PROCEEDINGS OF
VII. INTERNATIONAL AGRICULTURAL, BIOLOGICAL, LIFE SCIENCE CONFERENCE
AGBIOL 2025

07-10 SEPTEMBER 2025

ISTANBUL, TÜRKİYE

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Organized by
Trakya University
Istanbul Beykent University
International Researchers Association

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WELCOME NOTES

You are welcome to our VII. AGBIOL Conference that is organized by Trakya University, Beykent University and International Researchers Association. The aim of our conference is to present scientific subjects of a broad interest to the scientific community, by providing an opportunity to present their work as oral or poster presentations that can be of great value for global science arena. Our goal was to bring three communities, namely science, research and private investment together in a friendly environment of Edirne, Turkey in order to share their interests and ideas and to get benefit from the interaction with each other.

In September 2018, we organized the first AGBIOL Conference with more than 700 scientists and researchers from all over the world with over 800 scientific papers. Due to COVID-19 situation, II. AGBIOL 2020 has organized fully on-line event which was one of the biggest online conferences in recent years in the world with 499 papers and 1133 authors with 333 oral and 166 e-poster presentations from 55 countries. Due to COVID-19 situation, AGBIOL 2021 was organized online again. AGBIOL 2022 conference was organized with a worldwide participation from 44 countries over 522 papers contributed by over 1300 authors. AGBIOL 2023 was organized with a record and worldwide participation from 33 countries 833 papers contributed by over 2000 authors with 522 oral and 311 poster presentations. AGBIOL 2024 consisted of 835 papers contributed by about 2000 authors with worldwide recodr participation again from 55 countries with 522 oral and 311 poster presentations.

There is a worldwide record participation from 60 countries 988 papers contributed over 2300 authors with 400 oral and 588 poster presentations in AGBIOL 2025.

The AGBIOL 2025 is normal participation as well as with online participation in Beykent University in Istanbul, Turkey on 07-10 September, 2025. The program included oral talks by invited prominent scientists and oral and e poster presentations by participants in selected topics from the submitted abstracts focusing on Agriculture, Biology and Life Sciences topics.

With care for our nature and environment, we aim the green congress, meaning that as little as possible papers will be used. Abstract book is published in electronic book and is distributed to the participants by e mail for online participants. All the e-posters are prepared in electronic form and then submit to via the conference e mail and exhibited in electronical poster boards as well as in online e poster hall in our web page during the conference.

The participants with paid conference fee accessed all the normal and virtual presentation talks in each session, as well as to visit the virtual poster hall via preliminary provided. The abstracts were published in the Conference Abstract and Proceedings Book. Participants might send us their full papers, which based on their preferences are published either in our Conference Abstract and Proceedings Book or in selected International Indexed Scientific Journals.

Conference Topics:

Agriculture, Forestry, Life Sciences, Agricultural Engineering, Aquaculture and Biosystems, Animal Science, Biomedical science, Biochemistry and Molecular Biology, Biology, Bioengineering, Biomaterials, Biomechanics, Biophysics, Bioscience, Biotechnology, Botany, Chemistry, Chemical Engineering, Earth Sciences, Environmental Science, Food Science, Genetics and Human Genetics, Medical Science, Machinery, Pharmaceutical Sciences, Physics, Soil Science.

We would like to thank all of you for joining this conference and we would like to give also special thanks to TUBITAK and collaborators for giving us a big support to organize this event.

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FROM SOIL TO SURVIVAL: PGPB-TRIGGERED DEFENSE AND ADAPTATION IN PLANTS

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ABSTRACT

Plants and beneficial soil bacteria engage in dynamic and reciprocal interactions that influence plant development, nutrient acquisition, and stress resilience. Among these, plant growth-promoting bacteria (PGPB) have garnered considerable attention due to their ability to support plant health through a range of biochemical and physiological mechanisms. These bacteria produce a variety of bioactive compounds that enhance plant stress tolerance, improve nutrient availability, and offer protection against phytopathogens.

PGPB influence plant performance through both direct and indirect mechanisms. Direct pathways include the biosynthesis of phytohormones (such as indole-3-acetic acid), solubilization of essential nutrients like phosphate, zinc, and potassium, ammonia production, and atmospheric nitrogen fixation. Indirectly, they contribute by secreting siderophores, lytic enzymes, hydrogen cyanide, and antibiotics, which suppress harmful microorganisms and enhance plant immunity.

These functional traits position PGPB as valuable components in sustainable agriculture, especially for the development of bioformulants including biofertilizers, biopesticides, and biofungicides. Such alternatives reduce dependency on chemical inputs and contribute to environmentally responsible crop management. Nonetheless, despite the expanding repertoire of beneficial strains, the practical implementation of PGPB in agriculture remains challenging. Factors such as microbial survival, strain specificity, plant-microbiome compatibility, and fluctuating environmental conditions can influence their efficacy in field applications.

This review explores recent advances in understanding PGPB-mediated plant adaptations to abiotic and biotic stressors, with emphasis on molecular mechanisms, signaling pathways, and metabolite production. It also discusses formulation strategies and delivery systems designed to maximize their stability and performance. Ultimately, leveraging PGPB potential requires a deeper integration of microbiology, plant physiology, and environmental science to ensure their consistent and scalable use in sustainable agricultural systems.

Keywords: Plant Growth-Promoting Bacteria, stress tolerance, sustainable agriculture, biocontrol

INTRODUCTION

Through the release of bioactive chemical signals, bacteria and plants interact and communicate in a dynamic and ongoing co-evolutionary relationship. Both positive and negative interactions are possible (Wille et al., 2019). The plants gain from positive relationships because they help them acquire minerals, phytohormones, and other nutrients. By releasing a number of bioactive chemicals, these helpful bacterial species can also combat phytopathogens and help plants withstand a variety of stressful situations. Conversely, detrimental interactions are detrimental because infections infiltrate plant tissues, which causes the host plants to die (Dolatabadian, 2021; Adedayo et al., 2022). Utilizing these advantageous microbes can therefore help plants withstand stress that reduces their yield.

As part of the soil ecosystem, microorganisms have a major impact on the nitrogen cycle, soil fertility management, and plant diversity preservation. According to Zhou et al. (2020), a crucial area for important biological interactions between plants and microorganisms is the rhizosphere, a tiny area that surrounds the plant roots. Microorganisms such as bacteria, actinobacteria, fungus, algae, and protozoa aggressively compete for food and space in this productive area (Manghwar et al., 2023). Both the host and the microorganisms benefit from the ability of the plant growth promoting microorganism (PGPM) to live in and interact with plant roots; a population of rhizospheric bacteria and fungi may also serve as a home for other microbes (dos Lopes et al., 2021). The most prevalent of all the helpful microorganisms are bacteria, which are followed by fungus and actinobacteria (Poria et al., 2021). Through direct or indirect methods of nutrient absorption and assimilation, they have a beneficial effect on the plant (Kumari et al., 2018).

Food security is threatened by the world's population growth, which increases the need of fertilizers based on inorganic chemicals, which is bad for the environment and human health (Mitter et al., 2021). Because of the numerous environmental stressors that also contribute to low crop yields, organic farming that relies on microflora such as PGPM guarantees food availability while improving crop quality, productivity, and environmentally friendly farming practices (Jalal, et al., 2023). Therefore, by reducing the use of chemical fertilizers, crop production using PGPM provides sustainability and protects soil biodiversity (dos Lopes et al., 2021).

The majority of plant growth-promoting bacteria (PGPB) are proteobacteria. It includes genera like *Pantoea, Thiobacillus, Pseudomonas, Micrococcus, Rhodococcus, Azospirillum, Azotobacter, Acinetobacter, Acetobacter, Klebsiella, Enterobacter, Alcaligenes, Arthrobacter, Burkholderia, Azorhizobium, Achromobacter, Serratia, Bradyrhizobium, Flavobacterium, Mesorhizobium, Microrhizobium, Streptomyces, Bacillus, Azoarcus, Aeromonas, Azoarcus, Caulobacter, Chromobacterium, Delftia, Frankia, Flavobacterium, Gluconacetobacter, Paenibacillus, Rhizobium* and *Streptomyces* (Table 1).

Table 1. Plant growth promoting bacteria and their common host plant family (from Fanai et al., 2024).

Family	**Plant**	**Plant growth-promoting bacteria**
Fabaceae	*Phaseolus vulgaris*	*Rhizobium acidosoli, R. endophyticum, R. esperanzae, R. etli, R. hidalgoense, R. mesoamericanum, R. tropici, Acinetobacter* sp.
Poace	Rice, wheat, maize, soirghum, sugarcane	*Azospirillum* sp.
Asteraceae	Puticaria	*Bacillus cereus, Agrobacterium fabrum, Brevibacillus brevis, Bacillus subtilis, Paenibacillus* sp., *Acinetobacter radioresistant, Burkholderia* sp.
Solanaceae	*Artemisia annua*	*Brevibacillus* sp., *Bacillus* sp., *Pseudomonas* sp., *Azospirillum* sp., *Klebsiella* sp., *Enterobacter* sp., *Alcaligenes* sp., *Azotobacter* sp., *Streptomyces* sp., *Pantoea* sp., *Bacteroides* sp., *Proteobacteria* sp., *Radiobacter* sp., *Stenotrophomonas* sp.
Brassicaceae	*Brasica oleraceae*	*Pseudomonas* sp., *Enterobacter* sp., *Arthrobacter* sp., *Pantoea* sp.
Crasulaceae	*Echevari laui*	*Erwinia* sp., *Pantoea* sp.

In addition to helping plants tolerate a variety of biotic and abiotic stressors, the PGPB also promotes plant growth by promoting the solubility of various inorganic mineral nutrients, fixing nitrogen, releasing plant growth regulators, and producing a number of other biochemicals that either directly or indirectly increase plant productivity. Figure 1 shows the several ways that bacteria can promote plant growth.

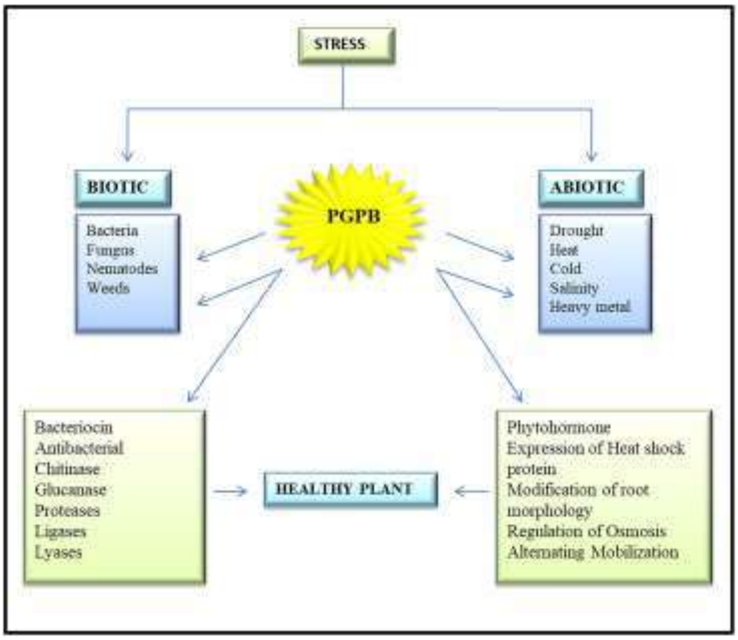

Figure 1. Functions that plant growth-promoting bacteria provide. The impacts of both biotic (caused by living things) and abiotic (induced by environmental variables) stress on plants demonstrate how PGBP helps to lessen the effects of stress. Through processes including siderophores, lytic enzymes, HCN, antibiotics & nitrogen fixation, hormone synthesis, etc., PGBP improve plant development, nutrient absorption, and stress tolerance (from Fanai et al., 2024).

One possible approach to a sustainable future is the use of helpful microorganisms as bioinoculants in agricultural systems. As an effective, environmentally friendly, and productive fertilizer that could help meet the growing demand for food from the world's population, it is a good substitute for chemical fertilizers. They improved the soil microbiota and preserved soil fertility in addition to promoting plant growth.

ABIOTIC AND BIOTIC STRESS FACTORS

Continuously subjecting plants to biotic and abiotic stressors has a negative effect on their growth and development, which lowers yield and quality (Singh et al., 2021). With the help of a naturally occurring PGPB that increases resistance against different phytopathogens by generating biochemicals and improving soil fertility, plants subsequently develop particular kinds of defense mechanisms for stress response (Leontidou et al., 2020). Figure 2 shows the various stressors and bacterial stress tolerance systems.

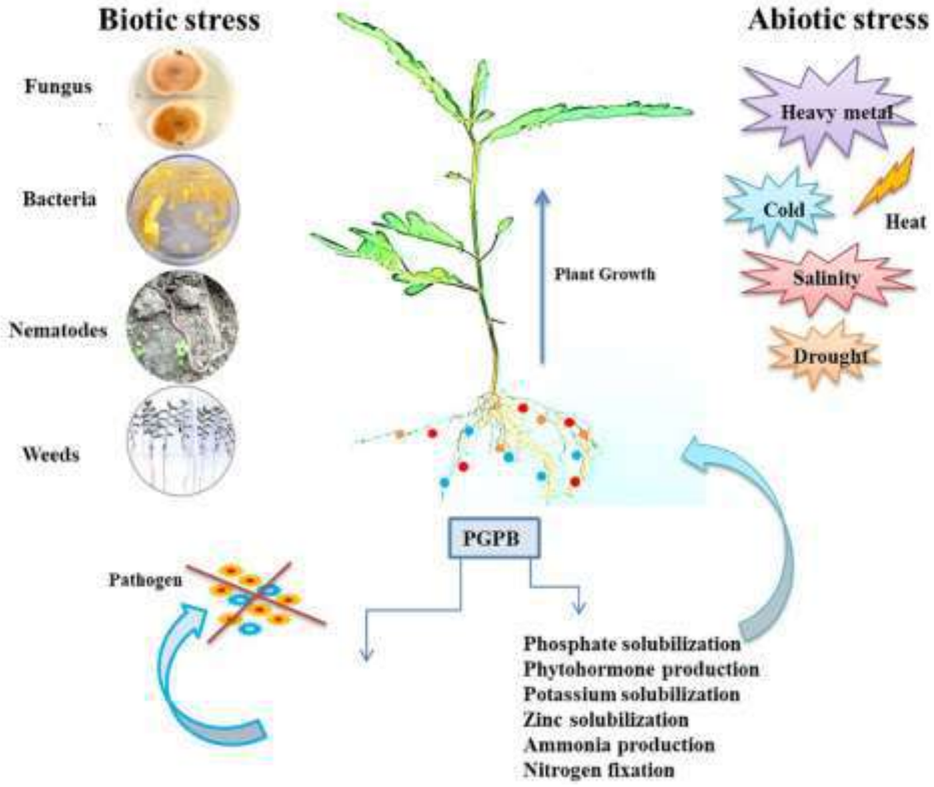

Figure 2. Various stressors and bacteria that support plant growth react to provide plant growth promotion. The impacts of both biotic (caused by living things) and abiotic (induced by environmental variables) stress on plants demonstrate how PGBP helps to lessen the effects of stress. By means of processes like nitrogen fixation, hormone synthesis, and biocontrol, PGBP improve plant growth, nutrient absorption, and stress tolerance (from Fanai et al., 2024).

Drought stress is categorized into hydrological, socio-economic, meteorological, and agricultural types, each leading to soil moisture deficits and the accumulation of reactive oxygen species that damage plant structure and function (Ahluwalia et al., 2021). Traditional mitigation measures—such as biochar amendments, nanoparticle treatments, film farming, and drought-resistant cultivars—have shown only limited benefits in real agricultural systems (Fadiji et al., 2022). By contrast, plant growth-promoting bacteria (PGPB) enhance drought tolerance through improved water uptake, root architecture modification, and production of protective phytochemicals (Khan and Bano, 2019). For example, inoculation with *Bacillus pumilus* and *Pseudomonas putida* improved maize drought resilience and nutrient acquisition (Kálmán et al., 2024), while *Bacillus subtilis* and *Azospirillum brasilense* increased osmolyte synthesis to support wheat germination under water deficit (Ilyas et al., 2020). Strains such as *Pseudomonas lini* and *Serratia plymuthica* enhance soil aggregate stability, and *Bacillus albus* together with *Bacillus cereus* boost seed vigor, pigment concentration, and antioxidant activity, collectively strengthening photosynthetic efficiency and stress defenses (Zhang et al., 2020; Ashry et al., 2022; Saleem et al., 2021). Other notable drought-tolerant bacteria include *Achromobacter xylosoxidans*, *Pseudomonas aeruginosa*, *Lelliottia adecarboxylata*, *Enterobacter cloacae*, *Pseudomonas fluorescens* S3X, and *Staphylococcus sciuri* (Danish et al., 2020; Khalilpour et al., 2021).

A rise in average global temperatures poses a significant abiotic challenge for crop productivity (Desaint et al., 2021). Heat-tolerant microbes—including *Bacillus cereus, Serratia liquefaciens, Pseudomonas putida, P. fluorescens* (Mitra et al., 2021), *Burkholderia phytofirmans, Curvularia protuberata* (Rana et al., 2021)*, Paraburkholderia phytofirmans,* and various *Bacillus* and *Pseudomonas* spp. (Ahmad et al., 2023)—mitigate thermal damage by modulating plant hormone levels (e.g., cytokinins, ACC deaminase) and activating antioxidant enzymes that control water uptake and induce heat-shock protein expression (Moumbock et al., 2021). Exogenous application of specific amino acids further alleviates heat-stress effects by enhancing stress-responsive pathways (Santos et al., 2022). Inoculation with *B. cereus* has been shown to boost overall biomass, chlorophyll content, and heat-shock protein accumulation (Khan et al., 2020b), while *Enterobacter* sp. SA187 increased wheat and *Arabidopsis* heat endurance, leading to higher grain yield, plant height, and seed weight. Moreover, *B. cereus* enhances carotenoid, protein, ascorbate peroxidase, chlorophyll, and superoxide dismutase levels (Bisht and Mishra, 2020), and strains such as *B. thuringiensis, B. subtilis, P. brassicacearum* (Ashraf et al., 2019), and *B. velenzensis* further demonstrate the promise of microbial inoculants for improving plant thermotolerance.

Soil salinization, driven by water scarcity and the accumulation of NaCl-rich compost from sewage and waste treatment, and the build-up of soluble ions—bicarbonate, magnesium, sodium, chloride, sulfate, carbonate, and calcium—alters soil composition, diminishes fertility, impairs germination, and disrupts chloroplast structure, leading to reduced pigment synthesis, ion toxicity, and osmotic imbalance (Ahmed et al., 2020; Krishnamoorthy et al., 2022). Salinity stress further reduces plant development, fruit yield, biomass, stomatal conductance, and water movement (Ansari et al., 2019). Plant growth-promoting bacteria counteract these adverse effects by inducing stress-responsive pathways that lower reactive oxygen species production, synthesizing Na^+-binding exopolysaccharides, and producing phytohormones to enhance root growth and water uptake (Subramaniam et al., 2020). For instance, *Bacillus amyloliquefaciens* GB03 releases volatile organic compounds that boost stress mitigation sixfold (Cappellari et al., 2020). Additionally, halotolerant strains of *Streptomyces*, *Aneurinibacillus aneurinilyticus, Paenibacillus* spp., *Pseudomonas azotoformans*, and other genera such as *Bacillus, Enterobacter, Klebsiella, Agrobacterium,* and *Ochrobactrum* can tolerate NaCl up to 150 g/L, highlighting their promise in reclaiming saline soils (Liu et al., 2021).

Plant growth-promoting microbes (PGPM) suppress biotic stresses from pathogenic fungi, bacteria, nematodes, insects, and weeds by activating systemic acquired resistance (SAR) and induced systemic resistance (ISR). SAR arises when PGPM directly inhibit pathogens, whereas ISR is triggered by bacterial elicitors such as volatile organic compounds (VOCs), microbe-associated molecular patterns (MAMPs), and bioactive secondary metabolites (Dubey et al., 2020). These microbes employ lytic enzymes, antibiotics, and VOCs for direct antagonism and enhance plant defenses indirectly through nitrogen fixation, siderophore production, phosphate solubilization, and phytohormone signaling (Migunova and Sasanelli, 2021). For instance, *Pasteuria penetrans* and *Brevibacillus laterosporus* secrete proteases that inhibit *Heterodera glycines* (Mohan et al., 2020), while *Bacillus megaterium* combats *Meloidogyne graminicola* similarly. Strains like *Pseudomonas aeruginosa, P. cepacia,* and *P. fluorescens* exhibit broad-spectrum antimicrobial and anthelmintic activities (Bhavya and Geetha, 2021), and *Bacillus subtilis* and *B. pumilus* produce chitinases and antifungal VOCs that disrupt nematode chitin synthesis. *Bacillus amyloliquefaciens* FZB42 and *Arthrobacter nicotianae* release bacteriocins and VOCs that inhibit *Meloidogyne* spp. By colonizing the rhizosphere and producing siderophores, phytohormones, and antibiotics, PGPM also inhibit soil-borne fungi, solubilize phosphate, and promote plant growth via indole-3-acetic acid synthesis. These combined actions outcompete pathogens for nutrients and induce ISR against bacterial genera—such as *Erwinia, Pectobacterium, Pantoea,* and *Xanthomonas*—that cause wilts, blights, galls, and root rots (Nazari and Smith, 2020; Nabila and Kasiamdari, 2021).

Table 2. Overview of Plant Growth-Promoting Rhizobacteria functions (from Priyanka et al., 2020)

Function of PGPR	**Description**	**PGPR strain**
Nitrogen fixation	Conversion of free atmospheric nitrogen into oxide form that can be used	*Enterobacter, Klebsiella, Burkholderia,* and *Stenotrophomona*
Phosphate solubilization	Conversion of insoluble phosphate into the soluble form absorbed by the plants	*Achromobacter, Agrobacterium, Bacillus,* *Enterobacter, Erwinia, Escherichia, Flavobacterium,* *Mycobacterium, Pseudomonas* and *Serratia*
Potassium solubilization	Conversion of potassium in the useful form	*Acidothiobacillus ferrooxidans, Bacillus* *edaphicus, Bacillus mucilaginosus, Burkholderia, Paenibacillus* sp. and *Pseudomonas*
Production of siderophore	Enhancing the source of iron in the soil that can be absorbed by the plants	*Aeromonas, Azadirachta, Azotobacter,* *Bacillus, Burkholderia, Pseudomonas,* *Rhizobium, Serratia* and *Streptomyces* sp.
Phytohormone production	Production of phytohormones such as auxin, cytokinins, gibberellic acid and ethylene	*Azotobacter*sp., *Rhizobium* sp., *Pantoea agglomerans, Rhodospirillum rubrum, Pseudomonas fluorescens, Bacillus subtilis* and *Paenibacillus* sp.

DIRECT AND INDIRECT MECHANISMS OF PGPB IN ENHANCING PLANT PERFORMANCE

Indirect mechanisms

Siderophore production: Bacteria secrete ferric-specific ligands (hydroxamates, phenolates, carboxylates) to solubilize iron for themselves and host plants, enhancing root colonization and outcompeting pathogens; common producers include *Bacillus, Chryseobacterium, Phyllobacterium,* and *Pseudomonas* spp. (Bhatt et al., 2019).

Protease secretion: Microbial proteases (alkaline, acidic, neutral)—notably from *Bacillus* spp.—hydrolyze pathogen proteins and generate antifungal metabolites (e.g., serine proteases, subtilisins), serving as an indirect plant defense; activity is screened on skim-milk agar by clear halo formation (Castaldi et al., 2021).

Catalase activity: Catalase-positive strains (e.g., *Bacillus marinus, B. sphaericus, Staphylococcus aureus*) detoxify H_2O_2 at root interfaces, mitigating oxidative damage under stress; detected by bubble formation in 3% H_2O_2 (Talaiekhozani, 2022).

Amylase production: Alpha-amylases from endophytes like *Bacillus amyloliquefaciens* and *B. licheniformis* degrade pathogen cell walls and contribute to industrial applications (detergents, stain removal); screened on starch agar via iodine-stained halos (Ismail et al., 2021).

Urease activity: Ureolytic bacteria hydrolyze urea into plant-available ammonium and nitrates, supporting nitrogen nutrition and biomineralization (soil enrichment, concrete repair); measured by pH-dependent color change in urea broth (Cui et al., 2022).

Hydrogen cyanide (HCN) release: Rhizobacteria (mostly *Pseudomonas* and *Bacillus* spp.) emit HCN to inhibit fungi, nematodes, insects, and weeds without harming the host plant; detected via alkaline-picrate colorimetric assay (Alemu, 2016).

Table 3. Mechanisms and functions of PGPB (*adapted from Olanrewaju et al. (2017) and Fanai et al. (2024))*

Mechanism	**Category**	**Primary Function**	**Reference**
Indole-3-acetic acid (IAA)	Direct	Stimulates root initiation, cell division, lateral root formation	Olanrewaju et al. (2017)
ACC deaminase activity	Direct	Degrades precursor of ethylene; alleviates abiotic-stress inhibition	Olanrewaju et al. (2017)
Cytokinin production	Direct	Promotes shoot growth, delays leaf senescence	Fanai et al. (2024)
Nitrogen fixation	Direct	Converts atmospheric N_2 into bioavailable NH_4^+	Fanai et al. (2024)
Phosphate solubilization	Direct	Releases organic acids to convert insoluble P into plant-available forms	Fanai et al. (2024)
Siderophore production	Indirect	Sequesters Fe^{3+}, suppresses pathogen growth, improves iron nutrition	Olanrewaju et al. (2017)
Lytic enzyme secretion	Indirect	Produces chitinases/proteases to degrade fungal and nematode walls	Olanrewaju et al. (2017)
Hydrogen cyanide (HCN) emission	Indirect	Volatile compound that inhibits soil-borne pathogens and weeds	Olanrewaju et al. (2017)
Antibiotic metabolite release	Indirect	Synthesizes antimicrobial compounds against bacteria and fungi	Olanrewaju et al. (2017)
Induced systemic resistance (ISR)	Indirect	Elicits plant defense pathways via MAMPs and VOCs	Fanai et al. (2024)

Direct mechanisms

Phytohormone production: Plant growth–promoting bacteria (PGPB) synthesize cytokinins, gibberellins, and especially indole-3-acetic acid (IAA), which regulate cell division, root initiation, and stress responses. Strains such as *Paenibacillus polymyxa, Rhizobium leguminosarum, Pseudomonas fluorescens* produce cytokinins (Mekureyaw et al., 2022), while *Bacillus pumilus* and *B. licheniformis* generate multiple gibberellins (Gutiérrez-Mañero et al., 2001). IAA producers, including *Azospirillum, Arthrobacter, Bradyrhizobium, Pantoea, Rahnella*, and *Enterobacter*, enhance root elongation and nutrient uptake (Rehman et al., 2020).

Phosphate solubilization: PSB release organic acids (citric, gluconic) that chelate cations and convert insoluble phosphates (tricalcium, rock phosphate) into bioavailable forms. Key taxa include *Pseudomonas putida, Azospirillum lipoferum, Bacillus firmus, B. polymyxa, Serratia marcescens,* and *Arthrobacter aureofaciens*. PSB inoculation boosts phosphorus availability and activates stress-responsive genes in crops like potato and sugarcane (Lin et al., 2023).

Ammonia production: Ammoniagenic PGPB such as *Pseudomonas putida, Klebsiella* spp., and *Enterobacter asburiae* generate NH_3, raising soil pH to suppress pathogens and supply inorganic nitrogen, which enhances root/shoot growth and biomass (Gohil et al., 2022).

Nitrogen fixation: Symbiotic genera (*Bradyrhizobium, Mesorhizobium, Sinorhizobium, Azorhizobium, Neorhizobium*) and free-living diazotrophs (*Azotobacter, Azospirillum, Burkholderia, Pseudomonas*, cyanobacteria) convert atmospheric N_2 into plant-available forms, supporting growth and yield (Basile and Lepek, 2021). Microbial consortia of *B. subtilis* and *A. brasilense* enhance root/shoot development, gas exchange, and grain yield in wheat, while co-inoculation of *Bradyrhizobium* and *Bacillus* improves nodulation and *Vigna unguiculata* productivity (Galindo et al., 2024; Gaspareto et al., 2023).

Zinc solubilization: Zinc is a vital enzyme co-factor, with optimal plant tissue levels at 30–100 $mg \cdot kg^{-1}$; deficiency impairs growth and causes necrotic lesions. Zinc-solubilizing bacteria secrete organic acids and iron-chelating enzymes to lower rhizosphere pH and release Zn^{2+} (Eshaghi et al., 2019). Key taxa include *Pseudomonas aeruginosa*, *Gluconacetobacter diazotrophicus, P. striata, P. fluorescens, Burkholderia cenocepacia, Serratia liquefaciens, S. marcescens, Bacillus thuringiensis*, *B. aryabhattai*, *B. subtilis, Thiobacillus thioxidans*, and cyanobacteria. *Rhizobium*, *Pseudomonas*, and *Bacillus* spp. enhance Zn translocation and grain biofortification, improving wheat quality via exopolysaccharide and siderophore production (Jalal et al., 2024). Co-inoculation of *B. subtilis* or *P. fluorescens* with foliar ZnO further boosts maize chlorophyll, amino acids, glutelin, and prolamin content. Bacterial Zn nanoparticles inhibit biofilm formation in pathogens and augment human oral microbiome antimicrobial activity (Lallo da Silva et al., 2019).

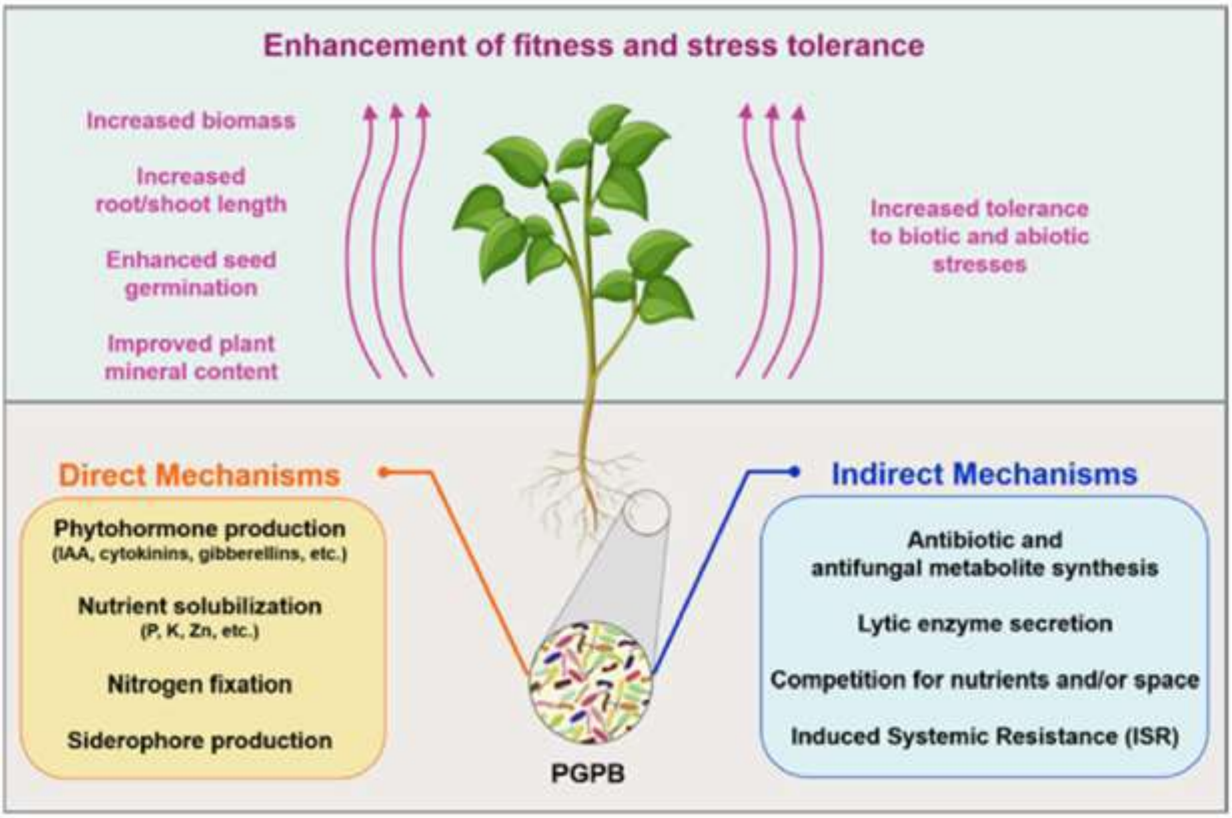

Figure 3. Overview of the main mechanisms used by PGPB to improve plant growth (from Vuolo et al., 2022)

Potassium solubilization: Although abundant in soils, K often exists in insoluble forms; PGPB release organic acids (citric, oxalic, tartaric) to chelate and solubilize K^+, facilitating uptake (Olaniyan et al., 2022). Potassium activates over 60 plant enzymes, regulates stomatal dynamics, enhances disease resistance, fiber strength, and produce quality, and mitigates water-stress sensitivity (Rawat et al., 2022). Notable K-solubilizers include *Acidithiobacillus, Burkholderia, Pseudomonas* spp., *Bacillus megaterium, Arthrobacter, Pantoea ananatis, Rahnella aquatilis, Enterobacter* sp., *Bacillus/Paenibacillus mucilaginosus*, *Bacillus licheniformis, P. azotoformans, B. edaphicus,* and *Pseudomonas putida* (Bakhshandeh et al., 2017).

CONCLUSION

Plant growth–promoting bacteria represent a cornerstone of sustainable agriculture by naturally supplying key metabolites—phytohormones, siderophores, lytic enzymes, hydrogen cyanide, and ammonia—and by solubilizing essential nutrients (P, Zn, K) or fixing atmospheric nitrogen. Their multifaceted modes of action not only enhance crop yield and quality under both biotic and abiotic stresses but also reduce reliance on synthetic agrochemicals, thereby protecting soil health and the broader environment.

To translate this promise into practice, future work must prioritize the development and field-ready formulation of robust biofertilizers and biocontrol agents tailored to specific crops and stress conditions. Equally critical is the systematic evaluation of PGPB–host compatibility to safeguard beneficial traits during root colonization, as well as the design of microbial consortia whose members coexist synergistically without compromising individual functionality. Addressing these challenges will pave the way for precision applications of PGPB, driving both productivity gains and ecological resilience in modern farming.

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