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Application of Innovative Bioremediation Technique Using Bacteria for Sustainable Environmental Restoration of Soils from Heavy Metals Pollution: A Review

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Abstract

Currently, heavy metals pollution has become one of the highly concerned worldwide environmental issues due to their harmful effects. Rapid industrialization, urbanization, and various natural processes have led to the increased release of these toxic heavy metals into the soil and water that causes serious threat to the ecosystem and human health. Hence, there is a greater need for remediation of contaminated soils and water with suitable approaches and mechanisms for sustainable environmental restoration of soils and water from heavy metal pollution. The conventional methods of physical or chemical remediation procedures involve the physical removal of contaminants, and their disposition are expensive, non-specific and often make the soil unsuitable for agriculture and other uses by disturbing the microenvironment. To overcome these problems, there has been increased attention in eco-friendly and sustainable approaches such as bioremediation for the cleanup of contaminated sites. Bioremediation is the use of natural and recombinant microorganisms such as bacteria, fungi, and plants for the cleanup of environmental toxic pollutants. They help in detoxification and degradation of toxic pollutants either through intracellular accumulation or via enzymatic transformation to lesser or completely non-toxic compounds. This review mainly focuses on the bacterial bioremediation for cleaning-up toxic heavy metals from polluted soils.

Keywords: Heavy metals; Pollution; Soil; Bioremediation; Bacteria

Introduction

Heavy metals are defined as the elements with high density greater than 4-5 g/cm^3 and classified as a general group of inorganic hazardous chemicals [1]. They are not essential for growth of microorganisms, animals or plants [2-4] however, they are toxic even at very low concentrations [5-8]. The examples of heavy metals are copper, lead, arsenic, mercury, silver, chromium, and cadmium [9-11]. These heavy metals have high economic significance in industrial use; but they cause pollution in the environment due to the release of industrial wastes. Pollution is defined as the presence of any toxic chemical that cause huge disturbances in the ecological balance and health of living organisms [12].The heavy metals pollution in the environment has become a serious threat to living organisms and ecosystem [2,13-17].It became a great environmental concern because of their bioaccumulation and non-biodegradability in nature [18,19].They pose a danger to humans and the ecosystem by affecting the food chain, drinking water, land usage, and food quality [1]. Due to their non-degradability, heavy metals persist in the soil for a long period of time. They are capable of reducing plant growth due to reduced photosynthetic activities, plant mineral nutrition, and reduced activity of essential enzymes [6,7]. These toxic metals could accumulate in the human body by consumption of food such as leafy vegetables grown in polluted soils or fish or oysters contaminated through the food chain and could lead to health problems including cancer [20,21].

Recently, heavy metals pollution in the soil and water became a worldwide problem, therefore remediation methods are necessary to find a solution for removal of heavy metals to protect the environment and human health [22].Many conventional methods such as physical and chemical techniques are available to remove these heavy metals. The physical remediation techniques include washing of soil, soil extraction, soil solidification, and soil stabilization of heavy metals. Physical methods include migrating contaminated land, disposal in landfills, replacement of soil to replace or partially replace the contaminated soil with clean soil to reduce the concentration of pollutants of the particular area [23,24]. The chemical remediation techniques include vitrify technology, chemical leaching, chemical fixation and electrokinetic technology. The vitrify technology increases the soil temperature at range of 1400-2000°C, to decompose the organic matter [25]. The chemical fixation includes the addition of reagents into the contaminated soil to form slightly insoluble materials, which reduces the movement of heavy metals into water, plants, and other environmental media causing soil remediation [26].The electro kinetic technology involves the application of very high voltage to create electric field gradient at the two poles resulting in movement of charged pollutants to poles through electro-migration, electro osmotic flow, and electrophoresis process [27]. These conventional physical and chemical methods are laborious, time consuming, and not economically viable methods. Most of these techniques are ineffective when the concentrations of heavy metals are less than 100 mg/L or 100 ppm [28]. In addition, salt compounds of most heavy metals are water-soluble and dissolved in wastewater, which means they cannot be separated by physical separation methods [29].

Bioremediation through the living organisms such as microorganisms and plants offer an attractive alternative to physico-chemical methods for removal of heavy metals by changing environmental pollutants into less toxic forms [30]. Hence, remediation by using bacteria is a possible solution for heavy metal pollution since it includes sustainable remediation technologies to remove completely or reduce the heavy metals levels and restore the ecosystem to its original condition of soil. In this review, sources of soil pollution with heavy metals, effects of heavy metals on soil microorganisms, toxic effects of heavy metals on humans, bioremediation of soil using bacteria are mainly discussed.

Sources of Soil Pollution with Heavy Metals

Soil contains heavy metals naturally in the form of rocks. They are also produced as byproducts during industrial processes. Soils are polluted with heavy metals through natural and anthropogenic sources. The natural sources are weathering of minerals, erosion and volcanic activities, forest fires and biogenic source and particles released by vegetation [20] and their concentrations in soils varies according to the nature of the rock, its location and age. Refining and mining of rocks, pesticides, batteries, paper industries, tanneries, fertilizer industries, solid wastes disposal including sewage sludge, wastewater irrigation and vehicular exhaust are the anthropogenic sources of heavy metals pollution in the soil (Figure 1).Mining and manufacturing industries are the main sources of heavy metals that pollute the soil. Due to increased urbanization and industrialization, different kinds of sewage, irrigation, industrial waste, and sludge containing heavy metals are released into the soil [31-38]. Heavy metals are introduced into food chains such as grains and vegetables grown in polluted soils [39].

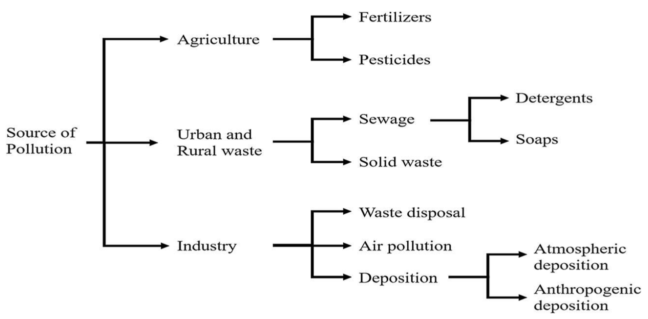

Figure 1: Graphical representation of pollution caused by different sources(Source: [34]).

Effects of Heavy Metals on Soil Microorganisms

Metals without biological function such as lead, mercury are generally toxic even in minute concentrations, whereas essential metals with biological functions such as iron, zinc are usually are toxicin higher concentrations [40]. The heavy metals show toxic effects on microorganisms like bacteria and influence microbial populations and their biological activities in soil which affect soil fertility [41,42]. Bacteria are the first biota that undergoes direct and indirect impacts of heavy metals. Heavy metals cause detrimental effects on microorganisms, and the toxicity depends on the bioavailability of heavy metal and the absorbed dose [2,43]. The toxicity involves several mechanisms via changing the structure and activity of enzymes, production of reactive oxygen species (ROS), destructing ion regulation, and directly affecting the formation of DNA as well as protein [44,45]. Chromium Cr (III) may change the structure and activity of enzymes by reacting with their carboxyl and thiol groups and also interact with negatively charged phosphate groups of DNA, which could affect transcription, replication, and cause mutagenesis [46]. Heavy metals like copper catalyze the production of ROS via Fenton and Haber-Weis reactions and can cause severe injury to cytoplasmic molecules, DNA, lipids, and other proteins [47,48]. Aluminum (Al) can cause DNA damage by stabilizing superoxide radicals [49]. Heavy metals can affect vital enzymatic functions by competitive or noncompetitive interactions with substrates that will cause configurational changes in enzymes and ion imbalance by adhering to the cell surface [44,50]. Cadmium (Cd) and lead (Pb) show deleterious effects on microbes through damaging cell membranes and destroying the structure of DNA by the displacement of metals from their native binding sites or ligand interactions [51]. As a whole, heavy metals affect the morphology, metabolism, and growth of microbes by changing the nucleic acid structure, causing functional disturbance, disrupting cell membranes, inhibiting enzyme activity, and oxidative phosphorylation [52,53]. The effects of all metals on microorganisms are summarized in Table 1 [2].

Arsenic	**Deactivation of enzymes**
Cadmium	Denature protein, destroy nucleic acid, hinder cell division and transcription
Chromium	Growth inhibition, elongation of lag phase, inhibition of oxygen uptake
Copper	Disrupt cellular function, inhibit enzyme activities
Selenium	Inhibits growth rate
Lead	Destroyed nucleic acid and protein, inhibit enzyme actions and transcription
Mercury	Denature protein, inhibit enzyme function, disrupt cell membrane
Nickel	Upset cell membrane, hinder enzyme activities and oxidative stress
Silver	Cell lysis, inhibit cell transduction and growth
Zinc	Death, decrease in biomass, inhibits growth

Table 1: Factors that influence bioremediation of heavy metals (Source: [2]).

Toxic Effects of Heavy Metals on Humans

Heavy metals have ability to accumulate in living tissues and cause adverse health effects in humans [54]. Numerous human health problems are associated with exposure to Pb such as anemia, reproductive failure, impatience, renal failure, and neurodegenerative damage [55]. Lungs, kidney, liver, and skeletal systems are adversely affected by Cd toxicity. Itai-Itai disease manifested by severe bone deformation was thefirst report of Cd toxicity in humans due to consumption of Cd contaminated rice in Japan after the Second World War. Other heavy metals, such as manganese, zinc, and copper, may cause hypophosphatemia, heart disease, liver damage, and sensory disturbance [56]. Excessive human intake of copper may lead to severe mucosal irritation and corrosion, widespread capillary damage, hepatic and renal damage and central nervous system irritation followed by depression. Severe gastrointestinal irritation and possible necrotic changes in the liver and kidney can also occur. The effects of Nickel exposure vary from skin irritation to damage to the lungs, nervous system, and mucous membranes [57]. The toxic effects of all metals on humans are shown in Table 2 [34].

Heavy metals	EPA(regulatory limits ppm)	Toxic effects
Ag	0.1	Exposure may cause skin and other body tissues to turn gray or blue-gray, breathing problems, lung and throat irritation and stomach pain
As	0.1	Affects essential cellular processes such as oxidative phosphorylation and ATP synthesis
Ba	2	Cause cardiac arrhythmias, respiratory failure, gastrointestinal dysfunction, muscle twitching, and elevated blood pressure
Cd	5	Dysfunction, muscle twitching, and elevated blood pressure, carcinogenic, mutagenic, endocrine disruptor, lung damage, and fragile bones, affects calcium regulation in biological systems
Cr	0.1	Hair loss
Cu	1.3	Brain and kidney damage, elevated levels result in liver cirrhosis, and chronic anemia, stomach and intestine irritation
Hg	2	Autoimmune diseases, depression, drowsiness, fatigue, hair loss, insomnia, loss of memory, restlessness, disturbance of vision, tremors, temper outbursts, brain damage, lung and kidney failure
Ni	0.2	Allergic skin diseases such as itching, cancer of the lungs, nose, sinuses, throat through continuous inhalation, immunotoxin, neurotoxic, genotoxic, affects fertility, hair loss
Pb	15	Excess exposure in children causes impaired development, reduced intelligence, short-term memory loss, disabilities in learning and coordination problems, risk of cardiovascular disease
Se	50	Dietary exposure of around 300 μg day^{-1} affects endocrine function, impairment of natural killer cells activity, hepatotoxicity, and gastrointestinal disturbances
Zn	0.5	Dizziness, fatigue etc

Table 2: The toxic effects of some heavy metals on the human health (Source: [34]).

Bioremediation of Heavy Metals in Soil Using Bacteria

Recently, bioremediation using living organisms, an alternative innovative technology to conventional physico-chemical methods for removal and recovery of the heavy metals in polluted water and soils is accepted as the standard practice for the restoration of heavy-metal-contaminated soils. It is an efficient, inexpensive, and eco-friendly technique. It was reported that bioremediation was able to reduce 50%-65% of cost in comparison to the conventional methods such as excavation and landfill [58,59]. It also offers high specificity in the removal of particular heavy metals of interest. In addition, the conventional methods produce significant amounts of toxic sludge and are ineffective when metal concentrations are low [60,61].

The basic principles of bioremediation involve changing pH, the redox reactions and adsorption of pollutants from polluted environment to reduce the solubility of pollutants and convert to less toxic chemicals that are more stable, less mobile or inert [62,63]. The effectiveness of bioremediation depends on several factors such suitability of environmental conditions for their growth and metabolism which include suitable temperature, pH, and moisture and the level of the pollutants in that polluted site [64,65]. Microorganisms such as bacteria and fungus and plants or both are used in bioremediation process [66-70]. It was reported that 51% of the respondents preferred bioremediation using microbes (35%) and plants (16%) in comparison to other methods for treatment of polluted areas [71,72].

Bacteria are the first line of defense against any toxic chemical or heavy metals pollution which have ability to develop various strategies for their survival in heavy metal-polluted habitats [73-76]. They do not degrade the heavy metals but transform these metals by changing their physical and chemical properties. They have evolved various adaptive mechanisms to survive in heavy metal contaminated environments. One of the mechanisms was through the variation of genetic material such as mer operon for mercury tolerance which can be located on plasmid(s), chromosome(s) or may even be a component of transposons [77-79]. Bacterial detoxifying mechanisms are primarily responsible for remediation process. They adopt different detoxifying mechanisms such as biosorption, bioaccumulation, biotransformation and bio-mineralization, and these mechanisms are exploited for bioremediation process. Several reports showed that bacteria have the ability to detoxify sewage sludge, industrial waste, and the remediation of sediments and soils polluted with heavy metals (Table 3) [34,35,80-86]. Many factors influence the bacterial bioremediation in the soil and are shown in Table 4 [2].

Heavy Metals	Microorganisms	References
Pb	*Micrococcus luteus, Bacillus subtilis, B. firmus, B. megaterium, Aspergillus niger, and Penicillium species, Brevibacterium iodinium, Pseudomonas spp., Staphylococcus spp., Streptomyces spp.*	[87-90]
Cd	*Pseudomonas aeruginosa, Alcaligenes faecalis, Bacillus subtilis, B. megaterium*	[88],[89]
Cu	Bacteria: *Staphylococcus sp., Streptomyces sp., Enterobacter cloacae, Desulfovibrio desulfuricans* (immobilize on zeolite), *Flavobacterium spp., Methylobacterium organophilum, Arthrobacter strain, Enterobactercloaceae, Micrococcus sp., Gemella spp., Micrococcus spp., Pseudomonas sp., Flavobacterium spp., A. faecalis (GP06), Pseudomonas aeruginosa (CH07)*	[87], [88],[91-96]

Ni	*Micrococcus sp., Pseudomonas spp., Acinetobacter sp. Desulfovibrio desulfuricans* (immobilize on zeolite)	[87],[97]
Hg	*Klebsiella pneumoniae, Pseudomonas aeruginosa, Vibrio parahaemolyticus (PG02), Bacillus licheni formis, Vibrio fluvialis*	[91],[98],[99]
Cr	*Bacillus cereus, Acinetobacter spp.* and *Arthrobacter sp.*	[88],[100]
Zn	*Bacillus firmus, Pseudomonas spp.*	[87],[101,102]
Co	*Enterobacter cloacae*	[91]

Table 3: List of microorganisms used in biological remediation of soil contaminated with heavy metals.

Factors	**Activities**
Microbial	Production of toxic metabolites Enzymes induction Mutation and horizontal gene transfer Enrichment of capable microbial populations
Substrate	Chemical structure of contaminants Too low concentration of contaminants Toxicity of contaminants Solubility of contaminants
Environmental	Inhibitory Environmental conditions Depletion of preferential substrates Lack of nutrients
Mass transfer limitations	Oxygen diffusion and solubility Solubility/miscibility in/with water Diffusion of nutrients
Growth substrate vs. co-metabolism	Microbial interaction(competition, succession, and predation) Concentration Alternate carbon source present
Biological aerobic vs. anaerobic process	Microbial population present in the site Oxidation/reduction potential Availability of electron acceptors

Table 4: The oxicity of heavy metals to microorganisms.

Bioremediation of soil with bacteria can be in situ or ex situ [81]. *In situ* bioremediation is an onsite clean-up process of polluted environments [82,83]. Ex situ bioremediation involves transfer of polluted soil from its original site to a different location for treatment [68,65]. Recently, a global survey was reported that showed the use of bioremediation technologies for addressing the environmental problems [84]. It mentioned that developed countries made higher use of low-cost in situ bioremediation technologies such as monitored natural attenuation, while their developing counterparts appeared to focus on occasionally more expensive ex situ technologies [84].

Bacterial bioremediation in the soil can be enhanced by biostimulation and bioaugmentation [85].In biostimulation process, the growth conditions of indigenous microorganisms are stimulated by optimizing factors such as nutrients, oxygenation, temperature, pH, possible addition of biosurfactants [85].Using recombinant DNA technology, the indigenous microorganisms are improved to degrade specific contaminants or new recombinant bacteria that have ability to tolerate metal stress by overexpression of metal-chelating proteins and peptides, and ability of metal accumulation are produced [82,83]. In bioaugmentation process, recombinant bacteria having better remediation ability are introduced into the soil. Recombinant Corynebacterium glutamicum that had overexpression of ars operons (ars1 and ars2) was used to decontaminate As-contaminated sites [86].

Conclusion

At high concentrations, heavy metal pollution poses a serious threat to the environment metals and are toxic to human, plants and microorganisms. They could be dispersed in soil and consequently in human beings through food chain biomagnifications that could cause serious health hazards. Microorganisms possess inherent biological mechanisms that enable them to survive under heavy metal stress and remove the metals from the environment. Importance of microorganisms, plants and fungi in bioremediation are immense as they perform multiple functions such as improved soil quality, enhanced plant growth, detoxification, and removal of heavy metal from soil. In the need of an ecologically and economically effective method for environmental remediation, bioremediation shows to be a promising solution, especially on a large scale. However, more information is needed to combat specific organism application.

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References

1. Okieimen FE, Wuana RA (2011) Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecol: 1-20.
2. Igiri B, Okoduwa S, Idoko G, Akabuogu E, Adeyi AO, et al. (2018) Toxicity and bioremediation of heavy metals contaminated ecosystem from tannery wastewater. A review J Toxicol: 1-16.
3. Aroraa R (2014) Adsorption of heavy metals: A review. Materials 18: 4745-4750.
4. Turpeinen R, Kairesalo T, Haggblom M (2002) Microbial activity community structure in arsenic, chromium and copper contaminated soils. J Environ Microbiol 35: 998-1002.
5. Ojuederie O, Babalola O (2017) Microbial and plant-assisted bioremediation of heavy metal polluted environments: A review.Int J Environ Res Public Health 14: 1504.
6. Nematian MA, Kazemeini F (2013) Accumulation of Pb, Zn, C and Fe in plants and hyperaccumulator choice in galali iron mine area, Iran. Int J Agric Crop Sci 5: 426-432.
7. Kabata-Pendias A (2010) Trace elements in soils and plants. CRC Press, New York, USA.
8. Duruibe J, Ogwuegbu M, Egwurugwu J (2007) Heavy metal pollution and human biotoxic effects. Int J Phys Sci 2:112-118.
9. Aziz MA, Ashour A, Madbouly H, Melad AS, El Kerikshi K (2017) Investigations on green preparation of heavy metal saponin complexes. J Water Environ Nanotechnol 2:103-111.
10. Sumiahadi A, Acar R (2018) A review of phytoremediation technology: Heavy metals uptake by plants. Earth EnvSci 142: 12-23.
11. Baker AJM, Brooks RR (1989) Terrestrial higher plants which hyper accumulate metal elements: A review of their distribution, ecology and phyto-chemistry. Bio-recovery 1: 81-126.
12. Jalal U, Aditya SG, Jagdeeshwar J (2017) Soil pollution and soil remediation techniques. Int Journal Adv Res Innov Technol 3: 582-593.
13. Siddiquee S, Rovina K, Azad S (2015) Heavy metal contaminants removal from wastewater using the potential flamentous fungi biomass: A review. J Microbial Biochem Tech 7: 384-393.
14. Su C (2014) A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. Environ Skep Critics 3: 24-38.
15. Hrynkiewicz K, Baum C (2014) Environmental deterioration and human health. Springer, Dordrecht.
16. Deepa NC, Suresha S (2014) Biosorption of lead (II) from aqueous solution and industrial effluent by using leaves of araucaria cookii: Application of response surface methodology. J Environ Sci Toxicol Food Technol 8: 67-79.
17. Okolo VN, Olowolafe EA, Akawu I, Okoduwa SIR (2016) Effects of industrial effluents on soil resource in challawa industrial area. J Global Ecol Environ 5: 1-10.
18. Soni S, Salhotra A, Suar M (2014) Handbook of Research on Diverse Applications of Nanotechnology in Biomedicine, Chemistry, and Engineering.
19. Wai WL, Kyaw NAK, Nway NHN (2012) Biosorption of Lead (Pb2+) by using Chlorella vulgaris. Proceedings of the International Conference on Chemical Engineering and its Applications (ICCEA).
20. Dixit R, Malaviya D, Pandiyan K, Singh U, Sahu A, et al. (2015) Bioremediation of heavy metals from soil and aquatic environment: An overview of principles and criteria of fundamental processes. Sustainability 7: 2189-2212.
21. De Voogt P (2013) Reviews of environmental contamination and toxicology. Spri Inter 237: 1-97.
22. Martin TA, Ruby MV (2004) Review of in situ remediation technologies for lead, zinc, and cadmium in soil. J Envirocle up cos Tech & Tech 14: 35-53.
23. Qian SQ, Liu Z (2000) An overview of development in the soil remediation technologies. Chem Ind Eng Process20: 10-12.
24. Zhang YF, Sheng JC, Lu QY (2004) Review on the soil remediation technologies. Gansu Agri Sci Technol10: 36-38.
25. GoswamiD and Das A K (2000) Removal of arsenic from drinking water using modified fly-ash bed. Inter J Water 1: 61-70.
26. Huang D, Hu C, Zeng G, Cheng M, Xu P, et al. (2016) Combination of Fenton processes and biotreatment for wastewater treatment and soil remediation. Sci Total Environ 574: 1599-1610.
27. Cabrera-Guzmán D, Swartzbaugh TJ , Weisman AW (1990) The use of electrokinetics for hazardous waste site remediation.J Ai Was ManaAsso40: 1670-1676.
28. Ahluwalia SS, Goyal D (2007) Microbial and plant derived biomass for removal of heavy metals from wastewater. Bioresour Technol 98: 2243-2257.
29. Hussein H, Farag S, Moawad H (2004) Isolation and characterization of pseudomonas resistant to heavy metals contaminants. Arab J Biotechnol7: 13-22.
30. KensaMV (2011) Bioremediation -an overview.Indus Pollu Cont 27: 161-168.
31. Niazi NK, Bishop TF, Singh B (2011) Evaluation of spatial variability of soil arsenic adjacent to a disused cattle-dip site, using model-based geostatistics. Environ Sci Tech 45: 10463-10470.
32. Niazi NK, Singh B, Minasny B (2015) Mid-infrared spectroscopy and partial least-squares regression to estimate soil arsenic at a highly variable arsenic-contaminated site. Intern J Envir Sci Technol 12: 1965-1974.
33. Shahid M, Khalid S, Abbas G, Shahid N, Nadeem M, et al. (2015) Crop production and global environmental Issues.
34. Dhaliwal S, Singh J, Taneja P, Mandal A (2020) Remediation techniques for removal of heavy metals from the soil contaminated through different sources: A review. Environ Sci Pollut Res 27: 1319-1333.
35. Chandrasekaran A, Ravisankar R, Harikrishnan N, Satapathy KK, Prasad MVR, et al. (2015) Multivariate statistical analysis of heavy metal concentration in soils of Yelagiri Hills, Tamilnadu, India-spectroscopical approach. Spectrochem Acta Mol Biomol Spectrosc 137: 589-600.
36. Rezania S, Taib SM, Din MFM, Dahalan FA, Kamyab H (2016) Comprehensive review on phyto-technology: heavy metals removal by diverse aquatic plants species from wastewater. J Hazard Mater 318: 587-599.
37. Wan J, Zhang C, Zeng G, Huang D, Hu L, et al. (2016) Synthesis and evaluation of a new class of stabilized nanochlorapatite for pb immobilization in sediment. J Hazard Mater 320: 278-288.
38. Karakagh RM, Chorom M, Motamedi H, Kalkhajeh YK, Oustan S (2012) Biosorption of cd and Ni by inactivated bacteria isolated from agricultural soil treated with sewage sludge. Ecohydrol Hydrobiol 12: 191-198.
39. Peciulyte D, Dirginciute-Volodkiene V (2009) Effect of long-term industrial pollution on soil microorganisms in deciduous forests situated along a pollution gradient next to a fertilizer factory. Abundance of bacteria, actinomycetes and fungia. Ekologija 55: 1
40. Haferburg G, Kothe E (2007) Microbes and metals: Interactions in the environment. Jbasimicrobio 47: 453-467.

41. Bruins MR, Kapil S, Oehme FW (2000) Microbial resistance to metals in the environment. Ecotoxicol Environ Safety 45: 198-207.
42. Minnikova T, Denisova T, Mandzhieva S, Kolesnikov S, Minkina T, et al. (2017) Assessing the effect of heavy metals from the Novocherkassk power station emissions on the biological activity of soils in the adjacent areas. J GeochemExplo 174: 70-78.
43. Rasmussen LD, Sørensen SJ, Turner R, Barkay T (2000) Application of a mer-lux biosensor for estimating bioavailable mercury in soil. Soil BiolBiochem 32: 639-646.
44. Gauthier PT, Norwood P, Prepas EE, Pyle GG (2014) Metal-PAH mixtures in the aquatic environment: A review of co-toxic mechanisms leading to more-than-additive outcomes. Aqua Toxicol 154: 253-269.
45. Hildebrandt U, Regvar M, Bothe H (2007) Arbuscularmycorrhiza and heavy metal tolerance. Phytochem 68: 139-146.
46. Cervantes C, Campos-Garcıa J, Devars S, Gutierrez-Corona F, Loza-Tavera H, et al. (2001) Interactions of chromium with microorganisms and plants. FEMS Microbiol Rev 25: 335-347.
47. Giner-Lamia J, L´opez-Maury L, Florencio FJ, Janssen PJ (2014) Global transcriptional profiles of the copper responses in the cyanobacteriumSynechocystis sp. PCC 6803.
48. Osman D, Cavet JS (2008) Copper homeostasis in bacteria. Adv Applied Microbiol 65: 217-247.
49. Booth SC, Weljie AM, Turner RJ (2015) Metabolomics reveals differences of metal toxicity in cultures of Pseudomonas pseudo alcaligenes KF707 grown on different carbon sources. Frontiers Microbiol 6: 1-17.
50. Chen S, Yin H, Ye J, Peng H, Liu Z, et al. (2014) Influence of co-existed benzopyrene and copper on the cellular characteristics of Stenotrophomonasmaltophilia during biodegradation and transformation. Bioresource Tech 158: 181-187.
51. Olaniran O, Balgobind A, Pillay B (2013) Bioavailability of heavy metals in soil: Impact on microbial biodegradation of organic compounds and possible improvement strategies. Int J Molecular Sci 14: 10197-10228.
52. Fashola MO, Ngole-Jeme VM, Babalola OO (2016) Heavy metal pollution from gold mines: Environmental effects and bacterial strategies for resistance. Int J Environ Res Pub Health 13: 1047.
53. Bissen M, Frimmel FH (2003) Occurrence, toxicity, speciation, mobility. Acta Hydrochimica Hydrobiol 31: 9-18.
54. Ngah WS, Hanafiah MA (2008) Removal of heavy metal ions from wastewater by chemically modified plant wastes as adsorbents: A review. BioresourTechnol 99: 3935-3948.
55. Rai A, Maurya SK, Khare P, Srivastava A, Bandyopadhyay S (2010) Characterization of developmental neurotoxicity of As, Cd, and Pb mixture: Synergistic action of metal mixture in glial and neuronal functions. Toxicol Sci 118: 586-601.
56. Grzegorczyk S, Olszewska M, Alberski J (2014) Accumulation of copper, zinc, manganese and iron by selected species of grassland legumes and herbs. J Elementol 19: 2-8.
57. Argun, ME, Dursun S, Ozdemir C, Karatas M (2007) Heavy metal adsorption by modified oak sawdust: Thermodynamics and kinetics. J Hazard Mat 141: 77-85.
58. Chibuike G, Obiora S (2014) Heavy metal polluted soils: Effect on plants and bioremediation methods. Appl Environ Soil Sci 2014: 1-12.
59. Blaylock MJ, Salt DE, Dushenkov S, Zakharova O, Gussman C, et al (1997) Enhanced accumulation of Pb in Indian mustard by soil-applied chelating agents. Environ Sci Technol 31: 860-865.
60. Ekperusi O, Aigbodion F (2015) Bioremediation of petroleum hydrocarbons from crude oil-contaminated soil with the earthworm: Hyperiodrilusafricanus. Biotech 5: 957-965.
61. Ayangbenro AS, Babalola OO (2017) A new strategy for heavy metal polluted environments: A review of microbial biosorbents. Int J Environ Res Public Health 2017 19:19-94.
62. JainS, Arnepalli D N (2016) Biominerlisation as a remediation technique: A critical review. IGC: 15-17.
63. TandonPK, Singh SB (2016) Redox processes in water remediation. Environ Chem Lett 2016: 199-253.
64. VermaJP, Jaiswal DK (2016) Advances in biodegradation and bioremediation of industrial waste. Front Microbiol 2016: 15.
65. Azubuike CC, Chikere CB, Okpokwasili GC (2016) Bioremediation techniques-classification based on site of application: Principles, advantages, limitations and prosdhapects. World J Microbiol Biotechnol 32: 180.
66. ChangJS, Kim YH, Kim KW (2008) The ars genotype characterization of arsenic-resistant bacteria from arsenic-contaminated gold-silver mines in the republic of korea. Appl Micro Biotech. 80: 155-165.
67. Ashokkumar P, Loashini VM, Bhavya V (2017) Effect of pH, temperature and biomass on biosorption of heavy metals by Sphaerotilusnatans. Int JMM 6: 32-38.
68. Ibeanusi VM, Phinney D, Thompson M (2003) Removal and recovery of metals from a coal pile runoff. Environ Monit Assess 84: 35-44.
69. Fu QY, Li S, Zhu YH (2012) Biosorption of copper (II) from aqueous solution bymycelial pellets of Rhizopusoryzae. Afr J Biotechnol 11: 1403-1411.
70. Mukhopadhyay S, Maiti SK (2010) Phytoremediation of metal mine waste. App Eco Environ 8: 207-222.
71. Environmental Agency (2015) Reporting the Evidence: Dealing with contaminated land in england and wales. A review of progress from 2000-2007 with part 2A of the environmental protection act.EPA,Washington, DC, USA.
72. Ibeanusi V, PathakA, Chauhan A, Hoyle-Gardner J, Cooper T, et al (2018) Genome-centric evaluation of Bacillus sp. Strain. Sig BioengBiosci 2: 157-164.
73. ChauhanA, Pathak A, Jaswal R, Edwards B, Chappell D, et al. (2018) Physiological and comparative genomic analysis of *Arthrobacter sp.* SRS-W-1-2016 provides insights on niche adaptation for survival in uraniferous soils. Genes (Basel) 9 : 31.
74. Agarwal M,Pathak A,Rathore R, Prakash O, Singh R (2018) Proteogenomicanalysis of burkholderia species strains 25 and 46 isolated from uraniferous soils reveals multiple mechanisms to cope with uranium stress. Cells 7 : 269.
75. Agarwal M, Rathore R, JagoeC, Chauhan A (2019) Multiple Lines of Evidences Reveal Mechanisms Underpinning Mercury Resistance and Volatilization by *Stenotrophomonas sp.* MA5 Isolated from the Savannah River Site (SRS). Cells 8: 309.
76. Hamlett NV, Landale EC, Davis BH, Summers AO (1992) Roles of the Tn21 merT, merP, and merC gene products in mercury resistance and mercury binding. J Bacteriol 174: 6377-6385.
77. Liebert CA, Hall RM, Summers AO (1999) Transposon tn21, flagship of the floating genome. Microbiol Mol Biol Rev 63: 507-522.
78. Summers AO, Silver S (1972) Mercury resistance in a plasmid-bearing strain of *Escherichia coli.* J Bacteriol 112: 1228-1236.
79. Bosecker K (1999) Microbial leaching in environmental clean-up programmes. Hydro Metallurgy 9: 533-536.
80. Blackburn JW, Hafker WR (1993) The impact of biochemistry, bioavailability and bioactivity on the selection of bioremediation techniques. Trend biotechnol 11: 328-333.
81. Mani, D, Kumar C (2014) Biotechnological advances in bioremediation of heavy metals contaminated ecosystemibeanusis: An overview with special reference to phytoremediation. Int J Environ SciTechnol 11: 843-872.
82. Rayu S, Karpouzas DG, Singh BK (2012) Emerging technologies in bioremediation: Constraints and opportunities. Biodegrad 23: 917-926.
83. Elekwachi, CO, Andresen, J, Hodgman, TC (2014) Global use of bioremediation technologies for decontamination of ecosystems. J BioremedBiodegrad 5: 1-9.
84. Guarino C, Spada V, Sciarrillo R (2017) Assessment of three approaches of bioremediation (Natural Attenuation, Landfarming and Bioagumentation-AssistitedLandfarming) for a petroleum hydrocarbons contaminated soil.Chemosphere 170: 10-16.
85. Mateos LM, Villadangos AF, de la Rubia AG, Mourenza A, Marcos-Pascual L, et al. (2017) The arsenic detoxification system in

corynebacteria: Basis and application for bioremediation and redox control. Adv App Microbiol 99: 103-137.

86. Kumaran NS, Sundaramanicam A, Bragadeeswaran S (2011) Adsorption studies on heavy metals by isolated cyanobacterial strain (nostoc sp.) from uppanar estuarine water, southeast coast of India. J ApplSci Res 7: 1609-1615.
87. De J, Ramaiah N, Vardanyan L (2008) Detoxification of toxic heavy metals by marine bacteria highly resistant to mercury. Mar Biotechnol 10: 471-477.
88. Puyen ZM, Villagrasa E, Maldonado J, Diestra E, Esteve I, Sole A (2012) Biosorption of lead and copper by heavy-metal tolerant Micrococcus luteus DE2008. BioresourTechnol 126: 233-237.
89. Abioye OP, Oyewole OA, Oyeleke SB, Adeyemi MO, Orukotan AA (2018) Biosorption of lead, chromium and cadmium in tannery effluent using indigenous microorganisms. Brazil J BiolSci 5: 25- 32.
90. Jafari SA, Cheraghi S, Mirbakhsh M, Mirza R, Maryamabadi A (2015) Employing response surface methodology for optimization of mercury bioremediation by Vibrio parahaemolyticus PG02 in coastal sediments of Bushehr, Iran. Clean 43: 118-126.
91. Kim SY, Kim JH, Kim CJ, Oh DK (1996) Metal adsorption of the polysaccharide produced from Methylo bacterium organophilum. Biotechnol Lett 18: 1161-1164.
92. Kim SO, Moon SH, Kim KW (2001) Removal of heavy metals from soils using enhanced electro kinetic soil processing. Water Air Soil Pollut 125: 259-272.
93. Roane TM, Pepper LI (2000) Environmental microbiology. Academic Press, London.
94. Marzan LW, Hossain M, Mina SA, Akter Y, Chowdhury AMMA (2017) Isolation and biochemical characterization of heavy-metal resistant bacteria from tannery effluent in Chittagong city, Bangladesh: Bioremediation viewpoint. Egypt J Aquat Res 43: 65-74.
95. Kumar PA, Loashini VM, Bhavya V (2017) Effect of pH, temperature and biomass on biosorption of heavy metals by Sphaerotilusnatans. Int J Microbiol Mycol 6: 32-38.
96. Congeevaram S, Dhanarani S, Park J, Dexilin M, Thamaraiselvi K (2007) Biosorption of chromium and nickel by heavy metal resistant fungal and bacterial isolates. J Hazard Mater 146: 270-277.
97. Al-Garni SM, Ghanem KM, Ibrahim AS (2010) Biosorption of mercury by capsulated and slime layer forming Gram-ve bacilli from an aqueous solution. Afr J Biotechnol 9: 6413-6421.
98. Saranya K, Sundaramanickam A, Shekhar S, Swaminathan S, Balasubramanian T (2017) Bioremediation of mercury by Vibrio fluvialis screened from industrial effluents. Biomed Res Int: 2017: 1-6.
99. Singh N, Tuhina V, Rajeeva G (2013) Detoxification of hexavalent chromium by an indigenous facultative anaerobic Bacillus cereus strain isolated from tannery effluent. Afr J Biotechnol 12: 1091-1103.
100. Salehizadeh H, Shojaosadati SA (2003) Removal of metal ions from aqueous solution by polysaccharide produced from Bacillus firmus. Water Res 37: 4231-4235.
101. Kim IH, Choi JH, Joo JO, Kim YK, Choi JW, Oh BK (2015) Development of a microbe-zeolite carrier for the effective elimination of heavy metals from seawater. J Microbiol Biotechnol 25: 1542-1546.
102. Muneer B, Iqbal MJ, Shakoori FR, Shakoori AR (2013) Tolerance and biosorption of mercury by microbial consortia: Potential use in bioemediation of wastewater. Pak J Zool 45: 247-254.