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Synergistic Interactions of PGPR and AM Fungi in Enhancing Crop Productivity – A Winning Microbial Combination

Gomathy Muthukrishnan[1], Sabarinathan Kutalingam Gopalasubramaiam[1]*, Priya John[2], Ananthi Karuppaiah[3] and Dilip Saikia[4]

[1]*Agricultural College and Research Institute, Tamil Nadu Agricultural University, India*

[2]*Navsari Agricultural University, India*

[3]*Agricultural College and Research Institute, Vazhavachanur, India*

[4]*Silapathur College, India*

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***Corresponding author:** Sabarinathan Kutalingam Gopalasubramaiam, Agricultural College and Research Institute, Tamil Nadu Agricultural University, India, Email ID: sabarinathan@tnau.ac.in

Abstract

Synergistic interactions between Plant Growth Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal (AM) fungi have been increasingly recognized as crucial contributors to enhancing crop productivity and sustainability. PGPR and AM fungi form mutualistic relationships with plants, promoting nutrient uptake, enhancing stress tolerance, and stimulating growth. Their combined application has shown remarkable effects on various crops, including increased nutrient acquisition, improved water-use efficiency, and enhanced resistance to biotic and abiotic stresses. This review explores the mechanisms underlying the synergistic interactions between PGPR and AM fungi and their implications for sustainable agriculture for improving crop productivity and reducing the environmental impact of conventional agricultural practices.

Keywords: Arbuscular Mycorrhizal fungi; PGPR; Mechanisms; Plant growth promotion

Introduction

Microbes that live in soil ecosystems are always closely associated with various plant systems; this relationship is known as a phytomicrobiome and the plant that is associated with microbes is called a holobiont [1,2]. Such relationship due to plant microbe interactions not only regulates microbial community but also plays vital role in the soil biogeochemical cycling. Microbes can survive in various environments including harsh conditions. They preferred to survive in the soil as it is rich in nutrients. The most suitable region for microorganisms in soil is the rhizosphere region where the nutrient availability is more and favourable for development of microorganisms [3]. It is a high nutrient zone where the presence of organic acids, amino acids, sugars, enzymes are more [4]. Plant growth-promoting rhizobacteria (PGPR), a group of microorganisms that live in the rhizosphere, are the main catalysts for enhancing soil fertility and nutrients, which produces amazing results in the area when compared to the bulk soil [5,6]. The bioformulation that contains good PGPR strains which helps in control of the plant pathogens and to increase the crop production. AM fungi also play a pivotal role in agriculture. AM fungi can explore larger volume of soil where plant roots cannot access and bring nutrients to the crop. AM fungi also help the plants to overcome biotic and abiotic stress of the environment. Combined inoculation of both PGPR and AM fungi can do marvelous tasks and helps for sustainable crop production. The present review article elucidates the synergistic interaction of PGPR and AM fungi for sustainable productivity.

PGPR

Root-releasing compounds have an impact on both microorganisms and plant growth. According to Uren [7], the root exudates, also known as rhizodeposits, contain phenolics, carbohydrates, fatty acids, amino acids, organic acids, sterols, putrescine, vitamins, and growth regulators that either attract or repel microorganisms. Rhizobacteria releases a variety of stimulants that help plants to absorb water and nutrients. It can directly assist plants for assimilation of nitrogen and phosphorus and alter the level of hormone and decrease population of bacterial pathogens [8]. Recent research showed that the growth of plants and productivity increased through the application of PGPR various conditions. In recent days more number of non-pathogenic rhizobacteria were monitored which improves the growth through the release of phytohormones such as auxins and cytokinin, siderophore production, act as biocontrol agent and promotes the induced systemic resistance of the host plant [9]. Both seed inoculation and foliar spray of *B. megaterium* PB50 significantly improved the plant growth under osmotic stress, protected plants from physical drought through stomatal closure, and improved carotenoid, total soluble sugars, and total protein content [10]. The production of phytohormones, such as indoleacetic acid (IAA), gibberellic acid (GA), abscisic acid (ABA), and cytokinin, hydrogen cyanide, siderophore and antagonistic activity against the foliar pathogens *Pyricularia oryzae* and *Helminthosporium oryzae* were evaluated and found as PGPR strains excelled well and showed its maximum potential [11].

Arbuscular Mycorrhizal Fungi (AMF)

AM fungi are one among the endomycorrhiza where the hyphae of the fungus not only grow inside the root of the plant, but penetrate the root cell walls, cortical cells and become enclosed in the cell membrane and forms arbuscles. The mutual association provides the plants to resist against many biotic and abiotic stresses through the metabolic pathways and increases the yield of crops by improving soil health, helps in uptake of nutrients and managing salt, moisture and nutrient stress in the environment. In plants, the AMF works against wide range of hosts through multi approach *viz*., change in root morphology, change in nutrition, activation of defense mechanisms, competes for colonization and photosynthates. AMF is considered as plant wealth/treasure in agriculture by the scientific community. In rice, various biotic stresses diminish the crop productivity mainly pathogens, insects *etc*., Among pathogens, soil borne diseases/pathogens were mainly managed by competing for nutrients and host whereas, other pathogens are managed mainly due to the interaction with host which stimulates/produces various plant growth hormones and chemicals such as strigolactones etc. Due to its multifaceted potential, AMF can be used as one of the tools for sustainable rice production. AMF play a vital role in nutrient management by providing rice with essential nutrient in its available form without superfluous application of fertilizers.

Mechanisms of PGPR

Antibiotic production

Antibiotic producing microorganisms are used directly in agricultural fields to fight against pathogenic microorganisms near plants or root surfaces. PGPR are the main antibiotic producing microorganisms and their secretions act as another method to chemical fertilizers and protect the plants from pathogens. They secrete lytic enzymes, bacteriocins and antibiotics [12] which kill or inhibit the pathogens. *Bacillus* and *Pseudomonas* produce antibacterial and anti-fungal agents such as subtilin, sublancin, TasA and subtilosin A that were ribosomal origin products and non-ribosomal peptide products namely, iturin, bacilysin, bacillaene, mycobacillin, Difficidin, chlorotetain, rhizocticins, lipopeptides, fengycin and surfactin [13].

Hydrolytic enzymes production

Biological control methods that incorporate enzyme-producing PGPRs have the potential to be a viable alternative to synthetic chemical methods, not only for effective plant pathogen management but also for the developement of a pollution-free environment. In host rhizosphere, a wide variety of PGPRs shows hyperparasitic activity against pathogens through secretion of several hydrolytic enzymes *viz.,* proteases, lipases, cellulases, chitinases and β-1,3 glucanases, which disturb the cell wall of bacterial and fungal pathogens by acting on glycolytic linkages of prokaryote and eukaryote cell wall [14]. The lytic enzymes like lysozyme are bactericidal, fungicidal and nematicidal in nature. Extracellular enzymes *viz.,* chitinases, β-1,4- glucanases, proteases, cellulases and xylanases secreted by PGPRs *Bacillus* sp. *B. thuringiensis*, *B. atrophaeus* and *B. subtilis* strain inhibit mycelial growth of fungal pathogens *viz., Fusarium oxysporum, F. solani, R. solani, Botrytis cinerea* [15,16].

Competition for niche

Rhizosphere region act as an important interphase between roots of plants and microorganisms, elucidated by different inorganic acids exudates by root surface i.e., sugars, vitamins, amino acids, organic acids, nucleosides, phenolic compounds and phytosiderophores. These nutrients act as chemical attractants for motile bacteria to migrate towards roots surface, providing niche to a diverse range of microorganisms, including pathogenic microbes [17]. In the rhizospheric region, competition for nutrients and physical occupation sites is an indirect mechanism utilized by competitive PGPRs against pathogenic microbes that depend on external sources [18].

Release of root exudates

Roots are able to release various chemical substances into the soil and it is known as root exudates. Roots regulating the soil microorganisms and change the physio-chemical properties of the soil and reduce soil plant pathogens. Root exudates are released by plants in two different forms. One through passive and the another through active secretions. The exudates are more in organic acids, amino acids, terpenoids, phenolic compounds, polyacteylenes, flavonoids, alkaloids, sugars, tannins, and secondary metabolites. Roots can secrete various types of proteins along with [19,20] higher molecular weight substances called as rhizo deposition that are released into the soil by plant roots that serve as nutritional source for rhizospheric microorganisms. Root exudates vary

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among the plant species, age and associated compounds [21].

Quorum sensing

Quorum sensing is an intercellular communication mechanism between bacteria, which is controlled by gene expression combined with cell concentration and facilitated by the diffusion of certain signal molecules such as N-acylhomoserine lactones (AHLs). It regulates expression of several phenotypes contributing bacterial pathogenesis in *Psuedomonas syringae, Pectobacterium atrosepticum, Dickeya solani, Erwinia amylovora, Ralstonia solanacearum, Agrobacterium tumefaciens*. In the rhizosphere region, certain PGPRs resists bacterial infections by adopting quorum-interrupting methods that interfere quorum sensing through enzymatic degradation of AHLs molecules, this mechanism is known as quorum quenching (QQ) and the PGPRs are known as QQ bacteria [22].

Siderophores production

Siderophores are less molecular weight (500-100Da) iron scavengers, that chelate iron from the environment and transport Fe^{3+} into microbial cell providing advantage to PGPR microbes [23]. When siderophores are released into the environment, they solubilize the iron and create an iron-siderophore complex that moves through the diffusion process until it reaches the cell membrane receptors of bacteria, where active transport takes place after recognition [24]. Bacterial siderophores are classified into four major classes they are phenol catecholates, carboxylate, pyoverdines and hydroxamates [25].

Indirect mechanisms

Induced resistance is defined as an improvement of the plant's defense system against a broad spectrum of pathogens and pests that is acquired after appropriate stimulation. The induced resistance produced by an inducing substance upon infection by a pathogen is called Induced Systemic Resistance (ISR) or Systemic Acquired Resistance (SAR) [26]. The induction of systemic resistance by rhizobacteria is referred to as ISR, whereas that by other substances is called SAR [27]. Once resistance is induced it will afford non-specific protection against pathogenic microorganisms as well as against several insects and nematodes.

Systemic acquired resistance

The expression of phytohormones, which suppress invasive species, is the result of a number of actions triggered by pathogen or insect exposure. During SAR, resistance reactions occur in the non-infected parts starting from the infection site. At the place of attack, the plants respond to pathogen infection through the cell wall modification, production of phytoalexins, production of pathogenesis related (PR) proteins and activation of programmed cell death or hypersensitive reaction (HR) [28]. Plants use a variety of cues, including the sense of touch [29].

Mechanisms of AM fungi in enhancing crop growth

a) **Changes in root growth and morphology:** AM colonization induces notable changes in root system morphology, altering the dynamics of pathogens and modifying microbial populations, with the possible stimulation of microbiota components with antagonistic activity toward certain root pathogens. Different production of exudates in AMF roots can influence the microbiota composition.

b) **Changes in host nutrition:** the increased nutrient uptake resulting from AM symbiosis makes the plant more vigorous and consequently, more resistant, compensating for the loss of root biomass or function caused by pathogens.

c) **Competition for colonization sites and photosynthates:** both the AM fungi and root pathogens depends on host photosynthates, and they compete for the carbon compounds reaching the root. However, AM fungi have primary access to photosynthates, and the higher carbon demand may inhibit pathogen growth.

d) **Activation of defense mechanisms:** with AM colonization, the host plant produces a great number of phytoalexins, enzymes of the phenylpropanoid pathway, chitinases, b-1,3-glucanases, peroxidases, pathogenesis-related (PR) proteins, callose, hydroxyproline-rich glycoproteins (HRGP) and phenolics that can act in biological control.

e) **Solubilization of minerals:** Acidification of the rhizosphere due to organic acids secretion by the AM fungi makes the minerals to be available to the crops as solubilization and mobilization of minerals happens in the rhizospheric region [30].

f) **Sequestration of heavy metals:** AM fungi inoculated plants produce lot of biomasses compared to uninoculated control plants [31]. Moreover, AM fungal hyphae release a super glue called glomalin that has the ability to sequester carbon and heavy metals [30].

Synergistic interaction of PGPR and AM fungi

Many researchers have noticed the synergistic interaction of PGPR and AM fungi and found a promising synergy between both the organisms on various plants. In *Avena sativa*, inoculation of *Glomus intraradices* and *Acinetobacter* sp showcased augmented growth even under hydrocarbon stress [32]. Devarajan et al. (2021) [33] noticed the combination of PGPR strains enhanced the drought tolerant nature of rice crop. [34] elucidated the role of *Burkholderia* on *Sedum alfredii* in heavy metal contaminated soil. Combination of endomycorrhizal mix and *Pseudomonas* species improved the nutrient uptake and growth of Zea mays [35]. Similarly iron absorption was maximum in *Sorghum bicolor* due to the AM fungi and PGPR [36]. In addition to that increased plant height was attained due to the synergistic influence of

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Funneliformis mosseae and PGPR inoculation [37]. Combination of these bacteria and fungus do wonders in remediation of contaminated sites making them as a promisible candidate to work under stress conditions [38]. This can address all types of soils with nutrient deficiencies and other contaminations and can able to go up to the level of bio fortification.

Changes in plant growth with colonization of PGPR and AM fungi

a) For phosphorous/nutrients acquisition from the soil: Helps in acquiring nutrients which are available in the soil by increasing the surface area with the mycelia.

b) Increased resistance to foliar pathogens: By triggering the defense mechanisms inside the host plant.

c) Increased drought and salt tolerance

d) Increased nutrient transfer from soil to the plants: By increasing the surface area with the help of mycelia and uptakes the nutrients through solubilization process.

e) Local resistance and systemic resistance to root pathogens: Because of the competition for colonization at the site of infection

f) Soil health improvement, increased resistance to heavy metal toxicity: By fertilizing the soil, soil texture improves over the period of time.

g) Production of Plant Growth-Regulating Substances by the PGPR and AM fungi which provides induced systemic resistance and plant growth hormones. Through this systemic resistance is inhabited in host plants against plant pathogens, insect pests etc.

h) Combined inoculation of PGPR and AM fungi enhances the growth and yield of green gram than individual inoculation alone [39].

Conclusion

Through deeper understanding of the underlying mechanisms driving the positive interactions between PGPR and AM fungi could pave the way for more targeted and efficient applications. Efficient selection of PGPR and AM fungi untap the synergistic potential for specific plant types and environmental stress conditions. Deep insight into these associations further unlocks the hidden secrets in agricultural crops paving the way for sustainable agriculture.

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