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1. Current Scenario of Endophytic Microbes: Promising Candidates for Abiotic and Biotic Stress Management for Agricultural and Environmental Sustainability

Dr. Ch. G. Gupta

Asst. Professor of Botany,
Dept. Of Botany,
SR and BGNR Govt. Arts and Science College (A).
Khammam, Telangana.

Abstract:

All plant species have endophytic microorganisms living in their tissues, including bacteria, fungus, and actinomycetes, without any negative effects or diseases. Endophytes coexist in symbiotic partnerships with a wide range of plant species and are able to control a wide range of host functions, including as immune system stimulation, growth and development, and resistance to biotic and abiotic challenges.

Furthermore, plant endophytes are extensively employed in numerous sectors and have a major role in the cycling of nutrients, biodegradation, and bioremediation. Endophytes are more likely to increase the solubility of minerals and metals in soil by secreting low molecular weight organic acids and metal-specific ligands (such siderophores), which change the pH of the soil and increase binding activity.

Plant microbiomes are beginning to recognize endophytes as essential constituents. While some of them generate valuable and/or intriguing secondary metabolites, others play crucial roles in plant growth and responses to pathogens and abiotic stressors.

Plant-pest synergism can be altered by biotic and abiotic stressors that increase the sensitivity of host plants to pests and reduce their ability to compete with weed plants. Plant development and survival are negatively impacted by the destructive impacts of stressors, which are exacerbated by climate change and include changes in precipitation patterns. Current Scenario of Endophytic Microbes:

Promising Candidates for Abiotic and Biotic Stress Management for Agricultural and Environmental Sustainability.

Keywords:

Endophytic Microbes, Abiotic, Biotic Stress, Management, Agricultural, Environmental Sustainability, Plant Endophytes, Plant Growth, Species, Plant–Microbe, Rhizosphere.

1.1 Introduction:

1.1.1 Endophytes Microbes: An Introduction:

Endophytes are microorganisms that live in the tissue or organs of their host plants without exhibiting any outward signs of infection. Similar to other epiphytic microorganisms, these endophytic bacteria have a complicated connection with the host plant and can influence its growth, development, and defense against pathogen invasion. However, a number of variables, including signaling molecules, are essential for controlling endophyte biology and functions as well as the host–endophyte connection.

The microbial communities that reside within, outside, and above the plant organs are diverse, and they are essential to the preservation of the health and productivity of the plants. Certain epiphytic microorganisms found on plant surfaces penetrate plant tissues and remain as an endophyte. A number of signaling molecules and associated proteins mediate the intricate process of endophyte entrance into plant tissues. The most favored locations for microbial entrance into the host tissues include wounds and natural openings like stomata, cotyledons, hydathodes, and the aerial sites of the root zones.

Plants engage in interactions with a wide range of microbial species that live in the rhizosphere and phyllosphere. This interaction leads to modifications in essential biological processes as well as defense mechanisms against different abiotic and biotic stressors. Plant growth-promoting bacteria (PGPB) in the rhizosphere and phyllosphere, as well as mycorrhizal fungi, can directly stimulate plant growth by raising the uptake of macronutrients and minerals and the concentrations of vital hormones. Alternatively, they can do so indirectly by reducing the detrimental effects of a variety of infections.

By synthesizing and secreting substances that promote plant development and enable host adaptation to specific environmental conditions, endophytes effectively establish symbiotic associations.

It is known that a number of bacterial, actinomycete, and fungal species contribute to the production and secretion of secondary metabolites and physiologically active substances. [1]

1.1.2 Beneficial Microbes for Sustainable Agriculture:

A. Plant Growth Promoting Bacteria and Biotic Stressors:

The over use of agrochemicals in agriculture has had detrimental effects on human health, the environment, and the fertility and health of the soil. Additionally, abuse of pesticides leads to an increase in the prevalence of hazardous microorganisms that cause disease, such as Rhizoctonia sp., Xanthomonas sp., and Rossetti sp.

Therefore, the use of beneficial plant microorganisms to increase crop productivity and lower the incidence of disease is driving the current trend towards "green" agricultural techniques. Numerous research conducted over the years have demonstrated that microorganisms can both prevent illness and lessen abiotic pressures on plants.

B. Plant Growth-Promoting Bacteria and Abiotic Stressors:

Abiotic stresses alter the metabolism and physiology of plants. Stress can adapt certain plants, but it can also overwhelm others. We discussed how PGPB controls disease by secreting hormones and enzymes in the section above. Plants can become acclimated to stress thanks to the secondary metabolites secreted by PGPB.

Numerous Pseudomonas, Rhizobium, Bacillus, and Enterobacter genera have been found to be suitable candidates for managing abiotic stress. Microbes are quickly changing creatures that can adsorb osmolytes, produce biofilms and exopolysaccharides (EPS), or remain dormant in order to quickly adapt to their surroundings. Plants also release hormones in response to these challenges that support continued growth and development.

C. The Application of PGPB in Sustainable Agriculture:

Microbes will be the main focus of sustainable agriculture in the future. In order to be used in the field, PGPB and fungi have been recognized, separated, and described. PGPB have a number of possible applications, particularly in improving the uptake and sequestration of nutrients.

It is known that these microbes develop symbiotic relationships with the root systems of the plants, extending root growth and increasing surface area to improve nutrient and water absorption. A few of these isolates have use in bioremediation, decomposition of hazardous chemicals, enhanced growth, and biocontrol.

It has been found that nitrogen-fixing organisms including Nitrosomonas sp., Nitrobacter sp., and Rhizobium sp. increase the availability of nitrogen for plants, increasing plant biomass and yield. [2]

1.1.3 Applications of Endophytes in Agriculture:

A. Plant domestication and loss of endophytic microbes:

In natural ecosystems, plants and endophytic bacteria coexist in symbiotic relationships that promote plant growth and shield plants from biotic and abiotic challenges. Nevertheless, long-term cultivation and domestication may result in the loss of symbiotic bacteria.

It was discovered that seven years of constant cultivation and seed cleaning led to the loss of symbiotic microbes and an increase in disease levels caused by fungal pathogens of the genera Fusarium and Alternaria in a cropping experiment utilizing an annual wild tobacco (Nicotiana attenuata).

When those bacteria were re-acquired from tobacco populations in the wild and applied to seedlings in culture, the consequence was resistance to the disease. Cotton seeds treated with acid to eliminate fibers also eliminated naturally occurring microorganisms that vectored seeds, making cotton seedlings more susceptible to disease and stress. [3]

1.2 Review of Literature:

Microbial communities known as endophytes now live in healthy plant tissues such stems, roots, leaves, and seeds without interfering with physiological plant functions or presenting indications of disease in the plant tissues.

Under normal circumstances, endophytes play significant roles in the growth of the host plant through the absorption of nutrients or secondary metabolites, or by blocking the induction of symptoms of plant diseases by various pathogens.

In addition to forming a network near to their host plants, endophytic microbes—which include bacteria, actinomycetes, and fungi—are protected from negative environmental changes and other unpleasant changes in the climate (Passari et al. 2017). [4]

Endophytes, which are fungi or bacteria, have enormous potential for usage as biocontrol agents. Endophytes exhibit antagonistic activity against phytopathogens that cause disease and lessen the harm that in relation to phytopathogens.

In addition to creating a variety of antioxidants to stifle infections, they also produce a number of bioactive antibacterial and antiviral metabolites (Gouda et al., 2016).

Furthermore, a wide variety of fungal species, particularly entomopathogenic fungi, have been shown to have long-term insect population prevention effects. Numerous bacteria, including Acidobacterium, Pedobacter, Pseudomonas, and Bacillus, are involved in the synthesis of metabolites, N2 fixation, and mineral solubilization. Beauveria bassiana, B. metarhizium, M. robertsii, Chaetomium globosum, and Acremonium spp. are among the fungal strains that are effective at protecting plants. [5]

Endophytes are a type of bacteria that live inside plant tissues without causing any visible symptoms of infection or other negative consequences on their host plants. Despite fitting this description of endophytes as well, mycorrhizae are not usually regarded as endophytes since they are phylogenetically limited to a certain class of fungi and establish unique interaction structures with their hosts.

All known plant species contain endophytes, which can live in a variety of plant compartments, including the leaf, stem, root, kernel, and flower. A number of endophytes have been demonstrated to benefit plants through nitrogen fixation, growth promotion, and disease suppression (Bertalan et al., 2009); nevertheless, the majority of the interactions between endophytes and plants remain poorly understood.

While it is uncommon to find archaebacteria, algae, protozoa, and nematodes living as endophytes, they nonetheless have a major impact on plants. The majority of plant endophytes are bacteria and fungi. [6]

Plants are subjected to damaging abiotic and biotic stressors during their lifetimes. "Biologic stress" is the term used to describe the harm that plants do to bacteria, fungus, viruses, nematodes, viroids, and insects. Plant growth may be impacted by biotic stress caused by rhizobacteria that stimulate plant development by producing phytohormones or making specific nutrients easier for plants to absorb (Tiwari et al., 2020). [7]

The literature has ample evidence of Bacillus spp.'s ability to biocontrol harmful fungus. An important biocontrol agent used in agriculture, Bacillus subtilis, exhibits both direct and indirect biocontrol mechanisms.

The first is typified by the synthesis of substances like hormones, antioxidants, and enzymes that enable plant defense, while the second is typified by the induction of acquired systemic resistance and the promotion of plant growth. Hashem et al. (2019) found that B. subtilis is particularly useful in reducing biotic stress in plants. [8]

Plant growth promotion by endophytes:

Three interrelated mechanisms—phytostimulation, biofertilization, and biocontrol—allow PGPEs to improve plant development. The process of producing phytohormones to control plant development is known as phytostimulation. Because of the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, the amount of the plant hormone ethylene often decreases. Numerous investigations have shown that the bacterial endophytes of Pseudomonas putida, the pepper plant, and Piper nigrum, the pea plant, both secrete ACC deaminase to promote plant growth (Ruduō et al, 2013).

Abiotic stress may be reduced by ACC deaminize production by regulating ethylene levels in plants, as elevated ethylene can hinder DNA synthesis, root and shoot growth, and cell division. The precise technique for improved plant development is still unclear, though. [9]

A lot of work has gone into understanding the diversity of endophytic organisms in plants, as well as their involvement in ecology, evolutionary biology, and defense mechanisms against biotic and abiotic stressors through the synthesis of various metabolites.

The efficient development of commercially, agriculturally, and industrially significant plants and their crops can be achieved by the application of endophytic biotechnology. According to Bani et al. (2015), the appropriate use of various endophytic organisms related to plants can enhance agricultural output, boost metabolite productivity in various plants, and increase tolerance to a variety of biotic and abiotic circumstances. [10]

1.3 Objectives:

- Current Scenario and Future Prospects of Endophytic Microbes.
- Promising Candidates for Abiotic and Biotic Stress
- Beneficial Microbes for Sustainable Agriculture.
- The Application of PGPB in Sustainable Agriculture

1.4 Research Methodology:

This study's overall design was exploratory. The research paper is an endeavor that is founded on secondary data that was obtained from reliable online resources, newspapers, textbooks, journals, and publications. The research design of the study is mostly descriptive in nature.

1.5 Result and Discussion:

Plants engage in interactions with a wide range of microbial species that live in the rhizosphere and phyllosphere. This interaction leads to modifications in essential biological processes as well as defense mechanisms against different abiotic and biotic stressors. Plant growth-promoting bacteria (PGPB) in the rhizosphere and phyllosphere, as well as mycorrhizal fungi, can directly stimulate plant growth by raising the uptake of macronutrients and minerals and the concentrations of vital hormones. Alternatively, they can do so indirectly by reducing the detrimental effects of a wide range of pathogens (Fig. 1.1). [11]

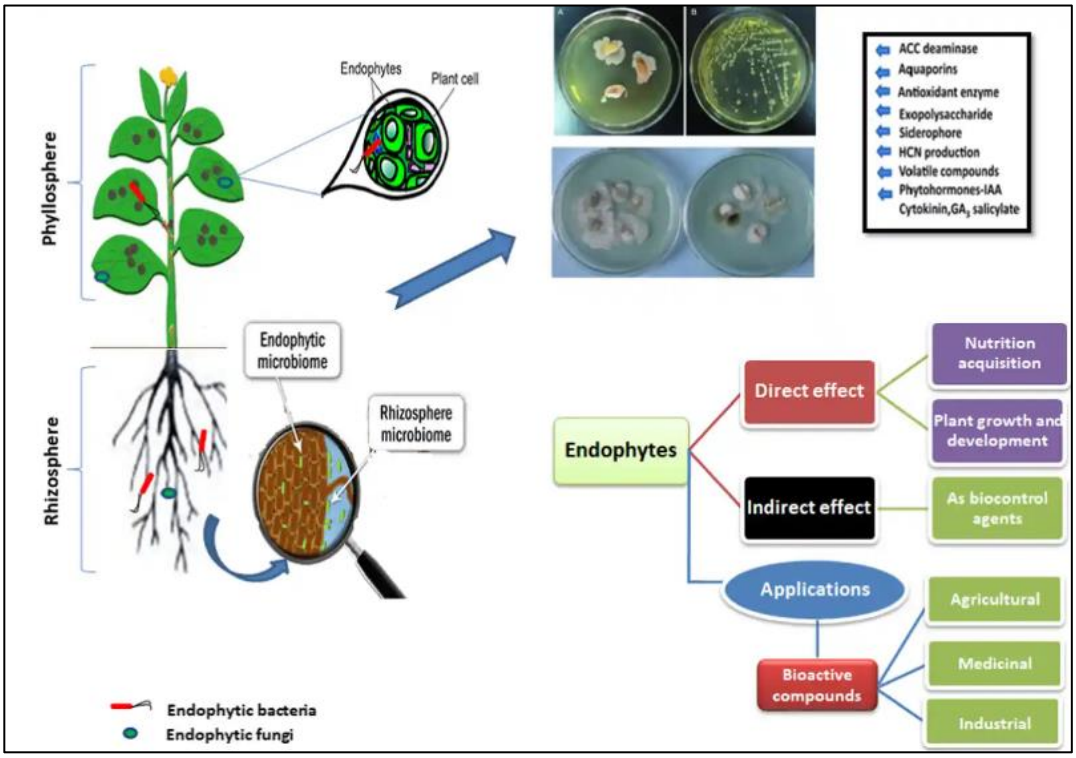


Figure 1.1: Plant Growth–Promoting Bacteria

An overview of the interactions between plants and microbes in the rhizosphere zone and phyllosphere:

Plant development can be directly stimulated by endophytic and rhizosphere microorganisms through increased uptake of macronutrients and minerals, or indirectly through plant defense against diseases. Bioactive substances that are naturally produced and have antibacterial properties can be used in a variety of industries, particularly in the medical and agricultural fields. Endophytes are microbial species that live inside plant tissues, while epiphytes are those that live on the surfaces of plants. De Barry first used the term "endophyte" in 1866 to describe any organism—bacteria, fungi, or their combinations—that multiplies intracellularly or intercellularly into host plants at least once during its lifecycle without exhibiting any overt symptoms of illness. Recent research has shown that these symbiotic microbial species are more important for the growth and development of host plants. Endophytes' function in promoting plant growth Different species and strains of endophytic bacteria can affect plant growth in different ways, therefore there is typically more than one mechanism at work to stimulate plant growth. Studies have been conducted on the potential of certain bacteria to encourage the growth of plants. Theoretically, bacterial endophytes that promote plant growth could have a direct or indirect impact on plant growth. Direct plant growth promotion happens when either (i) the bacteria that promote plant growth make it possible for plants to absorb nutrients from the environment, such as potassium, nitrogen, phosphorus, and iron, or (ii) the bacteria alter plant growth by supplying or controlling different plant hormones, such as cytokinin, auxin, or ethylene. endophytic bacteria's indirect stimulation of plant development via their generation of metabolites, HCN, and antibiotics that fight harmful bacteria and fungus. [12]

1.6 General Classification of Endophyte:

As seen in Figure 2, the two most prevalent microorganisms that exist as endophytes are bacteria and fungi.

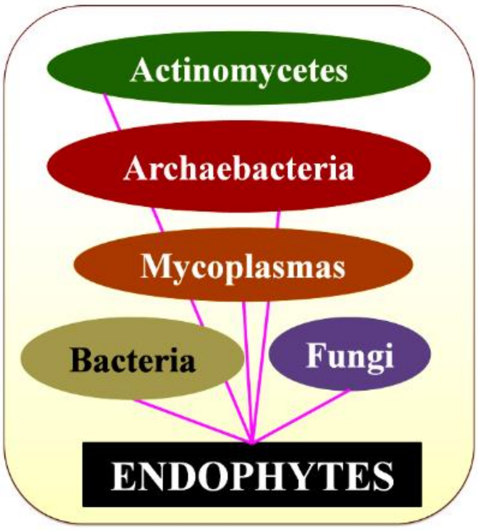


Figure 1.2: Types of Endophytes

Additional microorganisms found in plants as endophytes include mycoplasmas, actinomycetes (transitional forms between bacteria and fungi), and archaebacteria.

These are also shown in Figure 1.2. Gram-negative and gram-positive bacteria, including Enterobacter, Bacillus, Pseudomonas, Microbacterium, and Burkholderia, are among the diverse group of endo-phytic bacteria. Endophytic fungi have received particular attention in recent years due to their capacity to generate a significant quantity of bioactive secondary metabolites.

Members of the Ascomycota, Basidiomycota, Zygo-mycota, and Oomycota taxa are the majority of endophytic fungi. Non-clavicipitaceous endophytes (NC-endophytes) and clavicipitaceous endophytes (C-endophytes) are the two main categories of en-dophytic fungus.

Endophytes in the regulation of plant growth Numerous beneficial endophytes have been found to increase agricultural output and plant fitness in a variety of ways, including are schematically demonstrated in Figure 1.3. [13]

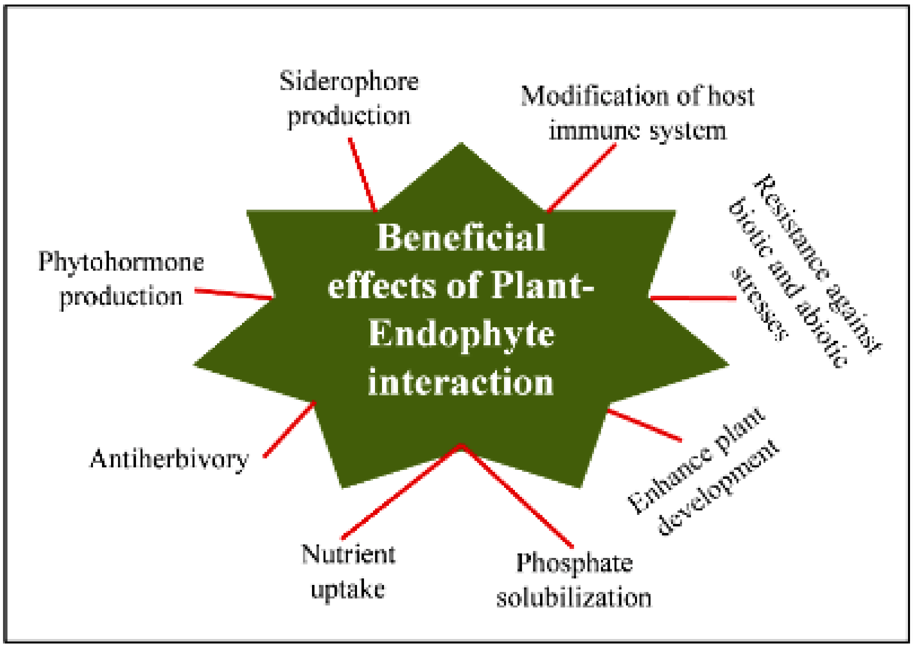
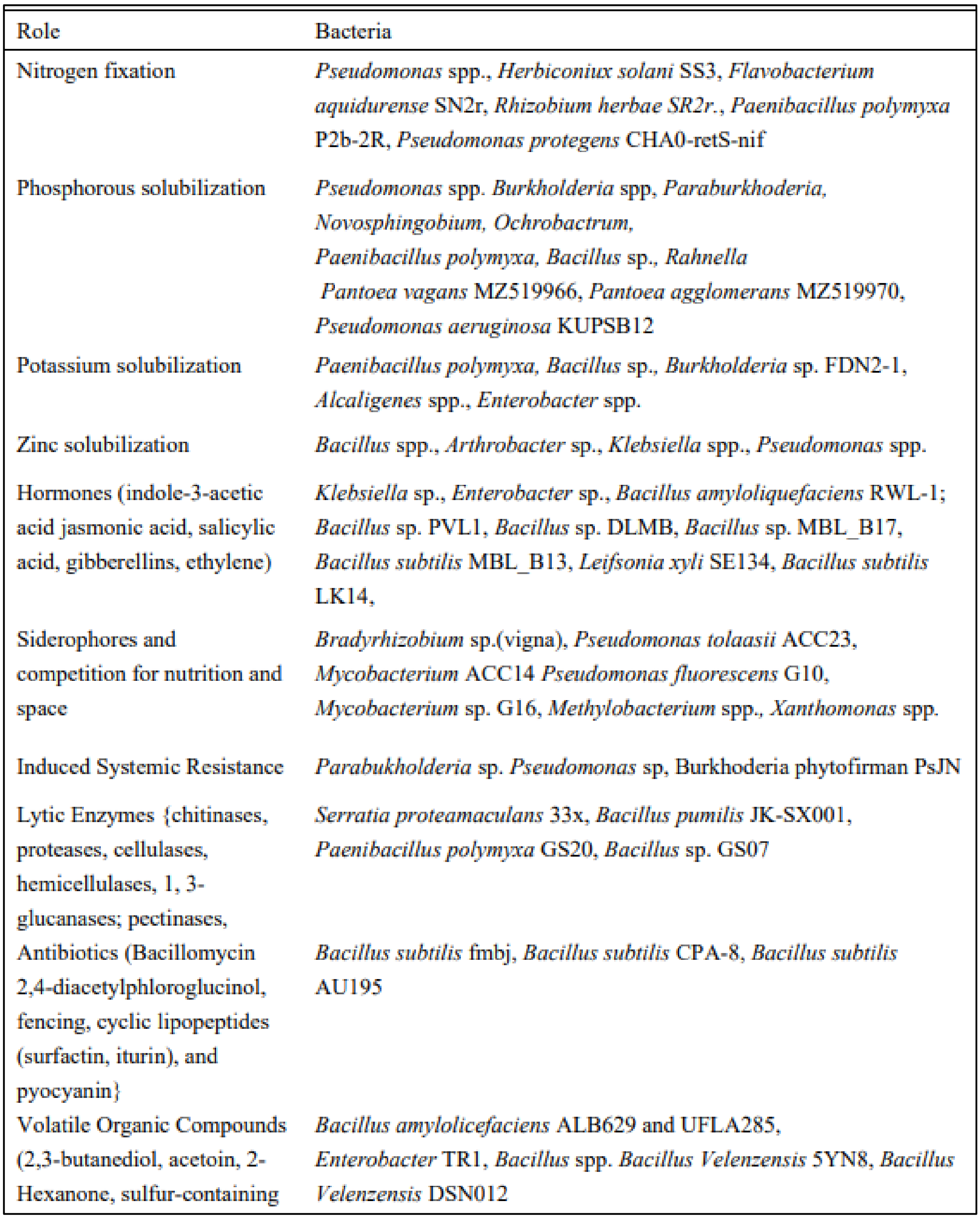


Figure 1.3: Endophytes-In plant growth regulation.

Table 1.1: Examples of some of the endophytic bacteria that have so far been isolated, identified and evaluated for their plant growth promotion and biocontrol effects.



Role	Bacteria
Nitrogen fixation	*Pseudomonas* spp., *Herbiconiux solani* SS3, *Flavobacterium aquidurense* SN2r, *Rhizobium herbae SR2r.*, *Paenibacillus polymyxa* P2b-2R, *Pseudomonas protegens* CHA0-retS-nif
Phosphorous solubilization	*Pseudomonas* spp. *Burkholderia* spp, *Paraburkhoderia, Novosphingobium, Ochrobactrum,* *Paenibacillus polymyxa, Bacillus* sp., *Rahnella* *Pantoea vagans* MZ519966, *Pantoea agglomerans* MZ519970, *Pseudomonas aeruginosa* KUPSB12
Potassium solubilization	*Paenibacillus polymyxa, Bacillus* sp., *Burkholderia* sp. FDN2-1, *Alcaligenes* spp., *Enterobacter* spp.
Zinc solubilization	*Bacillus* spp., *Arthrobacter* sp., *Klebsiella* spp., *Pseudomonas* spp.
Hormones (indole-3-acetic acid jasmonic acid, salicylic acid, gibberellins, ethylene)	*Klebsiella* sp., *Enterobacter* sp., *Bacillus amyloliquefaciens* RWL-1; *Bacillus* sp. PVL1, *Bacillus* sp. DLMB, *Bacillus* sp. MBL_B17, *Bacillus subtilis* MBL_B13, *Leifsonia xyli* SE134, *Bacillus subtilis* LK14,
Siderophores and competition for nutrition and space	*Bradyrhizobium* sp.(vigna), *Pseudomonas tolaasii* ACC23, *Mycobacterium* ACC14 *Pseudomonas fluorescens* G10, *Mycobacterium* sp. G16, *Methylobacterium* spp., *Xanthomonas* spp.
Induced Systemic Resistance	*Parabukholderia* sp. *Pseudomonas* sp, Burkhoderia phytofirman PsJN
Lytic Enzymes {chitinases, proteases, cellulases, hemicellulases, 1, 3-glucanases; pectinases,	*Serratia proteamaculans* 33x, *Bacillus pumilis* JK-SX001, *Paenibacillus polymyxa* GS20, *Bacillus* sp. GS07
Antibiotics (Bacillomycin 2,4-diacetylphloroglucinol, fencing, cyclic lipopeptides (surfactin, iturin), and pyocyanin}	*Bacillus subtilis* fmbj, *Bacillus subtilis* CPA-8, *Bacillus subtilis* AU195
Volatile Organic Compounds (2,3-butanediol, acetoin, 2-Hexanone, sulfur-containing	*Bacillus amylolicefaciens* ALB629 and UFLA285, *Enterobacter* TR1, *Bacillus* spp. *Bacillus Velenzensis* 5YN8, *Bacillus Velenzensis* DSN012

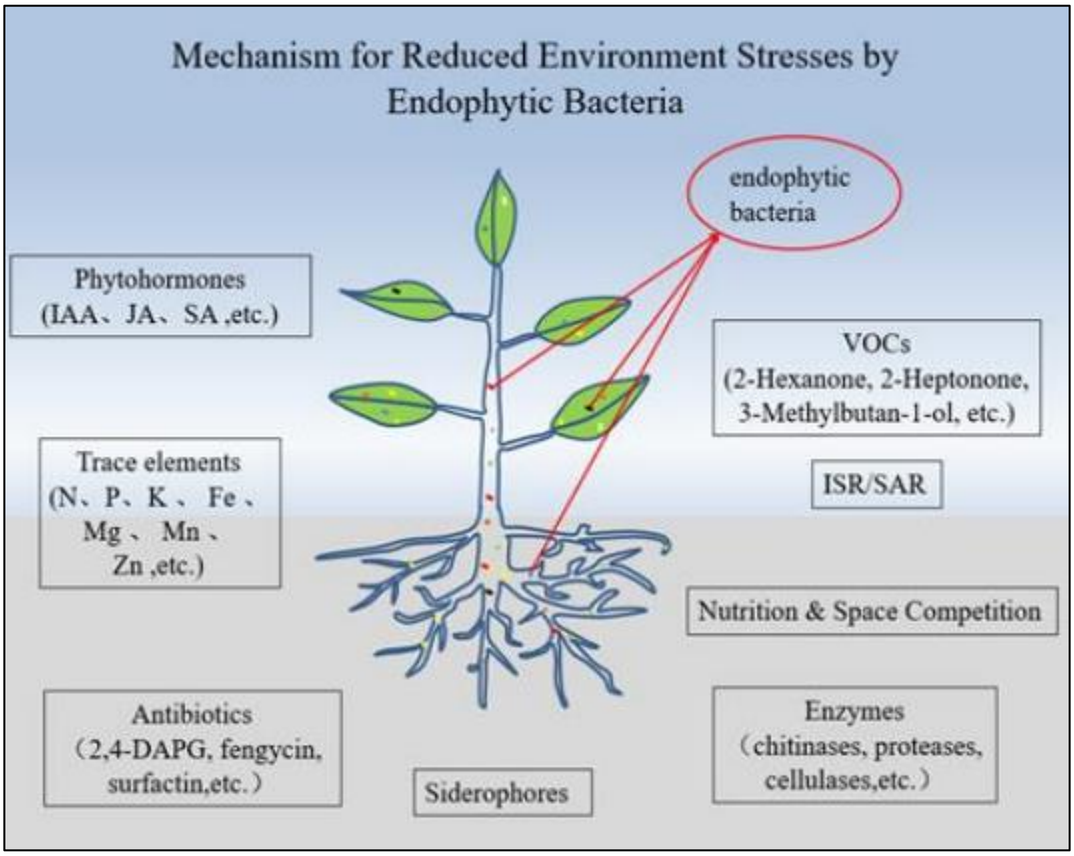


Figure 1.4: Summary of roles of endophytic bacteria in promoting plant growth and the biological control of plant pathogens. [14]

1.7 Role of PGPR In Agriculture: An Overview:

Because PGPR can be employed in synthetic fertilizers and insecticides, its application in organic farming is theoretically enhanced.

Numerous compounds that affect plant growth promotion in one way or another are produced by rhizobacteria.

The greatest strains of PGPR found in commercial biofertilizers are contributing to our growing knowledge of the function of PGPR.

Three categories—biopesticides, biofertilizers, and phytostimulators—can be used to group plant growth regulators.

As a result, multifunctional PGPR-based regimens for commercial agriculture have been developed.

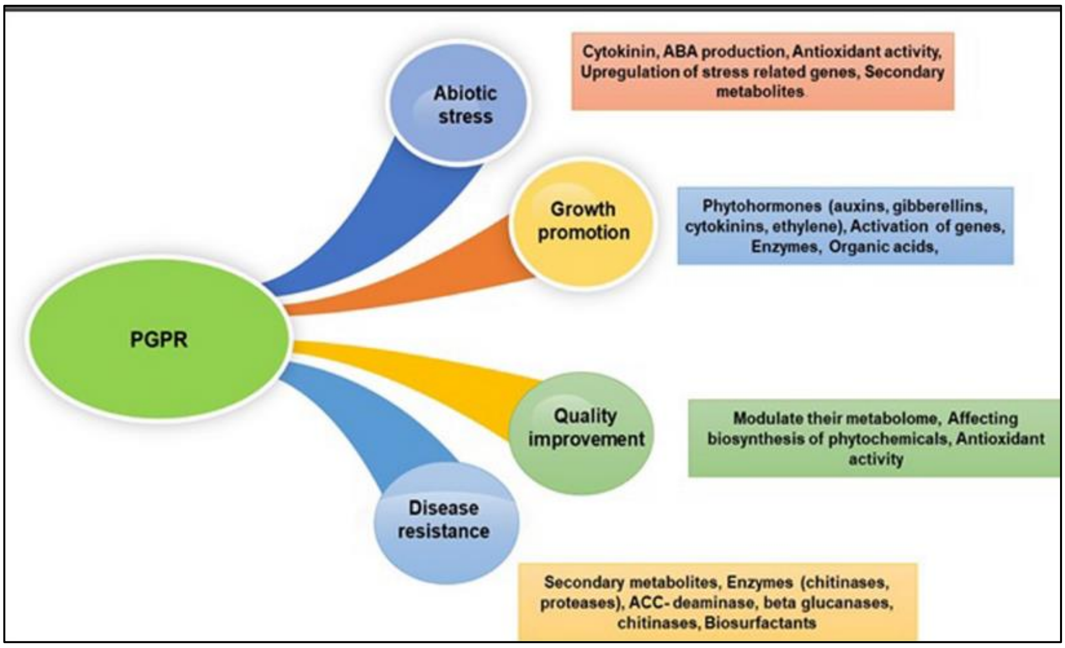


Figure 1.5: Plant-associated rhizobacteria and their role in plant growth and metabolism.

1.8 Role of Endophytes in the Management of Abiotic Stress:

A. Occurrence and Biodiversity of bacterial endophytes in agricultural crops:

According to recent estimates, there are over 300,000 plant species in the world, most of which are inhabited by microbial endophytes.

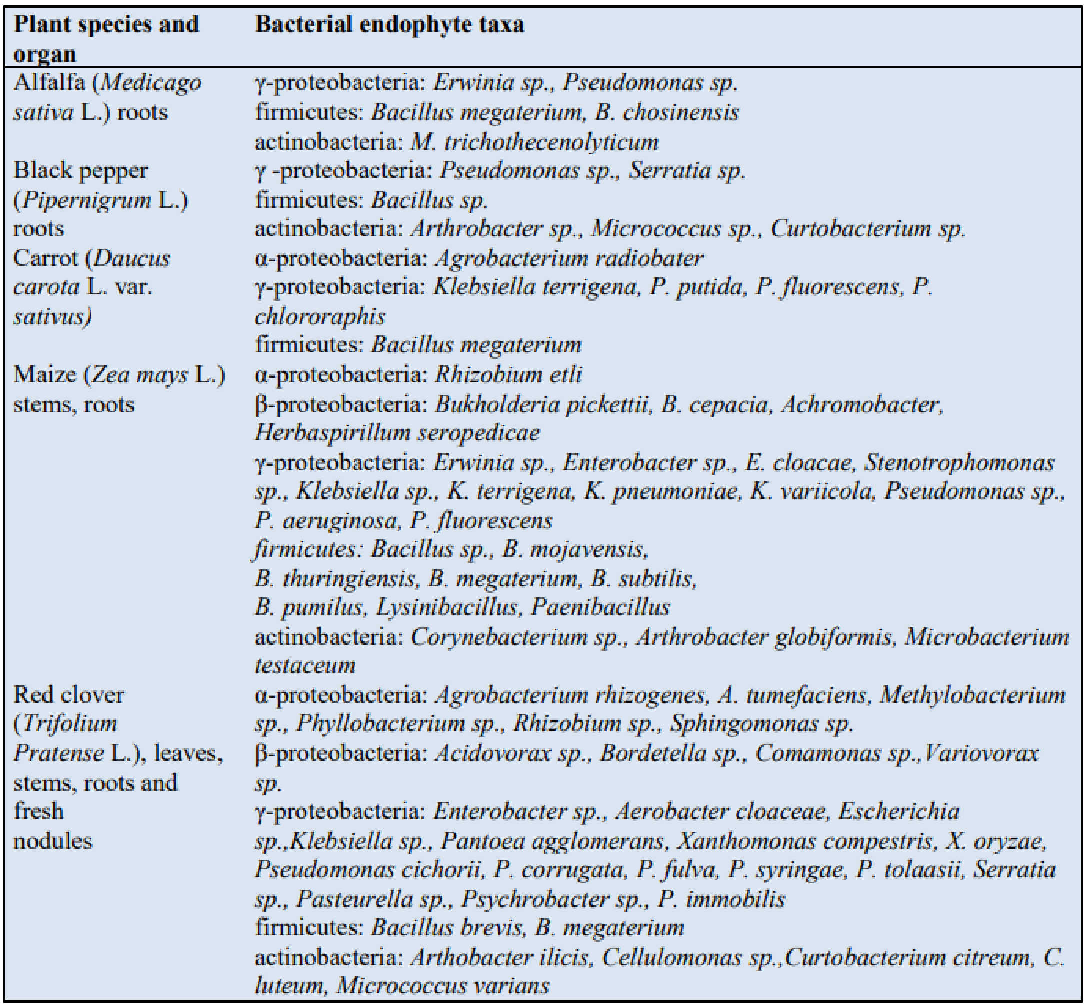
The distribution of endophytes within plants is determined by both their capacity for colonization and how plant resources are distributed.

In root fractures, below the root hair zone, and at the locations of lateral root emergence, root endophytes frequently invade and penetrate the epidermis.

These colonists have the ability to form intracellular and intercellular populations.

Certain endophytes have the ability to spread systemically, or by penetration of the vascular tissues, to other parts of the plant after initial colonization.

Table 1.2: Endophytic bacteria isolated from common agricultural crop plants:



Plant species and organ	Bacterial endophyte taxa
Alfalfa (*Medicago sativa* L.) roots	γ-proteobacteria: *Erwinia sp., Pseudomonas sp.* firmicutes: *Bacillus megaterium, B. chosinensis* actinobacteria: *M. trichothecenolyticum*
Black pepper (*Pipernigrum* L.) roots	γ -proteobacteria: *Pseudomonas sp., Serratia sp.* firmicutes: *Bacillus sp.* actinobacteria: *Arthrobacter sp., Micrococcus sp., Curtobacterium sp.*
Carrot (*Daucus carota* L. var. *sativus)*	α-proteobacteria: *Agrobacterium radiobater* γ-proteobacteria: *Klebsiella terrigena, P. putida, P. fluorescens, P. chlororaphis* firmicutes: *Bacillus megaterium*
Maize (*Zea mays* L.) stems, roots	α-proteobacteria: *Rhizobium etli* β-proteobacteria: *Bukholderia pickettii, B. cepacia, Achromobacter, Herbaspirillum seropedicae* γ-proteobacteria: *Erwinia sp., Enterobacter sp., E. cloacae, Stenotrophomonas sp., Klebsiella sp., K. terrigena, K. pneumoniae, K. variicola, Pseudomonas sp., P. aeruginosa, P. fluorescens* *firmicutes: Bacillus sp., B. mojavensis, B. thuringiensis, B. megaterium, B. subtilis, B. pumilus, Lysinibacillus, Paenibacillus* actinobacteria: *Corynebacterium sp., Arthrobacter globiformis, Microbacterium testaceum*
Red clover (*Trifolium Pratense* L.), leaves, stems, roots and fresh nodules	α-proteobacteria: *Agrobacterium rhizogenes, A. tumefaciens, Methylobacterium sp., Phyllobacterium sp., Rhizobium sp., Sphingomonas sp.* β-proteobacteria: *Acidovorax sp., Bordetella sp., Comamonas sp.,Variovorax sp.* γ-proteobacteria: *Enterobacter sp., Aerobacter cloaceae, Escherichia sp.,Klebsiella sp., Pantoea agglomerans, Xanthomonas compestris, X. oryzae, Pseudomonas cichorii, P. corrugata, P. fulva, P. syringae, P. tolaasii, Serratia sp., Pasteurella sp., Psychrobacter sp., P. immobilis* firmicutes: *Bacillus brevis, B. megaterium* actinobacteria: *Arthobacter ilicis, Cellulomonas sp.,Curtobacterium citreum, C. luteum, Micrococcus varians*

B. Role of bacterial endophytes in overcoming salinity and temperature stress:

Worldwide agricultural loss is primarily caused by abiotic stressors that affect plants, including oxidative stress, drought, water logging, high temperatures, and salinity.

It is likely that a combination of genetic modifications and phenotypic flexibility, as well as processes unique to the plant genome, enable plants to adapt to extreme stress circumstances. revealed that fewer species can survive in high stress settings, which usually have lower plant abundances than nearby low stress ecosystems.

However, it is thought that almost all plants in natural ecosystems are symbiotic with endophytes. These endophytes can have beneficial effects on plants, such as increased biomass in the roots and shoots, increased yield, and tolerance to biotic stresses like pathogens and herbivores as well as stresses like heat, salt, and drought.

C. Climate-Smart Agriculture: Facts and Faiths:

Socioeconomic well-being, productivity of sustainable agroecosystems, poverty reduction, nutritional security, adaptability, and stress reduction are all intimately correlated with climate-smart agriculture (CSA).

Strategies include improving resistance to extremely stressful situations, changing agriculture and food systems, formulating policies, and raising knowledge of ecosystem services are expected to lead to CSA (Figure 1.6).

Considering the aforementioned, there is a vast amount of study potential about the favorable effects of rhizosphere-forming beneficial symbiotic fungal endophytes on CSA.

Their worldwide occurrence, non-pathogenic nature, nutrient uptake stimulation, mineral solubilization, phytoremediation, improved vegetative and reproductive growth, ability to withstand stress and provide an optimal to high yield, etc., make them appropriate for planning comprehensive scientific investigations and care. Sea changes may result from crop enhancement mediated by fungi endophytes.

The colonization of a new host plant by a suitable endophyte, their symbiotic relationship, and the native end biome (their direct and indirect effect) are some of the connected bottlenecks that it faces.

Their genetics, gene expression, molecular patterns, altered behavior, etc. all have an additional impact on the connection.

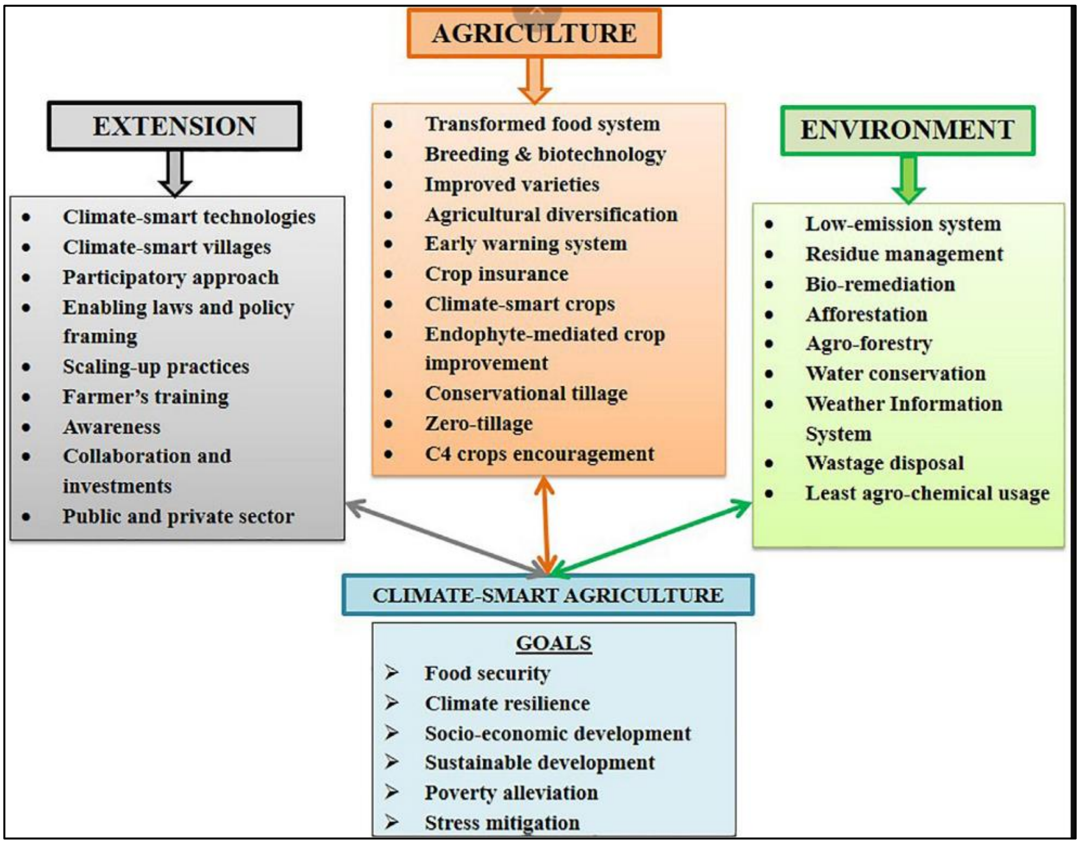


Figure 1.6: Various Components Succeeding CSA-Led Sustainable Agriculture Goals.

Fungal Endophytes for Abiotic Stress Management

Abiotic stressors significantly inhibit plant growth, and in order for a plant to withstand them, it needs an effective system or mechanism. Numerous microorganisms are typically found obtaining nutrition from different plants; certain relationships are advantageous to the host, while others are detrimental. [15]

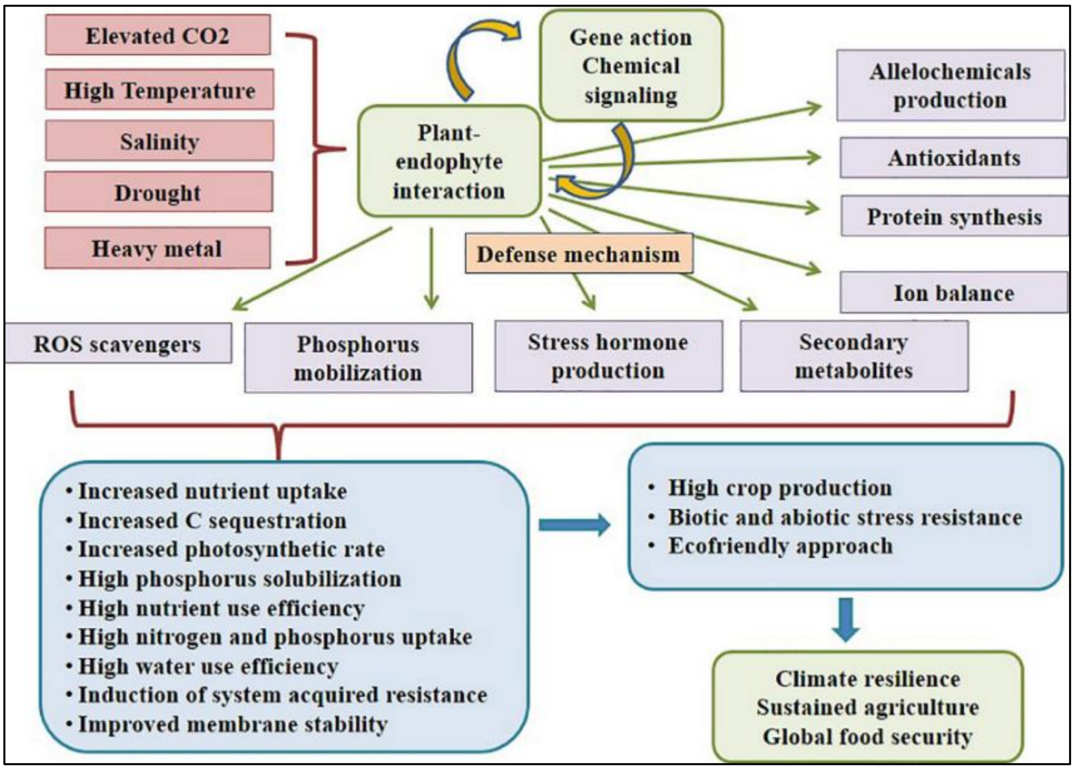


Figure 1.7: Plant-endophyte symbiotic interaction conferring abiotic resistance.

D. Fungal Endophytes for Biotic Stress Management:

The development of pesticide and agrochemical resistance in pathogens and pests calls for more environmentally friendly alternatives, ideally pesticide environmental stewardship under biocontrol agents. Isolates of non-pathogenic fungal endophytes been shown to be capable of strengthening other plants' resistance to later pathogen invasions. Bioactive molecules, phenolic compounds, antioxidants, phytoalexins, phytohormone synthesis, ecological occupancy, and other related processes are upregulated as a result of them.

1.9 Conclusion:

The widespread use of agrochemicals in agricultural techniques needs to be curbed in order to transition to sustainable agriculture. We have discussed how beneficial bacteria can improve field growth, development, and disease suppression in this paper.

Nevertheless, beneficial microorganisms have not proven to be very successful in outdoor settings. This is mostly because in order to reap the rewards, the recently added microorganisms need to flourish in the surroundings and preserve a consistent and stable population. In commercial crop plants, microbial endophytes and soil microorganisms could be used to directly improve plant health and productivity.

Benefits may also arise from endophytes' reduction of diseases, insect damage, and weedy plant competition. It can be difficult to use current agricultural practices to increase crop output without compromising food quality or damaging agricultural soil health by using agrochemicals.

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