in two oxidation states, Cr^{+3} and Cr^{+6}. The hexavalent Cr (VI) form is highly soluble (Thacker et al., 2006) and about 5 times more toxic in comparison to trivalent Cr (III) (Barceloux, 1999). Chromium (VI) has been listed as priority pollutant by US-EPA and included in list of top 20 toxic substances, placed under the category of "Class A human Carcinogens" (Costa and Klein, 2006).

Chromium plays important role in homeostasis; serves as micronutrient in cellular metabolism of cholesterol, glucose and fats. Cr plays essential role in action of liver hormones such as insulin (Mohanty et al., 2012). The lack of Cr can leads to interruption in insulin action followed by fluctuations in blood glucose resulting in diabetic condition along with deposition of cholesterol. Overload of chromium can cause oxidative stress; production free cells radicals (ROS) that are can cause lipids peroxidation, nucleic acid disruption (Katz and Salem, 1994).

Accidental intake or exposure to Cr (VI) can cause skin allergies, ulcers, respiratory infections such as bronchial asthma followed by serious lungs damage and ultimately cancer (Gibb et al., 2000).

Chromium toxicity is coped in bacteria primarily through two main mechanisms, efflux and reduction (Diaz et al., 2007). Chromium gains entry into bacterial system through sulfate (~SO_4) uptake system (Nies and Silver, 1989a). Efflux of chromium is mediated through CHRA transporters proteins by utilizing membrane potential as energy source (Diaz et al., 2007) (Fig. 4). *Ralstonia spp*. is classic example of utilizing both strategies; efflux and reduction for chromium detoxification (Peitzsch et., al. 1998). The detoxification of Cr (VI) into Cr (III) through chromate reductase enzyme is foremost reported mechanism for combating Cr toxicity. This process was first time evaluated in *Pseudomonas Fluorescens LB300* (Bopp and Ehrlich, 1988). Chromate reductase can catalyze reaction under both aerobic and anaerobic conditions, it is dependent on NAD(P)H and belongs to flavor protein *reductase* family (Diaz et al., 2007). The Chromium reductase activity for transformation of hexavalent Cr^{+6} into less toxic oxidation state trivalent Cr^{+3} is also reported in number of bacterial *spp*. including *Shewanella* (Myers et al., 2000), *Bacillus* (Liu et al., 2006), *E. Coli* (Shen and Wang, 1993), P*seudomonas spp*. (Ishibashi et al., 1990) and *Microbacterium spp* (Liu et al., 2012), *Streptomyces* MC1 (Polti et al., 2010) and *Arthrobacter* (Asatiani et al., 2010).

Batool et al., (2012) studied the reduction of Cr^{+6} in *Ochrabactrum intermedium* in industrial effluents, results were interpreted through reductase cell assays and Cr distribution was visualized on cell surface and membrane through scanning electron microscopy and transmission electron microscopy. *Bacillus spp*. obtained from tanneries waste in India demonstrated 85.9 % reduction in Cr (VI) within 96 hours of treatment (Smrithi and Usha, 2012). Jin et al., (2001) reported an alternative strategy for remediation of Cr contaminated soil through transformation of chromate reductase gene from *Pseudomonas aeruginosa* HP014 into tobacco plants by means of *Agrobacterium tumefaciens* as vector. Bacterial isolates (73.9 %) belonging to *Bacillus* and *Pseudomonas* from industrial zone in Turkey exhibited chromium resistance with maximal level of 2 mM (Sevgi et al., 2010). Selvi et al., (2012) reported that 30-70 % bacterial isolates from tanneries of Chennai, India showed resistance against both chromium and antibiotics.

Zinc (Zn)

Zinc is naturally occurring element present in soil and crustal rocks at concentration of 70 mg/Kg (Davies and Jones, 1988) and its concentration is rapidly increasing due to various types of industrial operations such as mining, electroplating and metallurgy. Besides these different types of manufacturing units such as alloys, textiles, paints, fertilizers, batteries, rubber and wood preservatives utilizes zinc as important constituent .(Abdelwaha et al., 2013; Arshad et al., 2008; Lee et al., 2004; Baig et al., 2009). Zinc is included in list US-EPA priority pollutants and kept with 13 other most toxic metals. Zinc is listed on 74th as potential water contaminants (Mishra et al., 2011a). Zinc is termed as important element required for the normal growth of plants, animals and humans (Sengil and Ozacar, 2009). Zinc serves as cofactors for variety of cellular enzymes such as nucleic acid binding zinc fingers proteins (Chou et al., 1998) alkaline phosphatase and superoxide dismutase (Mukhopadhyay et al., 1998). Zinc is important structural element of transcriptional factors and thus has role in gene expressions and it sustains the structural stability of biological macromolecules. About more than 300 enzymes constitutes zinc as co factor (McCall, 2000). Zinc concentration is regulated at narrow range its shortage can leads to stiffness of muscles, gastrointestinal disturbances and birth defects in humans (Greany, 2005). However its elevated concentration can cause extreme toxicity to biological system by inhibiting the aerobic respiratory chain and high exposure to humans can cause disturbance in nervous, renal and circulatory systems. The common responses to elevated zinc concentration are cholestatic jaundices, lethargy, pancreatitis, thrombocytopenia in human (Klein, 2000; Marin et al., 2009). Soil fertility is extremely affected due to increased zinc concentration beyond its threshold limits and ultimately lowering the growth and productivity of plants (Agorboude and Navia, 2009).

Bacteria combat zinc toxicity through different types of inbuilt resistance mechanisms such as efflux transporters, metallothioneines and metallochaperones. Efflux of zinc ions across the cell membrane takes place through p types ATpases efflux transporters in bacteria and RND (Resistance nodulation division) driven CBA transporters moves the zinc ions across the cell wall and outer membrane of gram negative bacteria by process known as Trans envelope transport (Nikaido, 1996; Paulsen et al., 1996; Saier, 1994). Cysteine rich proteins termed as metallothioneine have the ability to binds and sequester free metal ions such as Cd^{+2} and Zn^{+2} and lower the free metals concentration in the cytoplasm (Olafson et al., 1979) (Fig. 4). Metallochaperones are periplasmic proteins that plays role in zinc sequestration and protection of transmembrane protein are reported in number of bacteria (Noll et al., 1998). ZraP is periplasmic protein discovered in *E. coli* that is produced under high concentration of zinc and has ability to undergo metal induced cleavage process to produce 12 KDa protein fragment capable of binding Zn^{2+} in the periplasm (Noll et al., 1998). Biosurfactants of *Pseudomonas putida* T1 (8) isolated from oil contaminated soil has reported to have 6.5 % of Zn and 2.01 % of Cu removing capacity from paper industry sludge waste (Hidayati et al., 2014). The elimination of Zn (II) through ion exchange process is reported in *Saccharomyces cerevisiae* cells as biosorbents (Chen and Wang, 2007; Talos et al., 2009). Umrania, (2006) reported 35 % maximum absorption for Zn in chalcopyrite by acidothermophilic multi metal resistant bacterial isolate (ATH-14).

Nickel (Ni)

Nickel is among one of widely distributed element present in soil, air and water. Nickel is commonly employed in steel, electroplating and metal plating manufacturing units and is also released as result of mining, power stations and fossil fuels incineration into environment (Khodaddoust et al., 2004). Nickel occurs as trace element in bacteria and is essential components of enzymes involved in metabolism of anaerobic bacteria (Thauer et al., 1980). It plays key role in reactions catalyzed by enzymes such as ureases, NiFe hydrogenases and Co dehydrogenases. Nickel is bound to cysteine/histidine residues in active site of these enzymes, added through complex GTPase activity (Maier et al., 1993). Superoxide dismutase is also important protein containing nickel (Kim et al., 1998). Besides its essentiality the contamination of nickel also has adverse effects both on plants and humans and it was termed as “allergen of the year 2008”. The most common effects of nickel are allergy in form of contact dermatitis which is caused due nickel containing jewellery (Savolainen, 1996). Nickel toxicity can leads to lungs cancer, heart diseases, kidney malfunction, nervous system disorders (Salem et al., 2000; Khan et al., 2007; Dudachodak and Baszczyk, 2008). Nickel can induce genotoxic effects such as infertility, hair loss and chromosomal aberrations in population residing near refineries (McDonagh et al., 1992). At high concentration nickel toxicity in plants infers with processes linked to its growth and development and results in wilting, chlorosis and necrosis (Rao and Sresty, 2000). Nickel plays key role in pathogenicity of gram negative bacteria *Helicobacter pylori* that is causative agent for digestive system disorders such as peptic ulcer and gastritis in humans (Mobley et al., 1995b).

Two types of resistance mechanisms are observed in bacteria to overcome nickel toxicity; these include sequestration and efflux transport. Efflux of nickel ions through RND (Resistance Nodulation Division) transporters was reported in *Ralstonia spp.* CH34 (Macombera and Hausinger, 2011). Nickel is bound to histidine residues in *Saccharomyces cerevisiae* and disposed off into vacuoles through proton pumping ATPase and also mediated through chemiosmotic gradient (Nishimura et al., 1998) (Fig. 4). Nickel resistant bacteria isolated from sewage treatment plant in Guheswori identified as *Staphylococcus spp.* and *Bacillus spp.* showing resistance to nickel ions upto 150 µg/ml (Rajbanshi, 2008). *Pseudomonas fragi* isolated from industrial effluents showing growth up to 2.5 mmol/L of nickel ions in the medium (Spate et al., 2006). *Cupriavidus spp.* exhibited resistance to nickel ions in tris minimal media with concentration ranges from 1.0-10 mM (Arundhati amd Paul, 2010). Alboghobeish et al., (2010) isolated eight nickel resistant bacteria from industrial effluents and reported maximum resistance (8-24 mM) for three isolates identified as *Klebsiella oxytoca* ATHA6, *Methylobacterium sp* ATHA7 and *Cupriavidus sp* ATHA3. *K. Oxytoca* reduced 83 mg/ml of nickel in medium with incubation of 3 days.

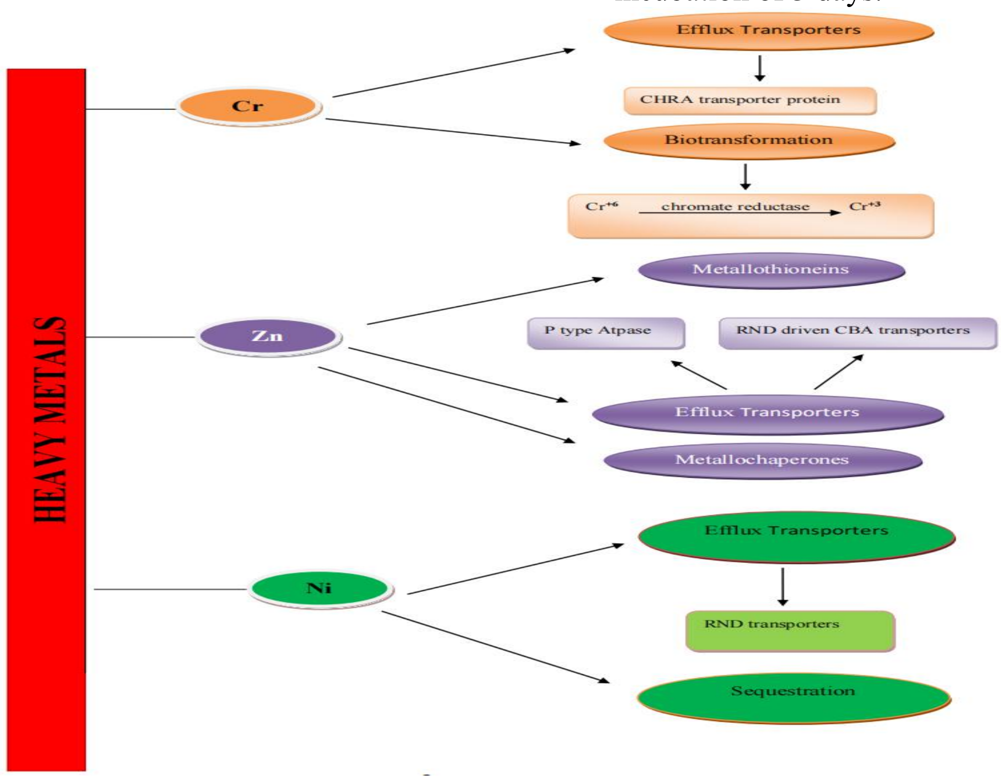

Figure 4. Different types of resistance mechanism employed by bacteria to remediate Chromium (Cr), Zinc (Zn) and Nickel (Ni) from the environment.

Mercury (Hg)

Mercury is the most toxic metal released as result of both natural and anthropogenic activities. Burning of coal and petrochemicals, volcanic eruptions led to release of mercury along with industrial emissions from manufacturing of lamps, caustic soda and peat (Lone et al., 2008). Mercury is also employed in manometers for pressure determination at oil/gas pipelines (Smith et al., 1995). It has been used in amalgam for tooth in ancient days (Lorscheider et al., 1995). Mercury is only metal that occurs in liquid state at stp (standard temperature and pressure) (Smith et al., 1995). Mercury is termed as the most “persistent bioaccumulative toxin” (Weiss and Wright, 2001). Contamination of water with mercury can result in formation of most toxic compound of mercury known as methyl mercury which magnify into food chain (Fatoki and Wofolu, 2003). Methyl mercury is known to be potent cellular toxin and severely affects the nervous system by interfering with production of neurotransmitter and also lowers the production of hormones such as testosterone and thyroid hormones (Fatoki and Wofolu, 2003). Mercury toxicity can lead to autoimmune diseases such as hypertension, insomnia, memory loss, drowsiness, tremors and brain, lungs and kidney damages (Neustadt and Pieczenik, 2007; Gulati et al., 2010).

Resistance mechanism has been developed in bacteria to detoxify mercury from toxic form (Hg^{+2}) into less toxic state (Hg^0) through series of enzymes catalyzed reduction reactions encoded by group of genes present in form of operon known as *mer* operon located on plasmid, chromosomal DNA and in form of transposons (Misra, 1992). Two types of *mer* genes known as *mer* R and *mer* A that codes for enzyme NADPH dependent flavoenzyme mercuric reductase, is involved in reduction of mercury (Hg^{+2}) into volatile, less toxic form (Hg^0) (Misra, 1992; Silver and Walderhaug, 1995). The more toxic compound of mercury other than Hg^{+2} are Organomercurial. Bacteria combat organomercurial toxic effects; if the *mer* resistance also encodes merB organomercurial lyase along with other *mer* gene encoded proteins (Silver, 1996) (Fig. 5). Raja et al., (2009) reported that bacterial isolates from sewage water of Madurai India were resistant up to 0.75 mM mercury ions in media. Mercury resistant bacteria isolates can be identified through detection of 431bp conservative mercuric reductase gene fragment through polymerase chain reaction (Martins et al., 2008). Ruiz et al. (2011) evaluated mercury bioremediation through metallothionein and polyphosphate kinase transgenic mt-bacterial strain. The transgenic bacteria showed resistance to mercury within range of 80-120 µM and also have the capacity to bioaccumulate 100 µM of Hg from media having 120 µM of mercury.

Arsenic (As)

Arsenic is utilized as semiconductors in industries and has application in refining of petroleum, wood preservatives, herbicides and coal plants. Smelting, mining and volcanic eruptions also contributes to arsenic contamination in soil and water (Lone et al., 2008). Arsenic has no biological role in both plants and humans however bacteria might utilize it during anaerobic respiration as electron acceptor (Laverman et al., 1995). Increased concentration of arsenic in water presents serious threat to all form of life (Wang et al., 2012). World Health Organization (WHO) has reported arsenic contamination in about 70 different countries of world, lying serious effects on the health of about 150 million people. This scenario is quite serious in Bangladesh and eastern India and has been termed as “worst mass poisoning” by WHO (Hassan, 2005). Chlorophyll a, carotenoids synthesis has been inhibited in *Microcystis aeruginosa* by application of 10 mg/L of arsenic stress for 48 hours. Arsenic toxicity can result in decreased production of erythrocytes and leukocytes, can interrupt heart rhythm, injure blood vessels and can leads to "needles & pins" sensation in fingers and toes (Abernathy, 2003). Prolong exposure to as can lead to serious disorders such as hyperkeratosis, leuko-melanosis, melanosis, neuropathy, black foot disease and cancer (Caussy, 2005). High prevalence of Arsenism (arsenic poisoning disease) was reported in peoples living in Xinjiang, China by consuming drinking water containing arsenic (0.12 mg/L) for 10 years (Wang et al., 1997).

Bacteria show resistance to arsenic through efflux pumps and biotransformation. Efflux of arsenic is mediated by set of proteins (ArsA, ArsB, ArsC) encoded by *ars* operon comprising of three genes *ars*A, *ars*B and *ars*C present on plasmid DNA (Chen et al., 1986). Methylation of arsenic to dimethyl arsenic, trimethyl arsenic has been reported in various bacterial species. First Arsenate is reduced to arsenite form, than its methylation is carried out (Husymans and Frankenberger, 1991; Tamaki and Frankenberger, 1992). These methylated arsenic compounds are volatile in nature but the methylated forms are more toxic (Michalke et al., 2000) (Fig. 5). Oxidation of As (III) to As (V) is alternate strategy to methlyation. As (V) is known to be less toxic and readily adsorbed (Ilialetdiov and Abdrashitova, 1981). Kermanshahi et al., (2007) isolated heavy metals resistant bacteria from soil of Isfahan, Iran and reported bacterial isolates were resistant to 5 mM of arsenic ions in the media. 19 % adsorption of arsenic in chalcopyrite was reported by heavy metal resistant isolate (ATH-14) (Umrania, 2006). *Bacillus spp*. and *Aneurinibacillus aneurinilyticus* isolated from affected groundwater of industrial area located in West Bengal India are resistant to 550 ppm of arsenate (AsO_4^{3-}) and 450 ppm of arsenite (AsO_3^{-3}). *Bacillus spp* has capacity to eliminate 51.45 % of arsenite and 53.29 % of arsenate, similarly *Aneurinibacillus spp.* has potential to remove 50.39 % of arsenate and 51.99% of arsenite (Dey et al., 2016). Lianthuamluaia et al., (2015) reported that *Pseudomonas spp*. and *Acinetobacter sp.* isolated from tubewell watersample of Bengal has resistance to 7 mM and 1.75 mM of arsenite with biosorption capacity.

Cobalt (Co)

Cobalt is listed among the naturally existing elements with wide range of similarity to iron and nickel in terms of its physiochemical properties. It is widely used in manufacturing of alloys, which have extensive usage in industries such as magnets, ceramics, paints and cutting tools and in military as aircraft engines. Cobalt is also employed in making of artificial body parts such as knee joints. The radioactive isotope of Co (^{60}Co) is employed for irradiation of food products mainly for the purpose of sterilization and storage (ATSDR, 2004).Cobalt is essential constituent of vitamin B12, which serves as cofactor in catalytic reaction involving the rearrangements of CAN, CAO, CAC bonds. Nitrile hydratases are also termed as cobalt containing enzyme (Kobayashi et al., 1996). The only stable form of cobalt is Co^{3+}. Infection in lungs has also been reported due to inhalation of cobalt (Nemery et al., 1994). Incidence of cobalt exposure can leads to severe effects on health such as pneumonia, asthma and wheezing (ATSDR, 2004).

Bacteria employs resistance to cobalt ions in the medium due the presence of trans envelope transport along with RND transporters for efflux of ions. Bacterial resistance mechanism against nickel/ zinc ions also serves as tolerance mechanism against cobalt ions in the medium (Schmidt and Schlegel, 1994) (Fig. 5). Afandi, (2010) reported that bacterial isolates from soil of non ferrous industrial location at Pending, Sarawa, Malaysia showed maximum resistance (36 %) to cobalt and nickel. Fives isolates exhibits multi resistance pattern to wide range of heavy metals with toxicity trends as Hg > Co > Cu > Ni > Fe > Zn. These five isolates were characterized as *Ralstonia spp*, *Pseudomonas spp*, *Klebsiella spp*. Sevgi et al., (2010) reported that 9.2 % of bacterial isolates from industrial area Kanzali in Turkey were found resistant to cobalt within range of 0.5-0.8 mM. *Bacillus spp.* isolated from waste dumping site in Kolkata, India showed MTC of 0.4 mg/mL to Co^{+2} (Samanta et al., 2012). Bacterial isolates belonging to *Curvibacter* and *Tardiphaga* genera isolated from the water sample collected from storage site of nuclear fuel show resistance to cobalt concentration in the media up to 3 mM (Dekker et al., 2014).

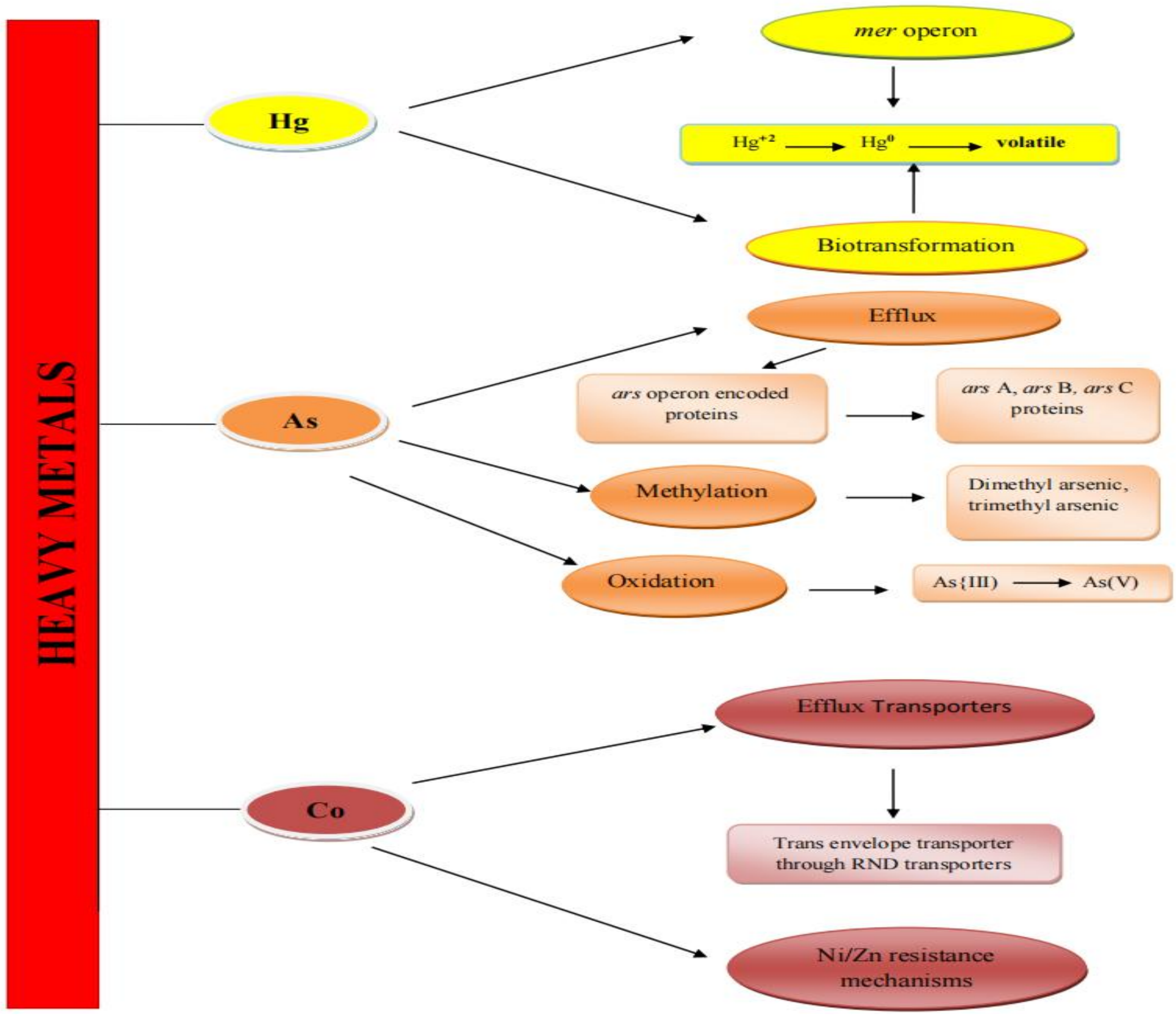

Figure 5. Different types of resistance mechanism employed by bacteria to remediate Mercury (Hg), Arsenic (As) and Cobalt (Co) from the environment.

References

Abdelwaha, O. N. K., Amin and Ashtoukhy, E. S. Z. 2013. Removal of zinc ions from aqueous solution using a cation exchange resin. Chem. Eng. Res. Des. 91: 165–173.

Abernathy, C. O., Thoma, D. J. and Calderon, R. L. 2003. Health effects and risk assessment of arsenic. J. Nutr. 133: 1536-8.

Adriano, D. C. 2001. Trace Elements in Terrestria Environments: Biogeochemistry, Bioavailability and Risks of Metals. New York: Springer, Verlag.

Afandi, B. N. B. 2010. Isolation and Characterization of Bacterial Strains that are Resistant to Nickel, Cobalt and Other Heavy Metals, Ph D Thesis, Faculty of Resource Science and Technology (FRST), Universiti Malaysia Sarawak (Unimas), Malaysia.

Agency for Toxic Substances and Disease Registry (ATSDR) 1997. Toxicological Profile for Nickel (Update). Public Health Service, U.S. Department of Health and Human Services, Altanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR) 2000. Toxicological profile for manganese, US Department of Health and Human Services, Atlanta Georgia, p. 1-466.

Agorboude, L and Navia, R. 2009. Heavy metals retention capacity of a non-conventional Sorbent developed from a mixture of industrial and agricultural wastes. J. Hazard. Mater. 167(1-3): 536-544.

Ahemad, M and Malik, A. 2011. Bioaccumulation of heavy metals by zinc resistant bacteria isolated from agricultural soils irrigated with wastewater. J. Bacteriol. 4: 1-7.

Ahmad, W. A. Shahir, S and Zakaria, Z. A. 2009. Mechanisms of Bacterial Detoxification of Cr (VI) from Industrial Wastewater in the Presence of Industrial Effluent as Potential Energy Source. Final Report - Universiti Teknologi, Malaysia.

Alboghobeish, H., Tahmourespour, A and Doudi, M. 2014. The study of Nickel Resistant Bacteria (NiRB) isolated from wastewaters polluted with different industrial sources. J. Environ. Health Sci. Eng. 12: 44.

Ali, H and Khan, E. 2018. What are heavy metals? Long-standing controversy over the scientific use of the term' heavy metals'-proposal of a comprehensive definition. Toxicol. Environ. Chem. vol. 100, no. 1, pp. 6–19, 2018.

Allen, J. G., Masters, H. G., Peet, R. L., Mullins, K. R., Lewis, R. D., Skirrow, S. Z and Fry, J. 1983. Zinc toxicity in ruminants. J. Comp. Pathol. 93(3): 363-77.

Amin, N., Ibrar, D and Alam, S. 2014. Heavy Metals Accumulation in Soil Irrigated with Industrial Effluents of Gadoon Industrial Estate, Pakistan and Its Comparison with Fresh Water Irrigated Soil. J. Agric. Chem. Environ. 3: 80-87.

Ahirwar, N. K., Gupta, G., Singh, R., & Singh,V. (2016). Isolation, identification and characterization of heavy metal resistant bacteria from industrial affected soil in central India. Int. J. Pure Appl. Biosci. 4(6): 88–93.

Appenroth, K. J., Sherameti I and Varma, A. 2010. Definition of heavy metals and their role in biological systems. In Soil heavy Metals, Soil Biol, Berlin: Springer. 19-29.

Arguello, J. M. 2003. Identification of ion-selectivity determinants in heavy-metal transport P1B-type ATPases. J. Membr. Biol. 195: 93-108.

Arshad, M., Zafar, N. M., Youns, S and R. Nadeem. 2008. The use of neem biomass for the biosorption of zinc from aqueous phase. J. Hazard. Mater. 157: 534–540.

Arundhati, P and Paul, A. K. 2010. Nickel uptake and intracellular localization in Cupriavidus pauculus kps 201. Adv. Biosci. Biotechnol. 1: 276–280.

Asatiani, N. V., Abuladze, M. K., Kartvelishvili, T. M., Bakradze, N. G and Sapojnikova, N. A. 2004. Effect of chromium(VI) action on Arthrobacter oxydans. Curr. Microbiol. 49: 321-326.

Aschner, M., Guilarte, T. R., Schneider, J. S and Zheng, W. 2007. Manganese: recent advances in understanding its transport and neurotoxicity. Toxicol. Appl. Pharmacol. 221: 131-47.

Baig, K. S., Doan, H. D and Wu, J. 2009. Multicomponent isotherm for biosorption of Ni^{+2} and Zn^{+2}. Desalination 249: 429–439.

Baladi, F., Vaughan, A. M and Olson, G. J. 1990. Chromium (VI) resistant yeast isolated from a sewage treatment plant receiving tannery wastes. Appl. Environ. Microbiol. 56: 913-918.

Bangash, F. K., Fida, M and Fazeelat. 2006. Appraisal of effluents of some selected industries of Hayatabad industrial estate, Peshawer. J. Chem. Soc. Pak. 28(1): 16-19.

Barbier, O., Jacquillet, G., Tauc, M., Cougnon, M and P. Poujeol. 2005. Effect of heavy metals on, and handling by, the kidney. Neph. Physiol. 99: 105–109.

Barceloux, D. G. 1999. Chromium. Clin. Toxicol. 37: 173–194.

Basha, S. A and Rajaganesh, K. 2014. Microbial Bioremediation of Heavy Metals from Textile Industry Dye Effluents using isolated Bacterial Strains.Int. J. Curr. Microbiol. Appl. Sci. 3(5): 785-794.

Batool, R., Kim, Y and Hasnain, S. 2012. Hexavalent Chromium Reduction by Bacteria from Tannery Effluent. J. Microbiol. Biotechnol. 22(4): 547–554.

Batool, R., Yrjala, K and Hasnain, S. 2014. Impact of environmental stress on biochemical parameters of bacteria reducing Chromium. Braz. J. Microbiol. 45(2): 573-583.

Bellinger, D. C. 2005. Teratogen update: lead and pregnancy. Birth Defects Research part A Clinical and Molecular Teratology 73: 409–20.

Bishop, P. L. 2002. Pollution Prevention: Fundamentals and Practice. Beijing: Tsinghua University Press.

Blancho, A. 2000. Immobilization of non viable cyanobacteria and their use for heavy metal adsorption from water. In Environmental Biotechnology and Cleaner Bioprocesses, ed. E .J. Oluguin, E. Sanchez, E. Hernandaz. Philadelphia: Taylor and AMP francis.

Boening, D. W. 2000. Ecological effects, transport, and fate of mercury: a general review. Chemosphere 40(12): 1335–1351.

Bopp, L. H and Ehrlich, H. L. 1988. Chromate resistance and reduction in Pseudomonas fuorescens strain LB300. Arch. Microbiol. 150: 426-431.

Bouton, C. M., FrelinL, Forde, P. C. E., Godwin, H. A and Pevsner, J. 2001. Synaptotagmin I is a molecular target for lead. J. Neurochem. 76: 1724-35.

Bruins, M. R., Kapil, S and Oehme, F. V. 2000. Microbial resistance to metals in the environment. Ecotoxicol. Environ. Saf. 4: 198-207.

Butler, E. J., Nisbet, D. I and Robertson, J. M. 1957. Osteoporosis in lambs in a lead mining area. 1. A study of the naturally occurring disease. J. Comp. Pathol. 67: 378–398.

Cameron, R.E. 1992. Guide to site and soil description for hazardous waste characterization. Vol. I, Metals. Environ. Pro. Agency EPA/600/4-91/029. Pp. 250.

Camner, P., Curstedt, T and Jarstrand, C. 1985. Rabbit lung after inhalation of manganese chloride: A comparison with the effects of chlorides of nickel, cadmium, cobalt, and copper. Environ. Res. 38: 301- 309.

Campbell, P. G. C. 2006. Cadmium-A priority pollutant. Environ. Chem. Lett. 3(6): 387–388.

Caussy, D. 2005. A field guide for detection, management and surveillance of arsenicosis cases. Regional Office for South-East Asia, World Health Organization.

Cefalu, W. T and Hu, F. B. 2004. Role of chromium in human health and in diabetes. Diabetes care 27: 2741–51.

Chaudhari, P. R., Gupta, R., Gajghate, D. G and Wate, S. R. 2012. Heavy metal pollution of ambient air in Nagpur city. Environ. Monit. Assess. 184: 2487-2496.

Chen, B., Liu, J. N., Wang, Z., Dong, L., Fan J. H and Qu, J. J. 2011. Remediation of Pb-Resistant Bacteria to Pb Polluted Soil. J. Environ. Prot. 2: 130-141.

Chen, C and Wang, J. L. 2007. Characteristics of Zn^{2+} biosorption by Saccharomyces cerevisiae. Biomed. Environ. Sci. 20: 478–482.

Chen, C. M., Misra, T. K., Silver, S and Rosen, B. P. 1986. Nucleotide sequence of the structural genes for an anion pump. The plasmid-encoded arsenical resistance operon. J. Biol. Chem. 261: 15030-15038.

Chou, A. Y., Archdeacon, J and Kado, C. I. 1998. Agrobacterium transcriptional regulator Ros is a prokaryotic zinc finger protein that regulates the plant oncogene ipt. Proceedings of National Academy of Sciences USA 95: 5293-5298.

Cooksey, D. A. 1994. Molecular mechanisms for copper resistance and accumulation in bacteria. FEMS Microbiol. Rev 14: 381–386.

Costa, M and Klein, C. B. 2006. Toxicity and carcinogenicity of chromium compounds in humans. Crit. Rev. Toxicol. 36: 155-63.

Das, S., Patnaik, S. C., Sahu, H. K., Chakraborty, A., Sudarshan, M and Thatoi, H. N. 2013. Heavy metal contamination, physico-chemical and microbial evaluation of water samples collected from chromite mine environment of Sukinda, India. Transactions of Nonferrous Metal Society of China 23: 484−493.

Davies, B. E and Jones, L. H. P. 1988. Micronutrients and toxic elements. In Soil Conditions and Plant Growth, W. A. Russell, 781–814, 11th edition, New York: John Wiley & Sons; Interscience.

Deepali, J. N. 2012. Study of ground water quality in and around SIDCUL industrial area, Haridwar, Uttarakhand, India. J. Appl. Technol. Environ. Sanit. 2(2): 129–134.

Dekker, L., Osborne, T. H. and Santini, J. M. 2014. Isolation and identification of cobalt and caesium resistant bacteria from nuclear fuel storage pond, FEMS Microbiol. Lett. 359(1):81-4.

Desai, C., Jain, K and Madamwar, D. 2008. Evaluation of in vitro Cr (VI) reduction potential in cytosolic extracts of three indigenous Bacillus sp. isolated from Cr(VI) polluted industrial landfill. Bioresour. Technol. 99: 6059-6069.

Dey, U., Chatterjee, S and Mondal, N. K. 2016. Isolation and characterization of arsenic resistant bacteria and possible application in bioremediation. Biotechnol. Rep. 10: 1-7.

Dhankhar, R and Guriyan, R. B. 2011. Strategies for Management of Metal Contaminated Soil. Int. J. Environ. Sci. 1(7): 1884, 1898.

Diaz, G. J., Julian, R. J and Squires, E. J. 1994. Lesions in broiler chickens following experimental intoxication with cobalt. Avian Dis. 38: 308–316.

Diaz, M. I. R., Perez, C. D. E., Vargas, H. R., Rosas, J., Garcia, C and Cervantes, C. 2007. Mechanisms of bacterial resistance to chromium compounds. BioMetals 21: 321–332.

Dillewijn, P. V., Caballero, A., Paz, J. A., Gonzalez-Perez, M. M., Oliva, J. M and Ramos, J. L. 2007. Bioremediation of 2, 4, 6 trinitrotoluene under field conditions. Environ. Sci. Technol. 41: 1378 1383.

Dixit, V., Pandey, V and Shyam, R. 2002. Chromium ions inactivate electron transport and enhance superoxide generation in vivo in Pea (Pisum Sativum L.cv.Azad) root mitochondria. Plant. Cell and Environ. 25: 687-693.

DOE (Department of Energy) (1997). Linking Legacies, DOE/EM-319. United States Department of Energy, Washington, DC, USA.

Duda-Chodak, A and Baszczyk, U. 2008. The impact of nickel on human health. J. Elementol. 13: 685–696.

Emsley, J. 2003. Manganese. Nature's building blocks: an A–Z guide to the elements, 249–253, USA: Oxford University Press.

Erikson, K. M and Aschner, M. 2003. Manganese neurotoxicity and glutamate-GABA interaction, Neurochem. Intern. 43: 475-80.

Fatoki, O. S Awofolu, R. 2003. Levels of Cd, Hg and Zn in some surface waters from the Eastern Cape Province, South Africa. Water South Africa 29: 375–80.

Fawzy, E. M. 2008. Soil remediation using in-situ immobilization techniques. J. Chem. Ecol. 24(2): 147-156.

Flemming, C. A and Trevors, J. T. 1989. Copper toxicity and chemistry in the environment: a review. Water, Air, and Soil Pollut. 44(1-2): 143-158.

Frery, N., C. Nessmann, F. Girard, J. Lafond, T. Moreau, and P. Blot. 1993. Environmental exposure to cadmium and human birth weight. Toxicol. 79: 109–18.

Fu, F and Wang, Q. 2011 Removal of heavy metal ions from wastewaters: A review. J. Environ. Manag. 92: 407-418.

Garbisu, C and Alkorta, I. 1997. Bioremediation: principles and future. Journal of Clean Tech and Environ Toxicol and Occupational Med. 6: 1-16.

Garbisu, C., Gonzalez, S., Yang, W. H., Yee, B. C., Carlson, D. E., Yee, A., Smith, N. R., Otero, R., Buchanan, B. B., and T. Leighton. 1995 a. Physiological mechanisms regulating the conversion of selenite to elemental selenium by Bacillus subtilis. BioFactors 5: 29-37.

Garg, N and Singla, P. 2011. Arsenic toxicity in crop plants: physiological effects and tolerance mechanisms. Environ. Chem. Lett.9 3): 303-321.

Gibb, H. J., Lees, P. S., Pinsky, P. F and Rooney, B. C. 2000. Clinical findings of irritation among chromium chemical production workers.Am. J. Ind. Med. 38: 127 131.

Greany, K. M. 2005. An assessment of heavy metal contamination in the marine sediments of Las Perlas Archipelago, Gulf of Panama, M.S. thesis, School of Life Sciences Heriot-Watt University, Edinburgh, Scotland.

Gulati, K., Banerjee, B., Bala, L. S and 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.

Gupta, N and Kumar, V. 2012. Identification and Isolation of Heavy Metal (Copper) Resistant Bacteria. Arch. Appl. Sci. Res. 4 (1): 577-583.

Gupta, S. D., Lee, B., Camakaris, J and Wu, H. C. 1995. Identification of cutC and cutF (nlpE) genes involved in copper tolerance in Escherichia coli. J. Bacteriol. 177: 4207– 4215.

Hassan, M. M. 2005. Arsenic poisoning in Bangladesh: spatial mitigation planning with GIS and public participation. Health Policy 74: 247–260.

Henderson, R. F and Rebar, A. H. 1979. Early damage indicators in the lungs. IV Biochemical and cytologic response of the lung to lavage with metal salts. Toxicol. Appl. Pharmacol. 51(1): 129-35.

Hernandez, D. A. B., Burgos, L. I. R., Páramo, E. D and Linares, L. F. 2012. Zinc and Lead Biosorption by Delftia tsuruhatensis: A Bacterial Strain Resistant to Metals Isolated from Mine Tailings. JWARP 4: 207-216.

Hidayati, N., Surtiningsih, T and Matuzahroh, N. 2014**.** Removal of Heavy Metals Pb, Zn and Cu from Sludge Waste of Paper Industries Using Biosurfactant. J Bioremediat Biodegrad 5: 7.

Hoekman, D., Hansch, C., Leo, A., Zhang, L and P. Li. 1995. The expanding role of quantitative structure activity relationships (QSAR) in toxicology. Toxicol. Lett. 79: 45-53.

Huck, D. W and Clawson, A. J. 1976. Excess dietary cobalt in pigs. Sci. J. Anim. Sci. 43: 1231-1246.

Huysmans, K. D and Frankenberger Jr, W. T. 1991. Evolution of trimethylarsine by a Penicillium sp. isolated from agricultural evaporation pond water. Sci. Total Environ 105: 13-28.

Ilialetdinov, A. N and Abdrashitova, S. A. 1981. Autotrophic arsenic oxidation by a Pseudomonas arsenitoxidans culture. Mikrobiologiia 50: 197-204.

Illhan, S., Nourbakhsh, M. N., kilicarslan, S and Ozdag, H. 2004. Removal of chromium, lead and copper ions from industrial waste water by Staphylococcus saprophyticus. Electron. J. Biotechnol. 2: 50-57.

Inoue, N and Makita, Y. 1996. Neurological aspects in human exposures to Manganese. In: Toxicology of metals, 415-421, (ed) Chang, L. W. FL-Boca Raton: CRC Press.

Ishibashi, Y., Cervantes, C and Silver, S. 1990. Chromium reduction in Pseudomonas putida.

Appl. Microbiol. Biotechnol. 56: 2268-2270.

Igiri, B.E., Okoduwa, S.I., Idoko, G.O., Aka buogu, E. P., Adeyi, A. O and Ejiogu, I. K. 2018. Toxicity and bioremediation of heavy metals contaminated ecosystem from tannery wastewater: A review. J. Toxicol. 1–16.

Iwamoto, T and Nasu, M. 2001. Current bioremediation practice and perspective. J. Biosci. Bioeng. 92(1): 1-8.

Jain, S and Bhatt, A. 2014. Molecular and in situ characterization of cadmium-resistant diversified extremophilic strains of Pseudomonas for their bioremediation potential. Biotechnol. 4: 297–304.

Jin, T. E., Kim, I. G., Kim, W. S., Suh, S. C., Kim, B. D and Rhim, S. L. 2001. Expression of Chromium (VI) Reductase Gene of Heavy Metal Reducing Bacteria in Tobacco Plants. J. Plant Biotechnol. 3(1): 13-17.

Kalidhasan, S and Rajesh, N. 2009. Simple and selective extraction process for chromium (VI) in industrial wastewater. J. Hazard. Mater.170(2-3): 1079-85.

Kamika, I and Momba, M. N. B. 2013. Assessing the resistance and bioremediation ability of selected bacterial and protozoan species to heavy metals in metal-rich industrial wastewater. BMC Microbiol. 13: 28-42.

Kanamaru, K., Kashiwagi, S and Mizuno, T. 1995. A copper-transporting P-type ATPase found in the thylakoid membrane of the cyanobacterium Synechococcus species PCC7942. Mole. Microbiol. 13: 369-377.

Karakagh, R. M., Chorom, M., Motamedi, H., Kalkhajeh, Y. K and Oustan, S. 2012. Biosorption of Cd and Ni by inactivated bacteria isolated from agricultural soil treated with sewage sludge. Ecohydrol. Hydrobiol. . 12(3): 191-198.

Katz, S. A and Salem, H. 1993. The toxicology of chromium with respect to its chemical speciation: a review. J Appl Toxicol . 13(3): 217-24.

Katz, S. A and Salem, H. 1994. The Biological and Chemistry of Environmental Chromium. USA: VCH Publishers, Inc.

Kennedy, S., Rice, D. A and Cush, P. F. 1986. Neuropathology of experimental 3-nitro-4-hyroxyphenylarsonic acid toxicosis in pigs. "Vet. Pathol.". 23: 454–461.

Kermani, A. J. N., Ghasemi, M. F., Khosravan, A., Farahmand, A and Shakibaie, M. R. 2010. Cadmium Bioremediation by Metal-Resistant Mutated Bacteria isolated from Active Sludge of Industrial Effluent. Iran. J. Environ. Health Sci. Eng. . 7(4): 279-286.

Kermanshahi, R. K., Ghazifard, A and A. Tavakoli. 2007. Identification of bacteria resistant to Heavy metals in the soils of Isfahan Province. Iran J. Sci. Technol. Trans. A Sci. 31(A1): 7-15.

Khan, M. A., Ahmad, I and Rahman I. 2007. Effect of environmental pollution on heavy metals content of Withania somnifera. J Chin Chem Soc 54: 339–343.

Khan, M. U., Malik, R. N and Muhammad S. 2013. Human health risk from heavy metals via food crops consumption with wastewater irrigation practices in Pakistan. Chemosphere 93: 2230-2238.

Khan, S., Cao, Q., Zheng,Y. M., Huang, Y. Z and Zhu, Y. G. 2008. Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. Environ. Pollut. 152(3): 686–692.

Khodadoust, P., Reddy, K. R. and Maturi M. 2004. Removal of nickel and phenanthrene from kaolin soil using different extractants. Environ. Eng. Sci 21(6): 691–704.

Kihampa, C. (2013). Heavy metal contamination in water and sediment downstream of municipal wastewater treatment plants, Dar es Salaam, Tanzania. Int. J. Environ. Sci. 3 **(**5): 1407-1415.

Kim, E. J., Chung, H. J., Suh, B. S., Hah, Y. C and Roe, J. H. 1998. Transcriptional and post-transcriptional regulation by nickel of sodN gene encoding nickel-containing superoxide dismutase from Streptomyces coelicolor. Muller. Mol. Microbiol. 27: 187-195.

Kim, J., and Vipulanandan, C. 2006. Removal of lead from contaminated water and clay soil using a biosurfactant. J Environ. Eng. 132: 777–786.

King, T. P and Bremner, I. 1979. Autophagy and apoptosis in liver during the pre haemolytic phase of chronic copper poisoning in sheep. J. Comp. Pathol. 89: 515–530.

Klein, C. J. 2000. Zinc supplementation. J. Am. Diet. Assoc. 100: 1137–1138.

Kobayashi, S., Miyabe, S., Izawa, S., Inoue, Y and Kimura, A. 1996. Correlation of the OSR/ZRC1 gene product and the intracellular glutathione levels in *Saccharomyces cerevisiae*. Biotechnol. Appl. Biochem. 23: 3-6.

Kord, B., Mataji, A and Babaie. S. 2010. Pine (Pinus eldarica Medw.) needles as indicator for heavy metals pollution. Int J Environ Sci Technol 7(1): 79-84.

Kotrba, P., Najmanova, J., Macek, T., Ruml, T and Mackova, M., (2009). Genetically modified plants in phytoremediation of heavy metal and metalloid soil and sediment pollution. Biotechnol. Adv. 27: 799–810.

Kratochvil, D and Volesky, B. 1998. Advances in the biosorption of heavy metals. Trends Biotechnol. 16: 291-300.

Kumar, R and Kartic, N. 2011. Removal of Cu^{2+} Ions from Aqueous Solutions Using Copper Resistant Bacteria. Our Nature 9: 49-54.

Kumar, R. R. 2014) Isolation, Molecular identification of metal tolerant bacteria and its heavy metal removal capacity. International Journal of Microbiology Biochemistry Molecular Biology 1-7. Available at http://www.scienceresearchlibrary.com

Laverman, A. M., Blum, J. S., Schaefer, J. K. E., Phillips, J. P., Lovley, D. R and Oremland, R. S. 1995. Growth of strain SES-3 with arsenate and other diverse electron acceptors. Appl. Environ. Microbiol. 61: 3556-3561.

Lee, T., Park, J. W and Lee, J. H. 2004. Waste green sands as reactive media for the removal of zinc from water. Chemosphere 24: 571–581.

Levinson, H. S and Mahler, I. 1998. Phosphatase activity and lead resistance in Citrobacter freundii and Staphylococcus aureus. FEMS Microbiol. Lett. 161: 135-8.

Levinson, H. S., Mahler, I., Blackwelder, P and Hood. T. 1996. Lead resistance and sensitivity in *Staphylococcus aureus*. FEMS Microbiol. Lett. 145: 421-5.

Lianthumluaia, J., Pandey, P. K., Purushothaman, C. S., Vennila, A and Zohmingthanga. 2015. Characterization of arsenic resistant bacteria from shallow tubewell and evaluation of their remediation capacity. Nat. Environ. Pollut. Technol. 14(1): 119-124.

Ling, W., Shen, Q., Gao, Y., Gu, X and Yang. Z. 2007. Use of bentonite to control the release of copper from contaminated soils. Aust. J. Soil Res. 45(8): 618–623.

Liu, D., Zou, J., Wang, M and Jiang. W. 2008. Hexavalent chromium uptake and its effects on mineral uptake, antioxidant defence system and photosynthesis in *Amaranthus viridis* L. Bioresour. Technol. 99(7): 2628–2636.

Liu, X. F., Supek, F., Nelson, N and Culotta. V. C. 1997. Negative control of heavy metal uptake by the Saccharomyces cerevisiae BSD2 gene. J. Biol. Chem 272: 11763-11769.

Liu, Y., Xu, W., Zeng, G., Li, X., and Goa H. 2006. Cr (VI) reduction by Bacillus spp. isolated from chromium landfill. Process Biochem. 41: 1981–1986.

Liu, Z., Wu, Y., Lei, C., Liu, P and Gao, M. 2012. Chromate reduction by a chromate-resistant bacterium, Microbacterium spp. World J. Microbiol. Biotechnol. 28: 1585–1592.

Lloyd, J. R and Lovely, D. R. 2001. Lovley Microbial detoxification of metals and radionuclides. Curr. Opin. Biotechnol. 12: 248–253.

Lone, M. I., He, Z. P., Stoffella, J and Yang, X.. 2008. Phytoremediation of heavy metal polluted soils and water: progresses and perspectives. J. Zhejiang Uni. Sci. B (Biomed. Biotechnol.) 9: 210-220.

Lorscheider, F. L., Vimy, M. J and Summers, A. O. 1995. Mercury exposure from silver tooth fillings emerging evidence questions a traditional dental paradigm. FASEB Journal 9: 504-508.

Lovley, D. R. 1993. Dissimilatory metal reduction. Annu. Rev. Microbiol. 47: 263-290.

Macombera, L. and Hausinger, R. P. 2011. Mechanisms of nickel toxicity in microorganisms. Metallomics, 3: 1153–1162.

Maier, T., Jacobi, A., Sauter, M and BoÈck A.. 1993. The product of the hypB gene, which is required for nickel incorporation into hydrogenases, is a novel guanine nucleotide-binding protein. J. Bacteriol. 175: 630-635.

Malik, R. N., Husain, S. Z and Nazir, I. 2010. Heavy metal contamination and accumulation in soil and wild plant species from industrial area of Islamabad, Pakistan. Pak. J. Bot. 42(1): 291-301.

Manahan, S. E. 2003. Toxicol. Chem.Biochem. ed. 3rd, Boca Raton.: CRC Press, Limited Liability Company (LLC).

Marin, A. B. P., Ortuno, J. F., Aguilar, M. I., Meseguer,V. F., Saez, J and M. Llorens. 2009. Use of chemical modification to determine the binding of Cd (II), Zn (II) and Cr(III) ions by orange waste. J. Biochem. Eng. 53(1): 2-6.

Martinez, C. E and Motto, H. L. 2000. Solubility of lead, zinc and copper added to mineral soils. Environ. Pollut. 107(1): 153–158.

Martinez, R. J., Beazley, M. J and. Sobecky, P. A. 2014. Phosphate-Mediated Remediation of Metals and Radionuclides. Adv. Ecol. 2014: 1-14.

Martins, A. S., Jesus, M. S. D., Lacerda, M., Moreira,J. C., Filgueiras, A. L. L and Barrocas, P. R. G. 2008. A Conservative Region of the Mercuric Reductase Gene (Mera) as

Amolecular Marker of Bacterial Mercury Resistance. Braz. J. Microbiol. 39: 307-310.

McCall, K. A., Huang, C and Fierke, C. A. 2000. Function and mechanism of zinc metalloenzymes. J. Nutri. 130: 1437S-46S.

McCaughey, W. 2007. Inorganic and organic poisons. In: Sheep Diseases, Ed. I. D. Aitken, London: Blackwell Scientific.

McDonagh, A. J., Wright, A. L., Cork, M. J. and Gawkrodger, D. J. 1992. Nickel sensitivity the influence of ear piercing and atropy. Brazil. J. Dermatol. 126: 16-18.

McGrath, S. P and Smith, S. 1990. Chromium and nickel, In Heavy Metals in Soils, ed. B. J. Alloway, 125–150, New York: Wiley.

McLaughlin, M. J., Hamon, R, E., McLaren, R. G., Speir T. W and Rogers, S. L. 2000. Review: A bioavailability-based rationale for controlling metal and metalloid contamination of agricultural land in Australia and New Zealand. Aust. J. Soil Res. 38(6): 1037–1086.

McLaughlin, M. J., Zarcinas, B. A., Stevens, D. P and Cook, N. 2000. Soil testing for heavy metals. Commun. Soil Sci. Plant Anal. 31(11): 1661–1700.

Meditext-Medical Management. 2005. Chromium Hexavalent Salts. TOMES Information System. CO: Micromedex, Inc. Denver.

Mergler, D., Baldwin,M., Belanger, S., Larribe, F., Beuter, A and Bowler, R. 1999. Manganese neurotoxicity, a continuum of dysfunction: Results from a community based study. Neurotoxicology 20: 327-42.

Michalke, K., Wickenheiser, E. B., Mehring, M., Hirner, A. V and Hensel. R. 2000. Production of volatile derivatives of metal(loid)s by microflora involved in anaerobic digestion of sewage sludge. Appl. Environ. Microbiol. 66: 2791-2796.

Mire, C. E., Tourjee, J. A., O'Brien, W. F., Ramanujachary, K. V and G. B. Hecht. 2004. Lead precipitation by Vibrio harveyi: evidence for novel quorum-sensing interactions. Appl. Environ. Microbiol. 70: 855–864.

Mishra, V., Balomajumder, C and Agarwal, V. K. 2011. Biosorption of Zinc (II) ion onto surface of Cedrus deodara sawdust: studies on isotherm modeling and surface characterization. Int. J. Chem. Sci. Appl. 2: 179–185.

Misra, T. K. 1992. Bacterial resistances to inorganic mercury salts and organomercurials. Plasmid 27: 4-16.

Mobley, H. L., Island, M. D and Hausinger R. P. 1995. Molecular biology of microbial ureases. Microbiol. Rev. 59: 451-480.

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

Mohanty, M., Pattnaik, M. M., Mishra, A. K and Patra, H. K. 2012. Bio-concentration of chromium- an in situ phytoremediation study at South Kaliapani chromite mining area of Orissa India. Environ. Monit. Assess. 184: 1015–1024.

Montelongo, L. R., Rodriguez, L. C. D. L. C., Farias, R. N and Massa, E. M. 1993. Membrane-associated redox cycling of cop- per mediates hydroperoxide toxicity in Escherichia coli. Biochimica et Biophysica Acta 1144: 77-84.

Moreno, J. L., Hernandez, T and Garcia, C. 1999. Effects of cadmium containing sewage sludge compost on dynamics of organic matter and microbial activity in an arid soils. Biol. Fertil. Soils 28: 230-237.

Morris, B. L., Lawrence, A. R. L and Chilton, P. J. C. 2003. Groundwater and its Susceptibility to Degradation: A Global Assessment of the Problem and Options for Management. United Nations Environment Programme, Nairobi, Kenya.

Mueller, E. G. 1996. A glutathione reductase mutant of yeast accumulates high levels of oxidized glutathione and requires thioredoxin for growth. Mol. Biol. Cell 7: 1805–1813.

Mukhopadhyay, U., Govindasamy, L., Ravikumar, K., Velmurugan, D and Ray, D. 1998. Synthesis and structural characterization of a triply bridged copper (II)–zinc(II) Schiff base complex with N, O coordination. Inorg. Chem. Commun. 1: 152–154.

Murugesan, A. G., and Maheswari, S. 2007. Uptake of hexavalent chromium from aqueous solution employing live, dead and immobilized bacterial biomass. J. Appl. Sci. Environ. Manag. 11(4): 71-75.

Mushtaq, N and Khan,K. S. 2010. Heavy metals contamination of soils in response to Wastewater irrigation in Rawalpindi region. Pak. J. Agri. Sci. 47(3): 215-224.

Myers, C. R., Carstens, B. P., Antholine, W. E., and Myers, J. M. 2000. Chromium(VI) reductase activity is associated with the cytoplasmic membrane of anaerobically grown Shewanella putrefaciens MR-1. J. Appl. Microbiol. 88: 98-106.

Naik, M. M., Pandey, A and Dubey, S. K. N. 2012. strain WI-1 from Mandovi estuary possesses metallothionein to alleviate lead toxicity and promotes plant growth. Ecotoxicol. Environ. Saf. 79: 129–133.

Nanda, M., Sharma, D and Kumar, A. 2011. Removal of Heavy Metals from Industrial Effluent Using Bacteria. International J. Environ. Sci. 2(2): 789-795.

Nasrullah, R. Naz, Bibi, H., Iqbal, M. and Durrani, M I. 2006. Pollution load in industrial effluent and ground water of gadoon amazai induatrial estate (GAIE) Swabi, NWFP. J. Agri. Biol. Sci. 1(3): 18-24.

Nath, S., Deb, B and Sharma, I. 2012. Isolation and Characterization of Cadmium and Lead Resistant Bacteria. Global Advances Research Journal of Microbiology 1(11): 194-198.

Naz, T., Khan, M. D., Ahmed, I., Rehman, S. U., Rha, E. S., Malook, I., & Jamil, M. (2015). Biosorption of heavy metals by Pseudomonas species isolated from sugar industry. Toxicol. Ind. Health, 1-9. DOI: 10.1177/0748233715569900

Nemery, B., Lewis, C. P and Demedts, M. 1994. Cobalt and possible oxidant-mediated toxicity. Sci. Total Environ. 150: 57-64.

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

Nies, D. H. 1995. The cobalt, zinc, and cadmium efflux system CzcABC from Alcaligenes eutrophus functions as a cation-proton antiporter in Escherichia coli. J. Bacteriol. 177: 2707-2712.

Nies, D. H. 1999 Microbial heavy-metal resistance. Appl. Microbiol. Biotechnol. 51: 730–750.

Nies, D. H and Silver, S.1989. Metal ion uptake by a plasmid-free metal-sensitive Alcaligenes eutrophus strain. J. Bacteriol. 171: 4073-4075.

Nikaido, H. 1996. Multiple efflux pumps of gram-negative bacteria. J. Bacteriol. 178: 5853-5859.

Nishimura, K., Igarashi, K and Kakinuma, Y. 1998. Proton gradient- driven nickel uptake by vacuolar membrane vesicles of Saccharomyces cerevisiae. J. Bacteriol. 180: 1962-1964.

Noll, M., Petrukhin, K and Lutsenko, S. 1998. Identification of a novel transcription regulator from Proteus mirabilis, PMTR, revealed a possible role of YJAI protein in balancing zinc in Escherichia coli. J. Biol. Chem. 273: 21393-401.

Nouri, J., Mahvi, A. H., Jahed, G. R and Babaei, A. A. 2008. Regional distribution pattern of groundwater heavy metals resulting from agricultural activities. Environ. Geol. 55(6): 1337-1343.

Noyce, J. O., Michels, H and Keevil, C. W. 2006. Potential use of copper surfaces to reduce survival of epidemic meticillin resistant Staphylococcus aureus in the healthcare environment. J. Hosp. Infect. 63(3): 289-97.

NSC, Lead Poisoning, National Safety Council. 2009. http:// www.nsc.org/news resources/Resources/Documents/Lead Poisoning.

NTP (National Toxicology Program) 1993. NTP Technical Report on toxicity studies of cupric sulfate administered in drinking water and feed to F344/N rats and B6C3F1 mice. United States Department of Health and Human Services. NIH Publication 93-3352.

Olafson, R. W., Abel, K and Sim, R. S. 1979. Prokaryotic metallothionein: preliminary characterization of a blue-green algae heavy-metal binding protein. Biochem. Biophys. Res. Commun. 89: 36-43.

Olafson, R. W., McCubbin, W. D and Kay, C. M. 1988. Primary- and secondary-structural analysis of a unique prokaryotic metallothionein from a Synechococcus sp. cyanobacterium. Biochem. J. 251: 691-9.

OtiWilberforce, J. O., Nwabue, F and Afiukwa,J. N. 2012. Analysis of Heavy Metals in Soils of Enyigba and Abakaliki Using Proton Induced X-Ray Emission (Pixe) Spectroscopy. Environ. Pollut. 1(2): 183-193.

Pal, R., Gupta, M. A and Tripathi, A. 2014. Assessment of heavy metals in suspended particulate matter in Moradabad, India, J. environ. Biol. 35: 357-361.

Palit, S., Sharma, A and Talukder, G.1994. Effects of cobalt on plants. Bot. rev. 60(2): 149-181.

Paulsen, I. T., Brown, M. H and Skurray, R. D. 1996. Proton-dependend multidrug efflux systems. Microbiol. Rev. 60: 575-608.

Peitzsch, N., Eberz, G and Nies, D. H. 1998. Alcaligenes eutrophus as a bacterial chromate sensor. Appl. Environ. Microbiol. 64: 453-458.

Pennington, J. A., Young, B. E., Wilson, D. B., Johnson, R. D and Vanderveen, J. E. 1986. Mineral content of foods and total diets: the Selected Minerals in Foods Survey, 1982 to 1984. J. Am. Diet. Assoc. 86: 876-91.

Phung, L. T., Ajlani, G and Haselkorn, R. 1994. P-type ATPase from the cyanobacterium Synechococcus 7942 related to the human Menkes and Wilson disease gene product. Proceedings of National Academy of Science USA 91: 9651-9654.

Polti, M. A., Amoroso, M. J and Abate, C. M. 2010. Chromate reductase activity in Streptomyces sp.MC1. Journal of General and Applied Microbiology 56: 11.

Quarterman, J., Morrison, J. N., Humphries, W. R and Mills, C, F. 1977. The effect of dietary sulfur and of castration on lead poisoning in lambs. J. Comp. Pathol. 87: 405–416.

Radhi, S. N. 2012. Optimization of heavy metals chlorides resistance by Staphylococcus aureus and its ability to remove them. Iraqi J. Sci. 53(4): 778-785.

Raja, C. E., Selvam, G. S and Omine, K. 2009. Isolation, Identification and Characterization of Heavy Metal resistant Bacteria from Sewage. International joint Symposium on Geodisaster Prevention and Geoenvironment in Asia, JS Fukouka, 205-211.

Rajbanshi, A. 2008. Study on Heavy Metal Resistant Bacteria in Guheswori Sewage Treatment Plant. Nature 6: 52-57.

Rani, J., Hemambika, M. B., Hemapriya, J and Rajeshkannan, V. 2010. Comparative Assessment of Heavy Metal Removal by Immobilized and Dead Bacterial Cells: A Biosorption Approach. Global J. Environ. Res. 4(1): 23-30.

Rao, M. K., and Srest, T. 2000. Antioxidative parameters in the seedlings of pigeonpea (Cajanus cajan (L.) Millspaugh) in response to Zn and Ni stresses. Plant Sci. 157: 113–128.

Raviraja, A., G. Babu, N. V., Bijoor, A. R., Menezes, G and Venkatesh, T. 2008. Lead toxicity in a family as a result of occupational exposure. Arh. Ind. Hig. Toxicol. 59: 127–33.

Rensing, C., Mitra, B and Rosen, B. P. 1997. Insertional inactivation of dsbA produces sensitivity to cadmium and zinc in *Escherichia coli*. J. Bacteriol. 179: 2769-2771.

Rensing, C., Sun, Y., Mitra, B and Rosen B. P. 1998. Pb(II)-translocating P-type ATPases. J. Biol. Chem. 273(32): 614-617.

Roane, T. M. 1999. Lead resistance in two bacterial isolates from heavy metal contaminated soils. Microb. Ecol. 37: 218-24.

Roane, T. M., Josephson, K. L and Pepper, I. L. 2001. Dual Bioaugmentation strategy to enhance remediation of co contaminated soil. Appl. Environ. Microbiol. 67: 3208-3215.

Rohwerder, T., Gehrke, T., Kinzler, K and Sand, W. 2003. Bioleaching review part A: Progress in bioleaching: fundamentals and mechanisms of bacterial metal sulfide oxidation. Appl. Microbiol. Biotechnol. 63: 239-248.

Ruiz, O. N., Alvarez, D., Ruiz, G. G and Torres, C. 2011. Characterization of mercury bioremediation by transgenic bacteria expressing metallothionein and polyphosphate kinase, BMC Biotechnol. 11: 82.

Siddiquee, S., Rovina, K., Azad, S.A., Nahe , L., Suryani, S., and Chaikaew, P. (2015). Heavy metal contaminants removal from wastewater using the potential filamentous fungi biomass: A review. J. Microb. Biochem. Technol. 7(6), 384–395.

Saier, M. H. J. 1994. Computer-aided analyses of transport protein sequences: gleaning evidence concerning function, structure, biogenesis, and evolution. Microbiol. Rev. 58: 71-93.

Salem, H. M., Eweida, E. A and Farag, A. 2000. Heavy metals in drinking water and their environmental impact on human health In: International Center for Economics Humanity and

Medicine, Cairo University, Giza, Egypt. 542–556.

Salt, D. E., Smith, R. D and Raskin, I. 1998. Phytoremediation. Annual Reviews in Plant. Physiol. Plant Mole.Biol. 49: 643-668.

Samanta, A., Bera, P., Khatun, M., Sinha, C., Pal, P., Lalee, A and Mandal, A. 2012. An investigation on heavy metal tolerance and antibiotic resistance properties of bacterial strain Bacillus sp. isolated from municipal waste. J. Microbiol. Biotechnol. 2(1): 178 -189.

Savolainen, H. 1996. Biochemical and clinical aspects of nickel toxicity. Environ. Health. Rev. 11: 167-173.

Scheuhammer, A. M. 1987. The chronic toxicity of aluminium, cadmium, mercury and lead in birds: a review. Environ. Pollut. 46: 263–295.

Schmidt, T and Schlegel, H. G. 1994. Combined nickel-cobalt-cadmium resistance encoded by the ncc locus of Alcaligenes xylosoxidans. Am. J. Bacteriol. 176: 7045-7054.

Sell, J. L. 1975. Cadmium in the laying hen: apparent absorption, tissue distribution and virtual absence of transfer into eggs. Poult. Sci. J. 54: 1674–1678.

Selvi, A. T., Anjugam, E., Devi, R. A., Madhan, B., Kannappan, S. and Chandrasekaran, B.2012. Isolation and characterization of bacteria from tannery effluent treatment plant and their tolerance to heavy metals and antibiotics. Asian J. Exp. Biol. Sci. 3(1): 34-41.

Sengil, I. A. and Ozacar, M. 2009. Competitive biosorption of Pb^{2+}, Cu^{2+} and Zn^{2+} ions from aqueous solutions onto valonia tannin resin. J. Hazard. Matter. 166 (2-3): 1488-94.

Seth, C. S., Chaturvedi, P. K and Misra, V. 2008. The role of phytochelatins and antioxidants in tolerance to Cd accumulation in *Brassica juncea* L. Ecotoxicol. Environ. Saf. 71: 76–85.

Sevgi, E., Coral, G., Gizir, A. M and Sangün, M. K. 2010. Investigation of heavy metal resistance in some bacterial strains isolated from industrial soils. Turk. J. Biol. 34: 423-431.

Shen, H., and Wang, Y. 1993. Characterization of enzymatic reduction of hexavalent chromium by Escherichia coli ATCC 33456. Appl. Environ Microbiol. 59: 3171-3777.

Siddiqui, M. K. J., Singh, J. S., Mehrotra, P. K., Singh, K and Sarangi, R. 2006. Comparison of some trace elements in blood, tumor free and tumor tissues of women, Environ. Int. 32: 630.

Silver, S. 1996. Bacterial resistances to toxic metal ions- a review. Gene 179: 9-19.

Silver, S and Walderhaug, M. 1995. Bacterial plasmid-mediated resistances to mercury, cadmium and copper. In: Toxicology of Metals, ed. R.A. Goyer, and M. G. Cherian, 435-458, Berlin: Springer- Verlag.

Silver, S., Misra, T. K and Laddaga, R. A. 1989. DNA sequence analysis of bacterial toxic heavy metal resistances. Biol. Trace Elem. Res. 21: 145-163.

Silverberg, B. A., Wong, P. T and. Chau, Y. K. 1976. Ultrastructural examination of Aeromonas cultured in the presence of organic lead. Appl. Environ. Microbiol. 32: 723–725.

Singh, V., Chauhan, P. K., Kanta, R., Dhewa, T and Kumar, V. 2010. Isolation and characterization of Pseudomonas resistant to heavy metals contaminants. Int. J. Pharm. Sci. Rev. Res. 3: 164–167.

Smith, L. A., Means, J. L and Chen, A. 1995. Remedial Options for Metals-

Contaminated Sites, Boca Raton USA: Lewis Publishers.
Smrithi, A and Usha. K. 2012. Isolation and characterization of chromium removing bacteria from tannery effluent Disposal site. Intern. J. Adv. Biotechnol. Res. 3: 644-652.
Soares, C. R. F. S., Grazziotti, P. H., Siqueira, J. O., Carvalho, J. G. D and Moreira, F. M. S. 2001. Zinc toxicity on growth and nutrition of Eucalyptus maculata and Eucalyptus urophylla in nutrient solution. Pesquisa Agropecuaria Brasileria 36(2): 339-348.
Sparks, D. L. 2005. Toxic metals in the environment: the role of surfaces. Elements 1: 193–197.
Spatel, J., Cpatel, P and Kalia, K. 2006. Isolation and characterization of Nickel Uptake by Nickel Resistant Bacterial Isolate (NiRBI). Biomed. Environ. Sci. .19: 297–301.
Stohs, S. J and Bagchi, D. 1995. Oxidative mechanisms in the toxicity of metal-ions. Free Radic. Biol. Med. 18: 321-36.
Taleb, S. M and Ghinani, T.T. 2008. Level of PM10 and its chemical composition in atmosphere of city of Isfahan. Iran. J. Chem. Chem. Eng. 4(3): 62-67.
Talos, K., Pager, C., Tonk, S., Majdik, C., Kocsis, B., Kilar, F and Pernyeszi, T. 2009. Cadmium biosorption on native Saccharomyces cerevisiae cells in aqueous suspension. Acta Univ. Sapientiae, Agric. Environ. 2009(1): 20–30
Tamaki, S and Frankenberger, Jr. W. T. 1992. Environmental biochemistry of arsenic. Reviews of Environmental Contamination and Toxicology 124: 9-110.
Thacker, U., Parikh, R., Shouche, Y and Madamwar, D. 2006. Hexavalent Chromium Reduction by Providencia sp. Process Biochemistry 41: 1332–1337.
Thacker, U., Parikh, R., Shouche, Y and D. Madamwar. 2007. Reduction of chromate by cell-free extract of Brucella sp. isolated from Cr (VI) contaminated sites. Biores.Technol. 98: 1541-1547.
Thauer, R. K., Diekert, G and Schoènheit, P. 1980. Biological role of nickel. Trends in Biochemical Sciences 5: 304-306.
Toppi, L. S. D and Gabbrielli R. 1999. Responses to cadmium in higher plants. Environmental and Exp. Bot. 41: 105-130.
Turner, J. S., Morby, A. P., Whitton, B. A., Gupta, A and N. J. Robinson. 1993. Construction of Zn^{2+}/Cd^{2+} hypersensitive cyanobacterial mutants lacking a functional metallothionein locus. Journal of Biol. Chem. 268: 4494-8.
Umrania, V. V. 2006. Bioremediation of toxic heavy metals using acidothermophilic autotrophies. Biores. Technol. 97: 1237–1242
United States Environment Protection Agency USEPA 1979. National ambient quality standards for particulate matter, federal registery, 62 (2): 138.
United States Environmental Protection Agency USEPA. 1999. Integrated Risk Information System (IRIS) on Nickel, Soluble Salts. National Center for Environmental Assessment, Office of Research and Development, Washington, DC.
Vangronsveld, J and Clijsters, H. 1994. Toxic effects of metals. In: Plants and the chemical elements, ed. M. G. Farago, V. Weinheim, 149, Germany.
Vanita, C., Piar, C., Avinash, N., Kaur, K. J and Yogesh, P. 2014. Evaluation of

Heavy Metals Contamination and its Genotoxicity in Agricultural Soil of Amritsar, Punjab, India. Int. j. res. chem. environ. 4(4): 20-28.

Vidali, M. 2001. Bioremediation an Overview. Pure Appl. Chem. 73: 1163-1172.

Walton, A., Ebdon, L and Millward G. 1988. Methylation of inorganic lead by Tamyar Estuary (UK) sediments. Appl. Organomet. Chem. 2: 87–93.

Wang, G. Q., Huang, Y. Z.,. Xiao, B. Y., Qian, X. C., Yao, H., Hu, Y., Gu, Y. L., Zhang, C and Liu, K. T. 1997. Toxicity from water containing arsenic and fluoride in Xinjiang. Fluoride 30: 81–84.

Wang, J and C. Chen. 2006. Biosorption of heavy metals by Saccharomyces cerevisiae. Biotechnol. Adv. 24: 427–451.

Wang, S., Zhang, D and Pan X. 2012. Effects of arsenic on growth and photosystem II (PSII) activity of *Microcystis aeruginosa*. Ecotoxicol. Environ. Saf. 84: 104–111.

Weiss, L and Wright. S. 2001. Mercury on the road to zero. Recommended strategies to eliminate mercury releases from human activities in Oregon by 2020. Oregon Environmental Council & the Mercury Solution Team, Oregon.

Wenzel, W. W. 2003. Chelate-assisted phytoextraction using canola (Brassica napus L) in outdoors pot and lysismeter experiments. Plant Soil 249: 83–96.

White, C., Sayer, J. A and Gadd, G. M. 1997. Microbial solubilization and immobilization of toxic metals: key biogeochemical process for treatment of contamination. FEMS Microbiol. Rev. 20: 503-516.

World Health Organization (WHO). 2006. Air quality guidelines for particulate matter, Ozone, nitrogen dioxide and sulfur dioxide, Global update 2005, Geneva, Switzerland.

Wu, S. 1994. Effect of manganese excess on the soybean plant cultivated under various growth conditions. J. Plant Nutr. 17: 993-1003.

Xiong, Z. T and Lu, P.2002. Joint enhancement of lead accumulation in Brassica plants by EDTA and ammonium sulfate in sand culture. J. Environ. Sci. 14: 216.

Yachandra, V. K., DeRose, V. J., Latimer, M. J., Mukerji, I., Sauer, K and Klein, M. P. 1993. Where plants make oxygen: a structural model for the photosynthetic oxygen-evolving manganese cluster. Sci. 260: 675-679.

Zhang, M. K., Liu, Z. Y and Wang, H. 2010. Use of single extraction methods to predict bioavailability of heavy metals in polluted soils to rice. Commun. Soil. Sci. Plant. 41(7): 820–831.

Zhu, W., Chai, L., Ma, Z., Wang, Y., Xiao, H and Zhao, K. 2008. Anaerobic reduction of hexavalent chromium by bacterial cells of Achromobacter sp. strain Ch1. Microbiol. Res. 163: 616- 623.