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Plant Growth-Promoting Rhizobacteria (PGPR) as a Biotechnological Tool for Enhancing Cropping Systems and Promoting Sustainable Agriculture

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ABSTRACT

The excessive utilisation of pesticides and chemical fertilizers in modern agriculture generates major problems for the environment, human health and soil quality. In this context, European policymakers, researchers, and farmers are increasingly focusing on alternative solutions that contribute to more sustainable agriculture. Plant growth-promoting rhizobacteria (PGPR) are regarded as biotechnological tools that align well with environmentally friendly alternatives. Numerous PGPR strains are being studied as an ecological alternative to environmentally harmful synthetic preparations (chemical fertilizers, pesticides) and tested for introduction into crop technologies under different formulations, in order to optimize plant growth and improve the production yield. These highly beneficial bacteria colonize on plant roots, stimulating their development through direct and indirect mechanisms. PGPR can improve nutrient availability (nitrogen fixation, phosphorus, potassium, zinc solubilization, etc.) and can influence optimal plant development by producing siderophores and regulating phytohormones. PGPR have the capacity to change the potential for water transport and absorption by roots. Additionally, they can contribute to plant protection by inhibiting pathogens or by stimulating host defence mechanisms, including the production of antibiotics, antioxidants, hydrolytic enzymes, exopolysaccharides, volatile organic compounds (VOCs), and osmotic balancing. The paper provides an overview of the current knowledge regarding PGPR and their importance to enhancing crop productivity and promoting sustainable agricultural practices.

1. Introduction

The global population has reached approximately 8.2 billion people, and demographic projections indicate continued growth over the coming decades, with a possible peak of around 10.4 billion in 2084. The world's urban population has grown rapidly from 751 million in 1950 to 4.2 billion in 2018. Today, the most urbanized regions include North America (with 82% of the population living in urban areas in 2018), Latin America and the Caribbean (81%), Europe (74%), and Oceania (68%) (United Nations, 2018). In this context, it has become necessary to increase production per unit area. However, the intensification of agriculture and the lack of sustainable agricultural practices have contributed to

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climate change and to alterations in the dynamics and abundance of soil microbial populations. Climate change has been associated with shifts in precipitation patterns and an increased frequency of drought events (Xu & Lan, 2017). Several researchers have highlighted the adverse effects of pesticides on the diversity and activity of soil microfauna, showing that certain pesticides can also negatively affect indigenous microbial communities (Ingram et al., 2005; Littlefield-Wyer et al., 2008; Niewiadomska, 2004; Baxter et al., 2008). Regarding food safety, recent research shows the harmful effects of pesticide use on human health as well (Ahmad et al., 2024). All these factors are exerting increasing pressure on food production systems.

New challenges are emerging in adapting crop technologies to current needs. Synthetic products are beginning to have environmentally friendly substitutes, obtained from biological preparations derived from nature. Also known as biopreparations, they achieve the stability of agroecosystems and contribute to increasing plant resistance to abiotic factors and stress (Brussaard, de Ruiter, & Brown, 2007).

In Europe, EU Strategies support the improvement of production systems by adopting sustainable agricultural practices and urge the creation of agri-food chains that bring food directly from the field as close as possible to consumers, without going through intermediaries (OECD, 2016). In turn, the population feels the repercussions of imbalances and begins to become aware, reorienting itself towards an increasingly high consumption of organic food resources.

Ensuring the development and implementation of sustainable solutions and maintaining production at a high level in the agricultural sector requires optimizing production systems and bringing them up to environmental sustainability standards (Kleyn & Ciacciariello, 2021). In this context, the transition from conventional to organic agriculture requires the integrated assessment of natural resources and their alignment with agricultural demands to ensure both productivity and ecosystem sustainability, alongside the advancement of biotechnology-driven research in agriculture. This is necessary to better understand the mechanisms influencing plant productivity, which depends not only on crop characteristics, climatic conditions, and cultivation practices, but also on soil microbiology and plant–microorganism interactions. The use of PGPR has gained increasing attention as a sustainable agricultural strategy, representing a viable alternative to synthetic fertilizers. PGPR play an important role in increasing plant tolerance to biotic and abiotic stresses, thus strengthening the resilience of agricultural systems.

This paper provides a comprehensive and critical review of plant growth-promoting rhizobacteria (PGPR), highlighting their essential roles in enhancing plant growth and development, as well as their potential to support sustainable agricultural practices.

2. Research methodology

This review is based on a descriptive and analytical approach aimed at synthesizing current knowledge on plant growth-promoting rhizobacteria (PGPR) and their role in sustainable agriculture. Relevant information was collected from peer-reviewed scientific articles, review papers, and research reports retrieved from major scientific databases. The selection of sources was focused on studies addressing the mechanisms of action of PGPR, their interactions with plants, and their effects on plant growth, productivity, and stress tolerance. Attention was given to recent publications to ensure up-to-date information. The collected data were critically analysed, compared, and organized thematically to provide a comprehensive overview of the topic.

3. Results and discussions

3.1. PGPR as a strategy to mitigate abiotic stress in plants growth

Stressors are abiotic in nature and include special climatic conditions, soil characteristics or problems arising from the irresponsible use of certain chemical fertilizers and nutritional deficiency.

Drought stress has a major negative impact on plants, triggering even irreversible changes in plant behaviour, at any stage of growth and development. Drought stress leads to the activation of stress response genes, the accumulation of osmolytes and the closure of stomata that try to rebalance the plant hydrolytically, while also protecting the cells from damage (Muhammad et al., 2023).

Depending on the level of the stressor, plants have certain ways to adapt in order to survive and protect themselves. One of these ways of adaptation is the reduction of leaf size. However, this triggers other dangers due to the exposure of the whole plant to more sunlight (Yavas et al., 2024). Even though the plant reduces respiration and water loss through the leaves, the surface area exposed to solar radiation increases. The closure and opening of stomata and microscopic pores on the surface of the leaf leaflet is another critical response to drought, their position changing depending on the time of day and the current climatic conditions. The closure of the stomatal cavity reduces water loss during transpiration. In practice, the plant breathes less.

Salinity stress is a major factor influencing crop zoning and agricultural practices, including the use of soil amendments, due to its significant impact on plants in cropping systems. It is due to the accumulation of high concentrations of soluble salts, often sodium chloride (NaCl), strongly threatening plant growth, development and productivity (Tiwari et al., 2024). Among the most important effects are the occurrence of osmotic and ionic imbalances in plant cells. These problems have negative impact on plant nutrition imbalances and ion toxicity, which prevent normal cellular functions (Chourasia et al., 2021). The accumulation of sodium ions ($Na+$) in the soil prevents the transport and absorption of potassium ($K+$) and calcium ($Ca2+$) (Mahmood et al., 2024).

Osmotic stress is due to a high concentration of salts outside the soil. This leads to a decrease in water absorption capacity and further to turgor pressure and even dehydration (Ozturk et al., 2021).

Stress resulting from *nutrient deficiency* is another important issue, as the development of all plant functions depends on macro- and micronutrients. Each nutrient supports plant health in its own way. For example, nitrogen deficiency causes chlorosis of basal leaves, because it ascends from the basal leaves to those in the upper floors (Doan et al., 2024). Phosphorus deficiency causes the entire plant to turn darker and overall growth to slow down, and potassium deficiency causes the tips of the plant's leaves to dry out and tighten (Plantix, 2023; West Virginia University, 2024).

To cope with stress factors, plants have developed various adaptive mechanisms that enable them to manage these conditions. One strategy involves limiting the entry of ions into the plant through the roots, thereby preventing their toxic accumulation. This process is regulated by specialized ion transporters specific to different types of ions. However, under severe stress conditions, these intrinsic mechanisms may be insufficient, and plant growth-promoting rhizobacteria (PGPR) can complement plant responses by enhancing ion homeostasis, improving nutrient uptake, and increasing overall stress tolerance. Plant growth-promoting rhizobacteria (PGPR) represent an effective biological approach, as they can enhance plant tolerance to a wide range of abiotic stresses, including drought, salinity, and nutrient deficiency. Through various direct and indirect mechanisms—such as the production of phytohormones, osmolytes, antioxidant compounds, and the improvement of nutrient availability—PGPR contribute to the maintenance of plant physiological balance under adverse environmental conditions. Therefore, the use of PGPR offers a promising and environmentally friendly alternative to conventional practices for improving crop resilience in stress-affected agricultural systems.

3.2. Rhizosphere – key environment for plant-microorganism interaction

In natural ecosystems, plants coexist and develop within complex networks, undergoing continuous dynamic changes while maintaining their fundamental structural and functional properties. In natural environments, multiple factors shape the characteristics of each crop, leading to the establishment of a specific microbiota composed of microbial communities that influence plant growth and development (Saravanan et al., 2011). Some of the influences can occur before the plants are placed on the final culture substrate (especially in plants where seedlings are used).

Soil is an important microbial reservoir, rich in various types of living organisms. In the research studies is reported that certain functions of the root system, more specifically root respiration and secretion, can exert a negative action on the rhizosphere, affecting it both quantitatively and qualitatively (Lazarovits & Nowak, 1997). The most common in soil are bacteria species. Soil bacteria meet the plant through the rhizosphere, where most of the colonies are concentrated. In the case of seedlings, when the plant roots meet a new substrate, the load of microorganisms automatically changes, increasing the diversity. Bacteria are commonly found throughout the soil (Miao et al., 2014), but they can also enter a symbiotic relationship with plant roots. In this case, they are very close to the plant roots, even penetrating inside them, where they subsequently live (Van Peer & Schippers, 1989).

It is possible that some of the connections that occur between the plant and bacteria are beneficial, but they can also be harmful, thus affecting the entire life of the plant. Thus, the microbiota can influence the normal development of plants and the yield of the entire crop. An important aspect is that PGPR can multiply and colonize differently within the same ecosystem, this ability varying depending on how complex the microflora is. The colonization and interaction of PGPR with the plant is different for each ecological niche and specific to each stage of plant development.

The rhizosphere microbiota is influenced by bacterial species, the developmental stage of the plant, soil characteristics, as well as the ecological features of the whole ecosystem (Vacheron et al., 2013). Some examples of PGPR involved in plant development are presented in Table 1.

Table 1. The types of PGPR involved in plant growth

Bacteria type	Main characteristics	Action mechanism	Role in plant growth
Bacillus Efthimiadou et al., 2020	Gram-positive bacteria, spore formation	Production of antibiotics, enzymes, phytohormones	Biocontrol, growth stimulation, stress tolerance

Bacteria type	Main characteristics	Action mechanism	Role in plant growth
Azospirillum Boonjawat et al., 1991; Elmerich et al., 1992; Dobereiner et al., 1995; Prasad, 2024	Gram-negative, associative bacteria, nitrogen fixers	N_2 fixation, auxin (IAA) production, root stimulation	Root growth, nutrient uptake, growth stimulation
Rhizobium Boonjawat et al., 1991; Elmerich et al., 1992; Dobereiner et al., 1995; Prasad, 2024; Hasan et al., 2024	Gram-negative, symbiotic, nodule-forming	Biological nitrogen fixation in symbiosis	Nitrogen nutrition, growth and productivity
Azotobacter Efthimiadou et al., 2020	Gram-negative, free-living in soil, aerobic	N_2 fixation, phytohormones production, siderophores	Soil fertility, growth stimulation, vegetative development
Klebsiella Liu et al., 2026	Gram-negative, facultative anaerobic	Nitrogen fixation, phytohormone production	Plant growth, nutrition improvement
Bradyrhizobium Marinković et al., 2025	Gram-negative, slow symbiotic, specific to legumes	Nitrogen fixation in nodules	Plant growth, nitrogen uptake, yield
Pseudomonas Czarnes et al., 2020; Fouzia et al., 2015	Gram-negative, motile, rhizospheric	Antibiotic production, siderophores, phosphorus solubilization	Biocontrol, growth stimulation, plant protection
Burkholderia Prajapati et al., 2013	Gram-negative, metabolically versatile	Nitrogen fixation, phosphorus solubilization, antibiotics	Plant growth, biocontrol, stress tolerance
Microbacterium Riaz et al., 2021	Gram-positive, actinobacteria	Phytohormone production, nutrient solubilization	Growth stimulation, root development
Mesorhizobium Babalola, 2010; Pérez-Montaño et al., 2014	Gram-negative, symbiotic	Nitrogen fixation in nodules	Nitrogen nutrition, plant growth
Enterobacter Riaz et al., 2021	Gram-negative, facultative anaerobic	Phosphorus solubilization, IAA production, siderophores	Plant growth, nutrition, development stimulation
Serratia Santoro et al., 2016	Gram-negative, secondary metabolite producers	Antibiotic production, lytic enzymes, IAA	Biocontrol, protection against pathogens

Thanks to their increased development and adaptability, some species of bacteria are able to absorb nitrogen, carbon, but also other macronutrients and micronutrients and enrich the availability of nutrients in the soil. Thus, they help plants to remain healthy (Shah et al., 2021).

The maintenance of soil fertility on the long term can be supported by PGPR when they are protected by environmentally friendly agricultural practices. The future of sustainable agriculture encompasses PGPR-based biopreparations in the biocontrol of phytopathogenic agents (Abbas et al., 2014). This new approach, recently introduced in sustainable agriculture, helps maintain soil health and promotes crop diversity and rotation to reduce the effect of specific stressors (M. Tahat et al., 2020).

3.3. Mechanisms of plant growth promotion by PGPR

Plant growth-promoting rhizobacteria (PGPR) support normal plant growth and development through direct and indirect mechanisms that facilitate nutrient uptake, activate and enhance plant hormone production, increase stress tolerance, and eliminate phytopathogenic agents. The occurrence of these various mechanisms often occurs simultaneously in the rhizosphere, giving PGPR the characteristic of being versatile tools in sustainable agriculture.

Both direct and indirect mechanisms include complex processes that greatly influence the growth and development of crop plants in various ways. Both types of mechanisms include biotic and abiotic factors. The schematic representation in figure 1 makes a connection between the mechanism, the type of stressor, the process, and the results of the process, and also illustrates the roles of PGPRs in plant life.

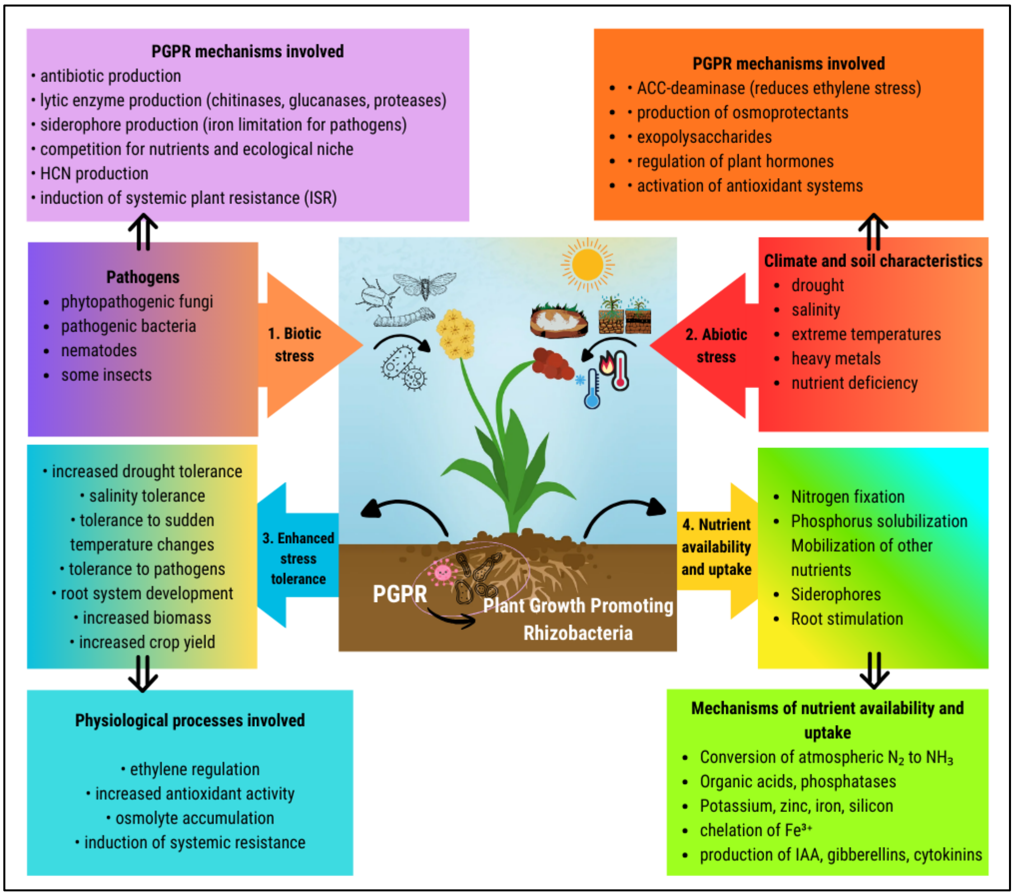

Figure 1. Correlation between mechanisms, mode of action and results of PGPR action in the plant

Direct mechanisms of PGPR are ways of action of rhizobacteria through which nutrients and micronutrients are made available, hormonal regulation of plants and changes in the potential for transport and absorption of nutrients in the plant.

3.3.1. Atmospheric nitrogen fixation

Most biochemical processes carried out on plants (e.g. photosynthesis, protein synthesis) are dependent on nitrogen. This chemical element is one of the most important minerals for optimal plant growth and development. Without it, plants cannot thrive (Alori, Dare & Babalola, 2017). Nitrogen represents approximately 78% of the atmosphere's composition, forms a triple covalent bond and has a relatively low reactivity, which means that plants cannot assimilate it directly. On a large scale, the most accessible method of enriching soils with nitrogen is the application of synthesized chemical fertilizers. The problem is that their irresponsible use has led to serious environmental problems. Studies in the field have shown that plants use only half of the applied nitrogen, and the other part is either lost through leaching or volatilization, or remains in the soil in complex and inaccessible chemical forms (Bouchet, Laperche, Bissuel-Belaygue, Snowdon, Nesi & Stahl, 2016). PGPR such as *Azospirillum and Rhizobium* (Boonjawat et al., 1991; Elmerich et al., 1992; Dobereiner et al., 1995; Prasad, 2024) have the ability to easily use the "fixation" process to convert atmospheric nitrogen into ammoniacal nitrogen, thus making this macronutrient available and accessible to plants. The availability of nitrogen implicitly leads to improved plant nutrition. In the soil there are free nitrogen fixers and nitrogen fixers that create symbiotic bonds with plants. The second type of nitrogen fixers are much better than the first, because they form an advantageous bond both for themselves and for the plants with which they interact. Bacteria such as *Rhizobium, Burkholderia, Mesorhizobium, Azoarcus, Frankia* and *Achromobacter* are part of this category of symbiotic bacteria (Babalola, 2010; Pérez-Montaño et al., 2014). (figure 2)

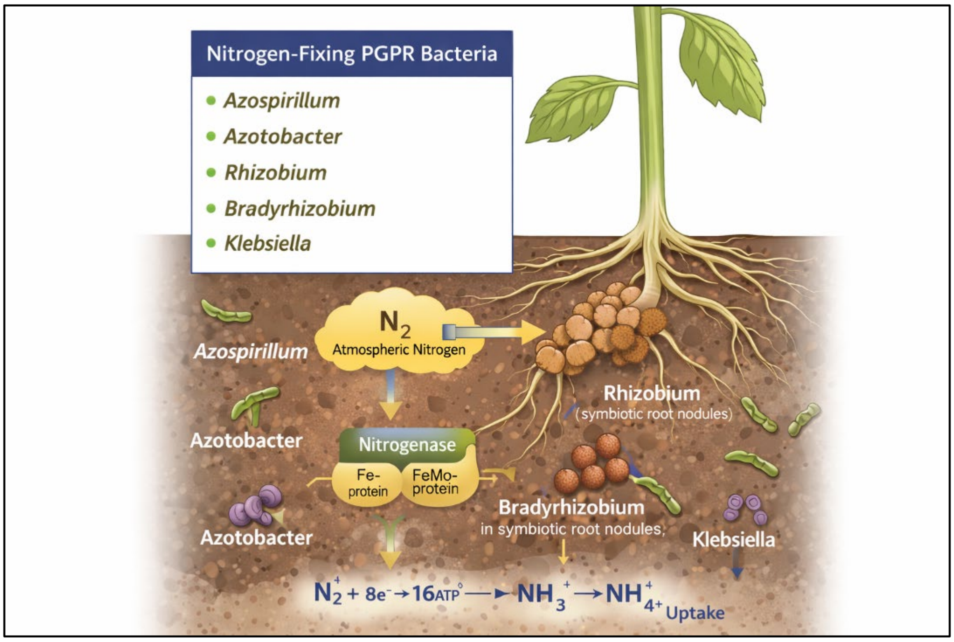

Figure 2. The mechanism of nitrogen fixation by PGPR

3.3.2. Solubilization of Phosphorus and Potassium

After nitrogen, the next most important chemical elements for supporting harmonious plant growth and development are phosphorus and potassium. PGPRs can solubilize phosphorus and other essential mineral nutrients, enriching the variety of plant nutrition. PGPRs are in constant competition for food, oxygen and rhizosphere colonization space with dangerous microorganisms. Consequently, they help reduce the number of pathogens and support plant health.

In plants, phosphorus influences respiration, photosynthesis, energy transmission, signal transduction, macromolecular biosynthesis (Hillel, 2008). Most forms of phosphorus in the soil are inaccessible to plants due to their limited solubilization capacity. (Archana et al., 2012). Plants can only absorb phosphorus that is in the forms of monobasic (H_2PO_4) and dibasic $(HPO_4)^{2-}$ ions. (Khan et al., 2009). As a method of phosphorus addition, the application of phosphorus fertilizers endangers the life of aquatic and terrestrial ecosystems through leaching (Adesemoye & Kloepper, 2009).

Regarding potassium, it is present in the soil in the form of mineral silicates and compact rocks, which is why the potassium reserve in the soil is low. In the absence of this chemical element, plant growth is slowed down and seed production is affected (Kumar et al., 2023). Bacteria such as *Bacillus megaterium* and *Bacillus circulans*, have the ability to release organic acids or enzymes capable of transforming insoluble and inaccessible forms of phosphorus and potassium to available forms for plants, naturally improving nutrient absorption (Bashan et al., 1996). *Pseudomonas sp*. and *Burkholderia* can also solubilize both phosphorus and potassium (Prajapati et al., 2013). PGPRs specialized in phosphorus solubilization are *Azotobacter, Rhizobium, Microbacterium, Bacillus, Mesorhizobium, Enterobacter, Serratia*, and *Flavobacterium*. (Riaz et al., 2021).

The method by which most bacteria solubilize organic acids and other metabolites is based on the need for phosphorus for their synthesis in the forms of gluconic acid and ketones, in which the chelated cations are then attached to the carboxyl and hydroxyl groups of phosphate (Heydari et al., 2007). Thus, they can be dissolved in the soil solution and become usable in direct plant nutrition. Unfortunately, due to various changes over time in cultural practices, research study reported a decrease of about 25% in the amount of phosphorus required by phosphorus-solubilizing bacteria (Bechtaoui et al., 2020). For the solubilization of potassium (K), there are bacterial and fungal forms of PGPR (Setiawati & Mutmainnah, 2016), such as *Ferrooxidans sp*., *Bacillus edaphicus*, and *Bacillus mucilaginosus* (Prajapati et al., 2013).

3.3.3. Zinc Solubilization

Zinc (Zn) is a micronutrient required by crop plants, being vital for the harmonious growth and development of plants (Goteti et al., 2013).

Certain soil properties, including available phosphorus, interact with the level of zinc availability to plants. Poorly crystalline iron oxides and phosphorus availability have a positive impact on zinc absorption (Saleem et al., 2022). Improving zinc nutrition in plants has reduced the toxicity of some heavy metals by enhancing some functions and performing some basic plant processes: physiological and biochemical functions, osmolyte accumulation, antioxidant activities, gene expression (Hassan et al., 2022). Zinc facilitates the production of chlorophyll and the biosynthesis of proteins, lipids and nucleic acids and stimulates the activation of enzymes that participate in glucose and auxin metabolism (Vaid et al., 2014). This nutrient also supports the plant in stressful and fluctuating climatic conditions such as drought (Hassan et al., 2020).

Moreover, zinc plays an important role in the development of plant defence mechanisms by enhancing protein synthesis, enzymatic activity, defence pathways, and antioxidant systems, thereby optimizing plant defence responses and maintaining membrane integrity (Bastakoti, 2023). Although zinc is important in complex plant nutrition, excessive levels of zinc can lead to phytotoxicity. In too high amounts, this microelement can affect plant growth and development, it can hinder photosynthesis and cause an imbalance in mineral nutrition due to facilitating the appearance of species that are reactive to oxygen (Kaur & Garg, 2021).

3.3.4. Siderophore production

Iron is found in abundance in most natural soils. It comes in two forms: ferrous (Fe^{2+}) and ferric (Fe^{3+}). These atoms are positively charged and stick to soil particles, because they are negatively charged. On the same principle as magnets, soil particles and atoms of the two forms form strong bonds, keeping the iron in place (Dubey & Pathak, 2023).

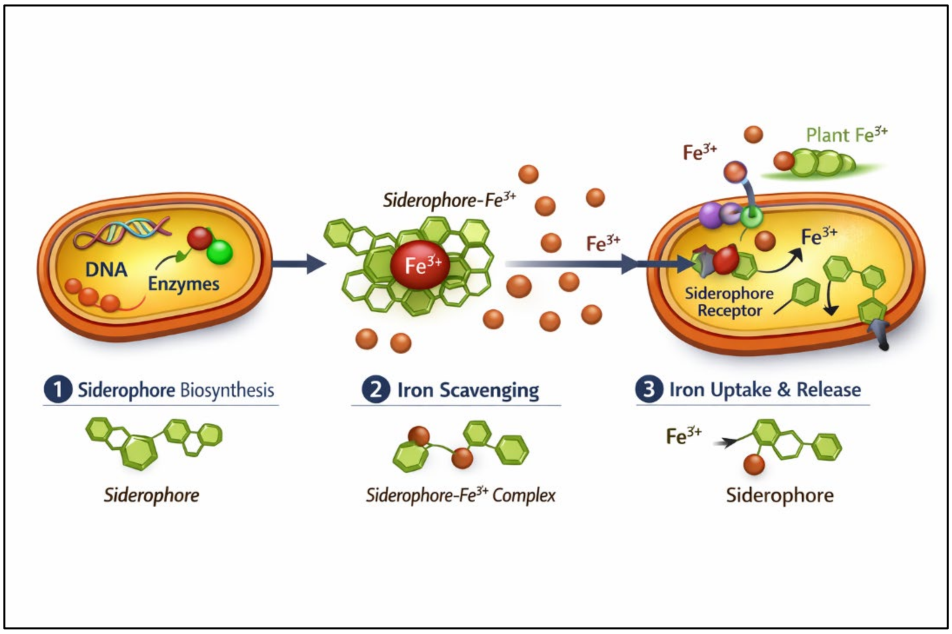

Figure 3. The formation of siderophores

Although iron occurs in the soil predominantly in stable (insoluble) forms, this is generally advantageous, as excessive iron availability may lead to toxicity and interfere with the uptake of other nutrients. In order to introduce iron into their systems, it is necessary for plant roots to extract iron from the soil structure. However, this is not always possible. Some PGPR that can produce siderophores come to their aid. Siderophores (from Greek: "*iron carriers*") are chelating agents with a fairly low molecular weight that help microorganisms capture iron when it is present in low quantities in the soil (Neilands, 1995). It is also worth mentioning that this role of PGPR helps to limit the availability of iron to pathogens (Crowley et al., 1991). Studies on siderophore production present the isolation and analysis of several microorganisms from different aquatic and terrestrial ecosystems and highlight the potential of microorganisms to produce siderophore (Řezanka, Palyzová, & Sigler, 2018). The main structures of siderophores are carboxylates, hydroxamates, phenolates and pyoverdines (figure 3). The best producers of siderophore are the Gram-positive bacteria *Pseudomonas* and *Enterobacter* (Czarnes et al., 2020).

3.3.5. Plant hormone production

Many PGPR have the ability to produce phytohormones. These include abscisic acid (ABA), indole-3-acetic acid (IAA), cytokinins, gibberellins, and ethylene. These phytohormones play important roles in the interaction of PGPRs with plants, vitally influencing plant growth by strengthening and developing the roots as well as increasing of biomass. The roles of microorganisms of this type in the plant relate to the regulation of cell division, elongation, and differentiation of plant cells (Santoyo et al., 2016; Arshad & Frankenberger, 1998)

3.3.6. Changing the transport and absorption potential in roots

In their studies, Bashan et al. reported that certain bacteria have the ability to change the transport mode of ions. This enhancing the intensity of nutrient absorption by modulating the electrical potential passing through the root membranes (Bashan & Levanony, 1991).

Indirect mechanisms help and protect the plant by creating repressive chemical substances with a role in stimulating resistance to stress and phytopathogenic agents. PGPR have roles such as biological control and induction of systemic resistance. PGPR are also involved in the production of antibiotics, antioxidants, hydrolytic enzymes (chitinases, cellulases, etc.), the formation of VOCs, the production of exopolysaccharides and the achievement of osmotic balance.

3.4. Biological control of PGPR-based biofertilizers

The biological control of phytopathogenic agents is particularly important for sustainable and economic agriculture. In this regard, PGPR-based biofertilizers have emerged that are important due to the qualities they have been shown to possess. These include increasing soil fertility, but also achieving a more natural production.

Biofertilizers are substances containing active microorganisms that, when applied to the soil, plant surfaces, or the rhizosphere, colonize these environments and promote plant growth. Some of these microorganisms remain in the rhizosphere, while others colonize internal plant tissues; all of them contribute to plant growth through various mechanisms (Ortiz and Sansinenea, 2021). Biofertilizers are natural and renewable, which makes them a suitable alternative to synthetic agricultural inputs (Husson et al., 2021). In addition to improving nutrient transport and exchange, biofertilizers increase crop yield and stress resistance. PGPR involved in biological control are commonly found in the rhizosphere, where they produce a diverse range of enzymes, regulatory compounds, and molecules that benefit the host plant (De la Fuente Canto et al., 2020; Basu et al., 2021; Prasad, 2022; Prasad, 2024a; Prasad & Pandey, 2024). Different types of biofertilizers include microbes such as: mycorrhizal fungi, *Azotobacter spp*., *Azospirillum spp., Acetobacter spp., Rhizobium spp., Fraturia spp*. (Prasad, 2025).

Many of the PGPR strains also act as natural pesticides, destroying dangerous microbes by producing antibiotics, hydrogen cyanide (HCN), lytic enzymes (chitinases, glucanases) and inducing systemic resistance in plants. In addition, there are PGPRs that have the ability to detoxify the soil of organic (hydrocarbons, pesticides, etc.) and inorganic (heavy metals) pollutants. These characteristics make PGPRs effective tools for the natural remediation of contaminated soils (Tarekegn et al., 2020), thereby supporting the health of the entire ecosystem. Biocontrol efficacy is significantly improved when PGPR strains are applied in combination with other bacterial or fungal species (Duffy, Simon, & Weller, 1996).

3.4.1. Antibiotic production

The production of antibiotics by beneficial microorganisms is vital for preventing the spread of disease-causing microorganisms. The best discovery has been the use of PGPR for the production of antibiotics and their use in various biocontrol mechanisms that have been widely investigated (Ulloa-Ogaz, Muñoz-Castellanos, & Nevárez-Moorillón, 2015). Similarly, many *Pseudomonas* species produce antibiotics such as oomycin A, viscosin, and ecomycins, while some strains are also capable of producing 2,4-diacetylphloroglucinol, pyoluteorin, pyrrolnitrin, and rhamnolipids. (Fouzia et al., 2015).

3.4.2. Antioxidant production

The production of antioxidants by PGPR helps to mitigate oxidative stress in plants when they face critical periods caused by drought, high salinity or nutritional deficiency. Oxidative stress is mitigated through the production of antioxidants and the induction of plant adaptive responses to this type of stress (Nivetha et al., 2021; Wahab et al., 2023a). Under normal conditions, when the stress level is low, plants are able to maintain a balance between the production and scavenging of reactive oxygen species (ROS) (Hasanuzzaman et al., 2020). However, under severe stress conditions, plants lose the ability to effectively regulate the production and scavenging of reactive oxygen species (ROS) (Lanza and Dos Reis, 2021) The main enzymes that participate in the processes of reducing oxidative stress are catalase (CAT), which divides hydrogen peroxide into water and oxygen; peroxidase (POD), which then reduces hydrogen peroxide and organic hydroperoxides; and superoxide dismutase (SOD), which has the role of catalyzing the dismutation of hydrogen peroxide and superoxide radicals into oxygen (Jomova et al., 2024). In cases where PGPRs act as stimulants of plant stress adaptation, a strong plant–bacteria interaction leads to the upregulation of antioxidant genes and, consequently, to increased levels of antioxidant molecules and enzymes (Wahab et al., 2023b).

3.4.3. Production of hydrolytic enzymes

PGPR can generate enzymes with a protective role and inhibit phytopathogenic agents. Following the biocontrol activity of PGPR mechanisms, plants are stimulated to grow and produce characteristic compounds with antibiotic and antifungal roles. Chitinase- and β-glucanase-producing bacteria inhibit the growth of phytopathogenic fungi. *Sinorhizobium fredii* KCC5 and *Pseudomonas fluorescens* LPK2 prevent *Fusarium udum*-induced wilt through the production of chitinases and β-glucanases. (Kumar et al., 2010).

3.4.4. Induction of systemic resistance through the formation of VOCs

The production of volatile organic compounds (VOCs) by PGPR contributes to the induction of systemic resistance in plants. These compounds help suppress phytopathogenic microorganisms and reduce fungal and nematode infections. Microbial genera such as *Pseudomonas, Stenotrophomonas, Bacillus, Serratia,* and *Arthrobacter* include species with important roles in plant growth. Notably, *Bacillus spp*. produce a diverse array of volatile organic compounds (VOCs), including 2-butanediol and acetoin, which suppress fungal growth and enhance plant growth (Santoro et al., 2016).

3.4.5. Production of exopolysaccharides (EPS)

Various types of plants, algae and bacteria have the ability to create biodegradable polymers called exopolysaccharides (EPS). They form EPS from glucose residues and their analogues (Sanlibaba & Çakmak, 2016). EPS have the role of supporting the host under stress conditions. Stress caused by saline soil, drought or excessive moisture can be mitigated by EPS by aggregating soil particles, maintaining water reserves and facilitating obligate rhizobacteria. *Rhizobium sp., Azotobacter, Rhizobium leguminosarum, Bacillus drentensis, Xanthomonas sp.,* and *Agrobacterium sp.* are capable of producing EPS, thereby improving soil properties and supporting agricultural productivity (Hasan et al., 2024).

3.4.6. Achieving osmotic balance

During periods of stress, caused by drought and salinity, an osmotic imbalance occurs in plant cells. This imbalance manifests as dehydration, which occurs as a result of the cells being unable to absorb water (Kumar et al., 2023). Under these conditions, PGPRs help minimize the detrimental effects of stress factors on plants by producing osmolytes and facilitating ion transport. Osmolytes such as proline and glycine betaine accumulate in plant cells in response to osmotic stress caused by salinity, drought, and water deficiency. These osmolytes protect cell structures, stabilize proteins and enzymes, managing to rebalance the osmotic balance (Haghpanah et al., 2024). Proline has an osmoprotective role and also acts as a scavenger of reactive oxygen species (ROS), thereby reducing oxidative damage and stabilizing cellular membranes and proteins (Pattnaik et al., 2021). By maintaining osmotic balance in the cytoplasm and vacuoles, Glycine betaine helps plants adapt to osmotic stress, while protecting them from excess of salt and drought. (Rasheed et al., 2024).

3.5. Biotechnological applications of PGPR

Biopreparations are produced based on beneficial microorganisms (PGPRs) or their metabolites and represent an important biological alternative to chemical fertilizers and pesticides, contributing significantly to maintaining of soil fertility and biodiversity and protecting agricultural ecosystems. Within the concept of sustainable agriculture, these products are valued for their ability to improve resource use efficiency, reduce pollution and support soil health on the long term. Among these, PGPR play an important role due to their complex interactions with plants in the rhizosphere and their ability to stimulate plant growth and development.

PGPR are frequently used in biotechnological formulations as microbial inoculants applied to seeds, soil, or aerial parts of plants, where they positively influence both the nutrition and physiology of agricultural crops.

Recent research studies reported the applying of microorganisms in the treatment of corn as soil inoculation (at the rhizosphere level), foliar application and their combination (soil + foliar) (Efthimiadou et al., 2020). The experiment used bacterial strains with biofertilizing potential, such as *Azotobacter* *chroococcum, Bacillus subtilis* and *Bacillus megaterium* are known for their nitrogen-fixing capacity, phosphorus solubilization, and phytohormone production. The results showed that all PGPR-treated variants exhibited significant improvements in growth and yield parameters compared to the control, with the combined application proving to be the most effective, resulting in the highest values of plant height, biomass, and yield. The increase in production was estimated at approximately 15–25%, accompanied by an improvement in 1000-grain weight and seed quality. The beneficial effects of PGPRs application were attributed to their influence on plant nutrition and physiology. Soil inoculation enhanced root colonization and nutrient availability, whereas foliar application stimulated metabolic activity, including photosynthesis and chlorophyll accumulation. In addition, PGPRs contributed to optimizing the absorption of mineral elements and regulating the hormonal balance of plants, through mechanisms such as biological nitrogen fixation, phosphorus solubilization and auxin synthesis. Thus, the application of these biopreparations positively influenced both the vegetative development and the productive performance of the corn crop, demonstrating their potential as a sustainable alternative to chemical fertilizers.

Another research study showed the effect of PGPRs on the germination and early growth of soybean, by applying them as a seed treatment (seed inoculation) before sowing. The seed treatment used in this study consisted of inoculating the seeds with different combinations of bacteria, including *Bradyrhizobium japonicum, Azotobacter chroococcum* and *Bacillus megaterium*, alone or in consortium, some variants being supplemented with a nutrient complex. The bacterial consortium combined with nutrients was the most effective treatment, leading to significant increases in germination energy, vigor index, root and stem length, and fresh and dry biomass compared with the control. The benefits are attributed to the stimulation of root system development and improved nutrient absorption, as well as the synthesis of phytohormones by bacteria (Marinković et al., 2025).

4. Conclusions

PGPRs enhance crop productivity by promoting normal plant growth and development. Their direct and indirect mechanisms of action affect plant growth through different pathways, each being beneficial individually, but especially in combination, by stimulating multiple defence responses and maintaining physiological balance in the plant.

Rhizobacteria are a natural fertilizer alternative, supporting the practice of sustainable agriculture. The application of PGPR-based biopreparations can positively influence the vegetative development, but also the productive performance of agricultural crops, demonstrating their potential as a sustainable alternative to chemical fertilizers.

Rhizobacteria can also have different roles in relation to the plant and can stimulate the activation of different host defence systems. PGPRs contribute to increasing nutrient availability through mechanisms such as biological nitrogen fixation and phosphorus solubilization, but also to stimulating metabolic processes by producing phytohormones and bioactive compounds. In addition, they play an important role in increasing plant tolerance to biotic and abiotic stresses, thus strengthening the resilience of agricultural systems.

PGPR treatments applied to seeds have the ability to act by intensifying early physiological processes and optimizing plant nutrition, leading to a faster and more uniform establishment of the crop and demonstrating the efficiency of these biopreparations as a biotechnological strategy in sustainable agriculture. The integration of PGPR into biopreparations represents an efficient and sustainable strategy for improving crop productivity, an aspect highlighted by numerous experimental studies, including those on seed treatment and soil or foliar application.

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