Harnessing the Power of Rhizosphere Bacteria for Pollution Remediation: Strategies, Mechanisms, and Environmental Impact: A Minireview

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ABSTRACT

This present review provides an in-depth exploration of the burgeoning potential of rhizosphere bacteria as a formidable tool for pollution remediation within the context of contemporary scientific understanding. The rhizosphere, a soil region intimately associated with plant roots, encompasses a dynamic and diverse bacterial community renowned for its distinctive capabilities in mitigating a wide spectrum of environmental pollutants. This article seeks to unravel the intricate strategies and mechanisms that underpin the pollution remediation abilities of rhizosphere bacteria, as well as to contemplate the prospective environmental impacts arising from their application. Rhizosphere bacteria are pivotal players in phytoremediation, a green and sustainable approach to addressing environmental contamination. Their exceptional abilities span a range of functions, including the enhancement of plant growth, the suppression of phytopathogens as biocontrol agents, and active involvement in bioremediation processes. These multifaceted roles underscore their significance within the domain of environmental restoration. A fundamental aspect of rhizosphere bacteria's pollution remediation capabilities is their adeptness at accumulating, transforming, and immobilizing contaminants. This proficiency is particularly valuable in the context of phytoremdiation, a process where plants are employed to remediate soil or water contaminated with various pollutants, such as heavy metals and organic compounds. The bacteria residing in the rhizosphere play a critical role in facilitating these processes by influencing the availability and mobility of pollutants in the soil. However, fully harnessing the potential of rhizosphere bacteria for pollution remediation demands a profound understanding of specific bacterial strains and the underlying molecular mechanisms governing their actions. Researchers are continually delving into the genomics and proteomics of these microorganisms to unlock the secrets behind their pollution mitigation prowess. Moreover, collaboration and interdisciplinary exploration are crucial in unraveling the complete potential of rhizosphere bacteria in pollution remediation, considering the complex interplay of plants, microbes, and the environment. Exciting avenues of investigation include the elucidation of bioremediation mechanisms, the manipulation of the rhizosphere microbiome, and the intricate interactions between plants and bacteria. Unveiling these mechanisms can lead to more effective and sustainable pollution remediation strategies. A comprehensive understanding of the diversity and abundance of rhizosphere bacterial communities is central to the triumph of phytoremediation endeavors. The composition of these communities can vary significantly depending on the plant species and environmental conditions.

Gaining insight into this diversity is essential for tailoring phytoremediation approaches to specific pollution scenarios and optimizing their efficiency. As we look ahead, the potential of rhizosphere bacteria offers a promising route toward a cleaner and more sustainable future. Their diverse mechanisms, proficiency in heavy metal remediation, and environmentally conscious approach position them as invaluable partners in pollution mitigation. With a growing interest in this field and the strides being made in research, optimism for the future of pollution remediation is well-founded. Harnessing the intricate and powerful capabilities of rhizosphere bacteria promises to significantly contribute to environmental restoration efforts in an ever-changing world.

KEYWORDS: Rhizosphere bacteria, Remediation, Pollution, Environmental impact

INTRODUCTION

Pollution is defined as the prelude of dangerous substances into the environment which can be natural or created by human activity (1). Some of the environmental implications of pollution are Air, Water, and Land Pollution. Air pollution can have severe consequences for all environmental components, including groundwater, soil, and air (2). It can also impact soil and water quality by contaminating precipitation and dropping into water and soil ecosystems. Long-term air pollution exposure can lead to cancer and damage to the immunological, neurological, reproductive, and respiratory systems (3). Water pollution can occur when pollutants such as chemicals, waste products, and untreated sewage are released into water bodies. Land pollution can occur when hazardous waste is not properly disposed of, or when chemicals from pesticides and fertilizers seep into the soil. This can harm plants and animals, and make soil unsuitable for agriculture. Pollution can also have economic and social implications. It has the potential to stifle economic progress, aggravate poverty and inequality in both urban and rural regions, and contribute considerably to climate change (4). Therefore, it is important to take measures to reduce pollution and protect the environment.

The rhizosphere is the soil zone that surrounds and influences plant roots. Rhizosphere bacteria are microorganisms that inhabit this area and play important roles in plant nutrition, growth promotion, and disease interactions (5). They have also been found to have significance in pollution remediation, particularly in the biodegradation of pollutants in the root zone, a process known as rhizosphere bioremediation (6). Rhizosphere bacteria have methods that enhance plant growth. They can enhance nutrient availability, produce growth-promoting substances, and improve soil structure, leading to healthier and more productive plants. Rhizosphere bacteria can also act as biocontrol agents, helping to control plant pests and diseases. They can produce antimicrobial compounds or compete with harmful microorganisms for resources, thereby protecting plants from pathogens. Rhizosphere bacteria can degrade and detoxify pollutants in contaminated soil. They can utilize pollutants as a carbon source and break them down into less toxic forms through processes such as bioaccumulation, biomineralization, biotransformation, and biosorption. Rhizosphere bacteria have been studied for their role in the remediation of heavy metal-contaminated sites. They can reduce the toxicity of heavy metals in soil and prevent their uptake by plants. These bacteria can also enhance the mobility and bioavailability of heavy metals, making them more accessible for remediation processes. Rhizosphere bacteria offer the potential for sustainable heavy metal detoxification strategies. They can be harnessed to remove heavy metals from polluted areas, providing an environmentally friendly and cost-effective approach to remediation (4).

Rhizosphere bacteria are effective in the biodegradation of various organic and inorganic pollutants. Rhizosphere bacteria can degrade a wide range of organic pollutants, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and petroleum hydrocarbons (7, 8). Petroleum-degrading rhizospheric bacteria, such as *Bacillus thurigiensis*, *Bacillus pumilus*, and *Rhodococcus hoagii*, have been isolated from contaminated soils and have shown potential for bioremediation. Rhizosphere bacteria can also remediate heavy metal-contaminated soils. They can reduce the toxicity of heavy metals and prevent their uptake by plants. Some examples of heavy metals that can be remediated by rhizosphere bacteria include lead, cadmium, and chromium. Rhizosphere bacteria are effective in the degradation of pesticides such as atrazine, chlorpyrifos, and diazinon [7]. Rhizosphere bacteria can also remediate nitrogen compounds such as nitrates and nitrites. They can convert these compounds into less harmful forms, such as nitrogen gas (5).

Overall, rhizosphere bacteria are valuable allies in pollution remediation, offering a natural and efficient means of degrading pollutants and improving soil quality. Their ability to promote plant growth, control pests and diseases, and detoxify contaminants makes them significant players in environmental restoration efforts.

Strategies Utilized by Rhizosphere Bacteria

Rhizosphere bacteria are microorganisms that reside in the rhizosphere, the soil region surrounding plant roots. They have been found to have beneficial effects on plant growth, biocontrol, and bioremediation of contaminated sites. Rhizobacteria have been shown to promote plant growth by various mechanisms, such as phytoaccumulation, phytostabilization, nitrogen fixation, phosphate solubilization, and production of plant growth hormones (9). Phytoaccumulation is a phytoremediation process in which plants absorb pollutants, usually heavy metals, along with other nutrients and water. The contaminant mass is not destroyed but ends up in the plant's roots, stems, and leaves. Phytoaccumulation is regarded as the simplest and cheapest technique of phytoremediation [10]. The process involves the use of native plant species that have the potential to accumulate heavy metals from polluted soils and wastewater effluent (11, 12). The ability of plants to accumulate heavy metals depends on various factors such as the type of plant, the concentration of the contaminant, and the duration of exposure (13). Phytoaccumulation is a promising technique for the remediation of contaminated soils and water bodies. Phytoaccumulation is a helpful phytoremediation process in which plants absorb and store pollutants, typically heavy metals, in their tissues. Metal hyperaccumulator plants and native plants can be used for phytoaccumulation, and the mechanism involves plants absorbing contaminants through their roots and storing them in their tissues. Phytoaccumulation is a type of phytoremediation that can be used in combination with other methods to remove contamination from soil, sediments, and water (14). Rhizodegradation and hemofiltration Rhizodegradation and rhizofiltration are two processes of phytoremediation that involve the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environment. Rhizodegradation is the process by which organic pollutants in the rhizosphere degrade into less harmful chemicals, whereas rhizofiltration is the utilization of plant roots to absorb, concentrate, and precipitate heavy metals from contaminated groundwater. Both processes can be enhanced by using various types of microorganisms (15). Microbial-assisted phytoremediation is a promising approach for the remediation of contaminated environments. It utilizes the synergy between plants and microorganisms to enhance the ability of plants to remove pollutants from the environment. Various types of microorganisms can be used for microbial-assisted phytoremediation, and it offers several benefits over traditional remediation methods. However, there are also challenges associated with the selection and optimization of microorganisms for effective remediation (16).

Plant growth-promoting attributes refer to the characteristics and activities of microorganisms that contribute to the growth and development of plants. These attributes can directly or indirectly enhance plant growth and improve plant health. Some bacteria can fix atmospheric nitrogen into a form that plants can use. This helps to increase the availability of nitrogen, an essential nutrient for plant growth. Certain bacteria can solubilize insoluble forms of phosphorus and potassium in the soil, making these nutrients more accessible to plants. Plant growth-promoting bacteria can produce phytohormones, such as auxins, cytokinins, and gibberellins, which regulate plant growth and development. Siderophores are compounds produced by bacteria that help in the acquisition of iron, an essential micronutrient for plants. Siderophore-producing bacteria can enhance iron uptake by plants (17). Some plant growth-promoting bacteria produce antimicrobial compounds that can inhibit the growth of plant pathogens, protecting plants from diseases. Plant growth-promoting bacteria can produce hydrolytic enzymes, such as cellulases and chitinases, which help in the breakdown of complex organic compounds in the soil, making them available as nutrients for plants. Plant growth-promoting bacteria can stimulate the plant's defense mechanisms, leading to induced systemic resistance against pathogens. This helps in protecting plants from diseases. Some plant growth-promoting bacteria can induce the antioxidative defense system in plants, helping them to cope with oxidative stress and improve their overall health (18).

Mechanisms Underlying Pollution Remediation

Pollution remediation is the elimination or mitigation of pollutants or contaminants from environmental media such as soil, groundwater, sediment, or surface water. Bioremediation is a process of using microorganisms such as bacteria, algae, fungi, and plants to break down, change, remove, immobilize, or sequester pollutants (19). Fungi, for example, can remediate contaminants through a variety of mechanisms such as biotransformation, biosorption, precipitation, and sequestration (20). Plant roots are employed in rhizofiltration to absorb and adsorb contaminants, primarily metals, from contaminated soils and aqueous waste streams. Another strategy is the Chemical oxidation process, which entails excavating the contaminated region into big bermed sections and treating them using chemical oxidation methods. Ex Situ Chemical oxidation has been utilized in the remediation of contaminated soil. If the contamination affects a river or bay bottom, then dredging of bay mud or other silty clays containing contaminants may be conducted.

Surfactant-enhanced aquifer remediation (SEAR) is a process that involves the injection of surfactants and cosolvents into contaminated groundwater to increase the solubility of the contaminants, making them easier to extract. Recent developments in biotechnological tools and molecular "Omic techniques" can improve the effectiveness of myco-remediation in polluted soils and water (21).

Environmental Impact and Sustainability

Environmental impact refers to the effects that human activities have on the environment, including emissions and the use of natural resources (22). Rhizosphere bacteria have the potential to contribute to environmental sustainability. Rhizospheric bacteria can be used for the biodegradation of lignocellulose, which can be used for biofuel production. This can help reduce dependence on fossil fuels and promote sustainable energy production while another way is biofertilization in which rhizosphere bacteria can be used as a soil amendment for plant growth promotion (23). This can help reduce the use of synthetic fertilizers, which can have negative environmental impacts. Rhizosphere bacteria can also be used for bioremediation and biofiltration of pollutants (24). This can help reduce the negative impacts of pollution on the environment and promote sustainability. Manipulating the rhizosphere microbiome can promote sustainable crop production (25). This can help reduce the negative environmental impacts of conventional agriculture practices. Plant leaves and leaf-associated microbes can be used for phytoremediation of air pollutants (26). This can help reduce the negative impacts of air pollution on the environment and promote sustainability. Overall, rhizosphere bacteria have the potential to contribute to environmental sustainability in various ways, including biodegradation of lignocellulose for biofuel production, biofertilization, bioremediation and biofiltration of pollutants, rhizosphere engineering, and phytoremediation of air pollutants. Further research and real-world applications are needed to fully understand the potential of rhizosphere bacteria in promoting environmental sustainability.

Case Studies and Successful Applications

Rhizosphere bacteria can be very helpful in reducing pollution. Changes in the bacterial populations of the rhizosphere during the cleanup of plants that accumulate heavy metals near the Xikuangshan mine in southern China. The study examined the alterations in each plant's bacterial community in the rhizosphere at contaminated sites and discovered that rhizospheric microorganisms play a role in reducing the toxicity of heavy metals in soil, preventing and controlling soil diseases, increasing the effectiveness of root nodulation, and adapting to the harsh environment of mine tailings. In harsh settings, plants' tolerance can be encouraged, which will be beneficial for phytoremediation (27). The rhizosphere provides a range of microhabitats rich in carbon, which can be inhabited by populations of helpful bacteria using such substrates. These bacterial populations can help in the remediation of heavy metals (28). In a nutrient-depleted polluted-rich environment, plants interact with the rhizosphere and root associated with microorganisms to survive in such conditions. The microorganisms in the rhizosphere can help in the remediation of pollutants to enhance remediation of pollutants by microorganisms–plant combination (29). Rhizosphere bacteria can play a significant role in pollution mitigation. They can help in the remediation of heavy metals, pollutants, and air pollution through various mechanisms. Overall, while there is limited research on field trials and real-world applications of pollution mitigation using rhizosphere bacteria, the existing studies suggest that rhizosphere bacteria have the potential to be effective in mitigating pollution. Further research and field trials are needed to fully understand the potential of rhizosphere bacteria in pollution mitigation and to develop practical applications for real-world use.

Challenges and Future Directions

Standardized protocols and monitoring techniques for rhizospheric soil microbes play a vital role in advancing our understanding of their interactions with plants and their contributions to soil health and ecosystem functioning (30). They promote consistency, comparability, and quality in research, enabling meaningful progress in the field (31). Need for standardized protocols and monitoring techniques such as the Cultivation of microbes many rhizosphere engineering strategies require the culturing of microbes to increase the cultivability of microbes present in the rhizosphere. However, it is not clear how these microbes will behave if they are exposed to different environmental conditions (32). The ability to manipulate plant-microbe cooperation is limited by an incomplete knowledge of the specific microbial traits involved in root colonization and nutrient mobilization (33). The effectiveness of rhizosphere bacteria-based strategies can be influenced by environmental factors such as soil type, pH, and moisture content (34). The use of genetically modified organisms (GMOs) in agriculture is subject to regulatory approval in many countries, which can be a significant hurdle to the deployment of rhizosphere bacteria-based strategies (35). The development and deployment of rhizosphere bacteria-based strategies can be expensive, particularly if they involve the use of GMOs or other advanced biotechnologies (36). Scaling up rhizosphere bacteria-based strategies from laboratory experiments to field applications can be challenging, particularly if the strategies involve the use of novel biotechnologies or require significant changes to existing agricultural practices (37).

Integrating rhizosphere bacteria into sustainable pollution management plans can be a promising approach. Rhizosphere bacteria are microorganisms that inhabit the soil surrounding plant roots and play a crucial role in plant growth and nutrient cycling (38). Biodegradation of pollutants: Rhizosphere bacteria can degrade various pollutants, including organic pollutants like polychlorinated biphenyls (PCBs). By harnessing the metabolic capabilities of these bacteria, they can be used to break down and detoxify pollutants in contaminated soils. Rhizosphere bacteria can enhance plant growth and nutrient uptake by promoting nutrient availability and solubilization (38). By incorporating specific strains of bacteria into the rhizosphere, plants can be supported in polluted environments, improving their ability to withstand pollution stress.

Rhizosphere bacteria can enhance plant growth and nutrient uptake by promoting nutrient availability and solubilization (38). By incorporating specific strains of bacteria into the rhizosphere, plants can be supported in polluted environments, improving their ability to withstand pollution stress. Rhizosphere bacteria can work in synergy with plants to remove pollutants from the soil through processes like biofiltration and phytoremediation. Biofiltration involves the use of plants and associated bacteria to filter and degrade pollutants, while phytoremediation involves the use of plants to extract and accumulate pollutants in their tissues, with the help of rhizosphere bacteria (39). Biochar, a type of charcoal produced from organic waste, can be used as a soil amendment to improve soil fertility and pollutant retention. By integrating rhizosphere bacteria with biochar, the remediation potential of both can be enhanced, leading to more effective and sustainable pollution management. The richness and diversity of bacterial communities in the rhizosphere can be influenced by root exudates and various rhizodeposits (40). By promoting a diverse microbial community, the ecosystem resilience and pollutant degradation potential can be improved.

CONCLUSION

In summary, it is imperative to recognize the profound potential that rhizosphere bacteria hold in the domain of pollution remediation. Their multifaceted contributions, encompassing the facilitation of plant growth, their roles as biocontrol agents, and their active participation in bioremediation initiatives, emphasize their pivotal role in addressing environmental contamination. Their remarkable proficiency in the sequestration, transformation, and immobilization of pollutants further underscores their significance within phytoremediation strategies. Nonetheless, the full realization of their capabilities necessitates ongoing investigations into specific bacterial strains, and the underlying molecular mechanisms governing their behavior. Collaboration and in-depth exploration remain critical components in unveiling the complete potential of rhizosphere bacteria for pollution remediation. Promising avenues of research encompass delving into the intricacies of bioremediation mechanisms, the manipulation of the rhizosphere microbiome, and the complex interactions between plants and bacteria. For the success of phytoremediation endeavors, it is paramount to hve a comprehensive understanding of the diversity and abundance of rhizosphere bacterial communities. Looking forward, rhizosphere bacteria present a compelling path toward a cleaner and more sustainable future. Their diverse mechanisms, efficacy in addressing heavy metal pollution, and environmentally conscious approach firmly establish them as indispensable partners in the mitigation of environmental contaminants. Given the growing interest in this field and the substantial progress in research, optimism about the future of pollution remediation is well-justified.

REFERENCES

1 Saeed, Q., Xiukang, W., Haider, F. U., Kučerik, J., Mumtaz, M. Z., Holatko, J., ... & Mustafa, A. (2021). Rhizosphere bacteria in plant growth promotion, biocontrol, and bioremediation of contaminated sites: A comprehensive review of effects and mechanisms. *International Journal of Molecular Sciences, 22*(19), 10529.

2 Guo, D., Fan, Z., Lu, S., Ma, Y., Nie, X., Tong, F., & Peng, X. (2019). Changes in rhizosphere bacterial communities during remediation of heavy metal-accumulating plants around the Xikuangshan mine in southern China. *Scientific reports*, *9*(1), 1947.

3 Mendes, R., Garbeva, P., & Raaijmakers, J. M. (2013). The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS microbiology reviews*, *37*(5), 634-663.

4 Joshi, S., Gangola, S., Bhandari, G., Bhandari, N. S., Nainwal, D., Rani, A., ... & Slama, P. (2023). Rhizospheric bacteria: the key to sustainable heavy metal detoxification strategies. *Frontiers in Microbiology*, *14*.

5 Lynch, James M., Melissa J. Brimecombe, and Frans AAM De Leij. "Rhizosphere." *e LS* (2001).

6 Kaushal, M. (2019). Climatic resilient agriculture for root, tuber, and banana crops using plant growth-promoting microbes. In *Climate Change and Agricultural Ecosystems* (pp. 307-329). Woodhead Publishing.

7 Segura, A., & Ramos, J. L. (2013). Plant–bacteria interactions in the removal of pollutants. *Current opinion in biotechnology*, *24*(3), 467-473.

8 Supreeth, M. (2022). Enhanced remediation of pollutants by microorganisms–plant combination. *International Journal of Environmental Science and Technology*, *19*(5), 4587-4598.

9 Nwachukwu, B. C., Ayangbenro, A. S., & Babalola, O. O. (2021). Elucidating the rhizosphere associated bacteria for environmental sustainability. *Agriculture*, *11*(1), 75.

10 Kamal, M., Ghaly, A. E., Mahmoud, N., & Cote, R. (2004). Phytoaccumulation of heavy metals by aquatic plants. *Environment international*, *29*(8), 1029-1039.

11 Irshad, M., Ahmad, S., Pervez, A., & Inoue, M. (2015). Phytoaccumulation of heavy metals in natural plants thriving on wastewater effluent at Hattar industrial estate, Pakistan. *International journal of phytoremediation*, *17*(2), 154-158.

12 Irshad, M., Ruqia, B., & Hussain, Z. (2015). Phytoaccumulation of heavy metals in natural vegetation at the municipal wastewater site in Abbottabad, Pakistan. *International journal of phytoremediation*, *17*(12), 1269-1273.

13 Kamal, M., Ghaly, A. E., Mahmoud, N., & Cote, R. (2004). Phytoaccumulation of heavy metals by aquatic plants. *Environment international*, *29*(8), 1029-1039.

14 Irshad, M., Ahmad, S., Pervez, A., & Inoue, M. (2015). Phytoaccumulation of heavy metals in natural plants thriving on wastewater effluent at Hattar industrial estate, Pakistan. *International journal of phytoremediation*, *17*(2), 154-158.

15 Kafle, A., Timilsina, A., Gautam, A., Adhikari, K., Bhattarai, A., & Aryal, N. (2022). Phytoremediation: Mechanisms, plant selection and enhancement by natural and synthetic agents. *Environmental Advances*, *8*, 100203.

16 Basit, A., Shah, S. T., Ullah, I., Muntha, S. T., & Mohamed, H. I. (2021). Microbe-assisted phytoremediation of environmental pollutants and energy recycling in sustainable agriculture. *Archives of Microbiology*, 1-27.

17 Kumar, M., Ahmad, S., & Singh, R. P. (2022). Plant growth promoting microbes: Diverse roles for sustainable and ecofriendly agriculture. *Energy Nexus*, 100133.

18 Bhattacharyya, C., Banerjee, S., Acharya, U., Mitra, A., Mallick, I., Haldar, A., ... & Ghosh, A. (2020). Evaluation of plant growth promotion properties and induction of antioxidative defense mechanism by tea rhizobacteria of Darjeeling, India. *Scientific reports*, *10*(1), 15536.

19 Bala, S., Garg, D., Thirumalesh, B. V., Sharma, M., Sridhar, K., Inbaraj, B. S., & Tripathi, M. (2022). Recent strategies for bioremediation of emerging pollutants: a review for a green and sustainable environment. *Toxics*, *10*(8), 484.

20 Kumar, A., Yadav, A. N., Mondal, R., Kour, D., Subrahmanyam, G., Shabnam, A. A., ... & Malyan, S. K. (2021). Myco-remediation: A mechanistic understanding of contaminants alleviation from natural environment and future prospect. *Chemosphere*, *284*, 131325.

21 Alsafran, M., Usman, K., Ahmed, B., Rizwan, M., Saleem, M. H., & Al Jabri, H. (2022). Understanding the phytoremediation mechanisms of potentially toxic elements: A proteomic overview of recent advances. *Frontiers in plant science*, *13*, 881242.

22 Omer, A. M. (2008). Energy, environment and sustainable development. *Renewable and sustainable energy reviews*, *12*(9), 2265-2300.

23 Nwachukwu, B. C., Ayangbenro, A. S., & Babalola, O. O. (2021). Elucidating the rhizosphere associated bacteria for environmental sustainability. *Agriculture*, *11*(1), 75.

24 Joshi, S., Gangola, S., Bhandari, G., Bhandari, N. S., Nainwal, D., Rani, A., ... & Slama, P. (2023). Rhizospheric bacteria: the key to sustainable heavy metal detoxification strategies. *Frontiers in Microbiology*, *14*.

25 Mahmud, K., Missaoui, A., Lee, K., Ghimire, B., Presley, H. W., & Makaju, S. (2021). Rhizosphere microbiome manipulation for sustainable crop production. *Current Plant Biology*, *27*, 100210.

26 Wei, X., Lyu, S., Yu, Y., Wang, Z., Liu, H., Pan, D., & Chen, J. (2017). Phylloremediation of air pollutants: exploiting the potential of plant leaves and leaf-associated microbes. *Frontiers in plant science*, *8*, 1318.

27 Guo, D., Fan, Z., Lu, S., Ma, Y., Nie, X., Tong, F., & Peng, X. (2019). Changes in rhizosphere bacterial communities during remediation of heavy metal-accumulating plants around the Xikuangshan mine in southern China. *Scientific reports*, *9*(1), 1947.

28 Barra Caracciolo, A., & Terenzi, V. (2021). Rhizosphere microbial communities and heavy metals. *Microorganisms*, *9*(7), 1462.

29 Supreeth, M. (2022). Enhanced remediation of pollutants by microorganisms–plant combination. *International Journal of Environmental Science and Technology*, *19*(5), 4587-4598.

30 Barillot, C. D., Sarde, C. O., Bert, V., Tarnaud, E., & Cochet, N. (2013). A standardized method for the sampling of rhizosphere and rhizoplan soil bacteria associated to a herbaceous root system. *Annals of microbiology*, *63*(2), 471-476.

31 Manfredini, A., Malusà, E., Costa, C., Pallottino, F., Mocali, S., Pinzari, F., & Canfora, L. (2021). Current methods, common practices, and perspectives in tracking and monitoring bioinoculants in soil. *Frontiers in Microbiology*, *12*, 698491.

32 Kumar, A., & Dubey, A. (2020). Rhizosphere microbiome: Engineering bacterial competitiveness for enhancing crop production. *Journal of Advanced Research*, *24*, 337-352.

33 Jacoby, R. P., Succurro, A., & Kopriva, S. (2020). Nitrogen substrate utilization in three rhizosphere bacterial strains investigated using proteomics. *Frontiers in Microbiology*, *11*, 784.

34 Basu, A., Prasad, P., Das, S. N., Kalam, S., Sayyed, R. Z., Reddy, M. S., & El Enshasy, H. (2021). Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: recent developments, constraints, and prospects. *Sustainability*, *13*(3), 1140.

35 Tyagi, R., Pradhan, S., Bhattacharjee, A., Dubey, S., & Sharma, S. (2022). Management of abiotic stresses by microbiome-based engineering of the rhizosphere. *Journal of Applied Microbiology*, *133*(2), 254-272.

36 Nadarajah, K., & Abdul Rahman, N. S. N. (2023). The Microbial Connection to Sustainable Agriculture. *Plants*, *12*(12), 2307.

37 Tyagi, R., Pradhan, S., Bhattacharjee, A., Dubey, S., & Sharma, S. (2022). Management of abiotic stresses by microbiome-based engineering of the rhizosphere. *Journal of Applied Microbiology*, *133*(2), 254-272.

38 Suman, J., Rakshit, A., Ogireddy, S. D., Singh, S., Gupta, C., & Chandrakala, J. (2022). Microbiome as a key player in sustainable agriculture and human health. *Frontiers in Soil Science*, *2*, 821589.

39 Mahmud, K., Missaoui, A., Lee, K., Ghimire, B., Presley, H. W., & Makaju, S. (2021). Rhizosphere microbiome manipulation for sustainable crop production. *Current Plant Biology*, *27*, 100210.

40 Nwachukwu, B. C., Ayangbenro, A. S., & Babalola, O. O. (2021). Elucidating the Rhizosphere Associated Bacteria for Environmental Sustainability. Agriculture 2021, 11, 75.