

# Microbial Potential in Heavy Metal Remediation a Systematic Approach

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**Abstract:** The increasing population has strengthened the food demand and consequently leading to extensive agricultural practices that contribute to heavy metal contamination. Industrialization, mining, and anthropogenic activities have significantly elevated heavy metal concentrations in terrestrial and aquatic environments. Heavy metals such as cadmium, lead, arsenic, copper, and mercury persist in soils for longer time periods and bio-accumulate through food chain and adversely affecting the crop yield and food quality. Heavy metal contamination also affects the soil microbial communities like diversity, metabolic processes, and biomass production. Several microbial strains, including *Pseudomonas aeruginosa*, *Bacillus amyloliquefaciens*, *Aspergillus niger*, and *Spirulina platensis*, have shown important bioremediation potential. Bioremediation is cost-effective, eco-friendly alternative to traditional remediation practices. However, its efficiency is influenced by environmental factors such as microbial strain specificity, and metal bioavailability. A synergistic approach integrating microbial and phytoremediation strategies may enhance heavy metal detoxification.

**Keywords:** Heavy metal, bioaccumulation, Microbial bioremediation, Toxicity

## 1. INTRODUCTION

The global population is increasing continuously, resulting in a corresponding growth in the demand for food (Yaashikaa and Kumar, 2022). The rapid advancement of the industrial revolution and the wide utilization of natural resources in metal mining and industrial processes have significantly impacted the environment, primarily through the proliferation of heavy metal pollution. Heavy metal contamination represents one of the most critical environmental threats, permeating atmospheric, terrestrial, and aquatic systems and causing widespread ecological and public health concerns (Asha & Sandeep, 2013; Raghunandan et al, 2014; Raghunandan et al, 2018). Heavy metals show the potential for bioaccumulation in humans and animals by migrating from contaminated soil and water into the food chain, thereby posing substantial risks to both ecological integrity and public health (Okereafae., 2020). Worldwide agricultural communities are increasingly

concerned about heavy metal contamination in soils, as these toxic elements, including cadmium, lead, copper, arsenic, and mercury, persist for extended periods. They pass into the soils through organic and inorganic fertilizers or industrial activities near agricultural areas and diminishing both crop yield and food quality (Uchimiya et al., 2020; Guan at al., 2022). This issue arises mostly from the overuse of agricultural inputs such as fertilizers, pesticides, and mulch, which contribute to the accumulation of heavy metals in the soil (Su.,2014).

## 2. CLASSIFYING KEY SOURCES OF HEAVY METAL CONTAMINATION IN THE ENVIRONMENT

Heavy metals are naturally occurring elements in the Earth's crust, formed during the planet's geological processes. However, the significant increase in anthropogenic activity involving heavy metal use has led to a substantial rise in

metallic concentrations within terrestrial and aquatic environments (Gautam et al.,2016). The primary anthropogenic sources of heavy metals include agricultural practices, industrial activities, and urbanization, which contribute significantly to their release and accumulation in various environmental compartments (Li et al, 2016). Volcanic eruptions can exert prolonged detrimental impacts on surrounding ecosystems and communities, particularly in agricultural regions, by depositing ash, releasing toxic gases, and altering soil composition, which can spoil crop productivity(Carrera et al., 2024). Heavy metal contamination primarily stems from anthropogenic activities, including mining, metal smelting, foundries, and other metal-based industries. Additionally, leaching of metals from landfills, waste dumps, livestock and poultry manure, sewage excretion, surface runoff, vehicular emissions, and road construction significantly contributes to environmental pollution. Agricultural practices act as secondary sources, with the application of pesticides, insecticides, fertilizers, and other agrochemicals leading to heavy metal accumulation in soil and water. Natural processes such as volcanic activity, metal corrosion, evaporation from soil and water, sediment resuspension, soil erosion, and geological weathering further exacerbate heavy metal mobilization, impacting ecosystems and human health (Gautam et al.,2016; Masindi and Muedi,2018; Walker et al.,2012; Tchounwou.,

2012; Shallari, 1998; Herawati et al., 2000; He et al., 2005). Heavy metals pose a significant threat to human health and other organisms, even at low concentrations. Once introduced into the human body, these metal ions can interact with and bind to critical biomolecules, including proteins and nucleic acids, disrupting their structural integrity and biological functions. Such interactions can interfere with enzymatic activities, impair cellular processes, and induce oxidative stress, ultimately leading to toxicity and adverse health effects (Ray and Ray,2009).

### 3. HEAVY METAL EFFECT ON MICROBES

Heavy metals present at trace concentrations are regarded as essential micronutrients, playing a critical role in the metabolic processes of living cells and contributing to their nutritional requirements (Leyval et al., 1997). Heavy metals are ubiquitous environmental pollutants. Their toxicity is fundamentally linked to their bioavailability, which refers to the proportion of metal ions that can be absorbed by living organisms. This process is facilitated through mechanisms such as adsorption, biological uptake, migration through environmental matrices, and chemical transformations that influence their mobility and reactivity within biological and ecological systems(Bruins et al.,2000). Study reveals that the production of microbial biomass in heavy metal-contaminated soils is significantly reduced compared to

Metal	Effect on microorganisms	Reference
Zinc	Mortality, biomass reduction, and growth inhibition	Fashola et al.,2016; Dixit et al.,2015.
Arsenic	Enzyme inactivation	Nagajyoti et al.,2010; Salem et al.,2000.
Nickel	Disrupt cell membrane, inhibit enzyme activities, oxidative stress	Fashola et al.,2016; Sebagodi and Babalola,2011; Sankarammal et al,2014.
Copper	Disrupt cellular function, inhibit enzyme activities	Sebagodi and Babalola,2011; Wang et al.,2012;Ali et al., 2013; Prabhu and Poulouse, 2012.
Cadmium	Damage to nucleic acids, protein denaturation, inhibition of cell division and transcription, and suppression of carbon and nitrogen mineralization	Fashola et al.,2016;; Sebagodi and Babalola,2011; Ali et al.,2013;Qian et al 2013; Wuana and Okieimen, 2011.
Mercury	Reduction in population size, protein denaturation, disruption of cell membrane integrity, and inhibition of enzymatic activity	Sebagodi and Babalola, 2011;; Mupa, 2013; Germ et al,2007.
Silver	Cell lysis, inhibition of cell signal transduction, and suppression of growth	Blais et al., 2008; Gordon and Bowser 2003.
Lead	Denaturation of nucleic acids and proteins, inhibition of enzymatic activity, and suppression of transcription	Sebagodi and Babalola,2011; Ali et al.,2013; Mudila et al.,2019; González-Dávila, 1995.
Selenium	Suppresses growth rate	Wang et al., 2012; Romera et al.,2007.
Beryllium	Chromosomal abnormalities and mutations	Kwak et al ., 201et al., 2006.

uncontaminated soils, primarily due to the physiological stress exerted by heavy metal toxicity. Under these adverse environmental conditions, microorganisms allocate more energy toward stress tolerance and survival mechanisms (Gumpu et al., 2015). Metals are fundamental to the physiological processes of microorganisms. Certain metals, such as cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), arsenic (As), nickel (Ni), and zinc (Zn), serve as essential nutrients and are crucial for metabolic functions. Conversely, other metals, including aluminum (Al), cadmium (Cd), gold (Au), lead (Pb), and silver (Ag), have

no known biological role and are considered nonessential (Bissen and Frimmel, 2003).

#### 4. MICROBIAL SOLUTIONS FOR HEAVY METAL REMEDIATION-

Microbial systems, encompassing algae, fungi, and bacteria play a pivotal role in removing heavy metals. These microorganisms exhibit unique metabolic and physicochemical mechanisms, such as biosorption, bioaccumulation, and bioprecipitation, enabling the effective removal of toxic metal ions from aqueous and terrestrial ecosystems (El-Naggar et al., 2018). Description of these are as follows-

Name of Algae	Eliminated Heavy Metal	Mechanism	Reference
<i>Asparagopsis armata</i>	Cadmium, zinc, lead, and nickel	Biosorption	Romera et al., 2007
<i>Spirulina platensis</i>	Chromium	Biosorption	Kwak et al., 2015
<i>Codium vermilara</i>	Lead, nickel, cadmium, and zinc	Biosorption	Romera et al., 2007
<i>Lessonia nigrescens</i>	Ar(V)	Biosorption	Hansen et al., 2006
<i>Gelidium amansii</i>	Lead	Biosorption	El-Naggar et al., 2018

#### 4.1. Algae

Phycoremediation is a complex bioremediation process that operates through a variety of mechanisms, influenced by several factors, including the type of heavy metal (HM) and its chemical speciation, the microalgal strain employed (whether living or non-living), and the prevailing environmental and operational conditions. The efficiency of the process is mostly governed by the bioavailability of the heavy metal, the physiological appearances of the microalgae, and environmental parameters such as pH, temperature, light intensity, and nutrient availability. These factors interact to determine the specific mode of action, which may involve metal adsorption, bioaccumulation, biosorption, extracellular precipitation, or enzymatic transformation. Through these processes,

microalgae enable the effective elimination, immobilization, and detoxification of heavy metals, reducing their environmental impact and enhancing the sustainability of ecosystems (Purchase et al., 2009).

#### 4.2. Fungi

Fungi have a remarkable capacity for the remediation of heavy metal contaminated soils. This capability is primarily attributed to the presence of biopolymers such as chitin, polysaccharides, phosphate groups, and glucuronic acid in their cellular structures, which play a key role in the adsorption and sequestration of heavy metals (Purchase et al., 2009). A research investigation revealed that various fungal strains exhibited a significant influence on the adsorption efficiency of heavy metals ((Iram et al., 2015).

Name of Fungi	Eliminated Heavy Metal	Mechanism	Reference
<i>Aspergillus niger</i>	Copper, lead, and Cr(VI)	Biosorption	Dursun et al., 2003
<i>Ganoderma lucidum</i>	Lead	Biosorption	Chang et al., 2020
<i>Botrytis cinerea</i>	Lead	Biosorption	Akar and Kiran, 2005
<i>Phanerochaete chrysosporium</i> BKMF-1767	Lead	biosorption and bioaccumulation	Huang et al., 2017
<i>Pleurotus platypus</i>	Silver	Biosorption	Das et al., 2010

### 4.3. Bacteria

So far, extensive research has been conducted by many scientists on diverse bacterial species to assess and characterize their potential for

bioremediation applications. Research has proved that numerous bacterial strains possess the capability to mitigate heavy metal toxicity and enhance plant growth in soils contaminated with heavy metals (Seth,2012).

Name of Bacteria	Eliminated Heavy Metal	Mechanism	Reference
<i>Sphingomonas paucimobilis</i>	Chromium	Enzymatic transformation	Ibarrolaza et al., 2011
<i>Enterobacter cloacae</i>	Pb	Biosorption	Kang et al., 2015
<i>Bacillus thuringiensis</i>	Nickel	Immobilization of Ni	Zhu et al., 2016
<i>Pseudomonas aeruginosa</i>	Co,Ni,Cr(III)	Biosorption	Kang et al., 2005
<i>Streptomyces sp. NRC21696</i>	Arsenic	Chelation	AL-Huqail and El-Bondkly, 2022.
<i>Acidithiobacillus</i>	Nickel	Bioleaching	Wu et al., 2020
<i>Bacillus sp. E1S2</i>	Cadmium	IAA production and ACC deaminase synthesis	Ma et al., 2015
<i>Bacillus amyloliquefaciens</i>	Chromium	Biosorption/Bioreduction	Fernández et al.,2018

## 5. MICROBIAL - FACILITATED REMEDIATION MECHANISMS

Bioremediation techniques continue to be observed as the most favourable strategy for environmental remediation, due to their cost-effectiveness, environmental safety, and the diverse mechanisms underlying bioremediation (Abo-Alkasem et al.,2023). The mechanisms of its can be categorized as follows-

### 5.1. Volatilisation

Ramasamy and Banu (2007) reported that process of microbial methylation facilitates the volatilization of metals, playing a key role in metal remediation. E.g., certain species of *Pseudomonas*, *Escherichia*, *Clostridium*, and *Bacillus* are capable of transforming metals such as mercury (Hg II), selenium (Se), arsenic (As), and lead (Pb) into their gaseous methylated forms.

### 5.2. Bioleaching

Microbes play an important part in bioleaching, functioning as reducing agents, and they are also used for the removal and recovery of heavy metals (Wang and Zhao, 2009). In the study of Chanmugathas and Bollag (1988) leaching of cadmium (Cd) is facilitated by the secretion of organic acids by certain microorganisms and in addition, the production of inorganic phosphate by *Citrobacter* species promotes the formation of a metal phosphate coating through precipitation was observed.

### 5.3. Biosorption

During biosorption, microbes depend on their cell structures to trap heavy metal ions, attaching them to specific binding sites on their cell walls (Malik, 2004)). Zhou et al (2012) reported some microbes which are work to produce biosorbents for removing heavy metal e.g., *Chaetomorphalinum*, *Saccharomyces cerevisiae*, *Magnetospirillum gryphiswaldense*, *Bacillus subtilis* and *Rhizopus arrhizus*. Numerous bacterial species, including *Pseudomonas*, *Enterobacter*, *Bacillus*, and *Micrococcus* display notable metal adsorption abilities. This can be recognized to their high surface-to-volume ratios and the presence of various active chemisorption sites, such as teichoic acids on their cell membranes. These structural characteristics enhance their capacity to efficiently bind and concentrate heavy metals, increasing their potential for environmental remediation(Mosa et al.,2016). Yeasts and molds are not only easy to grow but can also be adjusted in ways that make them even more beneficial. They produce a lot of biomass, which makes them efficient for various applications. One of their key roles is helping clean up polluted wastewater by removing toxic metals. Their ability to absorb and recover these metals was also observed in studies(Wang and Chen,2009; Dursun et al.,2003;Akar et al.,2005;Fu et al.,2012). Srivastava et al.,(2015) showed that red, green, and brown algae are commonly used in adsorption and are easily found in marine and

freshwater ecosystems. The ability of algae to absorb and recover cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) from water was assessed (Romera et al., 2007).

#### 5.4. Biotransformation

Microorganisms change toxic metal ions into safer, less harmful forms to the environment and living organisms (Pervaiz et al., 2013). Naturally, metals for e.g., chromium, selenium, uranium, and mercury are usually reduced by changing their oxidation state, making them less harmful. Biotransformation takes advantage of this method, depend on on the redox mechanisms driven by the cellular metabolic activity of microorganisms to convert these metals into safer forms (Abo-Alkasem et al., 2022; Abo-Alkasem et al., 2023; Lloyd et al., 2001; Chang et al., 2001; Brim et al., 2000).

#### 5.5. Biomineralization

Microbes play a vital role in a natural process known as biomineralization, where they produce mineral deposits that trap harmful metals. For this, they produce EPS (Extracellular Polymeric Substances) a group of complex organic compounds, primarily made up of polysaccharides, proteins, and nucleic acids (Qian et al., 2017). Microbes produce siderophores and polysaccharides that fix to heavy metals, thereby reducing the absorption and accumulation of these metals in plants. Additionally, these microbial metabolites trap the metals in the soil, mitigating their toxicity to plants (Tang et al., 2024).

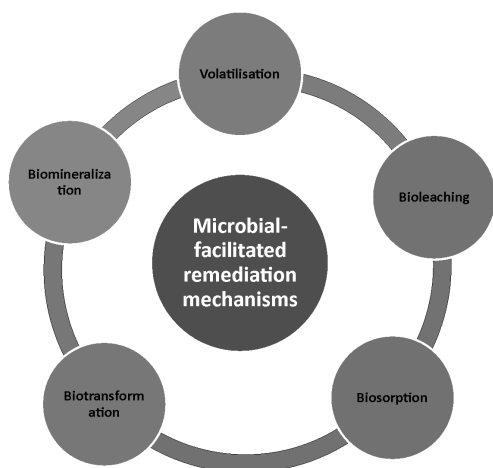


Fig. 1. Showing different types of microbial remediation.

## 6. CONCLUSION

From previous decades, important efforts have been made to challenge the growing issue of heavy metal pollution. While various strategies have been developed, bioremediation remains the most promising solution due to its low cost and environment friendly nature. Advantage of bioremediation make it adaptable to a wide range of conditions and environments and it is safe for the ecosystem. Depend on a single strategy for bioremediation may prove ineffective and inefficient. Therefore, combining microbial and plant-based approaches presents a promising method for remediating contaminated environments. Future research should focus on discovering the possibilities of microbial-based solutions for the effective remediation of heavy metals.

## REFERENCE

- Abo Alkasem, M. I., El-Abd, M. A. E. H., Maany, D. A., & Ibrahim, A. S. S. (2023). Hexavalent Chromium Reduction by a Potent Novel Haloalkaliphilic *Nesterenkonia sp strain NRC-Y* Isolated from Hypersaline Soda Lakes. *Egyptian Journal of Chemistry*, 66(6), 463-473.
- Abo-Alkasem, M. I., Hassan, N. M. H., & Abo Elsoud, M. M. (2023). Microbial bioremediation as a tool for the removal of heavy metals. *Bulletin of the National Research Centre*, 47(1), 31.
- Abo-Alkasem, M. I., Maany, D. A., El-Abd, M. A., & Ibrahim, A. S. (2022). Bioreduction of hexavalent chromium by a novel haloalkaliphilic *Salipaludibacillus agaradhaerens strain NRC-R* isolated from hypersaline soda lakes. *3 Biotech*, 12, 1-15.
- Akar, T.; Tunali, S.; Kiran, I. (2005). *Botrytis cinerea* as a new fungal biosorbent for removal of Pb(II) from aqueous solutions. *Biochem. Eng. J.* 25, 227-235.
- AL-Huqail, A. A., & El-Bondkly, A. (2022). Improvement of *Zea mays L.* growth parameters under chromium and arsenic stress by the heavy metal-resistant *Streptomyces sp. NRC21696*. *Int. J. Environ. Sci.* 19, 5301-5322.
- Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—concepts and applications. *Chemosphere*, 91(7), 869-881.
- Asha, L.P. & Sandeep, R.S. (2013) Review on bioremediation-potential tool for removing environmental pollution. *Int J Basic Appl Chem Sci* 3(3):21-33.

- Bissen, M., & Frimmel, F. H. (2003). Arsenic—a review. Part I: occurrence, toxicity, speciation, mobility. *Acta hydrochimica et hydrobiologica*, 31(1), 9-18.
- Blais, J. F., Djedidi, Z., Cheikh, R. B., Tyagi, R. D., & Mercier, G. (2008). Metals precipitation from effluents. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management*, 12(3), 135-149.
- Brim, H., McFarlan, S. C., Fredrickson, J. K., Minton, K. W., Zhai, M., Wackett, L. P., & Daly, M. J. (2000). Engineering *Deinococcus radiodurans* for metal remediation in radioactive mixed waste environments. *Nature biotechnology*, 18(1), 85-90.
- Bruins, M. R., Kapil, S., & Oehme, F. W. (2000). Microbial resistance to metals in the environment. *Ecotoxicology and environmental safety*, 45(3), 198-207.
- Carrera-Beltrán, L., Gavilanes-Terán, I., Idrovo-Novillo, J., Valverde, V.H., Rodríguez-Pinos, A., Paredes, C., Signes-Pastor, A.J. & Carbonell-Barrachina, Á.A., (2024). Environmental pollution by heavy metals within the area influenced by the Tungurahua volcano eruption—Ecuador. *Ecotoxicology and Environmental Safety*, 270,115919.
- Chang, Y.J., Peacock, A.D., Long, P.E., Stephen, J.R., McKinley, J.P., Macnaughton, S.J., Hussain, A.A., Saxton, A.M. & White, D.C. (2001). Diversity and characterization of sulfate-reducing bacteria in groundwater at a uranium mill tailings site. *Applied and environmental microbiology*, 67(7),3149-3160.
- Chanmugathas, P., & Bollag, J. M. (1988). A column study of the biological mobilization and speciation of cadmium in soil. *Archives of Environmental Contamination and Toxicology*, 17, 229-237.
- Chang, J., Zhang, H., Cheng, H., Yan, Y., Chang, M., Cao, Y., Huang, F., Zhang, G. & Yan, M., (2020). Spent *Ganoderma lucidum* substrate derived biochar as a new bio-adsorbent for Pb<sup>2+</sup>/Cd<sup>2+</sup> removal in water. *Chemosphere*, 241,125121.
- Das, D., Das, N., & Mathew, L. (2010). Kinetics, equilibrium and thermodynamic studies on biosorption of Ag (I) from aqueous solution by macrofungus *Pleurotus platypus*. *J. Hazard.Mater.* 184, 765–774.
- Dursun, A. Y., Uslu, G., Cuci, Y., & Aksu, Z. (2003). Bioaccumulation of copper (II), lead (II) and chromium (VI) by growing *Aspergillus niger*. *Process biochemistry*, 38(12), 1647-1651.
- Dixit, R., Wasiullah, X., Malaviya, D., Pandiyan, K., Singh, U.B., Sahu, A., Shukla, R., Singh, B.P., Rai, J.P., Sharma, P.K. & Lade, H., (2015). Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability*, 7(2),2189-2212.
- El-Naggar, N. E. A., Hamouda, R. A., Mousa, I. E., Abdel-Hamid, M. S., & Rabei, N. H. (2018). Biosorption optimization, characterization, immobilization and application of *Gelidium amansii* biomass for complete Pb<sup>2+</sup> removal from aqueous solutions. *Scientific Reports*, 8(1), 13456.
- Fashola, M. O., Ngole-Jeme, V. M., & Babalola, O. O. (2016). Heavy metal pollution from gold mines: environmental effects and bacterial strategies for resistance. *International journal of environmental research and public health*, 13(11), 1047.
- Fernández, P. M., Viñarta, S. C., Bernal, A. R., Cruz, E. L., & Figueroa, L. I. (2018). Bioremediation strategies for chromium removal: current research, scale-up approach and future perspectives . *Chemosphere* 208, 139–148.
- Fu, Y.Q., Li, S., Zhu, H.Y., Jiang, R., and Yin, L.F.(2012). Biosorption of copper(II) from aqueous solution by mycelial pellets of *Rhizopus oryzae*. *Afr. J. Biotechnol.* 11, 1403–1411.
- Gautam, P. K., Gautam, R. K., Banerjee, S., Chattopadhyaya, M. C., & Pandey, J. D. (2016). Heavy metals in the environment: fate, transport, toxicity and remediation technologies. *Nova Sci Publishers*, 60, 101-130.
- Germ, M., Kreft, I., Stibilj, V., & Urbanc-Berčič, O. (2007). Combined effects of selenium and drought on photosynthesis and mitochondrial respiration in potato. *Plant Physiology and Biochemistry*, 45(2), 162-167.
- González-Dávila, M. (1995). The role of phytoplankton cells on the control of heavy metal concentration in seawater. *Marine Chemistry*, 48(3-4), 215-236.
- Gordon, T., & Bowser, D. (2003). Beryllium: genotoxicity and carcinogenicity. *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis*, 533(1-2), 99-105.
- Guan, Q., Liu, Z., Shao, W., Tian, J., Luo, H., Ni, F., & Shan, Y. (2022). Probabilistic risk assessment of heavy metals in urban farmland soils of a typical oasis city in northwest China. *Science of the Total Environment*, 833, 155096.
- Gumpu, M. B., Sethuraman, S., Krishnan, U. M., & Rayappan, J. B. B. (2015). A review on detection of heavy metal ions in water—an electrochemical approach. *Sensors and actuators B: chemical*, 213, 515-533.
- Hansen, H. K., Ribeiro, A., & Mateus, E. (2006). Biosorption of arsenic (V) with *Lessonia nigrescens*. *Miner. Eng.* 19, 486–490.
- He, Z. L., Yang, X. E., & Stoffella, P. J. (2005). Trace elements in agroecosystems and impacts on the environment. *Journal of Trace elements in Medicine and Biology*, 19(2-3), 125-140.

- Herawati, N., Suzuki, S., Hayashi, K., Rivai, I. F., & Koyama, H. (2000). Cadmium, copper, and zinc levels in rice and soil of Japan, Indonesia, and China by soil type. *Bulletin of Environmental Contamination & Toxicology*, 64(1).
- Huang, C., Lai, C., Xu, P., Zeng, G., Huang, D., Zhang, J., Zhang, C., Cheng, M., Wan, J. & Wang, R. (2017). Lead-induced oxidative stress and antioxidant response provide insight into the tolerance of *Phanerochaete chrysosporium* to lead exposure. *Chemosphere*, 187, 70-77.
- Ibarrolaza, A., Coppotelli, B. M., Del Panno, M. T., Donati, E. R., & Morelli, I. S. (2011). Application of the knowledge-based approach to strain selection for a bioaugmentation process of phenanthrene- and Cr (VI)-contaminated soil. *J. Appl. Microbiol.* 111, 26-35.
- Iram, S., Shabbir, R., Zafar, H., & Javaid, M. (2015). Biosorption and bioaccumulation of copper and lead by heavy metal-resistant fungal isolates. *Arabian Journal for Science and Engineering*, 40, 1867-1873.
- Kang, C. H., Oh, S. J., Shin, Y., Han, S. H., Nam, I. H., & So, J. S. (2015). Bioremediation of lead by ureolytic bacteria isolated from soil at abandoned metal mines in South Korea. *Ecological Engineering*, 74, 402-407.
- Kang, S. Y., Lee, J. U., & Kim, K. W. (2005). Metal removal from wastewater by bacterial sorption: Kinetics and competition studies. *Environmental technology*, 26(6), 615-624.
- Kwak, H. W., Kim, M. K., Lee, J. Y., Yun, H., Kim, M. H., Park, Y. H., & Lee, K. H. (2015). Preparation of bead-type biosorbent from water-soluble *Spirulina platensis* extracts for chromium (VI) removal. *Algal Research*, 7, 92-99.
- Leyval, C., Turnau, K., & Haselwandter, K. (1997). Effect of heavy metal pollution on mycorrhizal colonization and function: physiological, ecological and applied aspects. *Mycorrhiza*, 7, 139-153.
- Li, J., Shi, Z., Liu, M., Wang, G., Liu, F., & Wang, Y. (2021). Identifying anthropogenic sources of groundwater contamination by natural background levels and stable isotope application in Pinggu basin, China. *Journal of Hydrology*, 596, 126092.
- Lloyd, J. R., Mabbett, A. N., Williams, D. R., & Macaskie, L. E. (2001). Metal reduction by sulphate-reducing bacteria: physiological diversity and metal specificity. *Hydrometallurgy*, 59(2-3), 327-337.
- Malik, A. (2004). Metal bioremediation through growing cells. *Environment international*, 30(2), 261-278.
- Masindi, V., & Muedi, K. L. (2018). Environmental contamination by heavy metals. *Heavy metals*, 10(4), 115-133.
- Ma, Y., Oliveira, R. S., Nai, F., Rajkumar, M., Luo, Y., Rocha, I., & Freitas, H. (2015). The hyperaccumulator *Sedum plumbizincicola* harbors metal-resistant endophytic bacteria that improve its phytoextraction capacity in multi-metal contaminated soil. *Journal of environmental management*, 156, 62-69.
- Mosa, K. A., Saadoun, I., Kumar, K., Helmy, M., & Dhankher, O. P. (2016). Potential biotechnological strategies for the cleanup of heavy metals and metalloids. *Frontiers in plant science*, 7, 303.
- Mudila, H., Prasher, P., Kumar, M., Kapoor, H., Kumar, A., Zaidi, M. G. H., & Verma, A. (2019). An insight into Cadmium poisoning and its removal from aqueous sources by Graphene Adsorbents. *International Journal of Environmental Health Research*, 29(1), 1-21.
- Mupa, M. (2013). Lead content of lichens in metropolitan Harare, Zimbabwe: Air quality and health risk implications.
- Nagajyoti, P. C., Lee, K. D., & Sreekanth, T. V. M. (2010). Heavy metals, occurrence and toxicity for plants: a review. *Environmental chemistry letters*, 8, 199-216.
- Okereafor, U., Makhatha, M., Mekuto, L., Uche-Okereafor, N., Sebola, T., & Mavumengwana, V. (2020). Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *International journal of environmental research and public health*, 17(7), 2204.
- Pervaiz, I., Ahmad, S., Madni, M., Ahmad, H., & Khaliq, F. (2013). Microbial biotransformation: a tool for drug designing. *Appl. Biochem. Microbiol.* 49, 437-450.
- Prabhu, S., & Poulouse, E. K. (2012). Silver nanoparticles: mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. *International nano letters*, 2, 1-10.
- Purchase, D., Scholes, L. N. L., Revitt, D. M., & Shutes, R. B. E. (2009). Effects of temperature on metal tolerance and the accumulation of Zn and Pb by metal-tolerant fungi isolated from urban runoff treatment wetlands. *Journal of Applied Microbiology*, 106(4), 1163-1174.
- Qian, H., Peng, X., Han, X., Ren, J., Sun, L., & Fu, Z. (2013). Comparison of the toxicity of silver nanoparticles and silver ions on the growth of terrestrial plant model *Arabidopsis thaliana*. *Journal of environmental sciences*, 25(9), 1947-1956.
- Qian, X., Fang, C., Huang, M., & Achal, V. (2017). Characterization of fungal-mediated carbonate precipitation in the biomineralization of chromate and lead from an aqueous solution and soil. *Journal of Cleaner Production*, 164, 198-208.

- Raghunandan, K., Kumar, A., Kumar, S., Permaul, K., & Singh, S. (2018). Production of gellan gum, an exopolysaccharide, from biodiesel-derived waste glycerol by *Sphingomonas* spp. *3 Biotech*, 8, 1-13.
- Raghunandan, K., Mchunu, S., Kumar, A., Kumar, K. S., Govender, A., Permaul, K., & Singh, S. (2014). Biodegradation of glycerol using bacterial isolates from soil under aerobic conditions. *Journal of Environmental Science and Health, Part A*, 49(1), 85-92.
- Ramasamy, K., Kamaludeen, & Banu, S. P. (2007). Bioremediation of metals: microbial processes and techniques. *Environmental bioremediation technologies*, 173-187.
- Ray, S., & Ray, M. K. (2009). Bioremediation of heavy metal toxicity-with special reference to chromium. *Al Ameen J Med Sci*, 2(2), 57-63.
- Romera, E., González, F., Ballester, A., Blázquez, M. L., & Muñoz, J. A. (2007). Comparative study of biosorption of heavy metals using different types of algae. *Bioresource technology*, 98(17), 3344-3353.
- Salem, H. M., Eweida, E. A., & Farag, A. (2000, September). Heavy metals in drinking water and their environmental impact on human health. In *Int conference on the environ hazards mitigation, Cairo Univ Egypt*.542-56.
- Sankarammal, M., Thatheyus, A., & Ramya, D. (2014). Bioremoval of cadmium using *Pseudomonas fluorescens*. *Open J. Water Pollut. Treat*, 1, 92-100.
- Sebogodi, K. M., & Babalola, O. O. (2011). Identification of soil bacteria from mining environments in Rustenburg, South Africa. *Life Sci. J*, 8, 25-32.
- Seth, C. S. (2012). A review on mechanisms of plant tolerance and role of transgenic plants in environmental clean-up. *The Botanical Review*, 78(1), 32-62.
- Shallari, S., Schwartz, C., Hasko, A., & Morel, J. L. (1998). Heavy metals in soils and plants of serpentine and industrial sites of Albania. *Science of the total environment*, 209(2-3), 133-142.
- Srivastava, S., Agrawal, S. B., & Mondal, M. K. (2015). A review on progress of heavy metal removal using adsorbents of microbial and plant origin. *Environmental Science and Pollution Research*, 22, 15386-15415.
- Su, C. (2014). A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. *Environmental Skeptics and Critics*, 3(2), 24.
- Tang, H., Xiang, G., Xiao, W., Yang, Z., & Zhao, B. (2024). Microbial mediated remediation of heavy metals toxicity: mechanisms and future prospects. *Frontiers in Plant Science*, 15, 1420408.
- Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Molecular, clinical and environmental toxicology: volume 3: environmental toxicology*, 133-164.
- Uchimiya, M., Bannon, D., Nakanishi, H., McBride, M. B., Williams, M. A., & Yoshihara, T. (2020). Chemical speciation, plant uptake, and toxicity of heavy metals in agricultural soils. *Journal of Agricultural and Food Chemistry*, 68(46), 12856-12869.
- Wang, J., & Chen, C. (2009). Biosorbents for heavy metals removal and their future. *Biotechnology advances*, 27(2), 195-226.
- Wang, J., Feng, X., Anderson, C. W., Xing, Y., & Shang, L. (2012). Remediation of mercury contaminated sites—a review. *Journal of hazardous materials*, 221, 1-18.
- Wang, S., & Zhao, X. (2009). On the potential of biological treatment for arsenic contaminated soils and groundwater. *Journal of environmental Management*, 90(8), 2367-2376.
- Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. *International Scholarly Research Notices*, 2011(1), 402647.
- Wu, C., Jiang, M., Hsieh, L., Cai, Y., Shen, Y., Wang, H., Lin, Q., Shen, C., Hu, B. & Lou, L. (2020). Feasibility of bioleaching of heavy metals from sediment with indigenous bacteria using agricultural sulfur soil conditioners. *Science of the total environment*, 703, 134812.
- Yaashikaa, P. R., & Kumar, P. S. (2022). Bioremediation of hazardous pollutants from agricultural soils: a sustainable approach for waste management towards urban sustainability. *Environmental Pollution*, 312, 120031.
- Zhou, W., Zhang, Y., Ding, X., Liu, Y., Shen, F., Zhang, X., Deng, S., Xiao, H., Yang, G. & Peng, H. (2012). Magnetotactic bacteria: promising biosorbents for heavy metals. *Applied microbiology and biotechnology*, 95,1097-1104.
- Zhu, X., Li, W., Zhan, L., Huang, M., Zhang, Q., & Achal, V. (2016). The large-scale process of microbial carbonate precipitation for nickel remediation from an industrial soil. *Environmental Pollution*, 219, 149-155.