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2. Role of Bacterial Endophytes in Agriculture: Present Status and Future Perspectives

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2.1 Introduction:

Endophytes are organisms that reside in host plants asymptomatically, possibly for a considerable span of their life cycles. De Bary (1866) first used the term "endophyte" to describe the organisms that live as epiphytes on the surface of plants. Endophytes are typically thought of as mutualists and belong to a variety of taxa, including bacteria, fungi, protists, and archaea.

According to Hallman *et al.* (2011), organisms isolated from surface-sterilized explants or from within the plant tissue are referred to as endophytes, given that they do not affect the host plant. In exchange for facilitating nutrient uptake and protecting the plant from biotic and abiotic challenges and pests, the endophytes obtain protection and sustenance from the host plants.

Endophytes have developed defenses against the plant's physical and chemical weapons, such as the anti-cancer substance, camptothecin, which binds to topoisomerase I and prevents cell division in plants like *Camptotheca acuminata*.

Fusarium solani, an endophytic fungus, altered the amino acids in its topoisomerase binding site to evade camptothecin's adverse effects (Kusari *et al*., 2011).

Endophytic bacteria have been found in a wide range of plant species, indicating that their association with almost all higher plants. The architecture of this community is influenced by biotic and abiotic soil factors affecting bacterial survival, host characteristics that facilitate colonization, and microbial determinants that alter endophytes' capacity to coexist and compete with their plant hosts (Gaiero *et al.*, 2013).

Internal plant tissues are invaded and colonized by bacterial endophytes, which evade host defense mechanisms while utilizing organic plant compounds for development and survival. Endophytes primarily enter plant tissues through the root zone; however, they can also enter through aerial tissues. Chemotactic signals are crucial for the initial colonization of the endophytes on the root surface.

Endophytes can also improve their performance in competition and control the expression of genes favoring plant tissue invasion (Compant *et al.*, 2005). Root endophytic bacterial communities may be distinct from bacterial communities in the rhizosphere as a result of the host plant's recognition and selection of the helpful bacteria. Colonization by endophytes fosters plant growth by several means.

They may defend against various bacterial and fungal infections, aid in the uptake of available nutrients, and enhance the host's capacity for ecological adaptations by enabling resistance or tolerance against biotic and abiotic stresses (Schulz and Boyle, 2005).

Overall, improved root and shoot biomass, increased yield, and increased tolerance to abiotic conditions like drought, salt, and heat are a few important positive effects endophytes can exert on plants.

According to an estimate, endophytes are valuable sources of secondary metabolites and bioactive chemicals; more than 80% of the natural medicines in the market come from medicinal plants and their endophytes.

Novel secondary metabolites found in endophytic bacteria are rich sources of medications with beneficial anti-arthritic, anti-microbial, anti-cancer, antidiabetic, anti-insect, and immunosuppressive properties (Rajamanikyam *et al*., 2017).

The potential applications of bacterial endophytes in various fields can be described as cited in the figure 2.1.

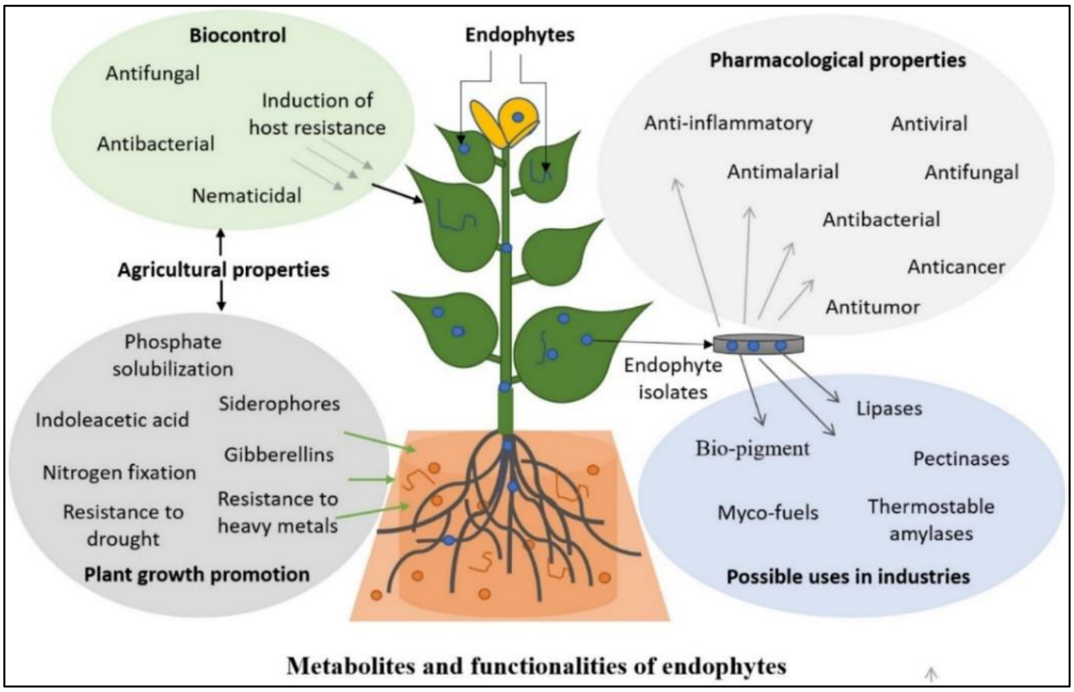

Figure 2.1: Applications for bacterial endophytes in various fields

2.2 Role of Bacterial Endophyte in Agriculture:

2.2.1 Plant Growth-Promoting Activities:

Numerous medicinal and biotechnological applications have recently done on endophytic bacteria and their metabolites. The majority of the 200 genera that include the bacterial endophytes belong to the Proteobacteria, Actinobacteria, and Firmicutes phyla. The ability of bacterial endophytes to influence many physiological and biochemical processes that control plant development and performance under diverse environmental conditions in plants.

Bacterial endophytes function as plant growth-promoting bacteria (PGPB) and influence plant growth by secreting lytic enzymes, phosphate solubilization, nitrogen fixation, siderophores production, hydrogen cyanide (HCN), and ammonia production.

PGPBs have been exploited to produce various kinds of biofertilizers, the benefits of PGPB-containing biofertilizers to agricultural sectors include increasing soil fertility, giving plants necessary nutrients, and strengthening plant resistance to both biotic and abiotic stresses. Some of these benefits are described below:

A. Phosphate Solubilization:

After nitrogen, phosphorus is the second-most crucial macronutrient for plants. The soil is the main source of phosphorus, but it is insoluble and complexed with iron, calcium, and aluminium, making it unavailable to plants. For plant metabolic activities, the amount of soluble phosphorus in the soil is insufficient, and this shortage may result in slower development and decreased leaf biomass of the plant.

Numerous chemical fertilizers that are utilized to meet this requirement, however none of them are eco-friendly. Bacterial endophytes are thus regarded as a better strategy that can supply soluble phosphorus without endangering the ecosystem.

These endophytes assimilate phosphorus from the soil by producing a variety of organic acids, including tartaric acid, succinic acid, oxalic acid, malic acid, 2-ketogluconic acid, glyoxylic acid, gluconic acid, fumaric acid, citric acid, and alpha-ketobutyric acid, as well as the enzymes phosphatase and phytase (Devi *et al*., 2020). All of these substances make the phosphorus soluble and provide it in an inorganic form that may be absorbed by plants. The most efficient phosphorus solubilizing endophytic bacteria include the genera *Pseudomonas, Bacillus,* and *Rhizobium* (Li *et al*., 2016).

B. Potassium Solubilization:

Potassium (K) is the second-most crucial element for plant and animal growth and development after phosphorus. It is essential for osmotic management, energy balance, protein and starch production, and enhancing pest and disease resistance. Over 90% of the potassium that is now in existence is found in rocks as insoluble silicate minerals. As a result, there is very little potassium in the soil, which presents a significant barrier for the sustainable plant nutrition.

In order to boost K availability to crops, K-solubilizing bacteria transform K from inaccessible forms to accessible forms. The most efficient potassium solubilizing endophytic bacteria include the genera *Bacillus, Burkholderia* and *Enterobacter* (Meena *et al*., 2016).

C. Zinc Solubilization:

The crucial micronutrient, zinc (Zn) is necessary for the growth, development, and reproduction of plants. The synthesis of auxins, carbohydrates, cytochromes, chlorophyll, and membrane integrity are all impacted by Zn deficiency in plants, and plants become more sensitive to heat stress (Singh *et al*., 2005). Because Zn minerals in soil are less soluble, Zn insufficiency in crops is very common around the world. The promising alternative for Zn nutrition and Zn enrichment in agricultural soil is Zn-solubilizing bacteria. The most efficient Zn-solubilizing endophytic bacteria include the genera *Bacillus* and *Pseudomonas*.

D. Siderophore Production:

One of the most important micronutrients for crop production is iron (Fe). It is important for several enzymatic processes. It plays a significant part in the production of chlorophyll due to its major functions in photosynthesis, the reduction of NO_2 and SO_4, and the accumulation of nitrogen (Rashid, 1996). A global issue for sustainable crop production is the lack of iron, especially in the calcareous soils of crops grown like peach, apple, peanut, and soybean. Some bacteria act as biocontrol agents by creating low-molecular-weight siderophore compounds, which have a high affinity for iron, especially when iron is scarce (Compant *et al*., 2005). They might solubilize and accumulate ferric ions, which they might then transfer to plants and nearby microorganisms, depriving pathogens of the necessary iron. The most efficient siderophore producing endophytic bacteria include the genera *Pseudomonas, Azotobacter, Bacillus, Rhizobium*, and *Enterobacter*.

E. IAA Production:

One of the primary signals involved in the communication between the host plants and endophytes is the plant hormone indole-3-acetic acid (IAA). Endophytes can produce IAA from scratch to affect the homeostasis of IAA in plants. IAA promotes lateral root development, cell elongation, tissue differentiation, and cell division (Frankenberger and Arshad, 1995). Tryptophan, a natural secretion from plant roots, affects the level of IAA generated by bacteria. A single bacterium may have many IAA production pathways. There are numerous known biosynthetic processes, including the indole-3-acetamide (IAM), indole-3-pyruvate (IpyA), indole-3-acetonitrile (IAN), tryptophan side chain-Oxidase, and tryptamine pathways (Li *et al.*, 2018). The most efficient IAA producing endophytic bacteria include the genera *Bacillus*, *Azotobacter, Pseudomonas* and *Azospirillum.*

2.2.2 *Plant Protection:*

Pests and plant diseases are regarded as the main factors limiting agricultural production. Pesticides are traditionally used to control diseases and pests, but these practices have the potential to harm both human and animal health as well as the environment. Endophytes create substances that are necessary for defense against plant pathogens.

Alkaloids, terpenoids, flavonoids, and steroids are examples of natural products from endophytes that have been identified and are known to have a variety of roles, including those of antibiotics, immunosuppressants, anticancer substances, and biocontrol agents (Joseph and Priya, 2011).

The endophytic bacterial species cause the induction of induced systemic response (ISR) through their flagella, lipopolysaccharides, siderophores, antibiotics, and quorum-sensing molecules (Van Loon, 2007). Stronger plant cell walls, altered host physiology or metabolic responses, increased production of plant defense, pathogenicity-related protein enzymes, etc. are all examples of how development of ISR regulation of numerous genes helps to strengthen the host plants (Niu *et al.*, 2011). By producing antibiotics, siderophores, and lytic enzymes, endophytes have the potential to impede the growth of fungal infections. According to Lugtenberg and Kamilova (2009), *Pseudomonas* could create antimicrobial compounds such as 2,4-diacetylphloroglucinol, phenazines, pyoluteorin, and pyrrolnitrin. It has been demonstrated that some endophytes used as biocontrol agents release siderophore, which chelates the soil's available iron and deprives of iron to harmful microbes (Compant *et al*., 2005).

By eliminating or drastically lowering the use of hazardous chemicals in agriculture, biocontrol organisms like endophytes have the potential to eradicate such dangerous species, and resolve environmental and health-related problems.

Some of the bacterial endophytes having plant growth promoting activities and/or plant protection abilities and exploited for commercial usage are cited in the Table 2.1.

Table 2.1: Examples Of Bacterial Endophytess in Commercial Production

Trade Name	Composition	Function
Phytosporin-M, Albit, Vitaplan	*Bacillus subtilis*	Displacement of pathogenic fungi and stimulation of plant growth
Trianum P	*Trichoderma harzianum*	Fungicidal effect and stimulation of tobacco seedling growth
Cedomon EO	*Pseudomonas chlororaphis*	Protection of barley seeds against *Pyrenophora graminea*, *Fusarium* spp., and *Bipolaris sorokiniana*
Cropaid	*Thiobacillus thiooxidans*, *T. thioparus*, *T. ferrooxidans*	Stimulation of production of proteins and amino acids that increase plant resistance to cold and frost damage
Symbion-N, Bio-cure F, Bio-health	*Azospirillum lipoferum*, *T. viride*, *B. megatherium*	Restriction of the pathogenicity of *F. solani* and *Rhizoctonia solani*

2.3 Future Perspective:

Depending on whether the connections are saprophytic or symbiotic, the interaction between the bacteria and plant may be advantageous or harmful. While the majority of plant-associated bacteria stay in the rhizospheric soil or rhizoplane, a small subpopulation known as "endophytes" is able to enter plant tissues and survive there.

Some endophytes create significant secondary metabolites or have an impact on plants grow and react to diseases, herbivores, and environmental changes. Since the majority of endophytes are not cultivable, molecular methods are used to analyze their variety and elucidate the molecular basis of their interactions with plants. Endophytic bacteria typically mineralize and solubilize nutrients including phosphate, zinc, and potassium as well as trace elements.

They can also produce phytohormones, ammonia, volatile hydrogen cyanide, and nonvolatile siderophores that function antagonistically to the pathogens. In order to increase agricultural production, new relationships and interactions between endophytes and their hosts could be investigated and the promising endophytes could be used by farmers as a tool to support their agricultural activities.

The biotechnological potential of effective plant-microbe collaborations could be realized with the help of genomics. However, in doing so, the procedure of choosing a plant's genotype, age, and compatible associative endophyte poses as a major challenge. By utilizing specific strain as bio-inoculants, we can increase productivity of specific crops.

The understanding of the endophytic colonization mechanism is also still in nascent stages. Thorough molecular studies may help us understand and thereby to improve the colonization process and finally to improve plant growth and productivity.

Plant genotype, abiotic and biotic factors like environment and climate, microbe-microbe interactions, and plant-microbe interactions all have an impact on the structure of the endophytic community.

The structure and operation of endophytic microbial communities are also significantly influenced by agricultural activities such as tillage, irrigation, pesticide use, and fertilizer application.

As a result, using farming methods that preserve the natural diversity of plant endophytic bacteria is an emerging area having potential to be crucial component of sustainable agriculture; such practices might guarantee plant productivity and the quality of agricultural output as well.

2.4 Conclusion:

The challenge of supplying balanced food for the entire humanity naturally falls to agriculture of the twenty-first century, and thinking about alternatives to conventional farming has numerous advantages for the system as a whole. The development of sustainable agriculture is greatly aided by the various endophytic microbial communities.

A thorough understanding of plant-microbe symbioses can offer numerous approaches to boost sustainable agriculture and guarantee enough balanced food for attaining food and nutritional security.

Besides, the climate change challenges, improved crop performance under stress conditions like cold, droughts, or contaminated soil could possibly be achieved by applications of endophytes or microbes from the rhizosphere as inoculants.

Due to the advantages realized from the mutualistic interactions between host plants and nonpathogenic microorganisms, the association known as endophytism presents a new and expanding frontier for research.

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