Symbiotic Endophytes of Glomalin AM Fungi, Rhizobium, and PGPR Potential Bio stimulants to Intensive Global Food Production for Sustainable Agriculture System

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Abstract

Endophytic microorganisms are symbionts that live inside plant tissues and have been studied for their potential growth-promoting effects on plants and their beneficial involvement in plants' responses to various stresses. Endophytic microorganisms play an important role in plant health, and this research looks at the processes they stimulate to increase plant tolerance to a variety of stresses. The endophytic microbial population boosts plant development by creating secondary active chemicals that defend the plant against pests and diseases. Endophytes also generate extracellular enzymes that are essential to the colonization of endophytes inside the plant host. Microbial endophytes may act as growth-promoting agents for plants by producing phytohormones and assisting plant development in polluted soils by degrading toxic chemicals. Endophytes regulate plant development via many mechanisms in response to stresses such as salt, drought, temperature, heavy metal stress, and nutritional stress.

The glycoprotein glomalin-related soil protein (GRSP) is produced by the arbuscular mycorrhizal fungus (AM fungi) and is crucial to ecosystem health, the production of high-quality food, and ecological restoration. Soil globulin levels are highly associated with aggregate water stability (WS) and soil quality (SH). Since globulin contains carbon, it makes a non-negligible contribution to the Earth's terrestrial carbon reservoir. The GESP-producing AM fungus are ubiquitous root symbionts that benefit plants in a wide variety of ways. Root nodules of legumes are home to soil bacteria (SB) called rhizobia, which fix nitrogen (LRN). Plant growth-promoting rhizobacteria (PGPR) are a class of free-living bacteria (FLB) that colonize the rhizosphere and improve root development (RG), which in turn improves plant growth (PG), productivity, and numerous plant growth-promoting substances (PGPS). During symbiosis, symbiotic fungi (SF) and bacteria reproduce using host resources to replenish the soil, endure between hosts in the soil, and discover and infect new hosts. The present publication emphasizes the significance of microbial symbionts and their interactions for nutrient management, effective for growth and productivity to the sustainable agricultural system (SAS), which boosts worldwide crop output.

Keywords: endophytic microorganisms, microbial endophytes, glomalin am fungi, rhizobium

Introduction

Chemical fertilizers (CF), pesticides, herbicides, and hormones all play a larger role in modern agriculture than they do in traditional farming [Prasad, 2015; Prasad, 2017; Prasad, 2021a, b; Prasad, 2022a, b, c]. Although it has been shown to boost crop, vegetable, and fruit yield [Tilman, 2002], it has also led to several detrimental consequences on the environment, such as water, soil, and food contamination, and deterioration of soil quality [Prasad, 2017; Prasad, 2021a; Guo,2015]. Additionally, the contemporary agricultural ecosystem's (CAS) plant and microbial biodiversity have decreased [Yu, 2015]. The food supply still contains a number of harmful substances, including those with high eco-toxicity and synergistic toxicity, which may accumulate up the food chain and pose a hazard to human health (HH) [Laetz,2009;

Prasad,2021a, b; Prasad,2022a, b, d, e]. Foods containing residues of herbicides and pesticides have been shown to cause serious health problems in HH [Cen et al. 2020; Prasad, 2021b, Prasad, 2022a, Prasad, 2022f]. Produced by AM fungus, GRSP is a massive glycoprotein crucial to ecosystem health, high-quality food production, and ecological restoration [Prasad,2021c]. Soil globulin levels are correlated with aggregate water stability (WS) and soil productivity (SP). Because of its carbon content, globulin represents a significant fraction of the Earth's total carbon stock. Agroecosystem management affects globulin concentrations in soil. The carbon-storing and function-facilitating roles of GRSPs are crucial. It has been challenging to biochemically characterize glomalin owing to the molecule's unusualness, resistance, and complexity.

More than 90% of vascular plant species have a symbiotic connection with glomalin AM fungus, a kind of soil microorganism (SM) [Prasad,2017; Prasad and Pandey, 2012; Prasad and Deploey, 1999; Prasad and 2000; Prasad, 2020; Prasad, 2021b, Prasad, 2022f, g]. Their widespread presence throughout GE is best shown by the widespread presence of well-known plant hosts across the globe [Prasad, 2017; Prasad, 2021 a, b; Wang and Qiu, 2006; Kivlin et al., 2011]. Fungi that produce AM belong to the subkingdom Mucoromycota and the phylum Glomeromycota, which has three classes (Glomeromycetes, Archaeosporomycetes, and Paraglomeromycetes [Tedersoo et al. 2018, Prasad et al., 2021a, b,]). 11 families and 25 genera make up the AM fungus [Schubler et al. 2001 and Spatafora et al. 2016]. There are now 336 different species of AM fungus, and only a few of dominating genera, including Acaulospora, Glomus, Gigaspora, Scutellospora, and Enterophospora, are more common in cultivated than in uncultivated areas. In terms of biostimulants production, the genus Glomus is by far the most common and widely available species in the globe [Prasad, 2021c]. [Prasad, 2021c; Siddiqui and Prechtel, 2008; Johns, 2020] The fungi of the genus Glomeromycota are obligate symbionts that rely on the carbon substrates given by their host plants (up to 20% of plant fixed carbon) for survival. Extraradical and intraradical hyphae, arbuscules, and the root apoplast interface all play a role in the fungi's ability to increase the availability of water and nutrients to their host plant [Prasad, 2017; Prasad, 2021c, d, e; Prasad, 2021b; Parniske, 2008, Prasad et al., 2021c]. AM fungal symbiosis is the most common kind of mutualistic relationship between plants and microorganisms [Prasad, 2021a; Prasad, 2020; Parniske, 2008]. It has been shown in a number of studies [Prasad, 2020; Prasad, 2021a; Siddiqui and Prechtel, 2008; Prasad, 2013; Prasad, 2020] that AM fungi are crucial to plant nutrition and development under stressful circumstances, and that they also boost other important ecosystem functions.

Endophytes are microbial communities that live in healthy plant tissues such as stems, roots, leaves, and seeds without disrupting physiological plant activities or giving any disease symptoms to the tissues. Endophytes play crucial roles in proper host plant development, either via the digestion of secondary metabolites or nutrients or by avoiding the formation of plant disease signs by various pathogens. Microbes such as bacteria, actinomycetes, and fungi that live in symbiotic relationships with plants, known as endophytes, often colonize a network around the host plant, where they are protected from weather extremes and other stresses (Zhao et al. 2011; Passari et al. 2017).

Below the line of vertical transmission in a plant, in the form of a seed, are hyphae that endophytic fungi use to get access to the kernels. Host plant cells invaded by endophytes were shown to be passed on in a somewhat different way both laterally and vertically (Tintjer et al. 2008). There has been a greater focus on understanding the transmission function of endophytic microbes, which has led to a greater focus on the processes involved in plant development with these microbes. The endophytic fungus species may spread from plant to plant within a population or community via the exchange of sexual spores or through asexual means (Tadych et al. 2014). Roots of host plants get colonized by microorganisms such as bacteria, algae, fungi, and actinomycetes (Saharan and Nehra 2011; Prashar et al. 2014). Actinobacteria are the second most prevalent microorganisms in the rhizosphere, and they make up more than 30% of the total microorganisms in the soil (Glick 2014). Through the seeds, endophytes may travel from one rhizosphere to another. Microbial phytopathogens or nematodes cause them, and they spread rapidly through the endo-rhizosphere through the lateral root connection (Chi et al. 2005). Root hairs and intercellular gaps in the root epidermis provide additional entry points for bacterial endophytes to colonize their host plants (Hardoim et al. 2008).

The rhizobia are the root-nodule symbionts (RNS) of leguminous plants and are thus considered soil bacteria (SB). Nitrogen fixed by rhizobia is comparable to that from synthetic ammonia synthesis on a global scale [Harwani et al., 2009; Gruber and Galloway, 2008]. However, certain rhizobia may grow

endophytically in non-legume plants (NLP), and non-symbiotic rhizobia (NSR) often outnumber symbiotic genotypes in soil [Segovia et al. 1991]. Direct and indirect processes are at work here, with increased plant growth and production attributable to PGPR colonization of root systems and enhanced root branching. For improved growth, production, and soil fertility (SF) in a sustainable agricultural system, PGPR and INM work together more effectively (SAS). Live bacteria that lack the PGPR gene have beneficial impacts on plants via both direct and indirect pathways. Positive effects on water and nutrient absorption, as well as resistance to abiotic and biotic stress, have resulted from the use of Constructive Microbes (CM). The purpose of this publication is to provide a comprehensive overview of GRSP AM fungi, including their beneficial effects on host plant development, yield quality, and symbiotic fungus (SH) accumulation (SAP).

Explanation of AM fungi

The GRSP AM fungal symbiosis has been around since the earliest land plants appeared, around 400-450 million years ago [Gautam SP, Prasad 2001; Smith and Read, 2010]. This symbiotic relationship between AM fungi and terrestrial plants is very common, maybe the most common of all mutualisms. Soil stability, carbon sequestration, and nutrient transfer on a global scale are all dependent on symbiotic relationships between plants and fungi [Prasad, 2020; Prasad, 2021c; Parniske,2008; Gautam and Prasad 2001; Siddiqui et al., 2015]. Fungi of the AM genus are obligate symbionts that obtain reduced carbon from plant roots in exchange for water and nutrients for their host. Up to twenty percent of a plant's photosynthate may be dedicated to feeding AM fungus. Approximately five billion metric tonnes of carbon dioxide are consumed annually by AM fungus. Once a fungal reproductive spore germinates and sends out hyphae in the direction of a host root, the life cycle of mycorrhizal fungi has officially begun. As a result of fungal signals, hosts undergo physiological changes that work against the plant immune program (Prasad, 2017; Prasad, 2021c; Prasad, 2020; Prasad and Kaushik, 2004; Kloppholz et al. 2011). Preparation of the ICE occurs actively inside the plant cell [Prasad, 2017; Prasad, 2021c; Prasad, 2020; Oono and Denison, 2010]. At sites of nutrition exchange, where the fungus has invaded the host parenchyma cortex, it has formed branch-like structures called arbuscules. Vesicles condense at the intracellular root hyphae (ICH) tips (RS). White-branched hyphae and other appendages invade the soil surface, where they drink up nutrients and water. In addition to a wide range of macro and micronutrients, the most prominently transported elements are phosphorus (P) and nitrogen (N). In exchange, the fungus gets carbon from the host and uses it to build cellular structures like mitochondria, chloroplasts, and ribosomes, or to produce reproductive structures like spores [Prasad, 2017; Prasad, 2021a; Prasad, 2020; Prasad and Pandey, 2012; Gautam and Prasad, 2001]. Hyphae may colonize new plants by developing from both spores and the roots of the host plant. Fungal fitness among the Glomalin AM fungi may be defined, by the presence or absence of arbuscules and vesicles. Contrary to the common belief that more arbuscules mean more symbiotic nutrition exchange, more vesicular colonization may be an indication that some fungi are hoarding their food supply.

Penetrating of AM fungi in New Hosts

Symbiotic AM fungi are able to infect new hosts even as they thrive in their current ones. Fungi have the ability to produce mycelia/hyphae up to one hundred times longer than root hairs, which gives them access to a far more extensive nutrition-foraging system than roots alone. Increased fungal colonization inside the host has the potential to increase carbon uptake and phosphorus (P) and other nutrient transfer. Fungi, on the other hand, can better search for resources and new hosts thanks to an enormous network of external hyphal (EH) cells.

Repopulating of AM Fungi in the Soil Environment and Host

AM fungus reproduces by the formation of thick-walled globular and sub-globular spores on the extraarticular hyphae. These spores have such sturdy walls that they may survive in the ground for years. This fungus group is made up of plant-root symbionts; they may be found in just about every ecology, and they reproduce asexually through multinucleate spores. Although spores of AM fungi are capable of germinating and producing hyphae in the laboratory, no one has yet been able to successfully cultivate the fungus without a root. AM fungal propagules are produced in large quantities using transformed root culture (TRC) in a laboratory setting using the nutritional medium that has been changed. The transformed root becomes infected with spores, which then germinate and multiply into new spore forms. A major reproductive strategy of GRSP-producing AM fungus is spore generation, which allows the fungi to spread, recover from disruption, and live without a host for up to ten years in certain situations [Giovannetti et al., 2010].

Amazingly dynamic, AM fungal glomalin spores send out hyphae that scout the soil but stop growing and retreat back inside the spore if they do not come across a host root [Bonfante and Genre, 2010]. When a spore host is removed, the spore germlings will stop developing and eventually die off after 8-20 days [Prasad, 2017].

Uptake of Nutrient and Exchange to Host

Rhizosphere soil microorganisms are obligatory hosts for AM fungus. Their saprobic abilities must be limited, and they must depend on the plant for carbon feeding [Prasad, 2021c; Prasad, 2020]. The hexoses produced by the photosynthesis of their plant hosts are ingested by AM fungus. [Prasad,2017; Prasad, 2021c; Prasad, 2020; Bolan, 1991; Pfeffer et al., 1999] Arbuscules and intraradical hyphae are two possible pathways for carbon transfer from plants to fungi. In the intraradical mycelium, AM fungi produce secondary metabolites from hexoses (ICM). Mycelia convert hexose to trehalose and glycogen. Rapidly generated and destroyed carbon storage forms like trehalose and glycogen should act as a buffer for the ICSC within the cell [Prasad, 2017; Pfeffer et al., 1999]. The oxidative pentose phosphate route is where IRH goes to become pentose for nucleic acids (NA). The intraradical mycelium is also the site of lipid production (IRM). Extraradical hyphae (ERH) are transported lipids to be stored or digested. The ERH is where gluconeogenesis, the conversion of lipids into hexoses, takes place [Pfeffer et al., 1999; Hamel, 2004]. About a quarter of the carbon that is transferred from the plant to the fungus is stored in the ERH [Hamel, 2004; Harley and Smith, 1983]. Another benefit of the AM fungus is the transfer of up to 20% of the host plant's carbon [Prasad and Deploey, 1999; Pfeffer et al., 1999]. This is the host plant's contribution to the pool of organic carbon below ground, as well as the large amount of carbon that the host plant invested in its mycorrhizal network. Phosphorus and other nutrients are taken up and transferred from the fungus to the plant [Prasad, 2017; Prasad, 2020; Prasad, 2013; Prasad, 2015; Bucking and Shachar, 2005]. In particular, phosphorus absorption has been identified as the primary advantage of AM fungus to plants.

Agriculture System Improve through AM Fungi

Mycorrhizal symbiosis is severely hampered by several in-vogue agricultural methods. Mycorrhizal symbiosis may be greatly aided by low-input agriculture's (LIA) approach to ecosystem management. It is more difficult for plants to create a symbiosis with AM fungi when conventional agricultural practices (CAM) are used, such as tillage, heavy chemical fertilizers (HCF) and fungicides, inefficient crop rotations (PCR), and selection for plants that survive these circumstances. When AM fungus has completely colonized a plant's root system, that plant will perform better and produce more than it would have without AM fungi. The symbiotic relationship between AM fungi and their host plant improves the host's ability to take in and use both macro and micronutrients [Prasad, 2017; Prasad, 2021a; Prasad, 2020; Prasad, 2013; Prasad, 2015; Prasad, 2021e]. All agroecosystems may benefit from encouraging AM fungus colonization, but it is especially important in organic and low input LIA systems in areas with low soil P. AM fungi are particularly attractive to plants that are not good at foraging for nutrients in the soil, allowing those plants to take in much-needed P as well as other macro- and micronutrients.

Enhance Soil Quality (SQ) and Health

The success of ecological restoration (ER) and, by extension, the rate of soil recovery, may be improved with the introduction of native AM fungus [Prasad, 2021c; Gautam & Prasad, 2001; Jeffries et al., 2003; Prasad & Rajak, 2001; Worchel et al., 2013]. Since AM fungi produce ERH and a soil protein (SP) called glomalin, they improve the stability of soil aggregates. A monoclonal antibody (Mab32B11) developed against ground-up AM fungus spores was used to successfully identify GRSP. Extraction conditions and antibody Mab32B11 response help characterize it precisely. There is growing evidence that AM fungi are responsible for producing glomalin. The quality of the SH and the land's production may be enhanced with the careful control of AM fungus within agroecosystems. Reduced tillage, limited phosphorus fertilizer use, and perennialized cropping systems are all examples of agricultural practices (AP) that foster beneficial mycorrhizal symbiosis (UMS).

Impact on Global Climate Change (GCC)

The populations of AM fungi and the relationships between AM fungi and their plant hosts are being altered by global warming [Prasad, 2021c]. Whereas recent meta-analyses have generally acknowledged that interactions between organisms might influence their response to GCC. Under simulated nitrogen deposition, AM fungi were shown to enhance plant biomass (PB) [Worchel et al., 2013; Kivlin et al., 2013]. However, under DC, AM fungi decreased PB. Evidence suggests that AM fungi themselves increase their biomass in response to rising

atmospheric CO_2 [Prasad, 2021c]. To AM, Prasad [Prasad, 2021c] spoke on how fungi have the potential to alter global climate.

AM Fungi Impact on Phytoremediation

Degradation of physical and biological soil characteristics (BSP), soil structure (SS), nutrient availability (NA), and soil organic matter (SOM) often follows the disruption of native plant communities in desertification-prone locations (SOM). When repairing degraded land, it's important to replace not only the above-ground vegetation but also the biological and physical soil properties (PSP) [Prasad, 2013; Jeffries et al., 2003]. In ecological phytoremediation, a relatively new method of recovering land, AM fungi are inoculated into the soil after new plants have been planted. Host plants have been able to establish themselves on damaged soil, increasing SQ and health as a result [Prasad, 2021c; Gautam & Prasad, 2021; Prasad & Rajak, 2000; Prasad & Rajak, 2001; Akhtar et.al., 2019]. After introducing a mix of native AM fungal species, soil quality measures increased significantly over time, especially when compared to non-nodulated soil and soil inoculated with a single alien species of AM fungi [Jeffries et al., 2003]. Higher legume nodulation (LN) within the presence of AM fungi led to better plant growth, higher phosphorus uptake [Fillion et al.,2001] and soil nitrogen content (SNC), higher soil organic matter (SOM) content, and improved water infiltration and soil aeration [Prasad, 2021c; Prasad, 2017; Gautam& Prasad,2001; Jeffries et al., 2003]. In order to increase HM (s) extraction from contaminated soils and restore the soil's health for crop production, native strains of AM fungus are used (Akhtar et.al, 2019, Akhtar et.al, 2020). For rhizobia, the potential benefits of symbiosis are eye-opening. In an extremely LRN, a single rhizobia cell may multiply a million times or more. Leguminous plants may gain a lot from rhizobia and symbiosis. It is common practice to inoculate legume crops with rhizobia in many parts of the globe, and the necessity of using inoculants that are particular to the legume being planted has long been recognized. Positive effects on nodulation, grain production, and protein content in peas and soybeans have been seen after inoculation with Rhizobium [Glick, 1985; McKenzie et.al, 2001; Prasad, 2021f; Meghavansi et.al 2008; Meghavansi et.al 2010; Meghavansi et.al 2005; Harwani et.al 2006]. Increasing N supply by BNF in rice-based cropping systems in warm and humid environments was discovered after inoculation with Azospirillum, Azotobacter, blue-green algae (BGA), and Azolla (a water fern) [Singh et al., 2010].

The function of Endophytes in Plant Health

Many studies have been conducted to better understand the evolutionary biology, ecological roles, and defense mechanisms against abiotic and biotic stress that endophytic organisms play in plants. Plants and their crops with commercial, agricultural, and industrial significance may benefit from the use of endophytic biotechnology. The appropriate use of various endophytic species found in plants may aid in the enhancement of agricultural products, the increase of metabolite production in various plants, and the modification of tolerance to a wide range of abiotic and biotic environments (Wani et al. 2015). Several novel, crucial bioactive compounds have been produced by endophytic organisms in recent years. It has been hypothesized that, in comparison to epiphytes or soil-associated microorganisms, the link between diverse endophytic species and their host plant in the synthesis of a vast number and variety of biologically active chemicals is connected together (Strobel 2003). Bioremediation and phytoremediation are two promising new technological applications for endophytic organisms (Li et al. 2012a). Endophytes contribute much to plant health via three distinct processes: biofertilization; Phyto stimulation; and biocontrol (Bloemberg and Lugtenberg 2001).

Plant Growth-Promoting Activity

Plants depend primarily on endophytic microorganisms to help them adjust to stressful situations and new habitats. Plants may create symbiotic partnerships with microbes to better survive in hostile conditions. These connections are mutually beneficial, allowing both partners to evolve and become more adapted to their respective habitats (Rodriguez et al. 2009). Plants' capacity to survive and function is impacted by factors such as limited water and nutrient availability, intense radiation, strong winds, and low temperatures (Convey 2011). The usage of the symbiotic interaction between plants and beneficial microbes is a tried-and-true method for alleviating stress without interfering with plant development. Plant development is stimulated by a wide range of metabolite chemicals, many of which are generated by an endophytic fungus (Waqas et al. 2015). Endophytic microorganisms promote plant development by producing enzymes and other bioactive compounds. Endophytic microorganisms, notably fungi like *Sebavermiformifera* and *Piriformospora indica* and several species of Colletotrichum and Penicillium, are notable for their superiority in stimulating plant development under adverse environments (Waller et al. 2005; Redman et

al. 2011; Hamilton and Bauerle 2012). While plant pathogenic viruses, fungi, bacteria, and nematodes are responsible for a wide range of plant ailments, the plant growth-promoting microorganisms (PGPM) that are naturally associated with many plant species offer several advantages. Plant hormone syntheses, such as indole-3-acetic acid (IAA), cytokinins, gibberellins, siderophores, phosphate solubilization, nutrient absorption, and antagonism to phytopathogens, occur in tandem with the primary functions of PGPM. Furthermore, PGPM may trigger induced systemic resistance in plants by causing chemical or physical changes associated with defense (ISR). Over time, PGPM has adapted to provide plants with permanent benefits when exposed to a wide range of abiotic stresses. Multiple studies have shown the importance of plant growth-promoting fungus (PGPF) in improving resistance to a variety of abiotic stressors (Khan et al. 2012). In contrast, osmotic stress is induced by conditions like salt and drought, and it is communicated through abscisic acid (ABA) independent or dependent pathways (Cao et al., 2014), and low levels of ABA productions were attained under fungal activity (Jahromi et al. 2008; Khan et al. 2014). Treatment with endophytic Penicillium spp. restores water balance in the plant, as described by Miransari (2012), requiring less effort from the plant to manufacture ABA and safeguard cell progress under stress. In order to maintain sustainable agriculture, plant growth-promoting bacteria (PGPB) are able to stimulate plant expansion through either stand-alone or interconnected methods (Compant et al. 2010; Palacios et al. 2014). PGPB shown various reactions to several stressors in plants (Kim et al., 2012), fought against plant infections (Raaijmakers et al., 2009), and supplemented the recovery of damaged cells or degraded components (Kim et al., 2012; de Bashan et al. 2012). It has been reported that endophytic bacterial species colonise host plant tissues (Yang et al., 2016; Tang et al., 2017); and that these bacteria can stimulate plant growth; fix nitrogen; and repress phytopathogens with induced systemic resistance (ISR) of this pathogen (Pieterse et al., 2014; Puri et al., 2016; Padda et al., 2017). One or more of the plant growth-promoting processes used by endophytic actinobacteria include nitrogen fixation, inorganic nutrient solubilization, phytohormone and siderophore excretion (Dudeja et al. 2012). The hormone indole acetic acid (IAA) is essential for the formation and growth of shoot and root cells in plants; it is produced by several microorganisms, including plant growth-promoting rhizobacteria (PGPR) (Hassan 2017). Gibberellins and indole-3-acetic acid

(IAA) are two examples of plant growth-promoting chemicals synthesized by soil microorganisms (Radhakrishnan et al. 2013; Limtong et al. 2014). Several studies showed in vitro that endophytic actinobacteria produce plant growth regulators such as auxins, cytokinins, gibberellins (gibberellic acid), and IAA (Ghodhbane-Gtari et al. 2010; Fouda et al. 2019b). Microbes, such as fungi, bacteria, and actinobacteria, that are thriving under low iron stress produce siderophores, which are tiny molecules with high-affinity iron chelators (soluble Fe_3^+-binding agents). It has been discovered that a wide variety of endophytic microorganisms may produce siderophores, which have a molecular weight of between 400 and 1500 daltons (Kannahi and Senbagam 2014). Bacteria produce four distinct classes of siderophores: catecholate, salicylate, hydroxamate, and carboxylate. Pseudonocardia, Streptomyces, Nocardia, Actinopolyspora, Micromonospora, Salinispora, Actinomadura, and Kibdelosporangium are only a few examples of endophytic actinobacteria that are known to generate siderophores (Gangwar et al. 2011; Kannahi and Senbagam 2014; Bhosale and Kadam 2015). A secondary defensive mechanism and plant growth regulator, siderophores are synthesized by endophytic actinobacteria (Rungin et al. 2012). And salicylic acid (SA) is a major phytohormone involved in several activities, including root development, seed germination, flowering, stomatal closure, and enhanced resistance to biotic and abiotic stressors. In plants, SA is produced by bacterial endophytes and is responsible for promoting plant growth in the face of water scarcity and suppressing the development of plant diseases such as fungus (Klessig et al., 2016).

Endophytic Microbes Acts Biocontrol Agents

Microorganisms found inside plants are called endophytes, and they are recognized as biocontrol agents that may be used in place of chemical pesticides. Insect herbivores are mostly kept under control by endophytic fungus, and this is true not just for grasses but also for conifers (Parker 1995). According to Tefera and Vidal (2009), the sorghum borer population was reduced with the application of the entomopathogenic endophytic fungus *Beauveria bassiana*. Additionally, throughout storage and shelf life, tomato fruits may be preserved against the acute rotting caused by fungal diseases. *Bacillus subtilis*, an endophytic bacterium isolated from *Speranskia tuberculate* (Bge.) Baill, has an antagonistic action in vitro against *Botrytis cinerea*, the pathogen responsible for the rotting of tomato fruits during storage (Wang et al. 2009). In order to combat poplar

canker, researchers conducted a biocontrol study using novel endophytes such as *Burkholderia pyrrocinia* JK-SH007 and *Bacillus cepacia* (Ren et al. 2011). Studies in biocontrol have recently taken a novel approach by inducing gene expression in an endophytic microbe to produce anti-pest proteins such as lectins for insect control. For the production of the *Pinellia ternate agglutinin* (PtA) gene, however, endophytic microorganisms were used. These strains included *Chaetomium globosum* YY-11, which was recovered from rape seedlings, as well as Enterobacter sp. and *Bacillus subtilis*, both of which were isolated from rice seedlings (Zhao et al. 2010). Multiple crop seedlings have benefited from the use of recombinant fungal and bacterial strains that express the PtA gene in order to combat sap-sucking pests. Another research demonstrated the efficacy of the recombinant endophytic bacterial strain *Enterobacter cloacae* expressing the PtA gene as a bio-insecticidal agent against the white-backed plant hopper, *Sogatella furcifera* (Zhang et al. 2011). As a novel method for controlling a wide variety of plant pests, the development of several anti-pest proteins by recombinant endophytic strains is a promising area of research. Copper nanoparticles generated using the endophyte *Streptomyces capillispiralis* Ca-1 have been shown to biocontrol *Culex pipiens* (Mosquito) and *Musca domestica*, according to research published by Hassan et al. in 2018. (housefly). Antimicrobial activity against four phytopathogenic fungi was found in copper oxide nanoparticles generated by two endophytic actinomycetes isolated from the *Oxalis corniculate* L. plant: *Streptomyces zaomyceticus* Oc-5 and *Streptomyces pseudogriseolus* Acv-11 (Hassan et al. 2019).

AM Fungi and Nitrogen Fixation

Endophytes help their host plants in several ways, including protecting them from harmful pathogens, creating beneficial phytohormones, providing nutrients, and fixing nitrogen (Rupple et al. 2013). Widespread nitrogen-fixing endophytes in roots (e.g., Azoarcus spp., Acetobacter diazotrophicus, and Herbaspirillum spp.). Nitrogen fixation improves a host plant's health and vitality when nitrogen levels are low. Even if only trace levels of fixed nitrogen are present in a given species, it is important to clarify whether or not they are meant to meet the needs of the microbes or the host plant. The poplar endophytic bacteria Paenibacillus P22 contributed to the host plant's total nitrogen pool and triggered metabolic shifts (Hardoim et al. 2015).

Bradyrhizobium Japonicum (BJ) and Rhizobium

Nitrogen-fixing (NFB) gram-negative bacteria like Bradyrhizobium and Rhizobium (class of the Alpha proteobacteria, order of the Rhizobia) may be found in soil as free-living organisms or in association with the roots of leguminous plants. Cohabitation results in the development of root nodules. Since bradyrhizobium symbiosis permits only moderate application of CF, it has considerable practical value in agriculture. Soybean is an N_2 fixing partner in the soil is the bacteria BJ. When the bacteroid is fully developed and nitrogen is fixed, acetate absorption rates rise during symbiosis.

Interaction and Suitability Advantages of Rhizobia

It is expected that a single rhizobial cell that establishes a root nodule population (RNP) will produce many more offspring than if it had stayed in the rhizosphere. Mean values from laboratory and field experiments range from 108 to 1011 BJ cells per soybean (Glycine max) nodule [Harwani et al. 2006, Prasad et al. 2005; Prasad et al. 2019; Prasad, 2011], while a Siratro (*Macroptilium atropurpureum*) nodule may contain more than 109 reproductively viable rhizobia [Ratcliff and Densi The ability to reproduce within a nodule is likely to exert strong selection on the kind of symbiosis, but there may be other benefits as well. Polyhydroxy butyrate (PHB), a source of energy, and phosphate may be stored in nodules by rhizobial cells, which may improve their chances of survival in the long run. Nodulating bacteria, such as *Sinorhizobium meliloti*, may store enough PHB per cell to allow for population growth in the absence of an external carbon source [Ratcliff et al., 2008]. To that end, a comparable amount of phosphate may be stored by BJ in a phosphorus-free culture for up to five generations [Harwani et al. 2006; Cassman et al. 1981] if the BJ is grown at a phosphorus level equivalent to that found in nodules. It is important to keep in mind that the benefits of nodulation for rhizobial suitability rely on the rhizobia's capacity to multiply inside a nodule and are thus only of indirect benefit to the host. There is some overlap between the goals of legumes and rhizobia; an extra nodule worth of rhizobia can fix more nitrogen, allowing for potentially more plant development and photosynthesis, which in turn might sustain even more rhizobia. In hosts where all rhizobia maintain reproductive capacity, there are known cases of sanctions against less advantageous rhizobia [Kiers et al., 2003; Simms et al., 2006].

Signaling and Host Range in Rhizobium-Legume Symbioses

Although Rhizobium legume symbioses (RLS) can fix a lot of atmospheric nitrogen, they are very important ecologically and agronomically. Nodules are specialized structures inside the roots of legumes that are formed as a consequence of symbioses; these nodules serve to convert nitrogen into ammonia that the host plant may utilize. Curling of root hairs, the creation of infection threads inside root hairs and, by extension, the root cortex, and the induction of a meristem within the inner root cortex, giving birth to the nodule, are all typical responses to rhizobial infection in legumes. Each rhizobium has a distinct host range, which may be anywhere from a few legume species to well over a hundred, and this uniqueness is a key element of RLS. Several nodulations (nod) genes that determine host range, infection, and nodule formation have been discovered by genetic research on nodulation in several Rhizobium species. Several of these genes, like nodD and nodABC, are ubiquitous in rhizobia as a whole, whereas others, known as host-specific nod genes, are present in a wide variety of permutations across the many rhizobium species. The nod genes regulate many signals between the rhizobium and the host plant. The presence of flavonoid plant signals activates the expression of the opposing (structural) nod genes, which are responsible for the production and excretion of extracellular signals, known as Nod factors, that are uniquely active on host plants.

Rhizobium Acts as Biofertilizer for Nitrogen Fixation (NF)

The use of Rhizobium species as a biofertilizer (BF) to develop an N_2 fixing symbiotic connection with leguminous agricultural plants has been widely used across the globe [Prasad et al. 2005, Prasad et al. 2019]. One hundred seventy-five million metric tonnes per year [Chafi and Bensoltane, 2009] nitrogen comes from beyond the continents in the world. Around 195 tonnes of nitrogen per year are fixed biologically in legumes containing Rhizobium species [Vitousek et al., 2013]. BNF of symbiotic role in legumes has been studied and recorded for its ecological significance. The release of flavonoids from the plant is the first step in a complex series of events that leads to the formation of a symbiotic relationship. Plants constantly manufacture these substances, but if the proper rhizobia are recognized in the rhizosphere, the concentration of these compounds increases [Hassa and Mathesius, 2012]. The specificity of the signals sent and received between partners may range from almost none to a high degree [Hirsch and Fujishige, 2012]. Nodules are structures that develop as a result of intracellular

colonization by rhizobia on the roots of their host plants. Despite the first signal exchange and the potential for nodule formation, meaningful symbiosis is not achieved between certain incompatible partners [Miller & Sharitz, 2000]. The bacterial partner in the RLS undergoes a process of differentiation into a non-dividing endo-cellular symbiont. These symbionts induce a nitrogenized complex that the host plant then consumes to fix atmospheric N_2 into NH_3/NH_4^+. Numerous earlier research on rhizobium species has mapped out strain diversity, phylogeny, and mechanisms of host specificity.

Plant Growth Promoting Rhizobacteria (PGPR)

PGPR has been so named because of the positive effect it has on plant development and yield. Direct biocontrol of root infections, indirect processes including enhanced nutrient availability and stimulated rhizobium nodulation (RN), and induced systemic resistance all contribute to the potential of PGPR benefits (ISR). The plant may be able to resist or even out-compete pathogens if its growth is stimulated by PGPR. Increased SER is one effect of PGPR, which also shortens the period of time a plant spends vulnerable to pre-emergence damping-off pathogens like Pythium spp. There are two major categories of beneficial rhizosphere bacteria: symbiotic rhizosphere bacteria (which live in symbiosis with the plant) and free-living rhizosphere bacteria (which live in the soil and on the roots) (Barriuso et al. 2005; Lugtenberg and Kamilova 2009). Numerous studies have shown that beneficial microorganisms may increase plant growth, development, and yield, and PGPR has been used to increase agricultural output for quite some time. Improvements in Nutrient Uptake and Yield from Legumes Exposed to Salt Stress via Co-inoculation 294 (Lugtenberg et al. 2001; Arora et al. 2008; Egamberdieva et al. 2010). Germination rates, emergence rates, root and shoot growth, total plant biomass, seed weight, grains, and yields are all improved by treatments with PGPR such as Alcaligenes, Arthrobacter, Azospirillum, Azotobacter, Enterobacter, Pseudomonas, Burkholderia, Bacillus, and Serratia (Mantelin and Touraine 2004; Joseph et al. 2007; Yasmin et al. 2007). Rhizobium has been shown in subsequent tests to increase chickpea growth, nodulation, and yield (Carter et al. 1994; Elsheikh and Elzidany 1997; Akhtar and Siddiqui 2009; Khosravi et al. 2010). Influencing root development and morphology is where rhizobacteria really shine in terms of their ability to stimulate plant growth (Dobbelaere et al. 2001; Creus et al. 2004) found that inoculation with bacteria led to the

development of long root hairs, promoted the growth of lateral roots, and increased root diameter and surface area. There is evidence that other PGPR species may aid many legumes in their quest for optimal development, nodulation, and nitrogen fixation (Egamberdieva et al. 2010).

PGPR Improves Plant Growth under Stressful Conditions

Plants are sessile creatures [Wani et al. 2016] that have no choice but to confront wherever they are and accept it, thus the systems that govern stress tolerance in plants are complex. Increasing plant varieties of resistance to stress by traditional breeding may take a long time and a lot of money, especially in areas where genetic engineering is controversial for ethical or societal reasons. There is a growing recognition of the use of beneficial bacteria (BM) in stress management (SM) and the creation of climate-change-resistant farming (CCRA). In order to boost crop growth and yield, reduce stress, and strengthen resistance to diseases and pests, modern research has made use of molecular methods (MT).

Plant Hormones Produced by PGPR to Improve Crop Productivity

Phytohormones serve a crucial role in controlling plant growth and PG. Together, they operate as molecular signals (MS) in reaction to environmental conditions (EF) that would otherwise restrict PG or be lethal if allowed to spiral out of control [Fahad et al., 2015]. Several RB in the rhizosphere is well-known for enhancing plant development and resistance to stress by secreting hormones for absorption by the roots. Numerous PGPR may generate auxins, which have profound impacts on both root development and plant architecture [Jha and Saraf, 2015; Vacheron et al., 2013]. To perform its intended task, exogenous IAA must first match the amounts of IAA already present in the internal systems of the plant. Bacterial IAA may have no impact, a positive effect, or a negative effect on PG at optimal concentrations in plants [Spaepen and Vanderleyden, 2011]. The PGPR that generates auxins has been shown to activate auxins response genes that boost PG [Ruzzi and Aroca, 2015], increase root biomass and decrease stomata size and density [Llorente et al. 2016], and elicit transcriptional changes in the hormone, defense-related, and cell wall-connected genes [Spaepen et al. 2014]. Cytokinins and gibberellins are produced by a plethora of PGPR [Gupta et al. 2015; Kumar et al. 2015]. Plant shoot growth (PSG) may be stimulated by higher levels of gibberellins in certain PGPR variants than in others [Jha and Saraf, 2015]. This is because their

interactions with auxins may cause changes to the root system [Vacheron et al., 2013]. Increased root exudate production by the plant is one possible outcome of PGPR's role in cytokinin production [Ruzzi and Aroca, 2015].

Supplementary Microbe-to-Plant Signal Molecules (PSM)

Secondary metabolites (SM) and volatile organic compounds (VOCs) generated by bacteria may increase stress tolerance (ST) and/or promote development in plants. In plants, polyamines provide crucial defensive and physiological functions. An increase in biomass-modified root architecture (RA), and enhanced photosynthetic capability are all the results of *B. megaterium's* induction of polyamine synthesis in Arabidopsis by the secretion of spermidine, a polyamine (PC). Subsequent water deficit stress (WDS) induced by polyethylene glycol (PEG) resulted in increased drought tolerance (DT) and abscisic acid (ABA) content in the inoculated plants [Zhou et al., 2016]. Kumar et al. (2015) found that one kind of PGPR may generate HCN, which has the potential to regulate the abundance of harmful microorganisms in the rhizosphere. The volatile organic compound (VOC) generated by PGPR activates PG, which in turn leads to increased shoot biomass (SB) and better plant stress resistance (PSR) [Ruzzi and Aroca, 2015; Billy and Weisskopf, 2012]. Many plant species have had their PG lengthened by microbe-to-plant signal molecules (lipo-chitooligosaccharides and thuricin) after plants have begun to develop under stressful circumstances [Subramanian and Smith, 2015; Subramanian, 2015; Zipfel, 2017]. This receptor system seems to have developed for disease detection almost two billion years ago [Spaink, 2009; Gust et al. 2012; Carotenuto et al. 2017]. The receptor for the lipo-chitooligosaccharides might be a LysM kinase for the LRS.

AM Fungi Tolerance Drought Stress

As one of the most significant abiotic stressors, drought limits the growth, development, and production of plants. Drought occurs when plants are deprived of water at the roots or when transpiration rates are very high (Anjum et al., 2011). Despite normal soil water levels, it has been shown that diurnal water stress occurs in the middle of the day for most plant species in temperate regions. The growth rate suffers as a result of this short-term drought stress (Granier and Tardieu 1999). Lower germination rates, compromised membranes, suppressed photosynthesis, and increased

production of reactive oxygen species are all effects of drought (Greenberg et al. 2008). Furthermore, the primary sources of osmotic stress on plants were prolonged periods of dryness and high salinity. Drought causes osmotic stress, salinity causes ionic or ion toxicity, and both types of stress have detrimental effects on cells (Zhu 2002). Symptoms of osmotic stress from salt in the shoot system, such as slow growth and leaf senescence, conflict with those of drought stress (Munns 2002). The water use and biomass of symbiotic plants (including rice, tomato, dune grass, and panic grass) were much lower and higher, respectively, than those of nonsymbiotic plants. Endophyte-associated plants may be more drought-resistant than noninfected plants due to increased solute accumulation in tissues, thicker cuticle development, reduced leaf conductivity, and a slower transpiration stream (Malinowski and Beleskey 2000). The main reaction to water shortages is an increase in ABA biosynthesis and/or a decrease in ABA breakdown (Bray 2002). ABA is thought to play a key role in drought-stricken plants, acting as a signal that regulates the ability of plants to cope with water stress. This is achieved primarily via the regulation of transpiration and the closure of stomata (Zhang and Outlaw 2001). Other data suggest that ABA helps plants absorb more water by encouraging root branching (De Smet et al. 2006). By-products of *Azospirillum brasilense* sp 245 cultures with the chemical enhancement of growth were analysed using full scan mass spectrometry, and ABA was identified as a by-product. NaCl supplementation of the culture medium resulted in an increase in bacterial ABA production, and ABA levels were enhanced in *Azospirillum brasilense* sp 245-inoculated *Arabidopsis thaliana* seedlings (Cohen et al. 2008).

Interaction between AM Fungi and Other Beneficial Soil Microorganisms (BSM)

Soil microorganisms are only one of the many things that an AM fungus communicates with [Prasad, 2017; Nelsen and Safir, 1982; Ortiz et al., 2015; Abbaspour et al., 2012]. Mycorrhizal associations and other rhizosphere microbes may benefit from, be unaffected by, or suffer damage from interactions [Osonubi et al. 1991; Ouledali et al. 2019; De and Dodd, 2016; Yosefi et al. 2018]. Nutrient absorption, biological control of root infections, improved plant tolerance to abiotic stress, and improved soil quality are all possible concerns [Laxa et al., 2019].

Functions of Microbes in Agriculture

Benefits from microorganisms extend beyond the realm of the bio-economy and may have an impact on commercial agriculture. Many economically important plants are produced in monoculture, and this kind of cultivation necessitates the use of supplements to promote healthy development, maximize production, and counteract the spread of disease. [Prasad, 2020; Prasad et al. 2019; Andreote and Pereira, 2017; Vejan et al. 2016; Prasad, 2011; Prasad, 2010; Prasad, 2006; Prasad, 2002; Prasad, 1998].

Beneficial Microbes Increasing Yield and Decreasing Fertilizer Inputs

Usage of AM fungi, rhizobium, and PGPR singles in the consortium has inconsistent effects on crop yield [Prasad, 2017; Prasad, 2021a; Prasad, 2021b; Prasad, 2021c; Prasad, 2021d; Prasad, 2021e; Prasad, 2021f; Prasad, 2011; Prasad, 2010; Prasad, 1998; Wu CH et al. 2009; Prasad et al. 2005). The blending of a bacterium (*B. amyloliquefaciens*) with a fungus (*Trichoderma virens*) improves yields of corn and tomato, among alternative crops [Akladious and Abbas, 2012; Molla et al. 2012]. Trichoderma with Bradyrhizobium improved the growth of soybean whereas combined AM fungi and Trichoderma for improved growth and treatment of pathogens present within the soil; both of that are commercially available. Inoculation with N-fixing bacteria (Azospirillum and Azotobacter) allowed half-rate N fertilizer application and increased sesame seed yield and oil quality [Shakeri et al. 2016]. Similar effects were shown for *Azospirillum vinelandii* inoculated *Brassica carinata* cv. *Peela raya* [Nosheen et al. 2016a; Nosheen et al. 2016b]. A consortium of bacteria reduced the incidence of root-knot nematode in tomatoes accumulating fruit yield and quality [Niu et al. 2016]. AM fungi and BJ improved growth and productivity in soybean and red soil-borne pathogens [Prasad et al. 2019; Prasad, 1998; Prasad, 2011; Prasad, 2011].

Beneficial Microbes Improving Disease Control and Reducing the Use of Agrochemicals

The use of biologicals is an alternate strategy for controlling plant diseases [Prasad and Rajak, 2001; Prasad, 1998; Prasad, 2011; Prasad, 2011; Harman, 2011]. It's possible that beneficial AM fungi, rhizobium, and PGPR release antibiotics and other chemicals that are hostile to plant diseases. Another prevalent biocontrol method is the production of antibiotics [Duponnois et al., 2003]. In most cases, pathogens will eventually become immune to antibiotics and other forms of biocontrol. When dealing with infections, it may be preferable to use a holistic strategy that employs numerous dominating techniques rather than relying too heavily on just one of them. The microbe's ability to fight infections by

evolving its mechanism of action over time is another factor in its success. Antimicrobial metabolites such as lipopeptides, polyketides, and antifungal metabolites are also produced by PGPR to combat microbial growth (Prasad et al. 2019).

Benefits of the Tripartite Symbiosis (AM fungi/Ectomycorrhizal Fungi (EMF), NFB PGPR

Improving PG and lowering pathogen levels are two further advantages associated with tripartite symbiosis [Prasad and Deploey, 1999; Harwani et al. 2009; Prasad, 1998; Prasad, 2011; Prasad, 2010; Prasad, 2022; Chilvers et al. 1987; Lesueur and Duponnois, 2005; Rajendran and Devaraj, 2004]. Inoculation of *C. equisetifolia* plants with a mixture of AM fungi, Frankia, Azospirillum, and Phosphobacteria was proposed by Rajendran and Devaraj [Rajendran and Devaraj, 2004]. This treatment considerably boosted the height and biomass of the plants. Trifecta-inoculated plants absorbed more nitrogen, phosphorus, potassium, calcium, and magnesium, according to the same scientists. Possible enhancement of PG by AM fungi in the presence of EMF [Duponnois, 2003; Chilvers et al. 1987; Lesueur and Duponnois, 2005; Rajendran and Devaraj, 2004]. Frankia and mycorrhizal synthesis in vitro using Casuarina equisetifolia revealed that combined inoculation with AM fungus and EMF greatly boosted biomass and P content compared to plants treated with AM fungi or EMF alone. Colonization by NF, AM fungi, and EMF was boosted when Frankia was introduced to *C. equisetifolia*. Once both symbionts were introduced, however, an antagonistic impact was seen, which was often caused by exposure to strong EMF [Duponnois, 2003].

Roadmap to Bioinoculum Production and Commercialization

Conventional agrochemicals may be replaced with more environmentally friendly alternatives, such as bioformulations of compounds that promote plant growth, increase soil fertility, and reduce phytopathogens (CAC). Products for the agricultural industry are created using live inoculum of a single species or many species or supporting isolated signal molecules. When it comes to signal compounds, one has the option of using microbe-to-plant signals, which have direct effects on the plants, or plant-to-microbe signals, which trigger enhanced production of the microbe-to-plant signals in the soil environment, presuming that the microbe is present in the soil. Both of these options are viable. It is possible to employ plant-to-microbe communications in conjunction with other methods in order to jointly manage the composition of the Phyto microbiome in ways that are advantageous to agricultural plants.

Conclusions

One or more endophytes may be found in around 3 million plant species worldwide. Each kind of endophyte has a unique function that promotes plant development and protects it from environmental stresses. As inoculants, endophytes help plants adapt to variable environmental circumstances and reduce their vulnerability to abiotic stressors. Given the growing focus on issues like sustainable agriculture, food security, and environmental protection, it is more important than ever to find ways to use beneficial endophytes. By creating a wide range of novel physiologically active metabolites that may be able to positively control plant physiologic problems, endophytes may also be a useful tool for increasing crop yields and improving product quality. They are useful for protecting plants from pathogens and getting rid of harmful chemicals left behind by pesticides, herbicides, and heavy metals. Furthermore, it rapidly boosts the host immune system.

Adaptation to biotic and abiotic stressors, as well as the amelioration of their impacts, are all areas in which AM fungi play a vital role in enhancing PG and production. Reduced exposure to harmful pesticides and industrial chemical fertilizers may be achieved thanks to their ability to increase PG and yield as well as resilience to disease and tolerance to biotic and abiotic stressors. In order to promote their industrial production on a massive scale and maximize their influence, it is crucial to employ biostimulants in genuine ecosystems and in sync with biogeographically zoned regions to provide sufficient nutritious food for every human being on the globe, both now and in the future. Researchers, businesses, and governments all have a role to play in boosting AM fungus production so that they may be more widely used, especially in underdeveloped nations where AM fungi inoculum are neither widely available nor affordably priced. However, only legumes are able to participate in the biological process of juvenile nitrogen-fixing root nodule symbiosis with bacteria, while the roots of higher plants may create an endosymbiotic relationship with soil fungus to generate AM fungi. Multiple receptors and signaling pathways regulate the widespread occurrence of AM fungus, rhizobia, the plant growth regulator (PGPR), and other components of a successful symbiosis.

Understanding the variety of AM fungi, rhizobium, and PGPR as well as their colonization potential, methods

of action, formulation, and application, thanks to current advancements in rhizospheric modification, should help them become trustworthy components in the management of eco-friendly and SAS. The safe approach of nutrient solubilization and plant growth-promoting activities provided by AM fungus and PGPR-mediated agriculture is rapidly gaining popularity throughout the globe for a broad variety of crops and controlled ecosystems (PGPA). This new era of genetic modification research and technology should begin quickly thanks to the novel tools of genetic modification in AM fungi and PGPR, such as the importation and unleashing of nutrients from fixed and uptake forms to plant available forms and natural enemies and improved germplasm, breeding, and field testing. Attempts to maximize nutrition solubilization and PGPA via the use of individualized application tactics are often hampered by gaps in our understanding (AS). There needs to be a more in-depth study on the impact of soil plant environmental system on rhizosphere microbial population dynamics and on the composition of the rhizosphere as it is modified (MPD). Although AM fungi and PGPR showed promise as commercial inoculants for SAS, they were yet to live up to their full potential. Plants that have evolved to a variety of challenges, including drought, salt, temperature, nutritional stress, and heavy metals, might benefit from the usage of endophytes as a secondary defense mechanism. Endophytes are beneficial microorganisms that live in symbiotic relationships with their host plants. More research is needed to fully understand these relationships and optimize endophytes' potential as growth promoters and plant protectors.

Conflict of Interest

There is no conflict of interest.

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