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REVIEW ARTICLE

ROLES AND INFLUENCE OF RHIZOBACTERIA ON DEVELOPMENT OF PLANTS : A REVIEW

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ABSTRACT

Rhizobacteria are a group of soil bacteria that inhabit the rhizosphere, the region surrounding plant roots, where they interact with the plants and soil environment. Bacteria are known to promote plant growth, suppress plant pathogens, and improve soil fertility. This review focused on the functions/roles of rhizobacterial communities in agricultural soils and their potentials in sustainable agricultural practices. Agricultural soils are particularly enriched with beneficial rhizobacteria such as *Acinetobacter*, *Arthrobacter*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Enterobacter*, *Pseudomonas*, *Rhizobium*, *Serratia*, and *Streptomyces* due to the continuous input of organic matter and the presence of plant roots. Rhizobacteria help to reduce over reliance on the use of chemical pesticides and fertilizers, thereby promoting sustainable and environmentally friendly crops production. Though, the abundance of rhizobacteria in soils can be influenced by several factors such as soil type, salinity, pH, moisture, nutrient availability, land use, and management practices, their positive impacts cannot be overemphasized in food production. Therefore, there is the need to fully understand the potential of these bacteria in order to develop effective strategies for their application in agriculture.

KEYWORDS

Biofertilizers, Beneficial bacteria, Biocontrol agents, Food production, Plant growth promoting bacteria

1. INTRODUCTION

Soil is considered the most suitable medium for farming due to its loamy and fertile qualities. Natural fertility in soil is determined by the rate at which inorganic nutrients are released from organic reserves to sustain rapid plant growth and development (Backer et al., 2018). Soil can exist in many varieties and textures but only a few of them can be appropriate for agricultural practices. Agricultural soils are home to various microorganisms including bacteria, fungi, and algae that breakdown and recycle organic matter and nutrients in the soil. The quality of soil depends on various factors such as fertility, texture, and aeration, resulting in various soil types such as loam and sandy soil (Javed et al., 2022).

Bacteria in soil have been used in crop production for decades and have essential functions such as supplying nutrients to crops, stimulating plant growth through the production of plant hormones, controlling plant pathogens, improving soil structure, and bioaccumulation or microbial leaching of inorganics (Chen et al., 2024 ; Wang et al., 2024). In sustainable crop production, the interactions between plants and microbes in the rhizosphere play a crucial role in nutrient transformation, mobilization, and solubilization to promote plant growth (Wang et al., 2024). The use of biological approaches, such as plant growth-promoting rhizobacteria (PGPR), is becoming more popular as an additive to chemical fertilizers to improve crop yields. PGPR has found potential in developing sustainable systems in crop production (Adeoyo, 2019). A variety of symbiotic

(*Rhizobium* sp.) and non-symbiotic bacteria (*Bacillus*, *Lactobacillus*, *Micrococcus*, *Pseudomonas*, *Serratia*, *Azotobacter*, and *Klebsiella*) are among bacterial species being used to enhance plant productivity (Singh et al., 2017 ; Adeoyo, 2019).

The comprehensive activity of microbes such as those of PGPR in soil involves increases in germination, seedling emergence, height, root system development, and yield. Similarly, production of exopolysaccharides to bind soil particles, retain water potential and aeration, solubilization of insoluble phosphate compounds, mineralization of organic phosphates, biological nitrogen fixation, sequestration and provision of micronutrients such as iron, calcium, zinc, and manganese in utilizable form, denitrification process to reduce excess nitrate load in the soil, and secretion of various plant growth-regulating metabolites such as auxins, gibberellins, cytokinins, and ethylene are just a few of the many characteristics of rhizobacteria that promote plant growth and development (Gopalakrishnan et al., 2015). PGPR also produce secondary metabolites like antibiotics, chelators like siderophores, bacteriocins, and are involved in competitive interactions with other soil microfauna for nutrients and niches in order to eliminate them (Backer et al., 2018). PGPR also serve as biofertilizers (Olanrewaju et al., 2017).

Many PGPR have special traits to live under stress conditions exerted by nutrient limitation, drought, salinity, cold temperature, or heavy metal pollution. Such rhizobacteria find immense environmental applications, such as (Krishna and Mishra, 2015 ; Olanrewaju et al., 2017). The

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important rhizobacterial genera showing potential for plant growth promotion and biocontrol are *Rhizobium*, *Bradyrhizobium*, *Acetobacter*, *Enterobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Proteus*, *Burkholderia*, *Serratia* and *Pseudomonas* (Adeoyo, 2019 ; Krishna and Mishra, 2015). In order to sustain ecosystem services that sustain life on Earth, microbial diversity is essential. Plant-microbial interactions, which include cell signaling, are microbial interactions with plants that cause nitrogen fixation, phosphate solubilization, induced systematic resistance, and benefits in plant growth.

1.1 Rhizosphere

The rhizosphere is a well-defined ecological niche surrounding plant roots, which contains a good number of microbial population that are influenced by root exudates (Hiremath et al., 2024 ; Thepbandit and Athinuwat, 2024). Similarly, the physical, chemical, and biological properties of the soil microbes in the rhizosphere affect their growth, interaction, number, and diversity (Javed et al., 2022). Moreover, the establishment and survival of PGPR in the rhizosphere and on plant roots depend on root exudates and microbial products (Hiremath et al., 2024). In the rhizosphere, a diverse range of chemical compounds is synthesized, accumulated, and secreted by plant roots. The exudation of these compounds modifies the chemical and physical properties of the soil, and thus regulates the structure of soil microbial communities in the immediate vicinity of the root surface (Hiremath et al., 2024). These root exudates include ions, oxygen, water, and a variety of organic compounds, such as sugars, organic acids, amino acids, enzymes, growth factors, and different carbon products. The composition of these exudates depends on the physiological status and species of plants and microbes (Kumar et al., 2017). However, the quantity and composition of root exudates vary with plant developmental stage and the proximity to nearby microbial species (Hiremath et al., 2024). A portion of these organic molecules derived from plants are then broken down by microorganisms as sources of carbon and nitrogen, while some molecules that are orientated toward microbes are subsequently reabsorbed by plants for growth and development.

1.2 Rhizobacteria

Bacteria that are found in the vicinity of plant roots (rhizosphere) are known as *rhizo* (root) bacteria (Thepbandit and Athinuwat, 2024). These bacteria can live either in a free-living state or in a symbiotic association with roots of plants, thus making the site that of intense microbial activity with different chemical, physical, and biological interactions (Lagos et al., 2015). In the plant rhizosphere, both beneficial and deleterious rhizobacteria are present (Table 1). Microbial activity is highly intense and stimulated in the rhizosphere because it is enriched with different types of root exudates, such as sugar, amino acids, fatty acids, and esters, secreted by the host plant (Fahde et al., 2023). The use of exudates as a source of carbon and energy support rhizobacteria, safeguard the host plant's growth and boost its production (Figure 1). This relationship between the plant and rhizobacteria is one of the most well-known instances of mutualistic relationships in soil (de Andrade et al., 2023). Plant development is promoted by a variety of processes, including nutrient cycling, breakdown of large organic compounds, and the synthesis of growth regulators. Because plant roots give the plant and related bacteria structural support, water, and nutrients, these activities are more concentrated in the rhizosphere (Backer et al., 2018). These rhizobacteria also provide pathogen protection and plant health maintenance. As a result, they conduct biocontrol functions include generating antagonistic metabolites and eliminating or suppressing phytopathogenic organisms (El-Saadony et al., 2022).

2. RHIZOBACTERIA AS AGENTS OF PLANT GROWTH-PROMOTION

Numerous microorganisms, including bacteria, actinomycetes, fungus, protozoa, nematodes, and microarthropods do inhabit the rhizosphere (Lagos et al., 2015). The rhizosphere is rich in lipids, carbohydrates, and amino acids, the exudates secreted by the root actively draw microbial populations that colonize the plant roots, promoting growth and managing stress or illness either directly or indirectly (Kumar et al., 2017 ; Singh et al., 2017 ; Fahde et al., 2023). These microorganisms positively affect the host plant's growth and yields (Singh et al., 2017). Through their ability to fix atmospheric nitrogen and transfer it to the plant, produce siderophores that give the plant soil iron, synthesize phytohormones that control plant development, make phosphorus available to the plant, and synthesize the enzyme deaminase, which can lower plant ethylene levels, rhizobacteria play a significant and advantageous role in plant growth and development (Larsen et al., 2015). Symbiotic nitrogen-fixers like *Azospirillum brasilense* and *Bradyrhizobium*, which can establish a symbiotic relationship with their host plant to fix atmospheric nitrogen, are among the varied group of soil microbes known as PGPR (Hungria et al., 2015).

| Table 1: Rhizobacteria and their functions in agriculture | | | |
|---|---|---|---------------------------------|
| S/N | Rhizobacteria | Function(s) | Reference |
| 1. | <i>Bacillus subtilis</i> , <i>Pseudomonas putida</i> | IAA, N ₂ fixation, phosphate solubilisation, siderophore production | El-Sayed et al., 2014 |
| 2. | <i>Bacillus subtilis</i> , <i>Pseudomonas mandelii</i> | Cytokinin, auxin production | Martynenko et al., 2022 |
| 3. | <i>Azospirillum brasilense</i> , | Cytokinin Production | Zaheer et al., 2022 |
| 4. | <i>Gluconacetobacter diazotrophicus</i> , <i>Azospirillum brasilense</i> | Siderophore production production (increased iron in the plants) | Delaporte-Quintana et al., 2020 |
| 5. | <i>Pseudomonas</i> sp. | Synthesize growth- stimulating plant hormones, and suppress pathogenic microbes | Sun et al., 2024 |
| 6. | <i>Rhizobium</i> sp., <i>Azospirillum</i> sp. | IAA, N ₂ fixation | Sev et al., 2016 |
| 7. | <i>Brevibacillus brevis</i> | Siderophore production | Sheng et al., 2020 |
| 8. | <i>Mesorhizobium panacihumi</i> | Siderophore production | Huo et al., 2021 |
| 9. | <i>Bacillus</i> spp. | Siderophore production, IAA, ammonia production, phosphate solubilisation, N ₂ fixation, and HCN production | Pahari and Mishra (2017) |
| 10. | <i>Bacillus megaterium</i> <i>Bacillus licheniformis</i> | Biological N ₂ fixation | Zambrano-Solórzano et al., 2024 |
| 11. | <i>Bacillus</i> sp. | Phosphate solubilization, siderophore production | Zambrano-Solórzano et al., 2024 |
| 12. | <i>Bacillus</i> spp | IAA, Phosphate solubilization, siderophore production | Adeoyo (2019; 2025) |

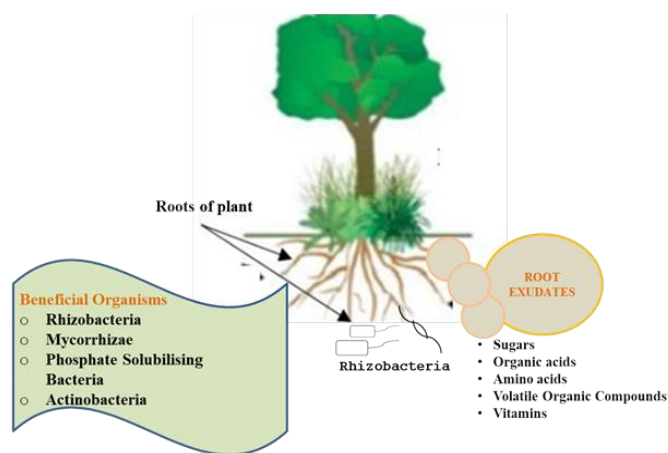


Figure 1: Plant-microbes interactions involving beneficial organisms, plant roots, and root exudates.

PGPR are classified into two main types, extracellular (ePGPR) and intracellular (iPGPR) (Martínez-Viveros et al., 2010). ePGPR like *Azotobacter* species are present in the rhizosphere and in the gaps between root cortex cells. *Frankia* species and endophytic

microorganisms like *Mesorhizobium* and *Rhizobium*, which fix atmospheric nitrogen especially for higher plants, are examples of iPGPR, which are primarily found inside specialized nodular structures in the root (Jeyanthi and Kanimozhi, 2018). The plant growth activities of several PGPR species, such as *Bacillus*, *Azotobacter*, and *Pseudomonas* (Qingwei et al., 2023). The plant growth-promoting properties of these bacterial species, which were isolated from the rhizosphere and root nodules of various plant species, were assessed (Figure 2). These activities included the production of ammonium, siderophores, and hydrogen cyanide, the production of plant hormone (indole acetic acid), antifungal activity, and phosphate solubilisation (Qingwei et al., 2023). Also, *Serratia marcescens* is a PGPR that promote plant growth and health by increasing nutrient availability, fixing nitrogen, and producing phytohormones (Sharma et al., 2020).

One genus of PGPR that lives in the roots of different plant species and promotes plant growth is *Azospirillum* (de Andrade et al., 2023 ; Sun et al., 2024). *Azospirillum brasilense*, *A. amazonense*, *A. irakense*, *A. lipoferum*, *A. oryzae*, *A. canadensis*, and *A. melinis* are among the bacterial species found in around the roots of corn and rice (Lin et al., 2019). *Azospirillum* and crop plants have an unrestricted relationship, and practically any crop plant that has never been treated with them can be inoculated with these bacteria. The rhizosphere of the majority of important crop plants contains *Azospirillum* species, which are microaerophilic—they can fix nitrogen in environments with little oxygen supply. The nitrogen-fixing bacterial species *A. macrocytogenes*, *A. paspali*, *A. chroococcum*, *A. armeniacus*, *A. beijerinckii*, and *A. nigricans* are all members of the genus *Azospirillum*, which can fix nitrogen from the atmosphere (Singh et al., 2017).

Plant roots can be colonized by the aerobic nitrogen-fixing bacterium species *Azoarcus*. The two major species that make up the *Azoarcus* genus are *A. communis* and *A. indigenus*. A study has indicated that these bacteria are able to significantly improve the growth and yield of different crops (Sivasakthi et al., 2014).

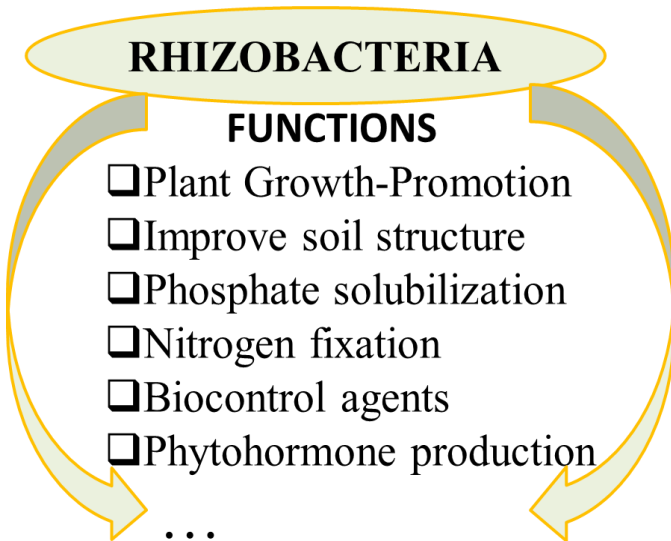


Figure 2: Functions of rhizobacteria in soil

Bacillus is the most significant genus of PGPR in the rhizosphere. The genus includes *B. subtilis*, *B. amyloliquefaciens*, *B. pumilus*, *B. megaterium*, *B. thuringiensis*, and *B. cereus*. One of the most important roles of *Bacillus* genus is ability to increase availability of soil nutrients (Lin et al., 2019). *Pseudomonas* is another PGPR that enhances plant growth and yield production. *Pseudomonas* species are the most potent and efficacious as they play a vital role in maintaining soil health due to their metabolic diversity and activity (Ejeagba et al., 2023). *Pseudomonas fluorescens*, *P. putida*, and others have exhibited a substantial increase in the growth and yield of various crop plants (Sun et al., 2024). These strains have the potential to colonize plant roots and induce plant growth.

2.1 Rhizobacteria as agents for improving soil structure

Exopolysaccharide (EPS) produce by rhizobacteria binds soil particles, retain water potential, and aeration (Alami et al., 2000 ; Fahde et al., 2023). Rhizobacteria improve soil structure and organic matter content, enhances resistance to stress, stabilizes soil aggregates and retain more soil organic nitrogen and other nutrients in the plant-soil system (Rahman

and Guoxiang, 2023). Numerous factors influence soil aggregates, including plant root growth, the physical and chemical characteristics of the soil, solid matter and pores make of the soil, and the activity of microbes. The presence of rhizobacteria genera including *Bacillus*, *Pantoea*, *Paenibacillus*, *Pseudomonas*, and *Rhizobium* would improve soil structure by causing microbial activity on soil aggregation through the formation of EPS (Alami et al., 2000). Thus, the knowledge of soil's aggregates stability is crucial to halting soil erosion, preserving soil fertility, and improving the capacity for sequestering carbon (Li et al., 2020).

2.2 Rhizobacteria as agents of phosphate solubilisation

Despite being a crucial macronutrient for plants, phosphorus (P) is frequently scarce in agricultural soils. The availability of phosphorus to plants is influenced by a number of factors, including soil pH, compaction, aeration, moisture, temperature, texture, organic matter, crop residues, plant root systems, root exudates, and soil microbes (Gopalakrishnan et al., 2015). This nutrient is an important limiting element for plant growth and is essential for a number of metabolic processes, including respiration, energy transmission, photosynthesis, and biosynthesis (Javed et al., 2022). Nonetheless, overuse of fertilizers has led to a high total P content in soils, and a significant amount of this P is inaccessible because it complexes with other soil elements and eventually disappears, resulting in eutrophication of surface water (Liu et al., 2021). Certain soil microorganisms referred to as phosphate-solubilizing bacteria (PSB) are capable of solubilizing insoluble forms of P, primarily through the secretion of organic acids (lactic citric, or succinic acid) or protons from NH_4^+ (Qingwei et al., 2023). PSB are mainly found in the genera *Bacillus*, *Enterobacter*, *Klebsiella*, *Burkholderia*, and *Pseudomonas* (Charana and Yoon, 2013).

3. RHIZOBACTERIA AS AGENTS OF NITROGEN FIXATION

Nitrogen is essential for living organisms because it is a component of amino and nucleic acids. Nitrogen is a limited nutrient for plant growth and agricultural production. Although nitrogen makes up 78% of the atmosphere, it is not readily available to plants in its molecular form. It must be converted into ammonia, which is the form that plants can use. Microorganisms such as rhizobacteria can convert atmospheric nitrogen into ammonia through biological nitrogen fixation process via the enzyme complex nitrogenase (de Andrade et al., 2023 ; Watanabe et al., 2023). Endophytic diazotrophs and rhizoplane-associated organisms, such as *Azotobacter*, *Acetobacter*, *Azospirillum*, *Burkholderia*, *Enterobacter*, *Pseudomonas*, and *Serratia* have been identified with the ability to fix atmospheric nitrogen. Non-symbiotic and symbiotic are two mechanisms of nitrogen fixation. Non-symbiotic nitrogen fixation is carried out by free-living diazotrophs that stimulate the growth of non-legume plants (Rahman and Guoxiang, 2023). Endophytic diazotrophs have an advantage over rhizoplane-associated microorganisms because they can colonize the root interior of plants and create their own niches, a condition that is more suitable for effective nitrogen fixation and transfer fixed nitrogen into host plants (Krishna and Mishra, 2015 ; Renoud et al., 2022). Non-symbiotic bacteria are limited in fixing atmospheric nitrogen due to the high energy requirements, low metabolic activity of the free-living diazotrophs, as well as competition for root exudates (Rahman and Guoxiang, 2023).

3.1 Rhizobacteria as agents of biocontrol

Rhizobacteria do produce secondary metabolites like antibiotics and siderophores (iron chelators) that are involved in competitive interactions with other soil microorganisms (mostly plant pathogens) for nutrients and niches in order to eliminate them (Petkova et al., 2025). Siderophores production is among the functions of rhizobacteria that enable them to acquire iron (III) in the environment. Siderophores produced by PGPR are low molecular weight with high binding affinity and specificity for iron (III), enabling their transport into the bacterial cell (Olanrewaju et al., 2017). These molecules are classified as catecholates, hydroxamates, and α -carboxylates, based on their nature and binding sites with the iron (Maheshwari et al., 2019). Siderophores are produced as free ligands that complex with iron and are then transported into the cell via specific transport receptor proteins. Although the total concentration of siderophores in the environment is low, they are often used by plants as a source of iron, contributing to plant nutrition. Rhizobacteria are involved in iron (Fe^{3+} or Fe^{2+}) immobilization by producing phytosiderophores which make iron unavailable to plant pathogens in soil (Qingwei et al., 2023 ; Sun et al., 2024). The production of antibiotics, a crucial element of PGPR, is another well researched biocontrol strategy against plant diseases (Backer et al., 2018 ; Olanrewaju et al., 2017). Numerous rhizobacteria have been tested for their ability to produce antibiotic metabolites; for instance, it was discovered that 70% of *Pseudomonas*' capacity to reduce *Pythium* root infection was due to oomycin-A (Sah et al.,

2021). Other antibiotics produced by *Pseudomonas* species include pyoluteorin, pyrrolnitrin, and 2,4-diacetylphloroglucinol (Sah et al., 2021).

3.2 Rhizobacteria as agents of phytohormone production

Rhizobacteria have a direct positive impact on plant growth by producing phytohormones such as auxins, also known as indole-3-acetic acid (IAA), cytokinins, gibberellins, as well as increasing the root surface and shoot biomass (de Andrade et al., 2023). IAA plays a key role in processes such as lateral and polar hair growth, vesicular tissue differentiation, and meristem maintenance (Kundan et al., 2015). The biosynthesis of IAA by microorganisms involves several pathways, including the formation of indole-3-pyruvic acid and indole-3-acetic aldehyde, and the transformation of tryptophan to indole-3-acetonitrile or indole-3-acetic aldehyde. *Pseudomonas*, *Rhizobium*, *Bradyrhizobium*, *Agrobacterium*, *Enterobacter*, and *Klebsiella* genera are among the most common IAA producers (Adeoyo, 2019). Similarly, cytokinins produced from *Arthrobacter*, *Azospirillum*, and *Pseudomonas* are responsible for stimulating cell division in plants, regulating root meristem differentiation, and inhibiting primary root elongation and lateral root formation (Timofeeva et al., 2024). Gibberellins *Azospirillum*, *Gluconobacter*, *Azotobacter*, *Bacillus pumilus*, *Bacillus licheniformis*, and *Rhizobium* spp produce plant hormones that stimulate the growth of stem tissue, as well as root elongation and lateral root extension (Gómez-Godínez et al., 2023). Ethylene by rhizobacteria is also an essential plant hormone that can hinder root elongation, auxin transport, nodulation, and promote seed germination, senescence, and abscission of different organs and fruit ripening (Timofeeva et al., 2024). PGPR plays a crucial role in the induction of systemic resistance in plants during associative and symbiotic plant-bacteria interactions (Gómez-Godínez et al., 2023).

4. AVAILABILITY OF RHIZOBACTERIA IN AGRICULTURAL SOILS

Rhizobacteria improve the general health of soil by boosting microbial diversity, accelerating organic matter decomposition, and improving soil structure. Although acidic and alkaline soils can inhibit bacterial growth, bacteria thrive in slightly acidic to neutral soils (pH 6-7.5). Rhizobacteria are impacted by the pH of the soil, which also affects the solubility of some metals and the availability of nutrients. A recent report has revealed that rhizosphere bacterial communities varied in response to soil physicochemical parameters such as pH and moisture content across various farms (Raimi et al., 2023). Nutrient-rich soils can support a higher abundance of rhizobacteria, while others may be more abundant in nutrient-poor conditions. For example, soils with low carbon, nitrogen, and phosphorus can favour rhizobacteria that produce IAA to promote root growth (Ng et al., 2024). In another study, rhizobacterial community was more sensitive to water supply than to nitrogen supply where bacteria such as *Candidatus*, *Koribacter*, and *Streptomyces* genera persisted across soil samples (Shi et al., 2025). Nitrogen level, phosphorus, and manganese concentrations can increase with increase in water supply (Shi et al., 2025). Similarly, it has been reported that soil nutrient management influences diversity of rhizobacteria in soil (Raimi et al., 2023).

Drought and waterlogged conditions can enhance the concentration of some mineral nutrients in soil. According to the study, drought or waterlogged conditions significantly enhanced nitrogen fertilization by increasing Cu, K, Fe, and Zn concentrations as compared to nitrogen starvation, whereas under the normal water treatment, there were no significant differences in nutrient concentrations between the nitrogen treatments (Shi et al., 2025). Also, salt is one of the major factors that affects the availability and abundance of rhizobacteria in soil. Nutrient uptake, yield, and productivity were adversely affected under drought conditions. Soil structure affects the movement of water and nutrients, thus, impacting rhizobacterial communities (Chen et al., 2024). Furthermore, tillage, crop rotation, and other agricultural practices can also alter the soil environment and affect rhizobacterial communities (Chen et al., 2024). Plant roots usually release some organic substances called root exudates. Through root exudation, plants can alter the rhizosphere microbiome, alter soil environment, and enhance plants' growth. The rhizosphere's enriched beneficial microorganisms are essential to the fitness, production, and health of plants and help plants to communicate with soil microorganisms (Chen and Liu, 2024).

4.1 Rhizobacteria as microbial inoculants

Microbial inoculants are formulations of living beneficial indigenous organisms which colonize the soil when applied to the rhizosphere of growing plants and increase nutrient availability considerably (Shahwar et al., 2023). They are environment-friendly and meant to supplement and reduce over reliance on synthetic usage of fertilizers (Table 2). Also, when apply to soil; they promote growth by increasing root biomass and

nutrient uptake capacity of plants. In order to be produced biofertilizers on a large scale and made available to farmers, they must be multiplied on sterile carrier (peat, lignite, farmyard manure, and charcoal powder). Plant nutrients in form of biofertilizers are affordable, efficient, and sustainable (dos Reis et al., 2024). A special characteristic of rhizobacteria worth mentioning is that they are able to produce exopolysaccharides (EPS), which aid their ability to withstand unfavourable conditions, and this play critical role in their use as biofertilizers. According to EPS can shield cells from a variety of stressors, including temperature, pH, drought, and NaCl. It can also give cells a source of carbon and energy when nutrition levels are dropping (Naseem et al., 2018 ; Kucuk, 2020).

Table 2: Rhizobacteria that have demonstrated ability to promote growth in some crops

| S/N | Rhizobacteria | Economic crop(s) | Reference |
|-----|---|---|--------------------------------|
| 1. | <i>Ochrobactrum</i> spp. | Soybean [<i>Glycine max</i> (L.) Merr] (<i>Glycine max</i> L.) | Yu et al., 2017 |
| 2. | <i>Pseudomonas</i> spp. | Rice (<i>Oryza sativa</i> L.) | Yasmin et al., 2016 |
| 3. | <i>Streptomyces</i> spp. | Tomatoes (<i>Solanum lycopersicum</i> L.) | Kaari et al., 2022 |
| 4. | <i>Azospirillum</i> spp. + <i>Pseudomonas</i> sp. | Wheat (<i>Triticum aestivum</i> L.) | Alaskar and Al-Shwaiman (2023) |
| 5. | <i>Pseudomonas rhodesiae</i> | Cucumber (<i>Cucumis sativus</i> L.) | Takeuchi et al., 2024 |
| 6. | <i>Bacillus</i> spp. | Maize (<i>Zea mays</i> L.) and mung bean [<i>Vigna radiata</i> (L.) R. Wilczek] | Ahmad et al., 2019 |
| 7. | <i>Rhizobium</i> spp. | Cowpea [<i>Vigna unguiculata</i> (L.) Walp] | Nyaga and Njeru, 2020 |
| 8. | <i>Bacillus</i> spp. | Sorghum [<i>Sorghum bicolor</i> (L.) Moench] | Muhammad et al., 2024 |

4.2 Influence of growth parameters on availability of rhizobacteria in soil

The presence of diverse microorganisms in the soil exerts a significant impact on plant nutrition and survival (Adeleke et al., 2024). Rhizobacteria inhabiting the soil-root environment play crucial roles in promoting plant growth by enhancing nutrient bioavailability, synthesizing phytohormones, inducing systemic resistance, and providing biocontrol efficacy against plant pathogens (Adedeji et al., 2020). The presence and activity of these bacteria in the soil are influenced by various environmental and physicochemical factors (Rekha et al., 2020). These factors, which vary across soil types, include soil pH, temperature, moisture content, nutrient availability, oxygen levels, root exudates, plant species, and soil texture and structure.

Soil pH is one of the major factors affecting microbial growth and activity (Batool et al., 2021). Some microorganisms thrive under acidic, neutral, or alkaline conditions depending on the soil type. Soil pH contributes to the structure of microbial communities and serves as a key determinant of plant health (Dinango et al., 2025), although its precise influence on pathogen infestation remains unclear. Changes in soil pH, often resulting from anthropogenic activities, can lead to soil acidification, a critical challenge to agricultural productivity due to its alteration of microbial activity and subsequent reduction in crop yield. Soil microorganisms play a vital role in nutrient recycling and plant protection against pathogens (Akanmu et al., 2021); therefore, soil pH can help predict the types and diversity of microorganisms present. Studies have shown that variations in soil pH influence microbial community composition and functionality (Xiong et al., 2024), thereby affecting plant growth and crop productivity. Assessing soil pH is essential for understanding microbial dynamics, particularly those capable of surviving under varying levels of acidity, neutrality, or alkalinity. Most microorganisms thrive at near-neutral pH, typically between 6.0 and 7.4. However, extreme pH conditions can adversely affect rhizobacterial survival and functionality. For instance, certain rhizobacteria are reported to colonize plant roots optimally at

neutral pH (Khanghahi et al., 2020).

Soil temperature also plays a crucial role in determining microbial populations and activity. Temperature affects microbial metabolism, reproduction, and enzymatic processes (Onwuka and Mang, 2018). Most microorganisms have defined minimal, optimal, and maximal temperature ranges for growth. Rhizobacteria, for instance, generally thrive at temperatures between 25 °C and 30 °C. Both low and high soil temperatures influence microbial abundance: low temperatures tend to retard microbial growth and metabolic activity, while high temperatures can cause thermal stress or cell death (Schmidt et al., 2015). Water availability helps regulate soil temperature and mediates microbial responsiveness to environmental fluctuations (Basu et al., 2017). Moisture is vital for microbial growth and nutrient diffusion in soil. Drought conditions, resulting from limited water availability, can hinder plant growth and microbial activity, ultimately reducing crop productivity (Muhammad et al., 2023). Conversely, excess water in waterlogged soils can create anoxic conditions that suppress aerobic rhizobacteria while favoring anaerobic ones (Kuzyakov and Razavi, 2019). Most rhizosphere bacteria are aerobic or facultative anaerobes, and their optimal growth is generally associated with well-drained, aerated soils (Khan and Mehmood, 2023).

Soil nutrients are equally essential for microbial growth and functionality. Key nutrients such as nitrogen, phosphorus, potassium, and carbon form the foundation of soil fertility and microbial metabolism (Puri et al., 2020). Although these nutrients often exist in bound, unavailable forms, PGPR can biotransform them into accessible forms for plant uptake. Root exudates released into the rhizosphere contain organic compounds, such as organic acids, sugars, and amino acids that serve as nutrient sources and signaling molecules, thereby supporting microbial proliferation (Mavrodi et al., 2021). The composition of root exudates influences bacterial abundance and diversity in the rhizosphere. Carbon compounds in root exudates provide energy for microbial activity (Huang et al., 2014). Nitrogen-fixing bacteria are commonly found in the roots of leguminous plants, where they form nodules and convert atmospheric nitrogen into bioavailable forms, improving nitrogen-deficient soils (Ayilara et al., 2022). Similarly, phosphate- and potassium-solubilizing bacteria enhance nutrient pools in the rhizosphere, contributing to improved soil fertility, microbial activity, and plant nutrition (Adeleke and Fakoya, 2025).

5. CONCLUSION

This review provides information on the importance of *Streptomyces*, *Pseudomonas*, *Arthrobacter*, *Serratia*, *Bacillus*, *Enterobacter*, *Acinetobacter*, and related organisms which can perform specific functions in improving growth and protection of plants. These organisms could help in production of biofertilizers, which are made of live microorganisms that primarily influence the growth and development of crops, as well as contributing to the control and management of crop diseases. Finally, more studies should focus on understanding the interactive network between root exudates, nutrient availability, and soil microbial communities for better plant growth and development.

CONFLICTS OF INTEREST

Authors declare that there are no conflicts of interest concerning the publication of this article.

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