MICROBIAL CONSORTIA AS A STRATEGIC APPROACH FOR SUSTAINABLE REMEDIATION OF HEAVY METAL CONTAMINATED SOILS: A COMPREHENSIVE REVIEW

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Abstract: Contamination with heavy metals in soil has become an increasingly critical problem owing to their inability to degrade, long-lasting impacts on the ecosystem, and possible hazards to human health. Various anthropogenic factors like industrial effluents, mining, and extensive agricultural practices have led to considerable accumulation of hazardous metals in the soil environment. Traditional approaches to soil contamination have been shown to be somewhat effective; however, they suffer from significant shortcomings in terms of their high cost and incompleteness, along with possible negative environmental consequences. Current developments in environmental biotechnology indicate the potential use of microbial communities as an advanced means of soil remediation from heavy metals. Consortia possess superior metabolic diversity, ecological adaptability, and stress resistance compared to individual microorganisms. The present review is focused on elucidating the principles of microbial community interaction, metal detoxification strategies, and their ecological dynamics during heavy metal remediation processes using microorganisms. In addition, novel approaches including bio-enhanced phytoremediation, nanotechnology-enabled bioremediation, and omics-based microbial engineering approaches are considered. In this review paper, a comprehensive evaluation is done on ecological interactions, metal tolerance mechanisms, and microbial interactions involved in the process of consortium-based remediation. Further, emerging methodologies such as microbial engineering using omics technology, nano-bioremediation, and phytoremediation assisted by microorganisms have been carefully analyzed. Finally, the key challenges in practical implementation of the process and possible solutions have been outlined.
***Keywords* - Heavy metals, microbial consortia, soil remediation, environmental biotechnology, biosorption, microbial ecology**

1. INTRODUCTION:

The pollution of soil ecosystems with heavy metals is a serious problem nowadays because of their persistence, high level of toxicity, and tendency to bioaccumulation. Heavy metals like cadmium, lead, chromium, and arsenic may appear in soils owing to industries, mining, and agriculture practices (Nagajyoti et al., 2010). Differing from other pollutants, heavy metals do not undergo decomposition processes and may stay for long in the environment, accumulating in living things and concentrating throughout food chains (Tchounwou et al., 2012; Jaishankar et al., 2014). Heavy metals adversely affect soil properties as well as the microbial populations necessary for nutrients' transformation. In addition, these metals pose serious threats to human health since their entry in crops results in such disorders as nervous system damage, organ injury, and cancer.

In spite of their efficiency, conventional soil pollution remediation techniques, like chemical precipitation, soil washing, and excavation, can be rather expensive and require much time to perform. That is why sustainable ways of soil decontamination are needed, and among eco-friendly options is bioremediation, which utilizes biological means of soil purification (Vidali, 2001). The use of microbial consortia is particularly attractive because of their mutual beneficial interactions allowing for immobilizing, transforming, or even eliminating heavy metals from polluted soils (Pande et al., 2022).

2. MICROBIAL CONSORTIA: STRUCTURE AND FUNCTION:

Microbial consortia represent a community of organisms involved in complex biochemical processes. Cooperation of metabolism is one feature of microbial communities that allows different types of microorganisms to work together and complete each stage of pollutant biotransformation successively (Little et al., 2008). It means that the functions required for efficient pollution bioremediation can be fulfilled by a microbial community that could not have been achieved by separate strains (Lashani et al., 2023).

Functioning as a whole, microbial consortia prove to be much more robust and stable than single microorganisms due to functional diversity and redundancy. The increased capacity for adaptation in terms of dealing with environmental stresses, such as heavy metal toxicity, while keeping metabolic functions active makes consortia-based systems better than those based on a single culture of microorganisms.

Another advantage of consortia includes the division of work among microbial strains. There are specific microorganisms responsible for bioaccumulation and biosorption of heavy metals, while other bacteria can oxidize or reduce substances, and even contribute to precipitation. Intercellular communication via quorum sensing is also typical of microbial consortia and ensures proper functioning of the bacterial system in polluted areas (Fuqua et al., 1994).

3. INTERACTIONS BETWEEN HEAVY METALS AND SOIL MICROBIOME:

The presence of heavy metals places a high selection pressure on soil microbial communities, leading to changes in microbial diversity and functionality. Microbial populations that are sensitive to the presence of heavy metals are often inhibited, while the resilient populations undergo changes via genetic and biochemical means to resist heavy metals. This adaptation allows microorganisms to persist under conditions where metals are present and still carry out vital metabolic processes.

There are several strategies employed by microorganisms to overcome the toxic effects of heavy metals, such as efflux pumps, intracellular accumulation, binding to external surfaces, and enzymatic detoxification (Nies, 2003). These adaptations not only allow microorganisms to withstand heavy metals but also help in immobilizing and transforming metals into less available forms in soils (Giller, 2009).

The activities carried out by microorganisms also play an important role in affecting metal behavior, including their mobility and toxicity in soils. Some bacteria, for instance, can transform highly toxic chromium (VI) to chromium (III), which is less harmful (Gadd, 2001).

4. METHODS FOR HEAVY METALS REMOVAL BY MICROBIAL COMMUNITIES:

Several mechanisms for heavy metal detoxification through the actions of microbial communities have been reported. One such mechanism involves biosorption, which is characterized by the binding of metal ions to the functional groups found on the surface of microbial cells (Volesky, 2007). On the other hand, bioaccumulation refers to the process by which metals are absorbed into the microbial cells.

The biotransformation mechanism involves the use of enzymes by the microorganism to transform the chemical nature of the metals, thus making them less toxic. It may be noted that certain microbial communities can convert dangerous forms of mercury to less-toxic forms. (Barkay et al., 2003) Another important mechanism for heavy metal detoxification is biomineralization, which involves the precipitation of the metals in insoluble mineral form. It is evident from the above discussion that the concurrent activities of multiple processes result in effective heavy metal detoxification (Zhang et al., 2023).

5. ANALYTICAL METHOD:

5.1. ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry)

ICP-OES is commonly applied in soil analysis due to its ability to determine several elements, high linearity dynamic range, and sensitivity. In this research work, ICP-OES has been used to measure the levels of heavy metals such as Pb, Cd, Cr, Cu, Zn, Fe, and Mn in soil samples that have been contaminated and have been treated with effective microorganisms. These soil samples were prepared via microwave-assisted acid digestion using HNO_3 and HF, and then analyzed through ICP-OES in accordance with the procedures specified by ISO 22036. ICP-OES with axial plasma detection provides a quick, precise, and affordable technique for analyzing soil, which can be seen from high recoveries attained from certified reference material. The decrease in levels of heavy metals obtained through ICP-OES after the treatment with microorganisms is an indication of the efficiency of these microorganisms in immobilization and/or transformation of heavy metals in reformed soil (Harris et al., 2018).

6. PHYSICOCHEMICAL PARAMETERS:

6.1. Soil pH

Soil pH is the indicator of soil acidity or alkalinity and serves as a vital parameter of soil health because it influences plant growth rates, nutrient levels, and microorganisms' activity. In the case of soils polluted with heavy metals, soil pH becomes especially significant as it directly influences the bioavailability and solubility of metals; under acidic conditions, their concentration is increased leading to enhanced toxicity to soil flora and crops (Dewangan et al., 2023). Soil pH was estimated before and after the introduction of effective microorganisms via creating a solution consisting of soil and water (in the ratio of 1:2.5) and measuring it with the help of a digital pH meter. In terms of soil fertility, it is especially important to prevent aluminium and manganese toxicity as it happens under conditions of low pH values (Mosley et.al., 2024). Thus, a change of soil pH towards neutrality becomes highly beneficial.

6.2. Soil Organic Matter (SOM)

The productivity of soils is largely dependent on the tiny fraction of the total soil mass, which consists of organic matter. Organic matter plays a great role in the physical, chemical, and biological processes taking place in soils (Manahan, 2022). As organic matter serves as an excellent means for immobilizing heavy metal ions in soils, it becomes critical in case of soils contaminated with heavy metals. Soils being highly acidic can utilize their soil organic carbon, mainly humic substances, to detoxify monomeric Al in the soils and immobilize heavy metal contaminants tightly, thus keeping them unavailable to plants' root systems (Gerke, 2022). In this research work, the Walkley-Black wet oxidation technique was applied to evaluate the increase in soil quality after the use of effective microorganisms to quantify the organic matter in the soils. There was observed an increase in organic matter after the use of effective microorganisms, thus demonstrating its importance for increasing organic carbon content in the soil.

6.3. Electrical Conductivity (EC)

Electrical conductivity (EC) is a quantitative index used to evaluate the electrical conductivity of soil water based on the concentrations of dissolved ions, such as anions (SO_4^{2-}, Cl^-, and NO_3^-) and cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+). The assessment of EC is suitable for measuring the efficiency of remediation in soils contaminated with heavy metals since EC takes into account the entire ionic charge load, which includes metal and salt ions dissolved in soil water. To determine if salt ions present in the soil affect crop growth, EC is important in assessing the mineral nutrients available in the topsoil layer. A conductivity meter was utilized in this study to detect the EC value for a 1:2.5 soil-water extract before and after beneficial microorganism treatment. Microbial metabolic activity, which releases mineral ions, could potentially explain the variation in EC following beneficial microorganism treatment, which implies a gradual improvement in the chemical properties of the soil throughout the reclamation period (Omar et al., 2024).

7. ECOLOGICAL BENEFITS OF MICROBIAL CONSORTIA:

Several ecological benefits arise from using microbial consortia instead of pure cultures to clean up contaminated soils. For example, increased metabolic flexibility enables microbial communities to transform various contaminants through complementary reactions. Thus, microbial consortia can work effectively in complex and diverse soils because of their metabolic diversity (Pande et al., 2022). Another

benefit provided by microbial consortia is increased resistance to environmental stresses, including changes in temperatures, pH values, moisture content, and contaminant levels. The coexistence of various species creates a backup, meaning that the death or inhibition of one microorganism cannot adversely impact the system. Besides that, microbial interactions like syntrophism, mutualism, and quorum sensing lead to effective metabolic activities (Fuqua et al., 1994; Little et al., 2008). As a result, microbes can efficiently utilize nutrients, remove toxic substances, and ensure stable growth in contaminated soils.

8. INTEGRATION WITH PLANT-BASED REMEDIATION TECHNIQUES:

The combination of microbial consortia with plant-based remediation methods has proved to be a powerful technique in enhancing heavy metal removal in polluted soils (Priya et al., 2023). In the rhizosphere, there is a mutual interaction between microorganisms and plant roots, forming an environment which is favorable for the growth of plants as well as microbes. Through this interaction, there is an enhancement of nutrients and soil health.

Microbial organisms that are capable of enhancing the growth of plants have been observed in the rhizosphere (Taj & Rajkumar, 2016). The microorganisms have phytohormone production abilities, nutrient solubility characteristics and detoxification abilities that allow the uptake and accumulation of heavy metals by plants without being toxic to them. This helps in the process of bioaccumulation and immobilization of heavy metals.

9. NOVEL TECHNIQUES IN MICROBIAL BIOREMEDIATION:

Modern technological progress has led to an increase in the effectiveness of methods for microbial bioremediation. Combination of nanotechnology and microbial communities allows enhancing the ability of microbes to adsorb metals and catalyzing their transformation (Zhou et al., 2023). Nanomaterials can increase stability of microorganisms and help perform targeted bioremediation in polluted areas.

The use of omics technology, comprising genomics, metagenomics, proteomics, and metabolomics, makes it possible to obtain important information about the structure and functioning of microbial communities (Lashani et al., 2023). This information can be used to identify key microorganisms and metabolic pathways responsible for detoxification of heavy metals, thereby contributing to the creation of effective microbial consortia.

Bioaugmentation and biostimulation are other approaches that can increase the effectiveness of bioremediation. In bioaugmentation, specific microbial consortia are introduced to polluted areas, while in biostimulation, native microorganisms are activated through adding nutrients.

10. CHALLENGES AND CONSTRAINTS:

Although microbial consortia offer significant promise for remediation processes, there are certain constraints that limit the feasibility of their use on a large scale. The variations in environmental parameters such as pH, temperature, moisture, and concentration of contaminants can affect the performance of microorganisms during the process of bio-reclamation. Apart from that, competition between the introduced microbial consortium and indigenous microorganisms poses another challenge to the application of microbial techniques. The unpredictable nature of interactions and relationships of the microbes within the soil ecosystems is also a constraint in microbial remediation (Little et al., 2008; Pande et al., 2022). Moreover, the absence of standard procedures and regulatory limitations restrict the application of microbial consortia on a large scale (Zhou et al., 2023; Vidali, 2001).

311. SOURCES ON HEAVY METAL DEGRADATION:

Lashani et al. (2023) - Use of Microbial Consortia in Bioremediation of Metalloid Polluted Environments

From this study, it is clear that bacteria are significant in dealing with metalloid contaminants due to their resistance through various methods including the presence of specific genes and proteins. Co-contamination has not received much attention due to the fact that most of the earlier research conducted on this has focused mainly on individual metalloids. Moreover, the lack of information available about biofilm-mediated interactions between microorganisms also reflects the importance of understanding microbial interactions in consortia when dealing with environments containing one or more metalloid pollutants.

Pande et al. (2022) - Microbial Interventions in Bioremediation of Heavy Metal Contaminants in Agroecosystem

This review suggests that microbes are a potential and sustainable solution for removing heavy metals from soils in agroecosystems where the effects of quick industrialization and high utilization of chemicals in agriculture have resulted in increased amounts of heavy metals in soils. Biological remediation processes including biosorption, bioaccumulation, biotransformation, and bioleaching play an important role in preventing heavy metal migration to the ecosystem. The study further notes that genetic engineering of microbes and rhizoremediation techniques exhibit superior performance compared to naturally occurring microbes.

Priya et al. (2023) - Clean-Up of Heavy Metals from Contaminated Soil by Phytoremediation: A Multidisciplinary and Eco-Friendly Approach
The review concludes that compared to other traditional methods, phytoremediation is an economic, eco-friendly, and manageable method of removing heavy metals from contaminated soil. The review points out some major processes involved in phytoremediation such as phytoextraction, phytovolatilization, phytostabilization, and rhizofiltration. It also stresses the need for knowing about sources of heavy metals and their effects on human life. Finally, the review states the requirement of integrating both traditional and modern biotechnological tools to make phytoremediation applicable on a larger scale and economically viable.

Zhang et al. (2023) - Heavy Metal Bioremediation Using Microbially Induced Carbonate Precipitation: Key Factors and Enhancement Strategies
MICP can be considered a very effective bioremediation method for fixing heavy metals within the environment based on the study's conclusions. The study emphasizes several methods that will improve the survival rate of the bacteria and the efficiency of MICP under heavy metal contamination conditions, including significant influencing factors such as pH, urease activity, and bacteria tolerance. This paper also discusses technical challenges and future directions for implementing MICP on a large scale in complex environments.

Zhou et al. (2023) - Microbial-Based Heavy Metal Bioremediation: Toxicity and Eco-Friendly Approaches to Heavy Metal Decontamination
Microbial bioremediation serves as a much safer and effective method than conventional methods of removing heavy metals from soil and water. This technique is also environmentally friendly compared to others. Some of the mechanisms that have been discussed in the paper include biosorption, bioaccumulation, redox reactions, biosurfactants and their production, and nanotechnology. Microbial bioremediation through nanoparticles has been pointed out as a field that holds huge promise for the future due to its ability to find novel genes for bioremediation purposes.

CONCLUSION:

The use of microbial consortia for bioremediation of contaminated soils with heavy metals represents a promising and cost-effective alternative remediation process that leverages microbial interactions, enabling detoxification via several mechanisms simultaneously. Technological progress within biotechnology and omics techniques is likely to contribute to improvements in the efficacy of microbial consortia. Further work in this area should be directed towards optimizing microbial interactions, improving their performance in the field, and incorporating cutting-edge technologies.

REFERENCES

[1] Barkay, T., Miller, S. M., & Summers, A. O. (2003). Bacterial mercury resistance from atoms to ecosystems. *FEMS microbiology reviews*, *27*(2-3), 355-384.

[2] Dewangan, S. K., Shrivastava, S., Kumari, L., Minj, P., Kumari, J., & Sahu, R. (2023). The effects of soil ph on soil health and environmental sustainability: A review. *Journal of Emerging Technologies and Innovative Research*, *10*(6), 611-616.

[3] Fuqua, W. C., Winans, S. C., & Greenberg, E. P. (1994). Quorum sensing in bacteria: the LuxR-LuxI family of cell density-responsive transcriptional regulators. *Journal of bacteriology*, *176*(2), 269-275.

[4] Gadd, G. M. (2001). Microbial metal transformations. *Journal of Microbiology*, *39*(2), 83-88.

[5] Gerke, J. (2022). The central role of soil organic matter in soil fertility and carbon storage. *Soil Systems*, *6*(2), 33.

[6] Giller, K. E., Witter, E., & McGrath, S. P. (2009). Heavy metals and soil microbes. *Soil Biology and Biochemistry*, *41*(10), 2031-2037.

[7] Gomez-Eyles, J. L., Sizmur, T., Collins, C. D., & Hodson, M. E. (2011). Effects of biochar and the earthworm Eisenia fetida on the bioavailability of polycyclic aromatic hydrocarbons and potentially toxic elements. *Environmental pollution*, *159*(2), 616-622.

[8] Harris, A., Xanthos, S. J., Galiotos, J. K., & Douvris, C. (2018). Investigation of the metal content of sediments around the historically polluted Potomac River basin in Washington DC, United States by inductively coupled plasma-optical emission spectroscopy (ICP-OES). *Microchemical Journal*, *142*, 140-143.

[9] Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary toxicology*, *7*(2), 60.

[10] Lashani, E., Amoozegar, M. A., Turner, R. J., & Moghimi, H. (2023). Use of microbial consortia in bioremediation of metalloid polluted environments. *Microorganisms*, *11*(4), 891.

[11] Little, A. E., Robinson, C. J., Peterson, S. B., Raffa, K. F., & Handelsman, J. (2008). Rules of engagement: interspecies interactions that regulate microbial communities. *Annu. Rev. Microbiol.*, *62*(1), 375-401.

[12] Manahan, S. E. (2022). *Environmental chemistry*. CRC press.

[13] Mosley, L. M., Rengasamy, P., & Fitzpatrick, R. (2024). Soil pH: Techniques, challenges and insights from a global dataset. *European Journal of Soil Science*, *75*(6), e70021.

[14] Nagajyoti, P. C., Lee, K. D., & Sreekanth, T. V. M. (2010). Heavy metals, occurrence and toxicity for plants: a review. *Environmental chemistry letters*, *8*(3), 199-216.

[15] Nies, D. H. (2003). Efflux-mediated heavy metal resistance in prokaryotes. *FEMS microbiology reviews*, *27*(2-3), 313-339.

[16] Omar, M. D. M., Shitindi, M. J., Massawe, B. H., Pedersen, O., Meliyo, J. L., & Fue, K. G. (2024). Modeling the electrical conductivity relationship between saturated paste extract and 1: 2.5 dilution in different soil textural classes. *Frontiers in Soil Science*, *4*, 1421661.

[17] Pande, V., Pandey, S. C., Sati, D., Bhatt, P., & Samant, M. (2022). Microbial interventions in bioremediation of heavy metal contaminants in agroecosystem. *Frontiers in microbiology*, *13*, 824084.

[18] Priya, A. K., Muruganandam, M., Ali, S. S., & Kornaros, M. (2023). Clean-up of heavy metals from contaminated soil by phytoremediation: A multidisciplinary and eco-friendly approach. *Toxics*, *11*(5), 422.

[19] Taj, Z. Z., & Rajkumar, M. (2016). Perspectives of plant growth-promoting actinomycetes in heavy metal phytoremediation. In *Plant growth promoting actinobacteria: A new avenue for enhancing the productivity and soil fertility of grain legumes* (pp. 213-231). Singapore: Springer Singapore.

[20] 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.

[21] Vidali, M. (2001). Bioremediation. an overview. *Pure and applied chemistry*, *73*(7), 1163-1172.

[22] Volesky, B. (2007). Biosorption and me. *Water research*, *41*(18), 4017-4029.

[23] Zhang, W., Zhang, H., Xu, R., Qin, H., Liu, H., & Zhao, K. (2023). Heavy metal bioremediation using microbially induced carbonate precipitation: Key factors and enhancement strategies. *Frontiers in Microbiology*, *14*, 1116970.

[24] Zhou, B., Zhang, T., & Wang, F. (2023). Microbial-based heavy metal bioremediation: toxicity and eco-friendly approaches to heavy metal decontamination. *Applied Sciences*, *13*(14), 8439.