Revista Facultad de Ciencias Básicas
2022 Vol. 18(2)
julio - diciembre ▪ ISSN: 1900-4699 · e-ISSN: 2500-5316 ▪ pp. 83-101

Editorial Neogranadina

DOI: https://doi.org/10.18359/rfcb.7055

Optimizing iron Manganese, and Zinc Fertilization in Rice (*Oryza sativa* L.) through *Bacillus, Pseudonomas*, and *Aspirilum* Bacteria*

Yenny Astrid Barahona Pico[a] ▪ Rocío Alexandra Ortíz Paz[b] ▪ Sandra López-Rayo[c]

Abstract: Rice (*Oryza sativa*) is a cereal crop crucial for global food security. However, the limited availability of micronutrients such asIron (Fe), Manganese (Mn), and Zinc (Zn) in calcareous soils can lead to metabolic disturbances in the plant, resulting in various anomalies. These disturbances can reduce yields and, in severe cases, lead to plant death. Plant growth-promoting microorganisms found in the soil rhizosphere can solubilize these micronutrients. These microorganisms have also been isolated from soils and utilized as biostimulants and biofertilizers, facilitating their use in optimizing rice cultivation. The objective of this study was to conduct a literature review on *Bacillus, Pseudomonas* and *Azospirillum* and their ability to solubilize Fe, Mn, and Zn rice cultivation. The study describes the nature, assimilation, and importance of these three micronutrients in soil and in rice cultivation, as well as the optimization of the microorganisms as ingredients that promote crop growth and productivity. Furthermore, it discusses their mechanisms, such as the secretion of the siderophores deoxymugenic acid (DMA) and mugenic acid (MA), the production of organic acids like indole-3-acetic acid (IAA) and abscisic acid, the production of phytohormones(e.g., cytokinins), and a network of metalloproteins that facilitate soil acidification. These mechanisms enable the solubilization of Fe, Mn, and Zn in the soil associated with the crop, making them available for absorption by the root system in the form of chelates. To sum up, the addition of *Bacillus, Pseudomonas* and *Azospirillum* facilitates the absorption of micronutrients in the crop and mitigates the negative effects caused by the constant application of chemical fertilizers, which can accumulate in plan tissue, soil, and water.

Keywords: Micronutrients; Iron; Manganese; Zinc; Bacteria; Biofertilizer; Biostimulant

Recibido: 26/12/2023 **Aceptado:** 19/02/2024 **Disponible en línea:** 30/05/2024

Cómo citar: Barahona Pico , Y. A., Ortiz Paz , R. A., & López Rayo , S. (2024). Optimizing Iron, Manganese, and Zinc Fertilization in Rice (*Oryza sativa* L.) through *Bacillus*, *Pseudomonas*, and *Azospirillum* bacteria. *Revista Facultad de Ciencias Básicas, 18*(2), 83-101. https://doi.org/10.18359/rfcb.7055

* Review article

a Master's Degree in Agroenviromental and Agri -food Sciences. Master's Degree in Comprehensive Quality Management. Specialist in Instrumental Chemical Analysis. Bachelor's degree in Chemistry. Professor of Chemistry, Universidad Internacional del Trópico Americano, Unitrópico. Yopal, Casanare, Colombia.
Email: jennybarahona@unitropico.edu.co; ORCID: https://orcid.org/0000-0003-2868-6940

b Master's Degree in Phytopathology. Agroforestry Engineering. Master Researcher, Corporación Colombiana de Investigación Agropecuaria - AGROSAVIA, CI La Selva. Rionegro,Antioquia, Colombia.
Email: rortiz@agrosavia.co; ORCID: https://orcid.org/0000-0003-2945-2118

c Ph. D. in Chemistry, Master's Degree in Agricultural Chemistry. Bachelor's Degree in Chemistry. Contracted Doctor Professor, Department of Agricultural Chemistry and Bromatology. Universidad Autónoma de Madrid- UAM, España.
Email: sandra.lopez@uam.es; ORCID: https://orcid.org/0000-0002-5035-0311

*Optimización de la fertilización con hierro, manganeso y zinc en arroz (*Oryza sativa *L.) a través de bacterias* Bacillus, Pseudomonas *y* Azospirillum

Resumen: El arroz (Oryza sativa) es un cultivo de cereal crucial para la seguridad alimentaria mundial. Sin embargo, la disponibilidad limitada de micronutrientes como el hierro (Fe), manganeso (Mn) y zinc (Zn) en suelos calcáreos puede provocar trastornos metabólicos en la planta, lo que resulta en diversas anomalías. Estos trastornos pueden reducir los rendimientos y, en casos graves, llevar a la muerte de la planta. Los microorganismos promotores del crecimiento vegetal presentes en la rizosfera del suelo pueden solubilizar estos micronutrientes. Estos microorganismos también se han aislado de suelos y se han utilizado como biestimulantes y biofertilizantes, facilitando su uso en la optimización del cultivo de arroz. El objetivo de este estudio fue realizar una revisión bibliográfica sobre *Bacillus, Pseudomonas* y *Azospirillum* y su capacidad para solubilizar Fe, Mn y Zn en el cultivo de arroz. El estudio describe la naturaleza, asimilación e importancia de estos tres micronutrientes en el suelo y en el cultivo de arroz, así como la optimización de los microorganismos como ingredientes que promueven el crecimiento y la productividad de los cultivos. Además, se discuten sus mecanismos, como la secreción de sideróforos ácido deoximugénico (DMA) y ácido mugénico (MA), la producción de ácidos orgánicos como el ácido indol-3-acético (IAA) y el ácido abscísico, la producción de fitohormonas (por ejemplo, citocininas) y una red de metaloproteínas que facilitan la acidificación del suelo. Estos mecanismos permiten la solubilización de Fe, Mn y Zn en el suelo asociado al cultivo, haciéndolos disponibles para su absorción por el sistema de raíces en forma de quelatos. En resumen, la adición de *Bacillus, Pseudomonas* y *Azospirillum* facilita la absorción de micronutrientes en el cultivo y mitiga los efectos negativos causados por la aplicación constante de fertilizantes químicos, que pueden acumularse en los tejidos de las plantas, el suelo y el agua.

Palabras clave: micronutrientes; hierro; manganeso; zinc; bacterias; biofertilizante; Biestimulante

*Otimização da fertilização com ferro, manganês e zinco em arroz (*Oryza sativa *L.) através de bactérias* Bacillus, Pseudomonas *e* Azospirillum

Resumo: O arroz (Oryza sativa) é um cultivo de cereal crucial para a segurança alimentar mundial. No entanto, a disponibilidade limitada de micronutrientes como ferro (Fe), manganês (Mn) e zinco (Zn) em solos calcários pode provocar distúrbios metabólicos na planta, resultando em diversas anomalias. Esses distúrbios podem reduzir os rendimentos e, em casos graves, levar à morte da planta. Os microrganismos promotores do crescimento vegetal presentes na rizosfera do solo podem solubilizar esses micronutrientes. Esses microrganismos também têm sido isolados de solos e utilizados como bioestimulantes e biofertilizantes, facilitando seu uso na otimização do cultivo de arroz. O objetivo deste estudo foi realizar uma revisão bibliográfica sobre *Bacillus, Pseudomonas* e *Azospirillum* e sua capacidade de solubilizar Fe, Mn e Zn no cultivo de arroz. O estudo descreve a natureza, assimilação e importância desses três micronutrientes no solo e no cultivo de arroz, bem como a otimização dos microrganismos como ingredientes que promovem o crescimento e a produtividade dos cultivos. Além disso, discutem-se seus mecanismos, como a secreção de sideróforos ácido deoximugínico (DMA) e ácido mugínico (MA), a produção de ácidos orgânicos como o ácido indol-3-acético (IAA) e o ácido abscísico, a produção de fitohormonas (por exemplo, citocininas) e uma rede de metaloproteínas que facilitam a acidificação do solo. Esses mecanismos permitem a solubilização de Fe, Mn e Zn no solo associado ao cultivo, tornando-os disponíveis para a absorção pelo sistema radicular na forma de quelatos. Em resumo, a adição de *Bacillus, Pseudomonas* e *Azospirillum* facilita a absorção de micronutrientes no cultivo e mitiga os efeitos negativos causados pela aplicação constante de fertilizantes químicos, que podem se acumular nos tecidos das plantas, no solo e na água.

Palavras-chave: micronutrientes; ferro; manganês; zinco; bactérias; biofertilizante; bioestimulante

Introduction

Rice (*Oryza sativa* L.) is a Poaceae plant that serves as a staple food for 3.5 billion people globally, with an average per capita consumption of 54.1 kg per year. In 2020, the global harvested area of rice reached 164,192,164 hectares, yielding 46,089 kg per hectare and totaling 756,743,722 tons in production. Asia accounted for 90% of the world's rice production, followed by Africa and Latin America (Nadeem and Farooq, 2019; FAOSTAT, 2020; Shrestha et al., 2020; Keerthana and Lavanya, 2022). Rice cultivation is historically rooted in tropical and subtropical regions with humid and temperate climates, typically found between 49° and 50° latitude North and 35° latitude South, and at elevations ranging from sea level to 2,500 meters. These regions typically experience temperatures between 16°C and 32°C and receive approximately 1,020 mm of annual precipitation (Maqueria et al.,2016; Azziz et al., 2017; Infoagro, n.d.).

Rain-fed and irrigated rice cultivation predominantly occurs on lands with slopes lower than 20% and soil pH ranging from 5.5 to 6.6, consisting of loamy, sandy clay, or clay loam soils. Conversely, upland rice is grown in soils with a pH levels lower than 5 or higher than 9 (Chauhan et al., 2017; Quintero, 2018; Infoagro, 2020). The rice crop has a life cycle of approximately 150 days, during which it extracts around 110 kg of N, 34 kg of P_2O_5, 156 kg of K_2O, 23 kg of MgO, 20 kg of CaO, 5 kg of S, 2 kg of Fe, 2 kg of Mn, 200 g of Zn, 150 g of Cu, 150 g of B, 250 kg of Si, and 25 kg of Cl per hectare from the soil (Chauhan et al., 2017; Quintero, 2018). These macronutrients are crucial for growth, while micronutrients such as iron (Fe), manganese (Mn), and zinc (Zn) play essential roles in protein synthesis, enzymatic activation processes, and biochemical activities contributing to high grain yields (Zayed et al., 2011; Nadeem and Farooq, 2019; Shrestha et al., 2020).

Biofertilizers containing microorganisms such as *Bacillus, Pseudomonas, and Azospirillum* have demonstrated benefits in promoting robust growth, high yields, and grain quality in rice cultivation. Their application is increasingly important for preserving ecosystem functional biodiversity (Saravanan et al., 2011a; Gontia-Mishra et al., 2017; Gusain and Sharma, 2019).

These microorganisms possess active mechanisms for solubilizing both macro and micronutrients, enhancing the absorption of less mobile nutrients by plant roots and meeting fertilizer requirements for optimal growth and development (Saravanan et al., 2011a; Alori and Babalola, 2018; Dal Cortivo et al., 2018; Dal Cortivo et al., 2020). Considering the aforementioned, a literature review was conducted to assess whether the utilization of microorganisms from the genera *Bacillus*, *Pseudomons,* and *Azospirillum* contributes to the solubilization of the micronutrients iron (Fe), manganese (Mn) and zinc (Zn) in rice cultivation.

Methodology

The methodology involved conducting a literature review on the three microorganisms (*Bacillus, Pseudomonas*, and *Azospirillum*), and their relation to the fertilization of the micronutrients Fe, Mn, and Zn in rice cultivation. The review proceeded in the following sequence:

1. Nature and importance of the three micronutrients for cultivation, focussing their assimilation. The search engines used were Sciencedirect (44%), Google Scholar (19%), SpringerLink (16%), Researchgate.net (9%), PubMed (6%), Scopus (4%), Books (1%).
2. Examination of the principal microorganisms responsible for solubilizing the three micronutrients. Seventeen articles were reviewed, gathered from Google Scholar (19%), Scopus (19%), SpringerLink (19%), Researchgate.net (19%), Google (12%). Frontiers (6); Sciencedirect (6%).
3. Exploration of the characteristics and application of key biofertilizers containing solubilizing microorganisms for the three micronutrients. This step involved reviewing six literatures sources, primarily from SpringerLink (50%), Google Scholar (25%), and Sciencedirect (25%).
4. Analysis of the mechanisms underlying the solubilization of the three micronutrients by *bacillus*, *pseudomonas*, and *azospirillum* microorganisms. A total of 29 reviews were

conducted, with sources including Scopus (35%), SpringerLink (17%), Google Scholar (17%), Books (10%), Sciencedirect (7%), Researchgate.net (7%), Frontiers (4%), PubMed (3%).

The reviews encompassed articles, books, conference proceedings, and technical documents, with 93% of the content in English and 7% in Spanish. Journals included in the review were indexed, with 73% of the reviews focusing on the past ten years.

Geographical distribution of the reviewed information included: 51% from Asia (India, Japan, China, Pakistan, Nepal), 17% from Europe (Germany, Italy, Spain, Switzerland, Brussels, France, Greece, the United States, Austria, the Czech Republic), 21% from the Americas (USA, Brazil, Mexico, Argentina, Chile, Colombia, Uruguay), 12% from Africa, and 4% from Oceania (Australia).

Commercially available biofertilizer information was sourced from the Spanish Ministry of Agriculture, Fisheries, and Food of the Government (MAPA) and the Colombian Agricultural Institute (ICA).

Results

The Nature, Assimilation, and Importance of Micronutrients Fe, Mn, and Zn in Rice Cultivation

Nature

In soil, iron (Fe) exists in various forms, including hematite (Fe_2O_3), magnetite (Fe_3O_4), ferrihydrite $Fe(OH)_3$, goethite (α-FeOOH), and amorphous iron (Lindsay, 1979; Navarro and Navarro, 2013, Wu et al., 2021). Fe_2O_3remains stable at high pH levels and persists under oxidizing conditions, contributing to the investigation of microbial reduction of Fe (III) (Li et al., 2018). Additionally, lepidocrocite and goethite (FeOOH) have been detected in significant quantities in soils, of 16 g kg^{-1}, along with amorphous iron minerals at 98.5 mg kg^{-1} (Chen, Dixon and Turner, 1980; Liu et al., 2010; He et al., 2021).

Manganese (Mn) minerals in soil include pyrolusite (MnO_2), hausmannite (Mn_3O_4) birnesite δ-MnO_2, manganite ($Mn_2O_3.H_2O$), and rhodochrosite ($MnCO_3$) (Navarro and Navarro, 2013; Suda and Makino, 2015; Sinha and Purcell, 2019). For instance, the addition of hausmannite to potted rice (at 1200 mg Mn kg^{-1} of soil) slows down the decrease in pH, demonstrating its influence on soil dynamics.

Zinc (Zn) in soil is present as minerals such as zincite (ZnO), sphalerite (ZnS), smithsonite ($ZnCO_3$), zinc sulfate ($ZnSO_4$), and franklinite ($ZnFe_2O_4$) (Saravanan, Kumar and Sa, 2011b; Kumar, Dewangan, Lawate, Bahadur, and Prajapati, 2019). These forms can exhibit various solubilities and availabilities, depending on factors such as soil pH, exchangeable, adsorbed, chelated, or in the form of secondary clay minerals or primary minerals (Alloway, 2008; Navarro and Navarro, 2013; Noulas, Tziouvalekas and Karyotis, 2018). The solubility of Zn oxides and carbonates in alkaline soils can be limited. These forms can exhibit various solubilities and availabilities, depending on factors such as soil pH, are not rock composition, organic matter content, the texture, temperature, flooding, and the pH (Pradhan et al., 2021).

Assimilation

The solubility of Fe in soil is influenced by pH, redox conditions, and soil composition (Lindsay and Norvell, 1978; Navarro and Navarro, 2013; Lucena and Hernández-Apaolaza 2017; Sheng et al. 2021). In calcareous soils, approximately 0.5% of the total Fe is predominantly regulated by Fe (III) oxides, with soluble oxides such as ferrihydrite in highly oxidized soils and siderite in reduced soils playing significant roles (Lucena and Hernández-Apaolaza, 2017; Thorat, 2021; Rasheed, 2023). Rice cultivation occurs in two ecosystems: non-flooded upland areas (aerobic) and flood-prone lowland areas (anaerobic), with a pH between 5.5 and 6.5 (Fageria, Wander, and Silva, 2014; Infoagro, 2020). Given the low availability of Fe in soil, it requires the use of Strategies I and II for absorption (Petrik, Zhai, Haas, and Decristoforo, 2017; Yang, Li and Chen, 2020; Roskova, Skarohlid, and McGachy, 2022).

On the other hand, Mn in soil exists in a reduced form as Mn^{2+} (highly soluble and available), and in oxidized form as Mn^{3+} and Mn^{4+} (insoluble and unavailable) for plants (Navarro and Navarro, 2013; Haque et al. 2015; K.B. et al. 2023). The presence of Mn in soil is influenced by physical, chemical, and microbiological factors, with pH and redox conditions being the most significant (Husson, 2013). In acidic soils with a pH less than 5.5, Mn oxides solubilize and release Mn^{2+} into the soil solution (Millaleo, Reyes-Díaz, Ivanov, Mora and Alberdi, 2010; Herndon and Brantley, 2011).

On the contrary, water-soluble and exchangeable Zn constitute the fraction directly available for absorption, existing as free ions (Zn^{2+} and $ZnOH^{+}$), soluble organic complexes, and labile Zn (unstable) (Noulas, Tziouvalekas and Karyotis, 2018; Liu et al., 2020). The dominance of Zn^{2+} or $ZnOH^{+}$ depends on soil pH, with $ZnOH^{+}$ prevailing at pH above 7.7 and $Zn(OH)_2$ dominating at pH above 9.1 (Alloway, 2008; Kaur et al., 2024). It has been observed that in soils with a pH below 5.8, the exchangeable Zn fraction increases from organically complexed Zn (Yang et al., 2010).

Two mechanisms for micronutrient adsorption by clays and organic matter are apparent: one occurring in acidic conditions, related to cation exchange, and the other in alkaline conditions, involving chemisorption and the formation of complexes by organic ligands. In lowland or flood conditions, Zn availability in rice crops decreases due to the low redox potential, leading to the formation of non-exchangeable Zn complexes bound to clay particles. Additionally, in alkaline soils, free Zn precipitates as $Zn(OH)_2$, raising the pH, or as ZnS in sodic and calcareous soils (Sharma et al., 2013; Rose et al., 2013; Kaur et al. 2024).

Zinc absorption by plants occurs through mechanisms such as mass flow of passive nutrient transfer, diffusion near the roots (from the rhizosphere to the roots), and root interception within the soil profile.

It is transported to above-ground plant parts and intracellularly for metabolic processes (Bashir et al., 2012; Haroon and Khan, 2022). Key genes involved in Zn absorption are OsZIP1 and OsZIP3, whilst those important to the translocation within the root include OsZIP4, OsZIP5, OsZIP8 (Bashir et al., 2012). Zinc translocation from the leaves to plant organs occurs through the symplast and apoplast via the xylem, with high levels of the micronutrient detected in the phloem (Liao et al. 2023Marschner, 1995).

The Importance

Iron, Magnesium and Zinc play pivotal roles in the growth, development, and yield of rice. However, 50% of rice soils are deficient in Zn, and 30% are deficient in Fe (Ullah et al., 2017; Nadeem and Farooq, 2019). Iron plays a role in electron transport, redox systems, sulfur and nitrogen metabolism, DNA synthesis, hormone production, coenzymes, chlorophyll biosynthesis, and heme synthesis by ferrochelatase (Zhang et al., 2012; Wang et al., 2017; Ning et al., 2023). In upland areas with alkaline and calcareous soils, Fe levels below 50 mg kg^{-1} an cause nutritional disorders, and reduced productivity (Marschner, 2011; Rice Knowledge Bank, s.f.). In alkaline soils with high bicarbonate concentrations, the solubility and absorption of Fe, Mn and Zn decrease, especially in Strategy I plants, which rely on inducible ferric reductases for the cellular transport of Fe (Lucena et al., 2003; Zhang et al., 2019; Castilla and Tirado, 2019). In New Delhi, Kumar, Dinesh, Singh and Rishi (2015) found that foliar pulverization of 2.0% Fe sulfate in rice crops increased the yield (5.24 t ha^{-1} compared to the control's 4.32 t ha^{-1}). In Nigeria, Sakariyawo, Oyedeji and Soretire (2020) obtained a yield of 196.40 g per plot in rice in upland areas with sufficient Fe (8.00 mg kg^{-1}), whereas in plants deficient in Fe (3.05mg kg^{-1}), the yield was 10,00 g per plot.

Mn is an enzymatic activator in the Krebs cycle and in urea (arginase). It is involved in chlorophyll synthesis, is essential in the Mg-protein complex which transports electrons from the water to the photosystem II, and is part of Mn-SOD (Manganese superoxide dismutase)- an isoenzyme present in mitochondria and peroxisomes and, less frequently, in chloroplasts (Marschner, 2011; Grundmeier and Dau, 2012). The appropriate Mn level ranges from 30 to 600 mg kg^{-1}; levels below 20 mg kg^{-1} cause interveinal chlorosis, shor-t leaves, and atrophy (Rice Knowledge Bank, s.f; Ullah et al., 2017).

This Mn deficiency is rarely seen in flooded rice. However, it has been observed in direct-seeded aerobic rice systems due to the oxidation of Mn^{2+}, a process with leads to the precipitation of Mn^{3+} and Mn^{4+} oxides. The application of Mn (0.02 mol l^{-1} Mn) in flooded and direct-seeded aerobic rice plants in Pakistan improved grain yield by 25.1% (Tao et al., 2007; Li et al., 2016). In China, it was found that the application of Mn in rice pots with sandy loam soil improved the rice quality. For early-season rice, the application of 1.100 mg of $MnSO_4$ resulted in 20.83% more panicles, and the application of 250 mg of $MnSO_4$ led to a weight increase of 12.96% in 1000 rice grains compared to the control (without Mn). Similarly, for late-season rice, the weight of 1,000 grains was 9.89% higher than the control, as found by Ullah et al. (2017).

Zinc is a micronutrient crucial for cytochrome synthesis, photosynthesis, phytohormone activity, and the metabolism of carbohydrates, nitrogen, lipids, and nucleic acids. It also plays a role in tryptophan and protein synthesis, as well as gene expression and regulation. Zinc stimulates enzymatic activities such as phosphatases and decarboxylases, contributes to the formation of flavonoid pigments and ascorbic acid, and serves as an auxin activator (Fageria, Dos Santos, and Cobucci, 2011; Saxena, Das, and Choudhury, 2017; Noulas, et al., 2018; Prakash, Sobhana, Sujithra and Hemalatha, 2019). The appropriate Zn level is 20 ppm. Levels below 10 mg kg^{-1} lead to red pigmentation in the lower leaves of plants, affecting flowering and anthesis. Leaf and root atrophy occurs, and grain yield reduces due to oxidative stress (Lee, Wissuwa, Zamora and Ismail, 2017; Gorain, Paul, and Parihar, 2022). In flooded conditions, rice's phosphate and bicarbonate concentrations increase, reducing Zn availability due to the low redox potential in the soil (Sharma et al., 2013; Prakash et al., 2019).

Fageria et al. (2011) reported a 97% higher increase in the grain yield in greenhouse-cultivated rice in Inceptisol soils in Brazil with 20 mg of Zn kg^{-1} compared to the control. Rengel, Cruz, Croce, Montaño and Chirinos (2012) reported a 63% increase in height and a 2.76% increase in rice grain weight following foliar application of Zn (350 g ha^{-1}). Ghoneim (2016) found that the applying 15 kg Zn ha^{-1} in the soil resulted in maximum plant height (100 cm) and the highest grain yield of 9.60 tons ha^{-1}. Utilizing Zn-solubilizing rhizobacteria is the most effective approach to correct Zn deficiency in a sustainable agricultural production system. Plant growth-promoting rhizobacteria (PGPR) colonize the rhizosphere and promote rice growth mechanisms (Pradhan et al., 2021).

Main Solubilizing Microorganisms for the Micronutrients Fe, Mn, And Zn in Rice Cultivation

Plant Growth- Promoting Bacteria (PGPR) such as *Bacillus, Pseudomonas* and *Azospirillum* promote the growth of rice plants and may possess properties that aid antibiosis and induction systematic resistance against pathogens.

Bacillus, a genus of Gram-positive bacteria from the Bacillaceae family, is rod-shaped and exhibits aerobic, or on occasion facultative anaerobic, growth. It thrives in neutral pH conditions and forms endospores, enabling survival in various extreme environmental conditions such as extreme temperature, pH, and salinity (Govindasamy et al., 2010). In crop rhizospheres, bacteria like *B. subtilis, B. licheniformis, B. megaterium, and B. pumilus* are commonly found (Griffiths, 2013; Tiwari et al., 2019).

Pseudomonas, a genus of polarized aerobic, Gram-negative rod-shaped bacteria from the Pseudomonadaceae family, exhibits optimal growth at a pH of 6 and a temperature of 30°C (Sivakamasundari and Usharani, 2012; Shruti, Arun, and Rai, 2013; Kumar et al., 2017; Meena et al., 2019).

Azospirillum, a rhizobacterium from the Rhodospirillaceae family, consists of curved Gram-negative rods. It is mobile via peritrichous flagella; strictly aerobic, and non-symbiotic nitrogen fixers that inhabit soil and easily adapt and grow in anaerobic, microaerobic, and aerobic conditions. *Azospirillum* thrives best at a pH between 6 to 8 (Botero, Castaño Zapata, and Saldarriaga, 2013).

Research indicates that rice plots treated with specific strains of *Pseudomonas Jesenii* (R62) and *Pseudomonas synxantha* (R81) at a concentration of 1 x 10^8 CFU showed improved Fe absorption, resulting in an increased average rice seed yield of 22.66 g ton^{-1}compared to the control yield of 15.61 g ton^{-1}. Conversely, rice plants inoculated with *Bacillus* sp. (14B) exhibited an average Fe concentration of 18.55 g ton^{-1} in rice seeds, surpassing the control of average of 15.61 g ton^{-1} (Gusain and Sharma; 2019).

Sharma, Shankhdhar & Shankhdhar (2013) in India, applied three standard PGPR strains (*Pseudomonas putida* MTCC 102, *Pseudomonas fluorescens* MTCC 103, *and Azospirillum lipoferum* MTCC 2694) to the roots of 21-day-old rice seedlings and found that the highest active Fe concentration was achieved with the inoculation of *Azospirillum lipoferum* in different rice genotypes. The Pusa basmati-1 genotype exhibited the highest concentration at 25.30 (µg g^{-1} DW) compared to the control's 14.39 (µg g^{-1} DW).

In Brazil, it has been reported that *Bacillus* sp. applied at a concentration of 1 x 10^8 CFU is the main Zn-solubilizing microorganism (Nascente et al., 2017). In Pakistan, *Bacillus* sp. SH-10 and *Bacillus cereus* SH-17 at a concentration of 1x10^9 CFU (Shakeel et al., 2015); in India, *Pseudomonas aeruginosa* at a concentration of 1 x 10^9 (Gontia-Mishra et al., 2017), *Pseudomonas fluorescens* and *Pseudomonas aeruginosa* at a concentration of 1 x 10^6 (Gontia-Mishra et al., 2016), as well as *Pseudomonas putida* MTCC 102, *Pseudomonas fluorescens* MTCC 103, and *Azospirillum lipoferum* MTCC 2694 at a concentration of 1 x 10^7 CFU (Sharma et al., 2014).

Furthermore, they report on *Pseudomonas jessenii* in combination with *Pseudomonas synxantha* (R62 + R81) and *Bacillus* sp. (14B) at a concentration of 1 x 10^8 CFU. In Pakistan, in the roots of basmati-385 rice and in basmati from clayey and saline soil, 234 isolates of *Bacillus* sp. were obtained at a concentration of 1x10^9 CFU, of which 27 solubilized Zn minerals, such as Zn phosphate, carbonate, and oxide. *Bacillus* SH-10 had the largest solubilization zone of 24 mm with Zn phosphate. *Bacillus cereus* SH-17 achieved a maximum solubilization of 15 mm with Zn oxides and carbonates. *Bacillus* sp. and *Bacillus cereus* improved Zn translocation to the grains and increased the yield of the mentioned varieties from 18% to 49% (Shakeel, Rais, Hassan & Hafeez, 2015).

Pseudomonas aeruginosa has shown Zn solubilization greater than 10 mm in supplemented media, probably due to the production of organic acids such as gluconic acid, 2-ketogluconic acid, 5-ketogluconic acid, and pentanoic acids (Gontia-Mishra et al., 2016; Gontia-Mishra et al., 2017; Gusain & Sharma 2019). In India, it was found that the application of *Pseudomonas jessenii* (R62) and *P. synxantha* (R81) at a concentration of 1 x 10^8 CFU to rice varieties Swarna, Swarna sub1, IR-64, and IR-64 sub1 twice at the time of seed sowing, and transplanting significantly affected Zn absorption, resulting in a micronutrient content in rice seeds of 22.75 g ton^{-1} compared to the control's 16.60 g ton^{-1}. The same authors determined that the Mn concentration in rice seeds was higher at 26.66 g ton^{-1} with the application of *P. jessenii* (R62) and *P. synxantha* (R81).

Nascente et al. (2017) found greater Fe and Mn absorption in rice seeds inoculated with *Pseudomonas* sp. at a concentration of 1 x 10^8 CFU, obtaining 169 mg Kg^{-1} and 2190 mg Kg^{-1} compared to the controls' 122 mg Kg^{-1} and 1.864 mg kg^{-1}, respectively. Similarly, seeds inoculated with *Bacillus* sp. had the highest Zn content at 48 mg Kg^{-1} compared to the control's value of 43 mg Kg^{-1}. Ikhajiagbe & Ohanmu (2019) found that after 13 weeks of applying *Bacillus subtilis* and *Pseudomonas aureginosa* at a concentration of 1.52 x 10^5 CFU/g to rice plants, the yield growth increased by 0.53 g compared to that obtained by the control, 0.28 g.

Characteristics And Main Use of Bacterial-Based Biofertilizers Promoting Fe, Mn, And Zn Nutrition

Utilizing biofertilizers containing *Bacillus* sp., *Pseudomonas* sp., and *Azospirillum* sp. represents a promising approach to achieving optimal crop nutrition while maintaining environment integrity (Velasco Sánchez, Delgado García, and Moreno Lora, 2017). Bacillus bacteria, belonging to the Bacillaceae family, are Gram- positive bacterias aerobic or facultative anaerobic growth. They thrive in neutral pH environments and can withstand extreme temperature and pH conditions, including saline conditions (Griffiths, 2013; Tiwari, Prasad & Lata, 2019). Common species include *B. sibtitlis*, *B. licheniformis*, *B. megaterium*, and *B. pumilus* (Tiwari et al., 2019; Tiwari, Prasad and Lata, 2019).

Pseudomonas, a genus of MIGULA (1894) found that Gram-negative bacteria of the Pseudomonadaceae family, have approximately 191 diverses species (Anzai, Kim, Park, Wakabayashi and Oyaizu, 2000; Sankari Meena et al., 2019). These bacteria exhibit optimal growth conditions at a pH of 6 and a temperatura of 30°C (Kumar et al., 2017; Sankari Meena et al., 2019; Shruti K, Arun K, 2013).

Azospirillum, a genus of bacteria from the Rhodospirillaceae family, comprises Gram-negative bacilli capable of thriving under anaerobic, microaerobic, and aerobic conditions. They exhibit optimal growth at a pH range of 6 to 8 (Botero, Castaño Zapata, and Saldarriaga, 2013).

An agricultural inoculant for the solubilization of soluble micronutrients in soil for promoting the production of physiologically active substances is a consortium of *Bacillus licheniformis* (7×10^9 CFU ml^{-1}), *Bacillus subtilis* (6×10^9 CFU ml^{-1}), and *Pseudomonas fluorescens* (7×10^9 CFU ml^{-1}). Biofertilizers containing *Bacillus megaterium* (1×10^8 CFU ml^{-1}) exhibit direct phytohormonal action on crop growth and productivity, favoring the absorption of minerals such as Fe, Mn, and Zn, as well as solubilizing macronutrients like phosphorous. Similarly, biofertilizers with *Pseudomonas* sp. (1×10^8 CFU mL^{-1}) enhance growth and yields (Kumar, Meena & Singh, 2016). *Pseudomonas fluorescens* also improves yield and provides biological control over pathogens through siderophores production.

Azospirillum sp. (7×10^8 CFU mL^{-1}) serves as a biological inoculant promoting plant growth when applied to soil or seeds. *Azospirillum brasilense* M3 (1×10^8 CFU mL^{-1}) supplies plants with essential N-P-K nutrients, stimulates phytohormones production, and fosters plant growth (Pereg, de-Bashan, & Bashan, 2016). In rice cultivation, *Azospirillum brasilense* (1×10^9 CFU mL^{-1}) stimulates the synthesis of indole-3-acetic acid (IAA) and plant growth regulators such as gibberellins, cytokinins, and ethylene (Bashan & de-Bashan, 2010).

Commercially available under various brand names, *Bacillus* sp., *Pseudomonas* sp., and *Azospirillum*- based biofertilizers are offered alone or in mixtures tailored for rice cultivation in countries such as Mexico, Colombia, and Spain (Portal Tecnoagrícola, 2023; Organización Pajonales SAS, 2023; ICA; 2023).

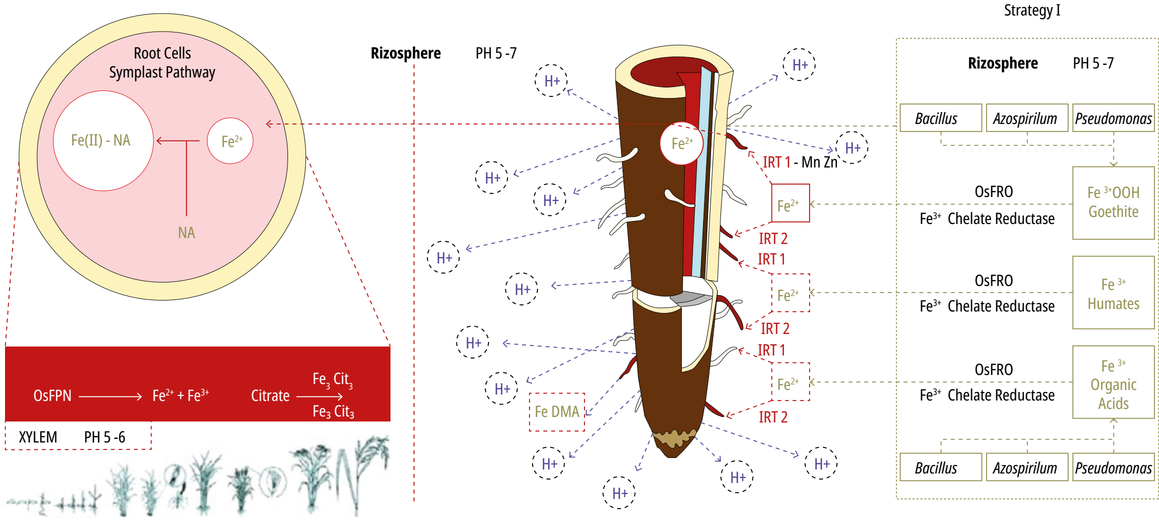
Mechanisms Involved in the Solubilization of The Micronutrients by the Microorganisms Bacillus, Pseudomonas, and Azospirillum

To address (Fe) deficiency in calcareous soils, rice employs Fe absorption mechanisms that integrate two strategies within a specialized system (Ishimaru et al., 2006; Kar & Panda, 2020). However, this crop can adapt to conditions where Fe^{2+} is more prevalent than Fe^{3+} (Aguado-Santacruz et al., 2012). In strategy I, first, protons (H^+) are released from the root plasma membranes, acidifying the soil and enhancing the solubility of Fe^{3+}. Secondly, the activity of ferric reductase-oxidase (OsFRO) enhances the ability to reduce chelated iron III (Fe^{3+}) to iron (II) Fe^{2+} on the root surface. Thirdly, Fe^{2+} is absorbed across the root plasma membrane, reduced by Fe(III) chelate reductase encoded by genes (iron transporters) IRT1 and IRT2, which encode Fe(II) transporters. Moreover, the IRT1 gene is responsible for Zn and Mn absorption as well (Ishimaru et al., 2006; Marschner, 2011; Wairich et al., 2019; Kar & Panda, 2020; Ning et al., 2023). (Refer to Figure 1).

Wairich et al. (2019) demonstrated that *Bacillus subtilis* GB03 acidifies the rhizosphere and activates strategy I's Fe absorption responses, resulting in a high content of endogenous plant iron. *Bacillus subtilis* bacteria can directly activate strategy I for Fe acquisition in *Arabidopsis thaliana* plants without colonizing the plant's roots. This mechanism is attributed to the production of volatile organic acids by the microorganism (Aguado-Santacruz et al., 2012).

In strategy II (refer to Figure2), rice plants synthesize and excrete phytosiderophores (PS) of the mugineic acid (MA) family, derived from deoxymugineic acid (DMA), to chelate Fe^{3+} into Fe^{3+}PS

Figure 1. Procedure for Iron Uptake, Symplastic Transport, and Xylem Transport in Rice



Source: Adapted from Ariga *et al.* (2014).

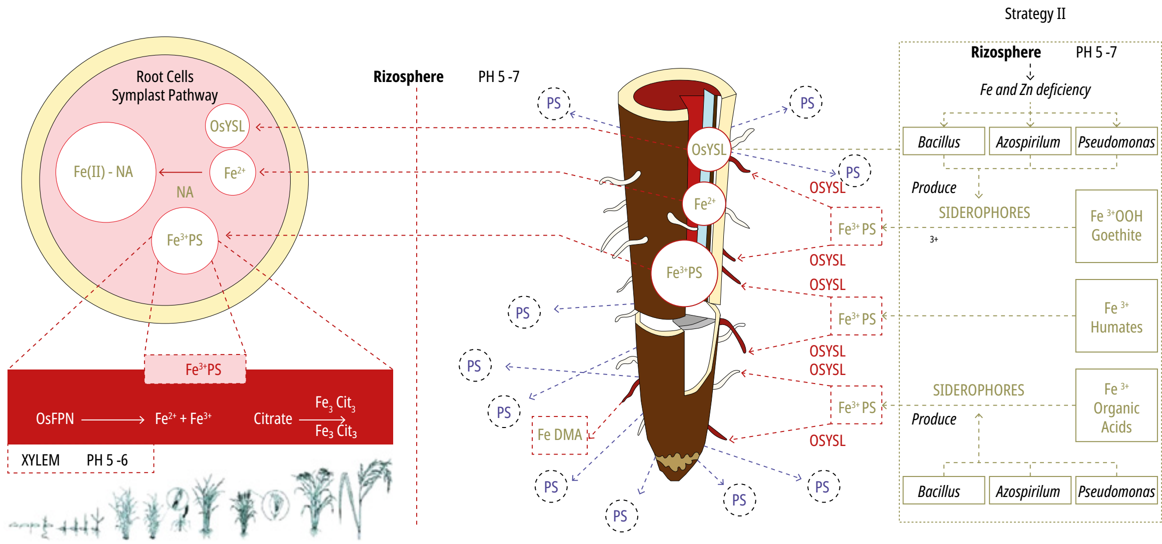
complexes in the plant root through the OsYSL15 protein. The OsYSL9 protein is possibly responsible for transporting Fe (III)-DMA and Fe (II)-nicotianamine (NA) into the endodermis of the root (Inoue et al., 2009; Nozoye et al., 2011; Senoura et al., 2017; Kawakami & Bhullar, 2018; Q. Wu et al. 2022). Internal translocation of Fe and Mn to the shoots and seeds is facilitated by the OsYSL2 protein. Meanwhile, regarding Mn transport and regulation in rice, there is limited research (Ishimaru et al., 2010; Petrik, Zhai, Haas, and Decristoforo, 2017). In rice plants with low Fe concentrations, both deoxymugineic acid (DMA) and mugineic acid (MA) were found, with PS (μM) and Fe (μM) concentrations ranging from 0.49 μM (Nozoye et al., 2011; Ariga, Hazama, Yanagisawa, and Yoneyama, 2014). The release of PS, akin to the uptake of Fe^{3+}-PS complexes by the plant, occurs after exposure to the first light rays, where the complex enters the cytoplasm through Fe^{3+}-PS transporters attached to protons on the plasma membrane of root cells (Ishimaru et al., 2006).

Under conditions of Fe and Zn deficiency, microorganisms synthesize and secrete low molecular weight Fe-chelating proteinaceous siderophores of the catecholate, hydroxamate, phenolate, and carboxylate types to enhance the availability of Fe^{2+} and transport across the plant cell membrane (Kumar et al., 2017; Hofmann, Retamal-Morales, and Tischler, 2020; Roskova et al., 2022).

Das, Prasad and Srivastava (2007) reported the large- scale synthesis of siderophores in species such as *Bacillus, Pseudomonas, Azospirillum*, among others. *Bacillus megaterium* has the capacity to produce siderophores (Santos, Neto, Machado, Soares, & Soares, 2014). Siderophores are synthesized from L-methionine and involve enzymes such as S-adenosylmethionine synthetase, nicotianamine synthase, nicotianamine aminotransferase, and desoximugineic acid synthase (Roskova et al., 2022). The synthesis of siderophores in rice plants was initially studied by Takagi (1976). Bacterial siderophores, like pyoverdine produced by *Pseudomonas fluorescens*, exhibit high affinity for iron (Yehuda et al., 1996; Bonneau, Roche & Schalk, 2020).

The availability of Mn in the soil varies and depends on numerous environmental and biotic soil factors. Plants require Mn^{2+} at a much higher concentration than fungi and bacteria (Marschner, 1995, Khoshru et al., 2023). Many bacteria have sophisticated mechanisms for coordinating the detection of Mn and the responding to oxidative stress. For instance, *Bacillus subtilis* possesses a coordinated network of metalloproteins, including a Fe^{2+} uptake regulator (plasma membrane), an

Figure 2. Process of Strategy II in Rice



Source: Adapted from Ariga *et al.* (2014).

Mn^{2+} transport regulator (MntR), and a Fe^{2+}/Mn^{2+} peroxide regulator repressor (PerR) of genes. This network regulates intracellular concentrations of Fe^{2+} and Mn^{2+}, detects H_2O_2 concentrations, and ultimately controls, through PerR, oxidative stress response genes (Herbig and Helmann, 2001; Sieprawska et al. 2024).

Zinc-solubilizing bacteria employ specific mechanisms to transform insoluble forms of Zn into soluble forms that are easily absorbed by plants. They achieve this through chelation, forming chelating compounds by binding with Zn, and through acidification, producing organic acids that reduce the soil pH, thereby facilitating the mobilization of Zn and improving root growth and absorption area (Neumann and Römheld, 2002; Subramanian, Tenshia, Jayalaskshmi, Ramach and Ran 2009). In such cases, the PGRP group of bacteria, especially *Bacillus* sp. and *Pseudomonas fluorescens*, demonstrate Zn solubilization across a wide range of Zn minerals. Additionally, *Bacillus megaterium* and *Bacillus edaphicus* increase Zn availability in the soil. These mechanisms also involve the secretion of root chemical exudates, providing an additional benefit to the solubilization process of this micronutrient (Maheshwari, 2012). For example, *Pseudomonas fluorescens* secretes gluconic and 2-ketogluconic acids into the rice crop during Zn phosphate solubilization (Di Simine, Sayer & Gadd, 1998). Some Zn solubilization mechanisms function via the production of indole-3-acetic acid (IAA), as determined by growing microorganism strains like *Pseudomonas* on LB agar plates supplemented with 100 µg mL^{-1} of tryptophan (Shrivastava and Kumar, 2011). Additionally, anions can chelate Zn and enhance its solubility (Jones & Darrah, 1994). Other mechanisms in Zn solubilization include the production of siderophores (Saravanan et al., 2011b; Northover et al. 2021), oxidoreductase systems in cell membranes, and chelating ligands (Singh et al., 2012). Strains of *Bacillus* sp. and *Bacillus cereus* have been found to enhance the translocation of Zn and other nutrients to the grains, thereby increasing rice variety yields (Shakeel et al., 2015; Barbosa et al., 2023).

The various mechanisms mentioned for the solubilization of the micronutrients Fe, Mn and Zn, associated with microorganisms *Bacillus*, *Pseudomonas* and *Azospirillum*, are presented in Table 1.

Table 1. Different mechanisms involved in the solubilization of the micronutrients Fe, Mn and Zn by the microorganisms *Bacillus*, *Pseudomonas* and *Azospirillum*.

Genus and species of microorganism	Mechanisms of action			References
	Fe	Mn	Zn	
Bacillus: B. sp.(1), *B. subtilis* (2), *megaterium* (3), *B.* sp. *B. megaterium* y *B. edaphicus*.(4) *B.* sp. y *B. cereus* (5) *B. subtilis*, *B. licheniformis*, *Azospirillum* (6)	Strategy II y Strategy II (1) secreción siderophore secretion of Fe (1), (2), (3), (5) Solubilization of Fe (1), (5), (6)	Solubilization of Mn (1), (3), (5), (6)	Solubilization of Zinc (1), (3), (4), (5), (6) siderophore secretion (4), (5)	Herbig & Helmann, 2001; Ishimaru et al., 2006; Das et al., 2007; Inoue et al. 2009; Nozoye et al., 2011; Marschner, 2011; Maheshwari, 2012; Aguado-Santacruz et al., 2012; Srivastava et al., 2013; Santos et al., 2014 ; Ariga et al., 2014; Shakeel et al., 2015; Kumar et al.., 2017; Senoura et al., 2017; Kawakami & Bhullar, 2018; Wairich et al., 2019; Hofmann et al., 2020; Kar et al., 2020; Panda, 2020; Roskova et al., 2022; Q. Wu et al. 2022; Barbosa et al., 2023; Ning et al., 2023; Sieprawska et al. 2024; ICA, 2020. www.ica.gov.co
Pseudomonas: *P. florescence*(1), *P. putida* MTCC 102 y *P. fluorescens* MTCC 103 (2), *P.* sp (3), *P. aeruginosa* y *P. fluorescens* (4), *P. jessenii* en combinación con *P. synxantha* (R62 + R81) (5), P. sp. (6)	Solubilization of Fe (2),(5), (6)	Solubilization of Mn (2), (6)	Solubilization of Zn phosphate. (Chelating Compounds) (1) Solubilization of Zinc (2), (4), (6) siderophore secretion (2)	Santos et al., 2014 Roskova et al., 2022 Saravanan et al. 2007; Northover et al. 2021; Shakeel et al., 2015; Meena et al., 2016 Gontia-Mishra et al., 2017 Bapiri et al., 2012 & Gontia-Mishra et al., 2016; Gontia-Mishra et al., 2017 Gusain & Sharma, 2019; Sharma et al., 2014 Sharma et al., 2014 Shakeel, Rais, Hassan, & Hafeez, 2015 Maheshwari, 2012 Di Simine, Sayer & Gadd, 1998
Azospirillum: *A. lipoferum* MTCC 2694 (1) *A. brasilense* M3 (Bulhnova), *A. brasilense* (2) *Azospirillum* sp. Dimazos SC (3)	Siderophore production (1)		Solubilization of Zn (1), (2),	Santos et al., 2014 Roskova et al., 2022 Sharma et al., 2014; Sharma et al., 2013 Flores et.al., 2010; Del Amor & Cuadra, 2011; Schoebitz, Mengual, & Roldán, 2014 https://www.probelte.es/productos/detalle/es/bulhnova/137 https://www.buscador.portaltecnoagricola.com/vademecum/esp/producto/KIPLANT%20iNmass ICA, 2020. www.ica.gov.co; Maheshwari, 2012 El-Sayed et al., 2014; Sharma et al., 2014; Abaid-Ullah et al., 2015

Discussion

The microorganisms *Bacillus, Pseudomonas*, and *Azospirillum* exert an effect on the availability of Fe, Mn, and Zn in calcareous soils for rice cultivation by secreting siderophore compounds that absorb micronutrients in the form of chelates through plant roots. *Bacillus megaterium*, *Pseudomonas putida*, *P. fluorescens*, and *P. aeruginosa* are commonly reported as producers of siderophores and for transporting minerals internally to plant cells, thereby enhancing crop nutrition (Das et al., 2007; Aguado-Santacruz et al., 2012; Srivastava, 2013; Sharma et al., 2014; Santos, 2014; Shakeel et al., 2015; Gusain & Sharma, 2019). However, Ariga et al. (2014) attribute the solubilization of unavailable micronutrients to phenols or aromatic compounds. Ishimaru et al. (2006) mention that carrier genes are required by plants to transport chelated minerals for micronutrient absorption, as seen with *Bacillus subtilis*, whose oxidative stress genes regulate Fe^{2+} and Mn^{2+} (Herbig & Helmann, 2001). Consequently, it can be inferred that these microorganisms contribute to micronutrient assimilation, not only through Siderophore production but also through the synthesis of phenols and other plant growth-promoting substances such as indole acetic acid, abscisic acid, and cytokinins (Nautiyal, 2016; Tiwari & Singh, 2017; Vimal et al., 2019).

When these microorganisms are applied in rice cultivation, they positively impact the panicles plant height, tillers numbers, and grain size and weight (Shakeel et al., 2015; Meena et al., 2016; Gontia-Mishra et al., 2017; Nascente et al., 2017; Yang, 2020). These mechanisms, at a biochemical level, may involve enzymatic reactions, influencing plant growth-promoting substances, thereby affecting rice plant and grain formation (Noulas et al., 2018; and Prakash et al., 2019). Additionally, environmental and edaphic conditions play a crucial role in plant development and grain quality. In this way, the concentrations of minerals such as Fe, Mn and Zn the depend on pH (between 5 and 7), soil texture, rice genetics, and crop nutrition (Marschner, 2011; Shakeel et al. 2015; Ullah et al., 2017; Gontia-Mishra et al., 2017; Infoagro, s.f).

In the market, registered biofertilizers containing *Bacillus, Pseudomonas*, and *Azospirillum* (Dimazos® SC-Biocultivos S.A., Bulhnova-Probelte, S.A.U, Kiplant iNmass®- Portal Tecnoagrícola, Fosfobacter®- Organización Pajonales SAS, Actifos SL Mycros®-Agro Valley SAS) have demonstrated favorable results in solubilization Fe, Mn and Zn micronutrients and can be used in rice agriculture.

However, further research is recommended on the application of *Pseudomonas* and *Bacillus* as biofertilizers to enhance Mn solubilization in rice cultivation, given its significance as a micronutrient for crop yield. The majority of research on these microorganisms focuses in solubilizing micronutrients Fe and Zn (Noulas, et al. 2018; Prakash et al. 2019). Similarly, expanding knowledge on azospirillium application is suggested, as it is the least mentioned genus of plant growth-promoting, when compared with pseudomonas and bacillus for the solubization of Fe, Mn in the aforementioned crops.

Conclusions

Iron, Mn, and Zn solubilizing microorganisms from the genera *Bacillus, Pseudomonas,* and *Azospirillum* have been extensively utilized in rice cultivation across various countries ncluding India (53%), Pakistan (13%), Brazil (7%), China (7%), Egypt (7%), Iran (7%), and Belgium (6%). The inoculation of *Bacillus, Pseudomonas,* and *Azospirillum* bacteria into rice varieties grown in calcareous soils with limitation in Fe,Mn, and Zn facilitates the availability of these micronutrients and the formation of siderophores by the plants. This process promotes soil acidification and aids in converting non-assimilable forms into soluble ones, thereby enhancing rice's metabolic and enzymatic processes, ultimately leading to improved crop development, yield, and grain quality.

Globally, more research has been conducted on *Pseudomonas* and *Bacillus* for the solubilization of Fe and Zn minerals compared to Mn, where fewer experiments in rice cultivation have been identified. *Azospirillum,* on the other hand, is less frequently utilized for Fe, Mn, and Zn fertilization. The utilization of these bacteria holds promise for increasing rice yield, quality, and productivity while mitigating negative environmental impacts associated with synthetic fertilizers.

Funding

This manuscript has been published with the financial support of the Spanish project PID2022-141721OB-C2, funded by the Ministry of Science and Innovation (MICIN), the Agencia Estatal de Investigación, and the Feder funds.

Acknowledgements

We extend our gratitude to the 'Universidad Internacional del Trópico Americano Unitrópico' and the 'Corporación Colombiana de Investigación Agropecuaria Agrosavia' for their invaluable contribution to data analysis and support in the preparation of the final manuscript. Special thanks to Andres Felipe Barahona Rojas for his assistan with image design, and to Cecilia Catmur for her English translation services.

References

[1] Acevedo, O., Ortiz, E., Cruz, M., & Cruz, E. (2004). Role of Iron Oxides in Soils. *Terra Latinoamericana*, *22*(4), 485–497. Retrieved from https://www.redalyc.org/pdf/573/57311096013.pdf

[2] Aguado-Santacruz, G. A., Moreno-Gómez, B., Jiménez-Francisco, B., García-Moya, E., & Preciado-Ortiz, R. E. (2012). Impacto de los sideróforos microbianos y fitosideróforos en la asimilación de hierro por las plantas: Una síntesis. *Revista Fitotecnia Mexicana*, *35*(1), 9–21.

[3] Aguilar-Bartels, Cindy et al. 2021. "Key Aspects for the Genetic Transformation of Rice (Oryza Sativa L.) Subspecies Indica by Agrobacterium Tumefaciens." Agronomia Mesoamericana 32(3): 764–78

[4] Alloway, B. J. (2008). Zinc in Soils and Crop Nutrition. *International Zinc Association, International Fertilizer Industry Association.*, 1–139. Retrieved from https://scholar.google.es/scholar?hl=es&as_sdt=0%2C5&q=Zinc+in+Soils+and+Crop+Nutrition&btnG=

[5] Alori, E. T., & Babalola, O. O. (2018). Microbial inoculants for improving crop quality and human health in Africa. *Frontiers in Microbiology*, *9*(SEP), 1–12. https://doi.org/10.3389/fmicb.2018.02213

[6] Ariga, T., Hazama, K., Yanagisawa, S., & Yoneyama, T. (2014). Chemical forms of iron in xylem sap from graminaceous and non-graminaceous plants. *Soil Science and Plant Nutrition*, *60*(4), 460–469. https://doi.org/10.1080/00380768.2014.922406

[7] Azziz, G., Monza, J., Etchebehere, C., & Irisarri, P. (2017). nirS- and nirK-type denitrifier communities are differentially affected by soil type, rice cultivar and water management. *European Journal of Soil Biology*, *78*, 20–28. https://doi.org/10.1016/j.ejsobi.2016.11.003

[8] Barboza-García, Adrián, Alexander Pérez-Cordero, And Lina Chamorro-Anaya. 2023. "Bacterias Endófitas Aisladas de Cultivo de Arroz (Oryza Sativa L.) Con Actividad Promotora de Crecimiento Vegetal." *Biotecnología en el Sector Agropecuario y Agroindustrial* 21(1): 28–38.

[9] Bashan, Y., & de-Bashan, L. E. (2010). How the plant growth-promoting bacterium azospirillum promotes plant growth-a critical assessment. *Advances in Agronomy*, *108*(C), 77–136. https://doi.org/10.1016/S0065-2113(10)08002-8

[10] Bashir, K., Ishimaru, Y., & Nishizawa, N. K. (2012). Molecular mechanisms of zinc uptake and translocation in rice. *Plant and Soil*, *361*(1–2), 189–201. https://doi.org/10.1007/s11104-012-1240-5

[11] Bonneau, Anne, Béatrice Roche, and Isabelle J. Schalk. 2020. "Iron Acquisition in Pseudomonas Aeruginosa by the Siderophore Pyoverdine: An Intricate Interacting Network Including Periplasmic and Membrane Proteins." *Scientific Reports* 10(1): 1–11.

[12] Botero, J., Castaño Zapata, C., & Saldarriaga. (2013). *Manual práctico de bacteriología vegetal*. Manizales, Colombia.

[13] Chauhan, B. S., Jabran, K., & Mahajan, G. (2017). Rice Production Worldwide. In *Rice Production Worldwide*. https://doi.org/10.1007/978-3-319-47516-5

[14] Chen, C. C., Dixon, J. B., & Turner, F. T. (1980). Iron Coatings on Rice Roots: Morphology and Models of Development. *Soil Science Society of America Journal*, *44*(5), 1113–1119. https://doi.org/10.2136/sssaj1980.03615995004400050046x

[15] Dal Cortivo, C., Barion, G., Ferrari, M., Visioli, G., Dramis, L., Panozzo, A., & Vamerali, T. (2018). Effects of field inoculation with VAM and bacteria consortia on root growth and nutrients uptake in common wheat. *Sustainability (Switzerland)*, *10*(9). https://doi.org/10.3390/su10093286

[16] Dal Cortivo, C., Ferrari, M., Visioli, G., Lauro, M., Fornasier, F., Barion, G., … Vamerali, T. (2020). Effects of Seed-Applied Biofertilizers on Rhizosphere Biodiversity and Growth of Common Wheat (Triticum aestivum L.) in the Field. *Frontiers in Plant Science*, *11*(February), 1–14. https://doi.org/10.3389/fpls.2020.00072

[17] Das, A., Prasad, R., & Srivastava, A. (2007). Siderophores: 1 Fungal Structure , Functions and Regulation. *Biotechnology*, *12*, 1–42.

[18] Di Simine, C. D., Sayer, J. A., & Gadd, G. M. (1998). Solubilization of zinc phosphate by a strain of Pseu-

domonas fluorescens isolated from a forest soil. *Biology and Fertility of Soils*, *28*(1), 87–94. https://doi.org/10.1007/s003740050467

[19] El-Sayed, W. S., Akhkha, A., El-Naggar, M. Y., & Elbadry, M. (2014). In vitro antagonistic activity, plant growth promoting traits and phylogenetic affiliation of rhizobacteria associated with wild plants grown in arid soil. *Frontiers in Microbiology*, *5*(DEC), 1–12. https://doi.org/10.3389/fmicb.2014.00651

[20] Fageria, N. K., Wander, A. E., & Silva, S. C. (2014). Rice (Oryza sativa) cultivation in Brazil. Indian Journal of Agronomy, 59(3), 350–358.

[21] Fageria, N. K., Dos Santos, A. B., & Cobucci, T. (2011). Zinc nutrition of lowland rice.

[22] Communications in Soil Science and Plant Analysis, *42*(14), 1719–1727. https://doi.org/10.1080/00103624.2011.584591

[23] Faostat. (2020). No Title. Retrieved from http://www.fao.org/faostat/es/

[24] Ghoneim, A. (2016). Effect of Different Methods of Zn Application on Rice Growth, Yield and Nutrients Dynamics in Plant and Soil. *Journal of Agriculture and Ecology Research International*, *6*(2), 1–9. https://doi.org/10.9734/jaeri/2016/22607

[25] Gontia-Mishra, I., S. Sapre, A. Sharma, and S. Tiwari. 2016. “Amelioration of Drought Tolerance in Wheat by the Interaction of Plant Growth-Promoting Rhizobacteria.” *Plant Biology* 18(6): 992–1000

[26] Gontia-Mishra, I., Sapre, S., & Tiwari, S. (2017). Zinc solubilizing bacteria from the rhizosphere of rice as prospective modulator of zinc biofortification in rice. *Rhizosphere*, *3*, 185–190. https://doi.org/10.1016/j.rhisph.2017.04.013

[27] Gorain, B., Paul, S., & Parihar, M. (2022). Role of soil microbes in micronutrient solubilization. *In New and Future Developments in Microbial Biotechnology and Bioengineering*. Elsevier., 131–150. https://doi.org/https://doi.org/10.1016/B978-0-32-385163-3.00018-1

[28] Govindasamy, V., Senthilkumar, M., Magheshwaran, V., Kumar, U., Bose, P., Sharma, V., & Annapurna, K. (2010). *Bacillus and Paenibacillus spp.: Potential PGPR for Sustainable Agriculture*. *18*, 333–364. https://doi.org/10.1007/978-3-642-13612-2

[29] Griffiths, M. W. (2013). Bacillus cereus and Other Bacillus spp. In *Journal of Petrology* (Vol. 369). https://doi.org/10.1017/CBO9781107415324.004

[30] Grundmeier, A., & Dau, H. (2012). Structural models of the manganese complex of photosystem II and mechanistic implications. *Biochimica et Biophysica Acta - Bioenergetics*, *1817*(1), 88–105. https://doi.org/10.1016/j.bbabio.2011.07.004

[31] Gusain, Y. S., & Sharma, A. K. (2019). PGPRs inoculations enhances the grain yield and grain nutrient content in four cultivars of rice (Oryza sativa L .) under field condition. *Journal of Pharmacognosy and Phytochemistry*, *8*(1), 1865–1870. Retrieved from http://www.phytojournal.com/archives/2019/vol8issue1/PartAE/8-1-333-575.pdf

[32] Haroon, M., & Khan, S. T. (2022). Microbial Biofertilizers and Micronutrient Availability. In *Microbial Biofertilizers and Micronutrient Availability*. https://doi.org/10.1007/978-3-030-76609-2

[33] He, Z., Zhu, Y., Feng, J., Ji, Q., Chen, X., & Pan, X. (2021). Long-term effects of four environment-related iron minerals on microbial anaerobic oxidation of methane in paddy soil: A previously overlooked role of widespread goethite. *Soil Biology and Biochemistry*, 161(July), 108387. https://doi.org/10.1016/j.soilbio.2021.108387

[34] Herbig, A. F., & Helmann, J. D. (2001). Roles of metal ions and hydrogen peroxide in modulating the interaction of the Bacillus subtilis PerR peroxide regulon repressor with operator DNA. *Molecular Microbiology*, *41*(4), 849–859. https://doi.org/10.1046/j.1365-2958.2001.02543.x

[35] Herndon, E. M., & Brantley, S. L. (2011). Movement of manganese contamination through the Critical Zone. *Applied Geochemistry*, *26*(SUPPL.), S40–S43. https://doi.org/10.1016/j.apgeochem.2011.03.024

[36] Hofmann, M., Retamal-Morales, G., & Tischler, D. (2020). Metal binding ability of microbial natural metal chelators and potential applications. *Natural Product Reports*, 37(9), 1262–1283. https://doi.org/10.1039/c9np00058e

[37] Husson, O. (2013). Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: A transdisciplinary overview pointing to integrative opportunities for agronomy. *Plant and Soil*, *362*(1–2), 389–417. https://doi.org/10.1007/s11104-012-1429-7

[38] Ikhajiagbe, B., & Ohanmu, E. O. (2019). Growth and yield assessment of rice (oryza sativa) after rhizo-inoculation with selected plant growth- promoting rhizobacteria in a ferric ultisol. Studia Universitatis “Vasile Goldiş”, Seria Ştiinţele Vieţii, 29(3), 134–143. Retrieved from http://www.studiauniversitatis.ro/pdf/29-2019/29-3-2019/Art. 5 Growth and Yield assesment of rice (Oryza sativa) after rhizo inoculation with selected plant growth promoting rhizobacteria in a ferric ultisol.pdf

[39] Información técnica agrícola, Infoagro. (s.f). El cultivo del arroz. https://www.infoagro.com/herbaceos/cereales/arroz.htm#:~:text=El%20arroz%20necesita%20para%20germinar,óptimo%20en%20los%2023%20ºC.

[40] Inoue, H., Kobayashi, T., Nozoye, T., Takahashi, M., Kakei, Y., Suzuki, K., … Nishizawa, N. K. (2009). Rice OsYSL15 is an iron-regulated iron (III)-deoxymugineic acid transporter expressed in the roots and is essential for iron uptake in early growth of the seedlings. *Journal of Biological Chemistry*, *284*(6), 3470–3479. https://doi.org/10.1074/jbc.M806042200

[41] Ishimaru, Y., Suzuki, M., Tsukamoto, T., Suzuki, K., Nakazono, M., Kobayashi, T., … Nishizawa, N. K. (2006). Rice plants take up iron as an Fe3+-phytosiderophore and as Fe2+. *Plant Journal*, *45*(3), 335–346. https://doi.org/10.1111/j.1365-313X.2005.02624.x

[42] Ishimaru, Y., Masuda, H., Bashir, K., Inoue, H., Tsukamoto, T., Takahashi, M., … Nishizawa, N. K. (2010). Rice metal-nicotianamine transporter, OsYSL2, is required for the long-distance transport of iron and manganese. *Plant Journal*, *62*(3), 379–390. https://doi.org/10.1111/j.1365-313X.2010.04158.x

[43] Jones, D.L., Darrah, P.R (1994). Role of root derived organic acids in the mobilization of nutrients from the rhizosphere. *Plant Soil* 166, 247–257.https://doi.org/10.1007/BF00008338

[44] Keerthana, K. S., & Lavanya, G. R. (2022). Heritability and Character Association among Yield Component Characters and Grain Yield in Rice (Oryza sativa L.). *International Journal of Plant & Soil Science*, 11(8), 1035–1044. https://doi.org/10.9734/ijpss/2022/v34i2231467

[45] Kumar, A., Verma, H., Singh, V. K., Singh, P. P., Singh, S. K., Ansari, W. A., … Abstract, 7. (2017). Role of Pseudomonas sp. in Sustainable Agriculture and Disease Management. *Agriculturally Important Microbes for Sustainable Agriculture*, *2*, 1–374. https://doi.org/10.1007/978-981-10-5343-6

[46] Kumar, L., Meena, N. L., & Singh, U. (2016). Zinc Transporter: Mechanism for Improving Zn Availability. *Biofortification of Food Crops*, 129–146. https://doi.org/10.1007/978-81-322-2716-8

[47] Kumar, V., Dinesh, K., Singh, Y. V., & Rishi, R. (2015). *Effect of iron fertilization on dry-matter production , yield and economics of aerobic rice (Oryza sativa). 60*(December), 547–553.

[48] Kumar, A., Dewangan, S., Lawate, P., Bahadur, I., & Prajapati, S. (2019). Zinc-Solubilizing Bacteria: A Boon for Sustainable Agriculture. 139–155. https://doi.org/10.1007/978-981-13-6536-2_8

[49] Kar, S., & Panda, S. K. (2020). Iron Homeostasis in Rice: Deficit and Excess. *Proceedings of the National Academy of Sciences India Section B - Biological Sciences*, *90*(2), 227–235. https://doi.org/10.1007/s40011-018-1052-3

[50] Kawakami, Y., & Bhullar, N. K. (2018). Molecular processes in iron and zinc homeostasis and their modulation for biofortification in rice. *Journal of Integrative Plant Biology*, *60*(12), 1181–1198. https://doi.org/10.1111/jipb.12751

[51] Khoshru, Bahman et al. 2023. "Enhancing Manganese Availability for Plants through Microbial Potential: A Sustainable Approach for Improving Soil Health and Food Security." *Bacteria* 2(3): 129–4

[52] Lee, J. S., Wissuwa, M., Zamora, O. B., & Ismail, A. M. (2017). Biochemical indicators of root damage in rice (Oryza sativa) genotypes under zinc deficiency stress. *Journal of Plant Research*, *130*(6), 1071–1077. https://doi.org/10.1007/s10265-017-0962-0

[53] Liao, Yumeng et al. 2023. "Response of Cd, Zn Translocation and Distribution to Organic Acids Heterogeneity in Brassica Juncea L." Plants: 1–16. https://doi.org/10.3390/plants12030479

[54] Li, M., Ashraf, U., Tian, H., Mo, Z., Pan, S., Anjum, S. A., … Tang, X. (2016). Manganese-induced regulations in growth, yield formation, quality characters, rice aroma and enzyme involved in 2-acetyl-1-pyrroline biosynthesis in fragrant rice. *Plant Physiology and Biochemistry*, *103*, 167–175. https://doi.org/10.1016/j.plaphy.2016.03.009

[55] Li, R., Jiang, Y., Xi, B., Li, M., Meng, X., Feng, C., … Jiang, Y. (2018). Raw hematite based Fe(III) bio-reduction process for humified landfill leachate treatment. *Journal of Hazardous Materials*, *355*(Iii), 10–16. https://doi.org/10.1016/j.jhazmat.2018.05.002

[56] Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA Soil Test for Zinc, Iron, Manganese, and Copper. *Soil Science Society of America Journal*, *42*(3), 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

[57] Lindsay, Willard L. (1979). TEN IRON. In Ed. John Wiley and Sons. (Ed.), *Chemical equilibria in soils*. New York, NY.

[58] Liu, X. M., Shaw, J., Jiang, J. Z., Bloemendal, J., Hesse, P., Rolph, T., & Mao, X. G. (2010). Analysis on variety and characteristics of maghemite. *Science China Earth Sciences*, *53*(8), 1153–1162. https://doi.org/10.1007/s11430-010-0030-2

[59] Liu, Y. M., Liu, D. Y., Zhao, Q. Y., Zhang, W., Chen, X. X., Xu, S. J., & Zou, C. Q. (2020). Zinc fractions in soils and uptake in winter wheat as affected by

repeated applications of zinc fertilizer. *Soil and Tillage Research*, *200*(June 2019), 104612. https://doi.org/10.1016/j.still.2020.104612

[60] Lucena, Juan J. 2003. "Fe Chelates for Remediation of Fe Chlorosis in Strategy I Plants." Journal of Plant Nutrition 26(10–11): 1969–84.

[61] Maheshwari, D. K. (2012). Bacteria in agrobiology: Stress management. *Bacteria in Agrobiology: Stress Management*, *9783642234*, 1–333. https://doi.org/10.1007/978-3-642-23465-1

[62] Maqueria, L., Torres, W., Pérez, S., Díaz, D., & Roján, O. (2016). Influencia de la temperatura ambiental y la fecha de siembra sobre la duración de las fases fenológicas en cuatro cultivares de arroz. 37(1), 65–70.

[63] Marschner, H. (1995). Mineral nutrition of higher plants.second edition. 889pp. London: Academic Press, £29.95 (paperback). *Annals of Botany*, *78*(4), 527–528. https://doi.org/10.1006/anbo.1996.0155

[64] Marschner, P. (2011). Marschner´s Mineral Nutrition of Higher Plants. In *Journal of Chemical Information and Modeling* (Vol. 53). https://doi.org/10.1017/CBO9781107415324.004

[65] Meena, V. S., Maurya, B. R., Meena, S. K., Meena, R. K., Kumar, A., Verma, J. P., & Singh, N. P. (2016). ¿Can Bacillus Species Enhance Nutrient Availability in Agricultural Soils? *Bacilli and Agrobiotechnology*, 1–416. https://doi.org/10.1007/978-3-319-44409-3

[66] Meena, B. L., Datta, S. P., Rattan, R. K., Singh, S., Kumar, A., Kaledhonkar, M. J., & Meena, R. L. (2019). A New Soil Testing Programme for the Evaluation of Intensity and Quantity Factors of Iron. *National Academy Science Letters, 42(3), 191–193.* https://doi.org/10.1007/s40009-018-0713-3

[67] Millaleo, R., Reyes-Díaz, M., Ivanov, A. G., Mora, M. L., & Alberdi, M. (2010). Manganese as essential and toxic element for plants: Transport, accumulation and resistance mechanisms. *Journal of Soil Science and Plant Nutrition*, *10*(4), 476–494. https://doi.org/10.4067/S0718-95162010000200008

[68] Nadeem, F., & Farooq, M. (2019). Application of Micronutrients in Rice-Wheat Cropping System of South Asia. *Rice Science*, 26(6), 356–371. https://doi.org/10.1016/j.rsci.2019.02.002

[69] Nozoye, T., Nagasaka, S., Takahashi, M., Sato, Y., Sato, Y., Uozumi, N., & Nishizawa, N. K. (2011). Phytosiderophore Efflux Transporters Are Crucial for Iron Acquisition in Graminaceous Plants. https://doi.org/10.1074/jbc.M110.180026

[70] Navarro, G. G., & Navarro, G. S. (2013). *Química agrícola: química del suelo y de los nutrientes esenciales para las plantas* (3a Edición; E. Mundiprensa, ed.).

[71] Ning, Xinyi et al. 2023. "Research Progress on Iron Absorption, Transport, and Molecular Regulation Strategy in Plants." Frontiers in Plant Science 14(July): 1–11.

[72] Nozoye, T., Nagasaka, S., Takahashi, M., Sato, Y., Sato, Y., Uozumi, N., & Nishizawa, N. K. (2011). Phytosiderophore Efflux Transporters Are Crucial for Iron Acquisition in Graminaceous Plants. https://doi.org/10.1074/jbc.M110.180026

[73] Northover, George H.R. et al. 2021. "Effect of Salinity on the Zinc(ii) Binding Efficiency of Siderophore Functional Groups and Implications for Salinity Tolerance Mechanisms in Barley." *Scientific Reports* 11(1): 1–12.

[74] Wairich, A., de Oliveira, B. H. N., Arend, E. B., Duarte, G. L., Ponte, L. R., Sperotto, R. A., … Fett, J. P. (2019). The Combined Strategy for iron uptake is not exclusive to domesticated rice (Oryza sativa). *Scientific Reports*, *9*(1), 1–17. https://doi.org/10.1038/s41598-019-52502-0

[75] Nascente, A. S., de Filippi, M. C. C., Lanna, A. C., de Souza, A. C. A., da Silva Lobo, V. L., & da Silva, G. B. (2017). Biomass, gas exchange, and nutrient contents in upland rice plants affected by application forms of microorganism growth promoters. *Environmental Science and Pollution Research*, *24*(3), 2956–2965. https://doi.org/10.1007/s11356-016-8013-2

[76] Nautiyal, N., Yadav, S., & Singh, A. D. (2011). Improvement in reproductive development, seed yield, and quality in wheat by zinc application to a soil deficient in zinc. *Communications in Soil Science and Plant Analysis*, *42*(17), 2039–2045. https://doi.org/10.1080/00103624.2011.596235

[77] Neumann, G., & Römheld, V. (2002). Root-induced changes in the availability of nutrients in the rhizosphere. I. Plant Roots:The Hidden Half. Marcel, 41–93.

[78] Noulas, C., Tziouvalekas, M., & Karyotis, T. (2018). Zinc in soils, water and food crops. *Journal of Trace Elements in Medicine and Biology*, 49(February), 252–260. https://doi.org/10.1016/j.jtemb.2018.02.009

[79] Pradhan, S., Meena, R. P., Ram, H., Rana, K., Parihar, M., & Singh, A. K. (2021). Zn-solubilizing microorganism: A novel perspective for sustainable agriculture. In Biofertilizers: Volume 1: Advances in Bio-inoculants. https://doi.org/10.1016/B978-0-12-821667-5.00025-7

[80] Prakash, P., Sobhana, E., Sujithra, P., & Hemalatha, M. (2019). Zinc: A Macro Micronutrient for Sustainable Rice Production. In Advances In Agronomy (pp. 01–19). Retrieved from https://www.researchgate.net/profile/Bishal_Mukherjee2/publication/335973589_

Water_Efficient_Rice_Cultivation_Technological_Interventions/links/5d87c1f2a6fdcc8fd6106441/Water-Efficient-Rice-Cultivation-Technological-Interventions.pdf#page=7

[81] Pereg, L., de-Bashan, L. E., & Bashan, Y. (2016). Assessment of affinity and specificity of Azospirillum for plants. *Plant and Soil*, *399*(1–2), 389–414. https://doi.org/10.1007/s11104-015-2778-9

[82] Petrik, M., Zhai, C., Haas, H., & Decristoforo, C. (2017). Siderophores for molecular imaging applications. Clinical and Translational Imaging, 5(1), 15–27. https://doi.org/10.1007/s40336-016-0211-x

[83] Quintero, C. (2018). templada argentina. *Archivo Agronómico*, *# 17*, 1–5. Retrieved from http://lacs.ipni.net/ipniweb/region/lacs.nsf/0/5F6E6EAE266A3B960325827500670DE1/$FILE/AA 17.pdf

[84] Rengel, M., Cruz, J., Croce, J., Montaño, J., & Chirinos, I. (2012). Efecto de la fertilización foliar con zinc y boro sobre los componentes del rendimiento en el cultivo de arroz (Oryza sativa L.) en suelos inundados. *Revista Cientifica UDO Agricola*, *12*(1), 158–166.

[85] Rice Knowledge Bank. (s.f.). Iron toxicity - IRRI Rice Knowledge Bank. Retrieved July 4, 2020, from http://www.knowledgebank.irri.org/training/fact-sheets/nutrient-management/deficiencies-and-toxicities-fact-sheet/item/iron-toxicity

[86] Rice Knowledge Bank. (s.f). Manganese (Mn) deficiency - IRRI Rice Knowledge Bank. Retrieved July 4, 2020, from http://www.knowledgebank.irri.org/training/fact-sheets/nutrient-management/deficiencies-and-toxicities-fact-sheet/item/manganese-deficiency

[87] Rice Knowledge Bank. (s.f). Zinc deficiency - IRRI Rice Knowledge Bank. Retrieved July 4, 2020, from http://www.knowledgebank.irri.org/training/fact-sheets/nutrient-management/deficiencies-and-toxicities-fact-sheet/item/zinc-deficiency

[88] Rose, T. J., Impa, S. M., Rose, M. T., Pariasca-Tanaka, J., Mori, A., Heuer, S., … Wissuwa, M. (2013). Enhancing phosphorus and zinc acquisition efficiency in rice: A critical review of root traits and their potential utility in rice breeding. Annals of Botany, 112(2), 331–345. https://doi.org/10.1093/aob/mcs217

[89] Roskova, Z., Skarohlid, R., & McGachy, L. (2022). Siderophores: an alternative bioremediation strategy? Science of the Total Environment, 819, 153144. https://doi.org/10.1016/j.scitotenv.2022.153144

[90] Sakariyawo, O. S., Oyedeji, O. E., & Soretire, A. A. (2020). Effect of iron deficiency on the growth, development and grain yield of some selected upland rice genotypes in the rainforest. Journal of Plant Nutrition, 43(6), 851–863. ttps://doi.org/10.1080/01904167.2020.1711936

[91] Sankari Meena, K. et al. 2019. "Agriculture Application Of." Plant Growth Promoting Rhizobacteria: 77–93.

[92] Santos, S., Neto, I. F. F., Machado, M. D., Soares, H. M. V. M., & Soares, E. V. (2014). Siderophore production by Bacillus megaterium: Effect of growth phase and cultural conditions. *Applied Biochemistry and Biotechnology*, *172*(1), 549–560. https://doi.org/10.1007/s12010-013-0562-y

[93] Saravanan, V. S., Kumar, M. R., & Sa, T. M. (2011a). Bacteria in Agrobiology: Plant Nutrient Management. *Bacteria in Agrobiology: Plant Nutrient Management*. https://doi.org/10.1007/978-3-642-21061-7

[94] Saravanan, V. S., Kumar, M. R., & Sa, T. M. (2011b). Microbial Zinc Solubilization and Their Role on Plants. In *Bacteria in Agrobiology: Plant Nutrient Management* (pp. 47–63). https://doi.org/10.1007/978-3-642-21061-7_3

[95] Saxena, M., Das, A., & Choudhury, S. (2017). *Chemical fractionation of zinc and its relationship with important properties of rice grown soils*. *5*(4), 1205–1211.

[96] Senoura, T., Sakashita, E., Kobayashi, T., Takahashi, M., Aung, M. S., Masuda, H., … Nishizawa, N. K. (2017). The iron-chelate transporter OsYSL9 plays a role in iron distribution in developing rice grains. *Plant Molecular Biology*, *95*(4–5), 375–387. https://doi.org/10.1007/s11103-017-0656-y

[97] Shakeel, M., Rais, A., Hassan, M. N., & Hafeez, F. Y. (2015). Root associated Bacillus sp. improves growth, yield and zinc translocation for basmati rice (Oryza sativa) varieties. *Frontiers in Microbiology*, *6*(NOV), 1–12. https://doi.org/10.3389/fmicb.2015.01286

[98] Sharma, A., Shankhdhar, D., & Shankhdhar, S. C. (2013). Enhancing grain iron content of rice by the application of plant growth promoting rhizobacteria. *Plant, Soil and Environment*, *59*(2), 89–94. https://doi.org/10.17221/683/2012-pse

[99] Sharma, A., Shankhdhar, D., Sharma, A., & Shankhdhar, S. C. (2014). Growth promotion of the rice genotypes by pgprs isolated from rice rhizosphere. *Journal of Soil Science and Plant Nutrition*, *14*(2), 505–517. https://doi.org/10.4067/S0718-95162014005000040

[100] Sharma, Ashish, Patni, B., Shankhdhar, D., & Shankhdhar, S. C. (2013). Zinc - An Indispensable Micronutrient. *Physiology and Molecular Biology of Plants*, *19*(1), 11–20. https://doi.org/10.1007/s12298-012-0139-1

[101] Shrestha, J., Shah, K. K., & Timsina, K. P. (2020). Effects of different fertilizers on growth and productivity of rice (Oryza sativa L.): a review. International Journal of Global Science Research, 7(1), 1291–1301. https://doi.org/10.26540/ijgsr.v7.i1.2020.151

[102] Shrivastava, U. ., & Kumar, A. (2011). A simple and rapid plate assay for the screening of Indole-3-acetic Acid (IAA) producing microorganisms. *Appl.Biol. Pharm.*, 120–123.

[103] Shruti K, Arun K, Y. R. (2013). *Potential Plant Growth-Promoting Activity of Rhizobacteria Pseudomonas sp in Oryza sativa Food Waste Managementa cheap source of Lacticc acid produced by Lactobacillus sp. View project*. *3*(4), 38–50. Retrieved from https://www.researchgate.net/publication/263655828

[104] Singh, Ranjay K., Nancy J. Turner, and C. B. Pandey. 2012. "'Tinni' Rice (Oryza Rufipogon Griff.) Production: An Integrated Sociocultural Agroecosystem in Eastern Uttar Pradesh of India." *Environmental Management* 49(1): 26–43

[105] Sinha, M. K., & Purcell, W. (2019). Reducing agents in the leaching of manganese ores: A comprehensive review. *Hydrometallurgy*, *187*(February), 168–186. https://doi.org/10.1016/j.hydromet.2019.05.021

[106] Sivakamasundari, R., & Usharani, G. (2012). Studies on the Influence of Pseudomonas fluorescens and Chemicals on the Biocontrol Sheath Blight Incidence in Rice. *International Journal of Pharmaceutical & Biological Archives*, *3*(4), 973–977.

[107] Suda, A., & Makino, T. (2015). *Geoderma Functional effects of manganese and iron oxides on the dynamics of trace elements in soils with a special focus on arsenic and cadmium : A review*. https://doi.org/10.1016/j.geoderma.2015.12.017

[108] Takagi, Sei Ichi. 1976. "Naturally Occurring Iron. Chelating Compounds in Oat- and Rice·rootwashings 1. Activity Measurement and Preliminary Characterization." Soil Science and Plant Nutrition 22(4): 423–33

[109] Tao, H., Dittert, K., Zhang, L., Lin, S., Römheld, V., & Sattelmacher, B. (2007). Effects of soil water content on growth, tillering, and manganese uptake of lowland rice grown in the water-saving ground-cover rice-production system (GCRPS). *Journal of Plant Nutrition and Soil Science*, *170*(1), 7–13. https://doi.org/10.1002/jpln.200625033

[110] Tiwari, P., & Singh, J. S. (2017). A plant growth promoting rhizospheric Pseudomonas aeruginosa strain inhibits seed germination in Triticum aestivum (L) and Zea mays (L). *Microbiology Research*, *8*(2), 73–79. https://doi.org/10.4081/mr.2017.7233

[111] Tiwari, S., Prasad, V., & Lata, C. (2019). Bacillus: Plant growth promoting bacteria for sustainable agriculture and environment. In *New and Future Developments in Microbial Biotechnology and Bioengineering: Microbial Biotechnology in Agro-environmental Sustainability*. https://doi.org/10.1016/B978-0-444-64191-5.00003-1

[112] Ullah, A., Farooq, M., Nadeem, A., Rehman, A., Asad, S. A., & Nawaz, A. (2017). Manganese nutrition improves the productivity and grain biofortification of fine grain aromatic rice in conventional and conservation production systems. *Paddy and Water Environment*, *15*(3), 563–572. https://doi.org/10.1007/s10333-016-0573-8

[113] Velasco Sánchez, Á., Delgado García, A., & Moreno Lora, A. (2017). *Efecto de inoculaciones microbianas en la acumulación de Zn , P y otros micronutrientes*.

[114] Vimal, S. R., Patel, V. K., & Singh, J. S. (2019). Plant growth promoting Curtobacterium albidum strain SRV4: An agriculturally important microbe to alleviate salinity stress in paddy plants. *Ecological Indicators*, *105*(March), 553–562. https://doi.org/10.1016/j.ecolind.2018.05.014

[115] Wang, Yuwen, Xu, C., Li, K., Cai, X., Wu, M., & Chen, G. (2017). Fe deficiency induced changes in rice (Oryza sativa L.) thylakoids. *Environmental Science and Pollution Research*, *24*(2), 1380–1388. https://doi.org/10.1007/s11356-016-7900-x

[116] Wu, Fei et al. 2021. "Facet-Specific Reactivity of Hematite Nanocrystals during Fe(II)-Catalyzed Recrystallization." Chemical Geology 583(July): 120460.

[117] Wu, Qiqi et al. 2022. "Zinc Regulation of Iron Uptake and Translocation in Rice (Oryza Sativa L.): Implication from Stable Iron Isotopes and Transporter Genes." Environmental Pollution 297(January): 118818.

[118] Yang, A., Li, Q., & Chen, L. (2020). The molecular mechanisms underlying iron deficiency responses in rice. *International Journal of Molecular Sciences*, *21*(1). https://doi.org/10.3390/ijms21010043

[119] Yang, W., Jingshuang, L., & Zheng, N. (2010). Effects of pH on the fraction transformations of Zn in black soil at the condition of freeze/thaw cycles. *Journal of Arid Land Resources and Environmental*.

[120] Zayed, B. A., Salem, A. K. M., & El Sharkawy, H. M. (2011). Effect of Different Micronutrient Treatments on Rice (Oriza sativa L.) Growth and Yield under Sa-

line Soil Conditions. *World Journal of Agricultural Sciences*, *7*(2), 179–184.

[121] Zhang, X., Zhang, D., Sun, W., & Wang, T. (2019). The adaptive mechanism of plants to iron deficiency via iron uptake, transport, and homeostasis. *International Journal of Molecular Sciences*, *20*(10). https://doi.org/10.3390/ijms20102424

[122] Zhang, Y., Xu, Y. H., Yi, H. Y., & Gong, J. M. (2012). Vacuolar membrane transporters OsVIT1 and OsVIT2 modulate iron translocation between flag leaves and seeds in rice. *Plant Journal*, *72*(3), 400–410. https://doi.org/10.1111/j.1365-313X.2012.05088.x