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Unlocking Nutrient Potential: Harness The Power Of Micro-Nutrient Solubilizing Bacteria: A Review

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Abstract

Micro-nutrient solubilizing bacteria (MSB) play a pivotal role in the growth and developmentof plants by enhancing the availability of essential micro-nutrients in the soil. These bacteria possess unique capabilities to solubilize otherwise unavailable forms of micro-nutrients, such as iron, zinc, copper, manganese, and others. As a result, they improve nutrient uptake, plant health, and overall crop productivity. The use of MSB in agriculture can reduce reliance on chemical fertilizers, which can be costly and have negative environmental impacts. By makingmicro-nutrients more available, MSB help optimize the use of existing soil nutrients.MSB canalso contribute to soil health and overall environmental sustainability. Additionally, MSB is adaptable to various soil types and climates, making them suitable for diverse agricultural settings. Their compatibility with sustainable practices aligns with efforts to promote environmentally friendly agricultural systems. Improving nutrient availability promotes balanced ecosystems and reduces the risk of nutrient runoff, which can harm water bodies. Some MSB has been reported to induce systemic resistance in plants against certain pathogens. They trigger the plant's defense mechanisms, making it more resistant to diseases. This review aims to provide an in-depth understanding of the mechanisms through which MSBexert their beneficial effects on plants and the potential implications for sustainable agriculture.It covers various aspects of MSB, including their identification, functions, interactions with plants, environmental factors influencing their activity, and their applications in modern agriculture.

Keywords: Bio-fertilizer, Plant micronutrient, Micro-nutrient solubilizing bacteria, Sustainable agriculture, soil health.

Introduction:

Agriculture is the backbone of human civilization, and to meet the ever-growing demand for food, there is a pressing need for sustainable agricultural practices. Micro-nutrients, though required in trace amounts, are crucial for plant growth, development, and stress tolerance. Unfortunately, these nutrients are often found in insoluble forms in the soil, limiting their accessibility to plants. Plants require a range of essential nutrients for healthy growth besides carbon, hydrogen, and oxygen obtained from CO2 and water.
These nutrients are divided into macronutrients (required in larger quantities) andmicronutrients (required in smaller quantities). Essential macronutrients include nitrogen (N),phosphorus (P), potassium (K), sulfur (S),

magnesium (Mg), and calcium (Ca). Essential micronutrients include iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni). Nutrient deficiencies are common in natural soils, limiting plant growth and development. Deficiency in each of the macronutrients and micronutrients leads to varying consequences at molecular and phenotypic levels (Andresenet al. 2018, Gong et al. 2020). Fertilization is a common strategy to improve plant nutrition, but it can be hindered by environmental factors and inefficiencies. Fertilization is a major approach for improving plant nutrition. Efficacy of fertilization in agriculture can be limited by environmental interferences, as exemplified by Zn fertilization with the water-soluble zinc sulfate, which is often precipitated as hydroxides, carbonates, phosphates and sulfides in the soil and consequently shows only 1–5% fertilizer use efficiency (Krithika andBalachandar 2016).
The low fertilizer use efficiency in this context refers to the fact that a significant portion of theapplied zinc is lost or rendered unavailable to plants due to precipitation reactions. This can range from 1% to 5% or even lower, depending on various factors such as soil properties, pH, microbial activity, and the specific zinc fertilizer formulation. The production and application of fertilizers pose environmental concerns, such as energy consumption and contributions to pollution. Plants live with a plethora of soil microbes, some of which are beneficial in that theycan promote plant growth and/or increase plant resistance to one or multiple stress conditions,including nutrient deficiency (Morcillo and Manzanera, 2021). In this review we have discussed regarding various beneficial MSB which we can use as biofertilizer purpose in agricultural sector.

Nutrient mobilization via microbial enrichment in soil microbiota

Iron (Fe): Iron is an essential nutrient for plants, but its uptake can be challenging due to its low solubility in certain soil conditions. Different plant species have evolved distinct mechanisms to overcome this challenge and acquire sufficient iron for their growth and development. *Graminaceous Monocots* release siderophores which helps in chelation of ferriciron ($Fe3+$) by converting it into a more soluble form (Rajkumar et al. 2010). Microbes can influence and enhance plant iron uptake by not only providing their own siderophores but also by triggering the plant's own production of compounds known as phytosiderophores. This phenomenon is part of a complex interplay between plants and microorganisms in the rhizosphere, where microbes can impact nutrient availability and uptake.In Sorghum (Sorghum bicolor), a type of plant with iron deficiency, certain genes involved inphytosiderophore production and iron uptake were induced by arbuscular mycorrhizal (AM) fungi. These fungi are symbiotic partners that can form beneficial associations with plant roots,aiding in nutrient uptake. Specifically, the genes SbDMAS2 (deoxymugineic acid synthase 2),SbNAS2 (nicotianamine synthase 2), and SbYS1 (Fe-phytosiderophore transporter yellow stripe) were upregulated in response to the presence of AM fungi (Prity et al. 2020).
Rhizosphere acidification is a critical mechanism that enhances the mobility and availability offerric iron ($Fe3+$) in the soil, making it more accessible to plant roots. This acidification processis often facilitated by microbes through the release of organic acids as part of their extracellularmetabolites. These organic acids help in neutral iron solubility increase via the reduction of ferric iron ($Fe3+$) to ferrous iron ($Fe2+$) and dissolving iron compounds that are tightly boundin the soil matrix thereby promoting its uptake by plants. volatile organic compounds (VOCs)produced by microbes, such as *Bacillus amyloliquefaciens* GB03, contain organic acids like glyoxylic acid, 3-methyl-butanoic acid, and diethyl acetic acid. These compounds can directlylead to a decrease in soil pH in the rhizosphere, creating a more acidic environment (Farag et al. 2006).
By directly contributing to rhizosphere acidification through the release of organic acids, microbes like *Bacillus amyloliquefaciens* GB03 (Zhang et al. 2009)play an important role inimproving plant iron acquisition. This interaction between microbes, organic acids, and iron availability is a fascinating example of the intricate relationships between plants and their associated microbial communities.
Relationship between beneficial microbes and plants goes beyond nutrient solubilization; it canalso involve signaling and gene expression that impact the plant's nutrient status and acquisition. In the case of Arabidopsis and the volatile organic compounds (VOCs) produced by *Bacillus amyloliquefaciens* GB03, exposure to these VOCs under iron-sufficient conditions triggered systemic iron-deficiency responses in the plants. These responses included the upregulation of key genes and the stimulation of enzyme activity associated with iron uptake and utilization, such as the $Fe3+$ reductase FRO2 and the $Fe2+$ transporter IRT1. Additionally,the plants exposed to these VOCs exhibited increased rhizosphere acidification, which further

contributes to iron availability (Freitas et al. 2015, Zamioudis et al. 2015, Zhou et al. 2016, Martínez-Medina et al. 2017, Montejano-Ramírez et al. 2020, Kong et al. 2021).
This phenomenon underscores the concept that beneficial microbes can influence plant physiology beyond simple nutrient supply. Microbes can act as signaling agents that induce systemic responses within plants, ultimately affecting nutrient uptake, gene expression, and overall plant health. These findings have implications for sustainable agricultural practices, asharnessing the capabilities of beneficial microbes can lead to improved nutrient acquisition, potentially reducing the need for external fertilizers. (Liu and Zhang 2015,Weisskopf et al. 2021)

Copper (Cu): AM fungi can improve a plant's ability to acquire copper when it is limited in the soil. The hyphal network of these fungi extends into the soil beyond the root zone, increasing the volume of soil explored for nutrient acquisition. This extended reach allows plants to access nutrients like copper that might be present but inaccessible to the roots alone (Ferrol et al. 2016). The extraradical mycelium of arbuscular mycorrhizal (AM) fungi, like*Glomus mosseae*, plays a vital role in improving plant copper (Cu) nutrition. The extraradical mycelium greatly expands the area that the mycorrhizal plant can access for nutrient uptake. Copper, like other nutrients, might be present in the soil but unevenly distributed or in forms that are not easily accessible to plant roots. The mycelium's extensive reach allows the plant toaccess a larger pool of nutrients, including copper.
The mycorrhizal association between *Glomus mosseae* and white clover resulted in an increasein plant copper uptake, regardless of phosphorus (P) availability. When additional phosphoruswas supplied to the soil, it led to alterations in the pattern of copper distribution between rootsand shoots. Specifically, there was a decrease in copper content in the roots and an increase incopper content in the shoots. Similarly, in the mycorrhizal cucumber plants, high levels of P supply to hyphae resulted in decreased root Cu concentrations (Lee and George 2005), thusdrawing attentions to the crosstalk among different nutrient improvements in mycorrhizal plants.
Bacterial interactions that impact the copper (Cu) nutrition of plants, specifically alfalfa (Medicago sativa) seedlings. Bacteria can play a significant role in enhancing plant nutrient uptake through various mechanisms, including the production of siderophores and the modulation of plant genes. Siderophores are tiny molecules produced by some bacteria to findand chelate iron (Fe) from the environment. Cu and Fe uptake was enhanced by two siderophores producing bacteria strains of P. fluorescens and Rhizobium leguminosarum bv phaseoli. These molecules can also play a role in facilitating the uptake ofother metals like copper, which share similar chemical properties with iron. The production ofsiderophores by bacteria can indirectly enhance plant copper nutrition by mobilizing and making copper more available for plant uptake. This can lead to improved growth anddevelopment of the plant. In cucumber plants under Cu deficiency of Cu and Fe, plant stress symptoms were alleviated by the plant-beneficial bacteria A. brasilense, accompanied by better root development and nutrient uptake (Marastoni et al. 2019).

Manganese (Mn): Manganese is an essential micronutrient for plants, but its availability foruptake can be influenced by soil conditions, such as pH and oxidation status.
In alkaline and oxidative soils, like well-aerated calcareous soils, manganese tends to form insoluble compounds like manganese oxides. This water-insoluble form of manganese is not readily available for plant uptake. This is why plants struggle to acquire sufficient manganese from such soils, which can lead to manganese deficiency in plants. Manganese can easily be oxidized from its divalent (Mn^{2+}) form to higher oxidation states, particularly under alkaline
and oxidative conditions. This oxidized form of manganese is less accessible to plant roots, further hindering effective manganese uptake (Andresen et al. 2018). Example, Acidophilicbacteria are known to play a crucial role in this bioleaching process, where they contribute to the solubilization and release of manganese from its solid mineral forms into solution suchas *Acinetobacter sp.* and *Lysinibacillus sp.*, which were used for Mn bioleaching from ores ormining wastewater (Sanket et al. 2017,Ghosh et al. 2018). Mn solubilizing fungal strains, such as *Aspergillus terreus* and *Penicillium daleae*, are isolated from low-grade Mn mine tailings, and their Mn solubilizing ability was a given to the mycelia production of organicacids such as oxalic acid, citric acid, maleic acid and gluconic acid (Mohanty et al. 2017).

Molybdenum (Mo): Molybdenum (Mo) is indeed an essential micronutrient for plants, albeitrequired in very small quantities. It's primarily taken up by plants in the form of molybdate ions (MoO_4^{2-}), which are usually present in soil solutions. While molybdenum is required byplants for various physiological processes, it is indeed one of the least abundant essential micronutrients needed for plant growth. While molybdenum deficiencies might be consideredrare in many agricultural regions, they can still occur under certain conditions, particularly in soils with low molybdenum content or in situations where factors like soil pH or the presence of other minerals affect molybdenum uptake by plants. (Kaiser et al. 2005). AM fungal colonization can enhance the concentration of molybdenum in both the shoots and roots of sweet sorghum plants, particularly in the presence of added MoS2 (molybdenite) in the soil. Arbuscular mycorrhizal fungi form a mutually beneficial symbiotic relationship with plants, where the fungi assist in nutrient uptake in exchange for plant-produced sugars. This relationship is particularly important for nutrient acquisition, especially in nutrient-poor soils.*Claroideoglomusetunicatum*, is shown to have a positive impact on plant molybdenum concentrations. This indicates that the fungus assists the plant in acquiring molybdenum fromthe soil (Shi et al. 2020). In maize plants growing in soil supplemented with different levelsof (NH4)2MoO4, the same *C. etunicatum* strain also enhanced plant Mo concentrations in shoots and roots, with reductions in the shoot-to-root Mo ratio when Mo was supplemented atthe levels considered as moderate and severe pollution (Shi et al. 2018).

Nickel (Ni): Nickel (Ni) is considered an essential micronutrient for plants, although it's required in very small amounts. Its primary known role in higher plants is linked to the enzymeurease. Urease is responsible for the hydrolysis of urea, converting it into ammonia and carbondioxide (Andresen et al. 2018).Nickel (Ni) can be present in fertilized soil due to its occurrence as a trace element in various raw materials used to produce fertilizers. One such example you mentioned is rock phosphate, which serves as a raw material for the production of phosphatic fertilizers. Rock phosphate can contain varying amounts of nickel, typically ranging from 16.8 to 50.4 mg kg^{-1} (Chauhan et al. 2008). *Bacillus* species are commonlyassociated with nickel solubilization. They are known for their versatile metabolic capabilitiesand are often found in the rhizosphere of plants. Examples include *Bacillus subtilis*, *Bacillus megaterium*, and *Bacillus cereus* (Veronika Pishchik, 1,2 Galina Mirskaya,2 Elena Chizhevskaya,1 Vladimir Chebotar,1 and Debasis Chakrabarty3). Important aspect of nickel (Ni) inthe context of environmental pollution and its impact on plant health.

Zinc (Zn): Zn-mobilizing microbes offer alternative tools for enhancing plant Zn acquisition. Certain microbes have the ability to enhance the availability and uptake of zinc by plants. A variety of bacteria such as Pseudomonas and Bacillus strains are there to increase plant growth with higher Zn contents, and the microbial mobilization of Zn were given to different mechanisms mediated through acidification of rhizosphere, sequestration by siderophores or anions from organic acids, and oxido-reductive systems on cell membranes (Kamran et al. 2017). These microbes can solubilize insoluble forms of zinc in the soil, converting them into a more plant-accessible form. This microbial activity can aid in making zinc more available to plant roots. The study utilized two different methods for providing zinc to rice seedlings: (a) direct application of soluble zinc sulfate (ZnSO4) and (b) application of insoluble zinc oxide bound with Zn-mobilizing bacteria. Despite the difference in the forms of zinc and their application methods, both approaches yielded similar results in terms of enhancing plant zinc accumulation (Krithika and Balachandar 2016). Helping plants with mycorrhizal Zn supply, fungi and bacteria may also regulate plant Zn transporters (Watts-Williams and Cavagnaro 2018).

Boron (B): Boron in soil exists primarily in the form of uncharged boric acid (H3BO3 or B(OH)3). This uncharged form of boron is the most common and biologically available form of boron for plants. It can be readily taken up by plant roots.
Boric acid is relatively mobile in soil and can move with water in the soil solution. Plants absorb boron through their roots as boric acid molecules enter the root cells by passive diffusion. Once inside the plant, boron plays essential roles in various physiological processes, including cell wall formation, sugar transport, and enzyme activation (Miwa et al. 2009). Boron (B) deficiency can indeed occur in various crops around the world, and it's an importantmicronutrient to manage for optimal plant growth. Various species of *Bacillus*, such as *Bacillus megaterium, Bacillus pumilus, Bacillus circulans*, and *Bacillus cereus*, have been reported to solubilize boron and promote plant growth.

Discussion and Future Perspectives:

Many microbes can solubilize nutrients in the soil, making them more available to plants. Thisincludes the solubilization of phosphorus, iron, zinc, and other essential nutrients that might beotherwise unavailable in their insoluble forms. The microbes achieve this through various mechanisms, such as the production of organic acids, siderophores, and enzymes that break down mineral compounds. Moreover, these organisms induce several things to induce plant growth like soil porosity enhancement, nutrient cycling through decomposition, abiotic stress tolerance etc and many more**.** Microbes can influence plant gene expression related to nutrient acquisition. For example, certain microbes can induce the expression of genes involved in nutrient uptake mechanisms like transporter proteins. This is often achieved through signalingmolecules produced by the microbes that trigger specific responses in plants. Due to these reasons MSBs are immerged as potential source of bio-fertiliser. can be mass-produced and formulated into biofertilizers. These biofertilizers, when applied to the soil or seedlings, can provide a sustainable and eco-friendly source of micronutrients to plants. It was proved that application of MSB as biofertilizers has been shown to increase crop yields, especially in micronutrient-deficient soils. Increased nutrient availability leads to better plant growth, higheryields, and improved crop quality. Their usage can reduce the environmental impact of agriculture by decreasing the need for excessive chemical fertilizers. This can help prevent nutrient runoff and contamination of water bodies (Krithika and Balachandar 2016).

Although, there may be some initial investment in producing and applying micro-nutrient solubilizing bacteria, the long-term benefits, including reduced fertilizer costs and increased yields, often outweigh the initial expenses. However, the process still faces lots of challenge like correct strain identification and proper way of application of these microbes into agricultural lands. Researchers are working on developing specific bacterial strains that are tailored to solubilize micronutrients. This allows for the development of customized formulations that address specific micronutrient deficiencies in different crops and regions. The research in this field is ongoing and interdisciplinary, involving microbiologists, plant biologists, geneticists, and molecular biologists. Understanding the intricate details of how beneficial microbes influence plant nutrient uptake and stress responses involves looking at molecular signaling, gene expression, metabolomics, and even the composition of the soil microbiome (Andresen et al. 2018, 2. Gong et al. 2020).

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