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ROLE OF SOIL MICROBES IN MINERAL TRANSFORMATION FOR PLANT NUTRITION

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ABSTRACT

Modern agriculture faces yield stagnation despite heavy fertilizer use, resulting in soil degradation and environmental harm. A key cause of reduced crop response is that many essential nutrients exist in insoluble or bound mineral forms, limiting plant availability. Microbe–mineral interactions help address this constraint by regulating nutrient transformations in soil. Microbial processes enhance macro- and micronutrient availability in the rhizosphere through mineral dissolution, transformation, and precipitation. Processes such as biological nitrogen fixation, phosphorus solubilisation, potassium mobilisation, and iron chelation improve nutrient uptake and use efficiency. Additionally, these interactions restore soil fertility and support bioremediation via toxic metal immobilization, offering a sustainable pathway to improved productivity and soil health.

KEYWORDS: Biofertilizers, bioremediation, heavy metal detoxification, nutrient transformation, soil-plant-microbes interactions, soil fertility

INTRODUCTION

Minerals are the basic building blocks of the Earth's crust and serve as the primary source of essential nutrients for plant growth. Mineral nutrients are vital for crop growth and productivity, as they regulate numerous physiological and biochemical processes in plants. Macronutrients like nitrogen (N), phosphorus (P) and potassium (K), as well as micronutrients like zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) are essential to many plant metabolic processes (Jabborova et al., 2021). These nutrients are necessary for essential physiological processes in plants, including respiration, photosynthesis, and enzymatic activity, all of which have a direct impact on crop quality, growth, and yield. In modern agriculture, chemical fertilizers are widely used to supply essential nutrients to crops. However, increasing evidence suggests that fertilizer application alone does not guarantee adequate nutrient uptake by plants. In many soils, nutrients remain bound in insoluble mineral complexes, which limit their direct availability to plant roots. Although minerals are abundant in soils, their contribution to plant growth largely depends on biological processes that govern nutrient transformation and release. Soil microorganisms play a crucial role in mobilizing these mineral-bound nutrients and making them available for plant uptake (Dong et al., 2022). Soil microbes enhance nutrient availability through their metabolic activities, including mineral dissolution and transformation processes. Through mineral solubilization, microorganisms convert insoluble mineral forms into bioavailable nutrients that plants can easily absorb (Kapadia et al., 2022). The secretion of organic acids, siderophores, and other chelating compounds further facilitates the solubilization of mineral nutrients and their assimilation by plants (Ribeiro et al., 2020).

It has been demonstrated that overuse of chemical pesticides and fertilisers negatively impacts the environment, microbial diversity, and soil health. As a result, it is becoming more and more important to employ sustainable farming methods that support beneficial microbes as affordable substitutes for agrochemicals. Thus, understanding the microbe–mineral interactions is essential for improving nutrient use efficiency, enhancing crop productivity, and maintaining soil health.

SOIL MINERALS AS NUTRIENT RESERVOIRS IN AGROECOSYSTEMS

Soil acts as the primary reservoir of both macro- and micronutrients essential for crop growth and productivity. Numerous minerals comprising nitrogen (N), potassium (K), phosphorus (P), magnesium (Mg) , calcium (Ca),) Iron (Fe, zinc (Zn), and manganese (Mn) are created in soils through long-term geological processes. These soil minerals are important sources of nutrients for plants and are essential for preserving soil fertility in agroecosystems. Despite their abundance, most soil minerals remain unavailable to plants because nutrients are tightly bound within mineral structures. Phosphorus is commonly fixed with iron or aluminium, while potassium is trapped within silicate minerals such as mica and feldspar. Due to these chemical constraints, even soils with high total nutrient content often fail to supply adequate nutrients to crops, resulting in poor nutrient uptake by plants (Kapadia et al., 2022). Natural mineral weathering is a slow process and, by itself, cannot meet the nutrient demands of modern cropping systems. Microorganisms in the soil are essential for speeding up the release of nutrients and the transformation of minerals. Microbes boost nutrient availability and mineral solubility in the soil solution by secreting organic acids, siderophores, and other metabolites. These soil–plant–microbe interactions significantly improve nutrient cycling, enhance nutrient use efficiency, and support sustainable soil health management in modern agriculture.

MICROBIAL PROCESSES GOVERNING MINERAL TRANSFORMATION

Interactions between microorganisms and soil minerals play a crucial role in driving biological processes and regulating nutrient cycling in soils (Ortiz-Castillo et al., 2021). Microbe–mineral interactions influence the mobility, availability, and transformation of nutrients and metals in agroecosystems. Various microbial processes such as mineral dissolution, precipitation, and transformation alter the chemical form of minerals and control nutrient dynamics in soils. Understanding these microbe-mediated processes is essential for improving soil fertility, nutrient availability, and sustainable agricultural production.

A) MICROBIAL MINERAL DISSOLUTION

The process of interactions between the solid mineral phase and the soil solution that leads to the chemical breakdown of minerals is known as microbial mineral dissolution. Soil microorganisms accelerate the dissolution of solid minerals through various biochemical reactions. This process primarily involves the release of organic acids and chelating compounds by microbes, which weaken chemical bonds within mineral structures and promote nutrient release.

Under iron-limited conditions, siderophore-producing microorganisms increase the availability of iron by forming stable complexes with ferric iron, thereby enhancing its uptake by plants (Ahmed and Holmstrom, 2014). Further encouraging mineral dissolution and nutrient availability in the rhizosphere, several bacteria also convert ferric iron (Fe^{3+}) to the readily soluble ferrous form (Fe^{2+}).

B) MICROBIAL MINERAL PRECIPITATION

By lowering metal toxicity in agricultural soils, microbial mineral precipitation is essential to soil detoxification and bioremediation. Through metabolic processes like oxidation, reduction, and biomineralization, some bacteria convert soluble metals into stable, insoluble mineral forms. By immobilising excess and hazardous metals, this method limits their uptake by plants and stops them from building up in the soil solution. Sulphate-reducing bacteria, which produce sulphide ions as metabolic byproducts, are a typical example. Metal sulphide minerals are created when these sulphide ions react with metals like iron and cadmium (Nnaji et al., 2024). By efficiently transforming soluble hazardous metals into insoluble forms, microbe-mediated mineral precipitation helps to promote soil health and sustainable agricultural management by eliminating them from soil and water systems.

EFFECTS OF MINERAL SOLUBILIZATION ON CROP NUTRITION

Plant–microbe interactions play a significant role in improving crop yield, biomass production, and resilience to both biotic and abiotic stresses. These interactions enhance the availability of essential nutrients to plants, thereby improving crop nutrient status, growth, and overall productivity. Microbe-mediated mineral solubilization is a key process through which nutrients locked in soil minerals are converted into plant-available forms, supporting efficient nutrient uptake and sustainable crop production.

a) **BIOLOGICAL CONVERSION OF ATMOSPHERIC NITROGEN (N_2)**

Nitrogen (N_2) in the atmosphere cannot be directly used by plants. When the nitrogenase enzyme complex is present, nitrogen-fixing microorganisms like Frankia and rhizobacteria transform atmospheric nitrogen into ammonium (NH_4^+). In addition to providing plant-available nitrogen, this biological nitrogen fixation lessens reliance on artificial nitrogen fertilisers and supports environmentally sound agriculture practices.

b) **SOLUBILIZATION OF MINERAL-BOUND PHOSPHORUS**

Phosphorus is a vital nutrient that plants need for different physiological processes, including photosynthesis, ATP generation, and genetic material synthesis. Despite being prevalent in soils, phosphorus is frequently found in less soluble forms like calcium or aluminium phosphates, which restrict its availability to crops. Organic acids like citric, oxalic, and gluconic acids are released by phosphate-solubilizing microbes like Bacillus and Pseudomonas, which dissolve these complexes and increase the amount of phosphorus available to plants (Miliute et al., 2015).

c) **POTASSIUM MOBILIZATION**

In plants, potassium is essential for osmoregulation and stress tolerance. Potassium is mostly found in bonded forms in feldspar, mica, and other silicate minerals in soils, which makes it difficult for plants to absorb (Baba et al., 2021). Potassium-solubilizing fungi like *Aspergillus* and bacteria such as *Bacillus* mobilize potassium through acidification and chelation processes, releasing it into the soil solution for plant absorption.

d) **IRON CHELATION**

Iron is predominantly present in soils as insoluble ferric (Fe^{3+}) compounds, especially under aerobic and alkaline conditions. Rhizobacteria such as *Rhizobium* and *Pseudomonas* produce siderophores that chelate ferric iron and facilitate its conversion into the more soluble ferrous (Fe^{2+}) form. This process enhances iron uptake by plants, prevents iron deficiency symptoms, and can also suppress soil-borne pathogens through competitive iron sequestration.

e) **SOLUBILIZATION OF MICRONUTRIENTS**

Micronutrients such as zinc are often present in insoluble forms in soils, leading to widespread deficiencies in crops. Zinc-solubilizing bacteria, including *Bacillus* and *Pseudomonas*, mobilize micronutrients through acidolysis, organic acid production, and siderophore secretion. These microbial processes enhance the solubilization and availability of micronutrients, supporting enzymatic activity, photosynthesis, and overall crop growth.

CROP RESILIENCE TOWARDS STRESSES

Soil microbial communities play a significant role in enhancing crop resilience against both biotic and abiotic stresses by regulating plant stress-responsive hormones and physiological processes. Microbe-mediated mechanisms help plants tolerate adverse conditions such as drought, salinity, nutrient deficiency, and pathogen attack. As summarized in Table 1, various microbial processes contribute significantly for improving crop resilience under severe environmental conditions.

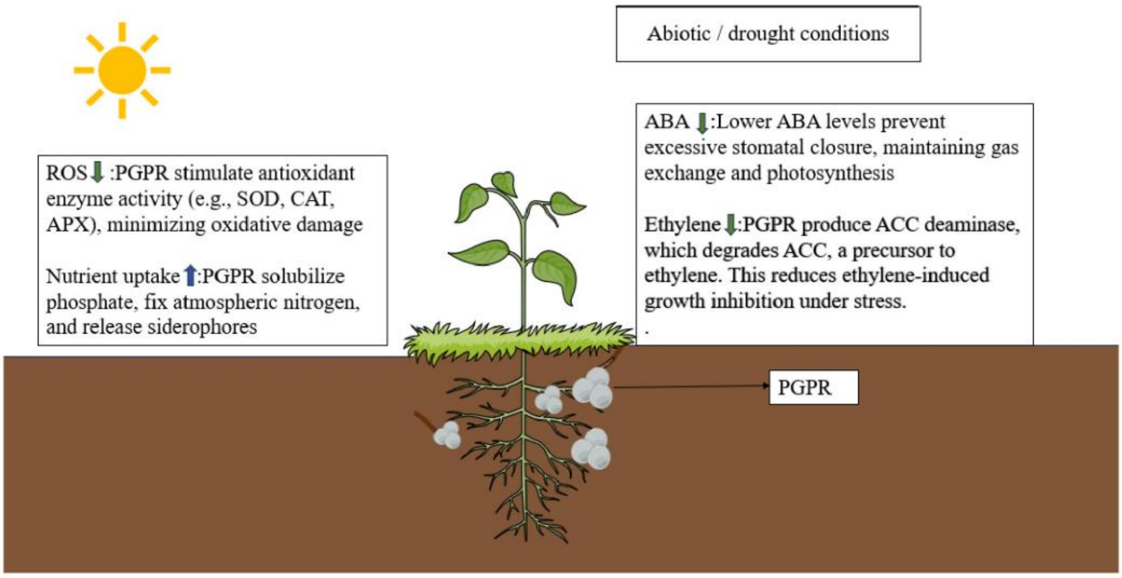

Figure 1 The graphic illustrates how plant growth-promoting rhizobacteria can reduce stress and boost plant development during drought (Pradhan et al., 2025).

MICROBE-MEDIATED IMPROVEMENT OF ROOT GROWTH

For plants to effectively absorb nutrients and adapt to stress, root architectural characteristics such as root hair elongation, lateral root branching, and overall root length are crucial. Soil microorganisms, especially arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR), have a significant impact on these characteristics. Under both normal and stressful situations, a plant's ability to explore soil nutrients and water is mostly determined by the amount of root hairs, branching density, and root elongation. By spreading fungal hyphae past the root surface, arbuscular mycorrhizal fungi improve nutrient uptake, particularly phosphorus, and increase the root absorptive area (Rawat et al., 2020).

Similar to this, phytohormones like indole-3-acetic acid (IAA), which increase root surface area and promote root elongation, are released by rhizobacteria that promote plant growth.

Table:1 Microbial strategies for reducing abiotic stress.

Abiotic stress	**Microbiological mechanism**	**Important micro-organisms**	**Impact on the plant**	**Reference**
Drought	Lower ethylene levels enhance vital antioxidant enzymes and ABA regulation.	*Bacillus subtilis, Glomus intraradices*	Improves drought resistance and water retention	Ahmad et al. (2022)
Salinity	Ionic balance and antioxidants	*Pseudomonas, Azospirillum*	Lessens oxidative stress and ion toxicity	(Ayuso-Calles et al., 2020)
Heavy metals	Metal transformation, biosorption, and siderophores	*Pseudomonas, Bacillus, and Azospirillum*	Enhances phytoremediation and reduces metal toxicity	(Saha et al., 2016)

Both overall plant vigour and the efficiency of nitrogen uptake are enhanced by these modifications. Additionally, secondary metabolites, carbohydrates, and amino acids secreted by plant roots promote the development and activity of nearby microbial populations in the rhizosphere. Furthermore, root architectural features have a significant impact on microbial interactions. While more lateral root branching offers more places for microbial adhesion, well-developed axial roots encourage microbial colonisation by increasing carbon deposition. Diverse microbial communities grow as a result, improving nutrient mobilisation, especially in areas with low phosphorus (Chen and Liu, 2024).

Overall, plant–soil–microbe interactions not only improve soil health but also optimize root architecture, leading to enhanced crop productivity even under resource-limited conditions (Saha et al., 2016).

CONCLUSION

For reducing dependency on chemical fertilisers, microbe-mediated nutrient transformation provides significant opportunities. Beneficial soil microorganisms enhance the availability of mineral-bound nutrients, thereby promoting nutrient recycling and improving nutrient use efficiency. This helps in fulfilling crop nutrient demands with lower dependency on external fertiliser inputs. Such an approach not only reduces the cost of production for farmers but also minimizes adverse environmental impacts. By providing biologically fixed nitrogen, solubilising phosphorus and potassium, and mobilising vital micronutrients, microbial biofertilizers contribute significantly to sustainable nutrient management. Their application preserves soil biological activity while promoting balanced plant nutrition. While including microbial inputs helps restore soil health and enhance soil organic matter, aggregation, and nutrient cycling, continuous application of chemical fertilisers alone can deteriorate soil structure and microbial diversity. The advantages of organic, biological, and chemical nutrient sources are combined when microbial biofertilizers are incorporated into the framework of Integrated Nutrient Management (INM). Long-term soil fertility, consistent agricultural productivity, and environmental sustainability are all guaranteed by this strategy. Therefore, developing robust and resource-efficient agronomic systems requires the adoption of microbe-based techniques.

REFERENCES

Ahmad, H. M., Fiaz, S., Hafeez, S., Zahra, S., Shah, A. N., Gul, B., Aziz, O., Mahmood Ur, R., Fakhar, A., Rafique, M., Chen, Y., Yang, S. H., & Wang, X. (2022). Plant Growth-Promoting Rhizobacteria Eliminate the Effect of Drought Stress in Plants: A Review. *Frontiers Plant Science, 13*, 875774. https://doi.org/10.3389/fpls.2022.875774

Ahmed, E., & Holmstrom, S. J. (2014, May). Siderophores in environmental research: roles and applications. *Microbial Biotechnology, 7*(3), 196-208. https://doi.org/10.1111/1751-7915.12117

Ayuso-Calles, M., García-Estévez, I., Jiménez-Gómez, A., Flores-Félix, J. D., Escribano-Bailón, M. T., & Rivas, R. (2020). Rhizobium laguerreae Improves Productivity and Phenolic Compound Content of Lettuce (Lactuca sativa L.) under Saline Stress Conditions. *Foods, 9*(9). https://doi.org/10.3390/foods9091166

Baba, Z. A., Hamid, B., Sheikh, T. A., Alotaibi, S. H., El Enshasy, H. A., Ansari, M. J., Zuan, A. T. K., & Sayyed, R. Z. (2021, Sep 23). Psychrotolerant Mesorhizobium sp. Isolated from Temperate and Cold Desert Regions Solubilizes Potassium and Produces Multiple Plant Growth Promoting Metabolites. *Molecules, 26*(19). https://doi.org/10.3390/molecules26195758

Chen, L., & Liu, Y. (2024, Feb 2). The Function of Root Exudates in the Root Colonization by Beneficial Soil Rhizobacteria. *Biology (Basel), 13*(2). https://doi.org/10.3390/biology13020095

Dong, H., Huang, L., Zhao, L., Zeng, Q., Liu, X., Sheng, Y., Shi, L., Wu, G., Jiang, H., Li, F., Zhang, L., Guo, D., Li, G., Hou, W., & Chen, H. (2022, Oct). A critical review of mineral-microbe interaction and co-evolution: mechanisms and applications. *Natural Science Review, 9*(10), nwac128. https://doi.org/10.1093/nsr/nwac128

Jabborova, D., Sayyed, R. Z., Azimov, A., Jabbarov, Z., Matchanov, A., Enakiev, Y., Baazeem, A., El Sabagh, A., Danish, S., & Datta, R. (2021, Sep). Impact of mineral fertilizers on mineral nutrients in the ginger rhizome and on soil enzymes activities and soil properties. *Saudi Journal Biological Sciences, 28*(9), 5268-5274. https://doi.org/10.1016/j.sjbs.2021.05.037

Kapadia, C., Patel, N., Rana, A., Vaidya, H., Alfarraj, S., Ansari, M. J., Gafur, A., Poczai, P., & Sayyed, R. Z. (2022). Evaluation of Plant Growth-Promoting and Salinity Ameliorating Potential of Halophilic Bacteria Isolated From Saline Soil. *Frontiers Plant Science, 13*, 946217. https://doi.org/10.3389/fpls.2022.946217

Miliute, I., Buzaite, O., Baniulis, D., & Stanys, V. (2015). Bacterial endophytes in agricultural crops and their role in stress tolerance: a review. *Zemdirbyste-Agriculture*, *102*(4), 465-478. https://doi.org/10.13080/z-a.2015.102.060

Nnaji, N. D., Anyanwu, C. U., Miri, T., & Onyeaka, H. (2024). Mechanisms of Heavy Metal Tolerance in Bacteria: A Review. *Sustainability*, *16*(24). https://doi.org/10.3390/su162411124

Ortiz-Castillo, J., Mirazimi, M., Mohammadi, M., Dy, E., & Liu, W. (2021). The Role of Microorganisms in the Formation, Dissolution, and Transformation of Secondary Minerals in Mine Rock and Drainage: A Review. *Minerals*, *11*(12). https://doi.org/10.3390/min11121349

Pradhan, N., Singh, S., Saxena, G., Pradhan, N., Koul, M., Kharkwal, A. C., & Sayyed, R. (2025). A review on microbe-mineral transformations and their impact on plant growth. *Frontiers Microbiology*, *16*, 1549022. https://doi.org/10.3389/fmicb.2025.1549022

Rawat, P., Das, S., Shankhdhar, D., & Shankhdhar, S. C. (2020). Phosphate-Solubilizing Microorganisms: Mechanism and Their Role in Phosphate Solubilization and Uptake. *Journal of soil science and plant nutrition*, *21*(1), 49-68. https://doi.org/10.1007/s42729-020-00342-7

Ribeiro, I. D. A., Volpiano, C. G., Vargas, L. K., Granada, C. E., Lisboa, B. B., & Passaglia, L. M. P. (2020). Use of Mineral Weathering Bacteria to Enhance Nutrient Availability in Crops: A Review. *Frontiers Plant Science*, *11*, 590774. https://doi.org/10.3389/fpls.2020.590774

Saha, M., Sarkar, S., Sarkar, B., Sharma, B. K., Bhattacharjee, S., & Tribedi, P. (2016, Mar). Microbial siderophores and their potential applications: a review. *Environmental Science Pollution Research International*, *23*(5), 3984-3999. https://doi.org/10.1007/s11356-015-4294-0

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