Sangwan S, et al., J Adv Microbiol Res 2023, 6: 026
DOI: 10.24966/AMR-694X/100026

HSOA Journal of
Advances in Microbiology Research

Review Article

Regulatory Role of Arbuscular Mycorrhiza Fungi and Helper Bacteria Associations in P and N Dynamics in Agriculture

Seema Sangwan[1]*, Garima Saxena[1], Ram Swaroop Bana[2] and Radha Prasanna[1]

[1]*Division of Microbiology, ICAR Indian Agricultural Research Institute, New Delhi, India*

[2]*Division of Agronomy, ICAR Indian Agricultural Research Institute, New Delhi, India*

Abstract

Interactions among microflora and plants represent a major pillar in rhizosphere biology for improving soil fertility and crop productivity. As the most important macronutrients in soil, the availability of Phosphorous (P) and Nitrogen (N) significantly affects plant growth and yield, across crops, and around the globe. In soil, bacteria and fungi constitute the major groups of microbes, existing, both as free-living and in symbiotic/ loose associations with other living forms, which find use as biofertilizers in integrated nutrient management. Among various types of fungi, Arbuscular Mycorrhiza Fungi (AMF) comprise symbiotic fungi which form an extensively dense network of mycelia around the plant roots, and improve the soil structure and increase the uptake of water, as well as nutrients such as P, N/ micronutrients by plants. Several bacteria capable of solubilizing phosphorous mainly via releasing a wide range of organic acids and chelating metabolites are also present in free living form and in association with AMF. Such bacteria associated with AMF hyphae and spores are called as Mycorrhiza Helper Bacteria (MHB) as they help in regulating the activity and functioning of AMF. Characterization of such bacteria and developing promising combinations of AMF and MHB, can be beneficial for improving the nutrient availability in soil and stimulating plant growth. This review summarises and discusses the current knowledge on the interactions among AMF and MHB towards enhancing the availability of N and P availability, and its uptake by plants, thereby, highlighting the research gaps that need attention and in-depth research.

Key Words: Arbuscular Mycorrhiza Fungi; Mycorrhiza Helper Bacteria; Nitrogen; Phosphorous; Synergism

Introduction

Replenishing the soil biological properties through the tools of microbial inoculation and addition of requisite quantities of nutrient inputs is the hall mark for keeping agricultural revolution evergreen. For getting optimum yields in a sustainable manner without any dire consequences to environment, it becomes necessary to provide a regular supply of these macronutrients, through fertilization (chemicals or biofertilizers). Phosphorous (P) and Nitrogen (N) are the primary nutrients required for the growth, development of plants and are essential because they actively participate in various processes e.g., carbon metabolism, energy generation, energy transfer, enzyme activation, membrane fixation and nutrient cycling [1-4]. Phosphorous is involved in formation of ATP, nucleic acids and phospholipids [5]. P deficiency is known to cause approximately 50% losses in all agricultural lands around the world [6,7]. Like P, N is also a primary major nutrient required by plants as it forms a part of the structure and functioning of some important macro and micro building blocks in plants such as chlorophylls, proteins and amino acids [5,8]. For improving the availability of P and N to the plants, chemical fertilizers are often used in an unbalanced manner, without knowing its long-term consequences and its ill effects on the environment. To mitigate this, the use of biological options to make available N and P to the plants is the sustainable way forward. Arbuscular Mycorrhizal Fungi (AMF) and their intimate relationship with Mycorrhiza Helper Bacteria (MHB), are getting more attention among various types of biofertilizers, as they effectively increase P, N uptake and crop productivity [9,10].

AMF represent an obligate biotrophic association with plant roots that establishes mutualistic symbiosis with 80% of the terrestrial plants such as cereals, pulses, fruit trees, vegetable, medicinal plants and other commercial crops such as sunflower, cotton and sugarcane [11]. In exchange for plant photosynthates, AMF facilitate the uptake and transfer of mineral nutrients such as P, N, S, Ca, Cu and Zn from the soil to the host plant through their Extra Radical Mycelium (ERM) [12]. ERM function as an efficient absorbing system that enables the uptake of nutrients beyond the depletion zone [13-15]. Besides providing nutrition to the plants, AMF also facilitates the completion of several biochemical cycles, enhances tolerance to biotic and abiotic stress [16], sequesters carbon, improves soil aggregation [17] and plays an important role in synthesis of health promoting phytochemicals [18]. In the mycorrhizosphere, MHB which are associated with AMF spores and hyphae, thereby, playing an important role in nutrient uptake and overall growth of the plant, as they are potent bioenhancers of plant-AMF associations [19]. They help in improving hyphal growth, spore germination and establishment of mycorrhizal symbiosis. MHB isolated and characterized till date are gram-positive Actinobacteria and Firmicutes (e.g., *Streptomyces, Brevibacillus,*

***Corresponding author:** Sangwan S, Division of Microbiology, ICAR- Indian Agricultural Research Institute, India 110012, Tel: 011-25847649, E-mail: cmasangwan123@gmail.com

Citation: Sangwan S, Saxena G, Bana RS, Prasanna R (2023) Regulatory Role of Arbuscular Mycorrhiza Fungi and Helper Bacteria Associations in P and N Dynamics in Agriculture. J Adv Microbiol Res 6: 026.

Received: September 12, 2023; **Accepted:** October 06, 2023; **Published:** October 13, 2023

Bacillus, Rhodococcus, Arthrobacter, Paenibacillus) and *Azospirillum, Pseudomonas, Rhizobium, Burkholderia, Enterobacter, Agrobacterium, Azotobacter, Bradyrhizobium* and *Klebsiella* which come under the category of gram negative Proteobacteria. Species of *Streptomyces, Pseudomonas* and *Corynebacterium* have been shown to improve the germination of F. *mosseae*, G. *versiformae* and G. *margarita* spores [19,20]. Actinobacteria are a group of bacteria frequently associated with AMF spores able to hydrolyze chitin found in the spore wall [21,22]. Other MHB such as *Klebsiella pneumonia* and *Paenibacillus validus* have been reported to increase germling hyphae growth [23] and *Oxalobacteria* enhance both spore germination and germling growth along with root colonization. ERM development is promoted by *Penibacillus spp*., *Azospirillum spp*. and *Pseudomonas spp*. [24]. Additionally, MHB:

- Promote mycorrhizal symbiosis by several direct and indirect means including- improvement in root receptiveness of fungi [25].
- Modulate plant-fungi recognition and symbiosis establishment.
- Accelerate EMF propagule germination as well as spore survival and mycelial growth.
- Modify soil chemical properties e.g., for a better connectivity with the soil fungus, protection against pathogen and promote defence mechanism [26].

MHB are also known to help breakdown molecules to a usable form as they can utilize both organic and inorganic nutrients in soil through a process called “mineral weathering” which aids in the recycling of nutrients in the rhizosphere environment. MHB help to make available, P from soil [27,28] and phosphorus solubilizing rhizobia are the most common MHB involved in P uptake. They release compounds in soil to break down organic inorganic P for further use by mycorrhizae. They are active even under P limited conditions, helping mycorrhiza to establish and grow [29]. Several MHB also have the capability to acquire nitrogen and fix N in the soil, without plant modification, as done by legumes to help in N fixation [28]. Researchers reported the significant contributions of *Bacillus spp*. to N fixation [30] (Table 1).

Ecological function	AMF	Crop	Reference
N, P, K, Fe and Zn	*Glomus mosseae*	Rice	[31]
C, N, P, K	*Glomus spp.*	Finger millet peanut, pigeon pea	[32]
N, P	*Rhizophagusintraradices, Glomus versiformae, Claroideoglomusetunicatum, Claroidioglomusclaroideum*	Tomato	[33]
C, N, P	*Funneliformismosseae, Rhizophagusirregularis*	Apple	[34]
N	*Funneliformismosseae, Diversisporaversiformis*	Chrysanthemum morifolium	[35]

Table 1: Ecological role of AMF to facilitate P and N uptake.

Plant Response to Deficiency of P and N in Soil: Plants exhibit several biochemical, physiological and morphological adaptations to deal with N and P deficiency, which work in a linked manner. To increase P and N acquisition capacity, plants show “P and N starvation response” as shown in Figures 1&2. Recent scientific advances have helped to provide a better understanding of the signalling pathway of plant response to N limitation by microarray and sequencing-based transcription profiling, e.g. genome scale expression in many plants e.g., rice, corn [36-38]. Arabidopsis adapts itself to limited nitrogen through NLA gene (nitrogen limitation adaptation) by inducing the anthocyanin synthesis [39].

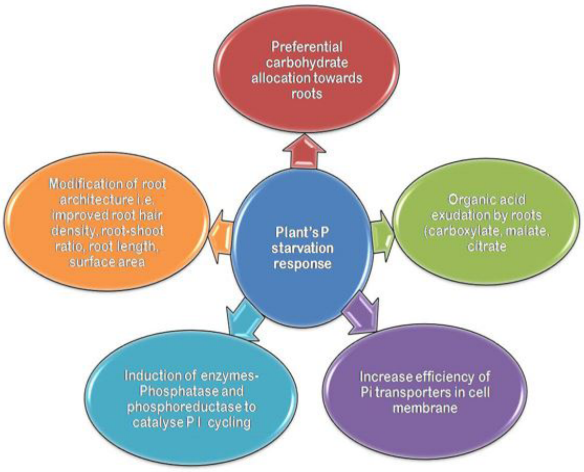

Figure 1: Response of plant to P starvation.

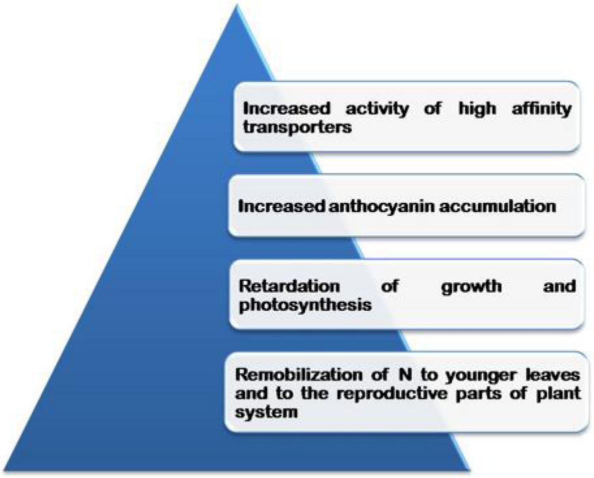

Figure 2: Response of plant to N starvation.

Mechanism of AMF for P Mobilisation and uptake: The benefits of AMF in various plants are documented and its significance in P uptake is the most noteworthy. AMF being obligate biotrophs, they form a symbiotic relationship with the roots of plant for their survival [11,40]. These fungi penetrate the root cortical cells, establish arbuscules, and mediate the exchange of nutrients such as P [41]. AMF expands the extent of the mycorrhizal hyphae network up to 25 cm around the root in the mycorrhizosphere and creates a niche for other microbes, to facilitate better availability of plant nutrients like P and N [11]. It has been established that 50% of P uptake in the mycorrhizal plants is supported by the AMF [42] and the P uptake mechanisms include-

i. P uptake rate (influx) per unit of arbuscular mycorrhizal root increases due to the greater absorption surface area of mycorrhizal roots compared to the cylindrical root surface of plant systems [43].

ii. AMF enhances the root zone absorption by 10-100% and improves the plant's ability to reach more soil resources due to ERM by increasing absorption area of root through ER hyphae which extend beyond the P depleted zone, leading to greater bioavailability of Pi [43].

iii. These hyphae with small diameter allow the ERM to access small cores to achieve greater P intake, improve P acquisition plant possess the ability have to overcome the depletion zone and improve root surface area [11].

iv. AMF store P in polyphosphate form so that they can keep their Pi level low to efficiently transfer Pi from the soil to extra radical hyphae and then to intra radical hyphae [28,44].

v. In addition, organic exudates (citrate, malate) which chelate Ca, Al ions and dissolve aluminum and calcium phosphate are secreted in soil [45].

vi. AMF also release some chemicals such as glomalin (a glycoprotein) which are reservoirs of C in soil and aid in uptake of Fe, and P [46,19].

vii. Improve the functioning of cell-specific Pi transporters (Figure 3) which transfer Pi to the host plant also known as plant Phosphate Transporters (PTs) [47,48]. They facilitate the acquisition of inorganic Phosphate (Pi) and maintain its homeostasis within the plant.

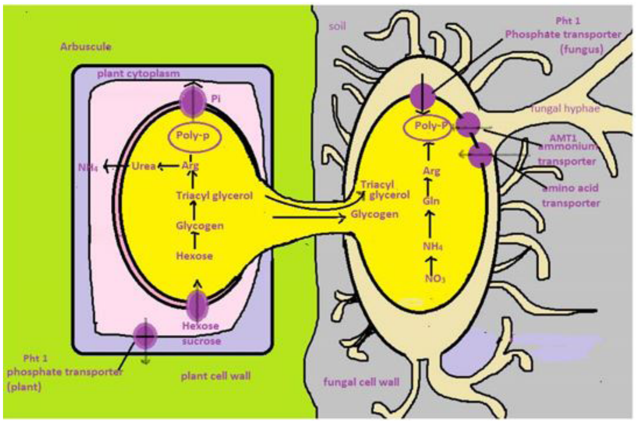

Figure 3: Phosphate and Nitrogen transport between the plant cell and fungus.

(Phosphate and nitrogen acquisition by fungus and transport to the plant cell through Pht1 i.e. phosphate transporters; nitrogen through AMT1 i.e. nitrogen transporters).

Mechanism of AMF for N Availability: It is also indicated that AM fungi can influence the uptake of other nutrients e.g., nitrogen which is necessary for plant growth and yield [49]. Results from the root organ culture studies suggest that up to 50% of the root N is acquired through AMF route [50]. A "Trade balance model" was proposed to explain the apparent nitrogen paradox [51]. This model suggested that fertilization with N will be only beneficial, if plant is limited by P and will therefore benefit from providing C to the roots and mycorrhizal fungi. AMF can acquire N in various ways:-

i. Inorganic nitrogen in the form of ammonia and nitrate [52,53].

ii. Directly facilitate the uptake of glycine in *Glomus mosseae* through a mechanism, as depicted in Figure 3, in which AMF acquires organic N directly from the soil substrate. Researchers have provided evidence for the uptake of organic N by dipeptide transporters in the intraradical mycelium of *Rhizophagus irregularis* [54].

iii. In arid regions, where N mobility/nitrate mobility is low, AMF can be effective under such conditions to absorb inorganic N [55,56] indicating that even in such stress conditions, AMF can help to increase the uptake of N.

iv. Plant ammonium transporter activation in the presence of AMF has been reported similar to P [57]. Using labelled N, it has been demonstrated that the hyphae of AMF are able to utilise inorganic N efficiently and transfer it to 10-30 cm [58,59,25].

v. AMF utilise the inorganic N reused from organic source such as like amino acids [60,61].

vi. To mineralise N, it also produces hydrolytic enzymes such as pectinase, xyloglucanases, cellulases which are able to decompose SOM, under humid conditions. This also helps to reduce the leaching of nitrate in the soil [62].

Under low N availability, competition for N between AMF and plant has been documented resulting in non-mycorrhizal plants becoming more efficient than mycorrhizal plant [63]. AMF-mediated P uptake could also have a significant positive effect on BNF [64]. There are various modes of N uptake in the rhizosphere, so it is difficult to distinguish the most important process- biotrophic, nutrient cycling or transfer through root exudates [61,65]. There is limited evidence from experiments involving quantum dot technology that the organic N fragment could have been taken up by the AMF and uptake of N in the form of amino acid has also been reported to be as high as compared to non-mycorrhizal plants (Figure 4).

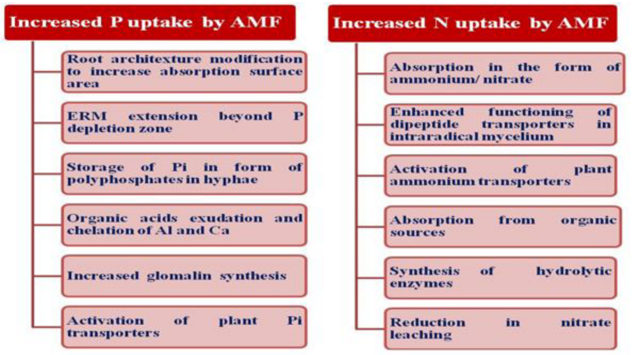

Figure 4: Mechanisms employed by AMF for P and N uptake.

Organic N uptake by AMF: AMF development favours the release of nutrients from soil through mineralisation (specifically NH4+ ions) [66]. AMF is found to possess a weak exoenzyme repertoire [67], such as exophosphatase activities. However, they are very unlikely to mineralise on their own. AMF rely on other saprophytic /hyper symbiotic microbes for the N mineralisation [68]. There are some microbial grazers who excrete a large amount of NH4+ ions in the soil when they digest other microbes in soil, thereby returning the N to soil-free ammonium pool. It can be easily utilised by AMF [61,66]. As of now, there is very scanty information regarding ERM to be able to directly take organic N molecules such as amino acids, peptides and nucleosides from the soil solution [53].

Chitin as a Source of Organic N for AMF: Chitin is a polymer rich in N (>6%) by weight which is present abundantly in the soil micro and microfauna. It has been reported that the addition of crab shell chitin during plant cultivation as substrate can promote AMF species sporulation [69]. The genes responsible for the breakdown of NAG (N acetyl glucosamine); a subunit of chitin polymer, are present in the membrane in *Rhizophagus irregularis* [70]. The transporter genes have also been identified in intra-radical hyphae only. After the chitinolytic degradation of chitin by various fungi and microbes, it gets transported by the AMF and while the decomposers are eaten up by grazers and the N returns to the ammonium pool. But there is a chance of competition between AMF and ammonium oxidising bacteria in the soil solution [66].

Mechanism of MHB for P uptake: In order to develop strategies to promote mycorrhization of AMF and improve uptake of P from soil, there is a need to elucidate the aspects of metabolic signalling pathway of MHB and illustrate their functional significance. MHB are known to help break down molecules to a more usable form [28]. They obtain both organic and inorganic nutrients from the soil through a direct process called "mineral weathering" which aids in recycling the nutrients e.g., *Pseudomonas, Burkholderia*. Phosphate Solubilizing Rhizobacteria (PSRB) are the most common MHB which aid in the phosphate uptake. They release the phosphate degrading compounds to break down organic and inorganic phosphate, thus creates a phosphate pool that mycorrhiza can further use. PSB are also called as PGPR [28,71,72] as the improved availability of P improves plant growth. PSB solubilise P by producing phenolic compounds, organic acids, siderophores and hormones [73]. The acids destroy the P-bound structure, such as those of dicalcium phosphate, hydroxyl phosphate, tricalcium phosphate, rock phosphate, and make P available to plant in the form of dihydrogen phosphate or hydrogen phosphate [28]. As a result of all these mechanisms, it has been found that PSB can increase the growth of cereals, legumes, fibre crops, horticultural and oil seed crops [22]. The details of these mechanisms are given as:

Production of Organic Acids: The dissolution of P bearing compounds is pH dependent i.e., P uptake occurs at a pH of 6.5-7 so PSB produce organic and inorganic acids by mineralization [74,75]. Organic acids like malic, aspartic, tartaric, oxalic, gluconic are produced by bacterial metabolism, due to oxidative respiration. Organic acids can solubilize P from mineral surfaces by ligand exchange or ligand promoted dissociation. PSB indirectly reduce the pH and increase the P level by enhancing root exudates that increase the P availability by maintaining electro-neutrality in the soil [75]. Such organic acids sometimes also compete with phosphate at the fixation site but the siderophores (chelating agent) present in root exudates facilitate the soluble complex formation and improve Pi precipitation [76]. Root exudates attract the MHB and lead to the production of more organic acids and reduction in pH.

Production of Inorganic Acids: MHB also include Sulfur Oxidizing Bacteria (SOB) and Nitrifying Bacteria (NB) belonging to the genera *Thiobacillus* and *Nitrobacter* which participate in the production of inorganic acids (carbonic acid, hydrochloric acid, nitric acid, sulphuric acid) reported to solubilize P by reducing the pH and increasing the P availability in the soil [77,78]. SOB oxidizes sulphur compounds in the presence of oxygen to produce sulphuric acid and NB oxidizes inorganic nitrogen to produce nitric acid.

Siderophore Production: Plant and microbes both produce siderophores under low iron conditions. Siderophores are the organic compounds having iron chelating ability which makes iron available to both plants and microbes [79]. These siderophores also bind to various metals like Cd, Pb, Zn, Al, Ca, Mn, and Mo. Several PSB also reported to produce siderophore [80] and mediate solublising / dissolution of the insoluble P bearing minerals [77].

IAA and ACC Deaminase Production: PGPB and PSB and other MHB can improve P uptake by plant, by promoting phytostimulation i.e., stimulating root growth through increased branching as a result of hormonal stimulation, or root hair development by the production of IAA and ACC deaminase [81-83]. The IAA and ACC deaminase promote effective root architecture, branching, increase root exudation to lower the rhizospheric pH and improve P solubilization [84,85]. Many PSB were reported to produce IAA and ACC deaminase, as also IAA producing PSB similarly solublising Pi by increasing surface area and root exudates [82,86]. This synergy of IAA production and P solubilization being intricately linked is beneficial for plant growth [87].

P Hydrolyzing Enzymes: Organic P contributes 40-80% of soil total P. To hydrolyze organic P compounds, plant and microbes both produce enzymes. PSB mineralize organic P by secreting phosphatase enzymes [28,77] while microbes derive phosphatase mainly combine with phosphate and help in releasing orthophosphates from soil organic P [28,77,88]. Phytases are enzymes secreted by microbes which convert phytate into esters, followed by action of phosphatase to break down to Pi [5,89]. According to Le-Chateliers principle, lowering the concentration of Pi in soil solution promotes the production of Pi by indirect dissolution of K-apatite or calcium phosphate [90].

Mechanism of MHB for N uptake: MHB in the rhizosphere often have the capability to acquire nitrogen that the plant can use. Such MHB are able to fix N in the soil and create pools of available nitrogen [28,91]. However, MHB do not bring about any plant modification, as legumes do, to help with nitrogen fixation [61,91]. Nitrogen fixation is done in the surrounding soil in relation to mycorrhiza. A Bacillus functioning as MHB contributed to the nitrogen fixation and among other factors helped the plant grow when inoculated with fungus and tripartite interaction with AMF [92], host plant and soil microbes enhancing the nitrogen fixation capacity in Rhizobium. The P uptake pathway positively affects the rhizobium N fixation by influencing the energy-producing pathway. Inoculation of diazotrophic bacteria such as *Gluconaacetobacter*, *Diazotrphicus*, *Burkholdera tropica*, *Azospirillum amazonese*, *Herbaspirillum rubisubalbicans*, and *Herbaspirillum seropeduca* has been show to distinctly influence and promote N fixation in sugarcane [93]. Except for sugarcane, the use of non-rhizobial N fixing MHB in other non-leguminous crops has met with limited success [94] (Table 2).

Improving P and N Availability through Synergism between AMF and MHB

"MHB are known to influence AMF fitness" i.e., the synergistic relationship between MHB and AMF can be described as one in which MHB leads to increase in plant growth parameters by stimulating the native AMF association, spore germination, hyphal growth, rate of colonisation and effectively access soluble P and N sources [101-103]. The presence of MHB on the surface of the spores belonging to *Rhizophagus irregularis*, is illustrated using Scanning Electron Microscopy (SEM), wherein they are visible as members of the sheet

Crop	MHB	Nutrient uptake	Mechanism involved	Reference
Finger millet, Maize, Amaranth, Buckwheat, French bean	*Bacillus spp.*	P	P solubilisation	[95]
Ficus benjamina	*Bacillus coagulans, Trichoderma harizanum*	P	Positively affecting mycorrhizal fungi	[96]
Wheat	*Azotobacter chroococcum*	P	P solubilisation and hormone production	[97]
Wheat	*Bacillus circulans,Cladosporiumherbarrum*	P	P solubilisation and interact with AMF	[98]
Tomato	*Enterobacter agglomenans*	N, P	P solubilisation also positively affects mycorrhizal fungi	[99]
Maize and sunflower	*Pseudomonas alcaligenes, Bacillus polymyxa*	N, P, K	Hormonal effect on root growth	[100]
Chickpea	*Rhizobia*	N	N fixation	[10]

Table 2: MHB functions in P and N uptake.

forming biofilms, and shown to enhance growth in such associations (Figure 5). *Glomus mosseae* spores were reported to be stimulated in terms of mycelial growth by PGP rhizobacterium [104]. Such bacteria also help to enhance root colonization of indigenous and inoculated AMF [92,105]. Bacterial IAA is known to loosen plant cell walls to release root exudates for providing additional nutrition to support microbial growth. These exudates contain several enzymes such as amylase, urease, phosphatases and plant hormones like IAA, ABA, and gas [106], which help in mineralisation of P and N for AMF [107,108] and flavonoids to facilitate root colonization [109]. MHB sometimes release exudates and create a biofilm; this biofilm represents a means of long-distance migration and acquisition of nutrients from distant locations. In onion crop, MHB strains *Enterobacter spp.* and *Bacillus subtilis* were seen to enhance the uptake P from rock phosphate when inoculated alone with *Rhizophagus irregularis* [105]. A mixed biofilm was developed constituting the *Bradyrhizobium eklanii* along with phosphate solubilizing fungi that could solubilise the rock phosphate. AMF also establish extensive network creating a dedicated niche for bacteria and its hyphae are the C-rich source to MHBs [21,72]. PSB can grow alongside AMF hyphae in and out of root in sterile conditions as well as with an indigenous microbial community [110,111]. AMF release *myc* factors similar to nod factors of Rhizobium that activate nodulation factors inducible gene i.e., MtEnod 11 [61]. This gene enhances lateral root formation and mycorrhization leading to increased nodulation and symbiotic nitrogen fixation in mycorrhizal legumes [112]. It also lowers down the root zone pH by uptake of ammonium ions and release hydrogen ions into the soil solution which increase the solubility of P and also increases the nitrogen flow to the plant. PSB mobilise orthophosphate and also decomposes organic matter in turn to improve N and P availability for AMF and plants [113]. Co-inoculation of AMF-MHB by different formulations is efficient for P and N uptake and needs to be advocated across crop and ecologies.

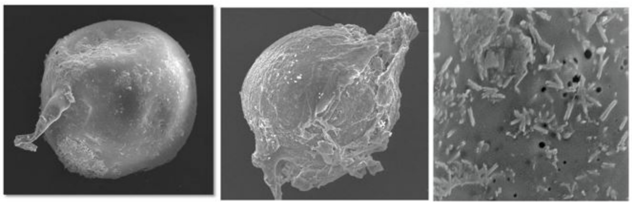

Figure 5: SEM images demonstrating the association of MHB with *Rhizophagus irregularis*. (a) Bacterial cells present in form of sheet like biofilms (yellow arrow) on AMF spore surface (scale bar: 50 µm); (b) and (c) presence of bacterial isolates (white arrow) on AMF spore surface, (scale bar: 20 µm and 2 µm).

Improvement in Product Quality and Yield by AMF and MHB: The quality of plant products and their derived foods and ingredients represent the main area of focus in sustainable agriculture, which is also in the best interests of farmers, consumers, and producers. Recently, the concept of food quality, traditionally based on nutritional and sensory properties, has acquired an additional meaning, referring to the health-promoting properties of plant foods, thereby representing an important societal issue, highly demanded by consumers. The potential of AMF in enhancing the crop yield and grain quality have been very widely studied since decades. Their inoculation causes improvement in plant nutrition, photosynthesis, and stress resistance which results in 25-30% increase in overall shoot and root biomass [114]. The potential effects of AMF alone and in synergism with beneficial microbes have been attested in some crops yield including wheat [115], barley [116], soybean [117], and chickpea [118-120]. AMF and associated bacteria enhance plant growth and health, and affect the production of polyphenols and carotenoids, and the activity of antioxidant enzymes. The diversity and content of phytochemicals in plant products are affected by different variables, such as plant genotype, agronomic factors, and Arbuscular Mycorrhizal Fungi (AMF), which establish mycorrhizal symbioses with most crops, including cereals, legumes, vegetables, fruit trees, sunflower, cotton, and sugarcane. The production of health-promoting phytochemicals was shown to be differentially modulated by different AMF isolates and bacterial strains, in several food plants, i.e., tomato, lettuce, strawberry, artichoke, maize, grapevine, sunflower. Here, we provide an overview of recent studies concerning the multiple roles played by AMF and associated bacteria in the modulation of the biosynthesis of plant secondary metabolites with health-promoting activity, and discuss the development of designed multifunctional consortia to be used in sustainable agriculture [121]. However, the beneficial effect of AMF whether alone or in synergism with MHB is always regulated by the functional group of crops, across agroecologies.

Future Perspectives

The multiple beneficial activities of AMF and their associated bacteria with complex networking in the mycorrhizosphere are functionally important for plant growth, nutrition and overall health. Very little is known about their phylogenetic interactions and intraspecific diversity of AMF and MHB. Recent studies confirmed the occurrence of diverse beneficial taxa in a commercial AMF inoculum in which 14 isolates showed the best combination of PGP traits, while 6 of them were able to solubilise P i.e., *Bacillus spp*., *Enterobacter* and Streptomyces [21]. This highlights the need for more such studies using different AMF species and associated bacteria, both singly and in various combinations to identify the best performing inoculants. The areas requiring focussed attention include:

- In-depth studies on elucidating the mechanisms underlying the resilience to diverse environmental conditions such as drought, salt and metal stress, pesticides [122] and etc.
- Transcriptomic or genomic studies to reveal the expression level of P transporter genes and ammonium transporter genes in fungal hyphae. Molecular level studies are needed to understand the transporter mechanisms using tools such as Real Time PCR (RT-PCR), Phospholipid derived Fatty Acid (PLFA) / Neutral derived Fatty Acid (NLFA) ratio.
- Commercial production of newly designed multifunctional microbial consortia for use as a bioenhancer for a sustainable production system
- Rapid and automated methods for identification and screening criteria for quick and efficient selection of performing bacteria and fungi.
- Deciphering the signaling mechanism(s) involved in the interaction of AMF and the metabolites that benefit the microorganisms. Although previous research has suggested the significance of physical interaction of AMF leading to competition for nutrients [123,124], and AMF hyphal exudation directly or indirectly manipulating the communities.
- Targeted research to identify the combinations and PGP characters that are critically affecting fungal secretion and growth along with the synergistic interaction between AMF and PSB. It is not clear whether PSB is able to attach to extraradical AMF hyphal or not. Nitrogen Limitation Adaptation (NLA) genes and their function at molecular level in nitrogen deficiency conditions and the mineralization of organic N and their uptake mechanism need to be elucidated, which underpin their role as the future hope of organic farming.
- Efforts to characterize unculturable bacteria in the mycorrhizosphere and develop synthetic microbial-AMF as an option to enhance the AMF-PSB combinations efficacy.

It is difficult to distinguish the transfer of the N, as it is biotrophic and mediated through root exudates and nutrient cycling. This can be traced by monoxenic cultures or tissue culture-based experiments. By using isotopically labelled compounds, uptake of simple amino acids has been tested. There has been no specific information about the identity of any primary organic N decomposers associated with AMF. Also, an interesting question that needs to be explained in the future is - can AMF utilize N from exogenous chitin, without the contribution of any helper bacteria and if there is any significance of N uptake depending upon rate of N release. In addition to this, future experimentation should focus on complex N/C-rich compounds such as plant biomass or litter for deeper understanding of mechanism(s) underlying the utilisation of organic sources by AMF and the associated plant.

Conclusion

A number of macromolecules that support life on this earth contain Phosphorous (P) and Nitrogen (N) as integral components e.g., in polysaccharides, proteins, nucleic acids and many secondary metabolites. It is very important to think about the roles played by the omnipresent, yet still broadly under-appreciated Arbuscular Mycorrhizal Fungi (AMF) and associated helper bacteria which need to be highlighted such that the tri-partite association between plant and microbes can be utilized for accelerating agricultural sustainability and promoting human welfare. To improve environmentally sustainable agricultural practices, basic findings about the efficiency of organic P and N recycling in soils using microbes can be translated in the form of applied research by improving our understanding the mechanism underlying the interactions of AMF with its microbiome. In order to ensure enough food on this planet for every human being, there is an urgent need to improve the efficient and sustainable production of agriculture, without any decrease in productivity, which is a challenge itself. To ensure sustained food availability on this planet for every human being now and in the future, it is vitally important to take up this challenge and come up with novel options, including broadening the scope of use of AMF and its multifunctional attributes which provide immense benefits to agriculture.

References

1. Bechtaoui N, Rabiu MK, Raklami A, Oufdou K, Hafidi M, et al. (2021) Phosphate-dependent regulation of growth and stresses management in plants. Front Plant Sci 12: 679-916.
2. Carstensen A, Herdean A, Schmidt SB, Sharma A, Spetea C, et al. (2018) The impacts of phosphorus deficiency on the photosynthetic electron transport chain. Plant Physiol 177: 271-284.
3. Malhotra H, Vandan S, Sharma S, Pandey R (2018) Phosphorus nutrition: plant growth in response to deficiency and excess. Plant Nutrients and Abiotic Stress Tolerance: 171-190.
4. Powers S, Mirsky E, Bandaranayake A, Thavarajah P, Shipe E, et al. (2020) Field pea (Pisum sativum L.) shows genetic variation in phosphorus use efficiency in different P environments. Sci Rep 10: 18940.
5. Marschner M, Dell B (1994) Nutrient uptake in mycorrhizal symbiosis. Plant Soil 159: 89-102.
6. Lynch JP (2011) Root phenes for enhanced soil exploration and phosphorus acquisition: tools for future crops. Plant Physiol 156: 1041-1049.
7. Ringeval B, Augusto L, Monod H, Apeldoorn D, Bouwman L, et al. (2017) Phosphorus in agricultural soils: drivers of its distribution at the global scale. Global Change Biol 23: 3418-3432.
8. Roch GV, Maharajan T, Ceasar SA, Ignacimuthu S (2019) The Role of PHT1 Family transporters in the acquisition and redistribution of phosphorus in plants. Crit Rev Plant Sci 38: 171-198.
9. Saia S, Tamayo E, Schillaci C, Vita PD (2020) Arbuscular Mycorrhizal Fungi and Nutrient Cycling in Cropping Systems. Carbon and Nitrogen Cycling in Soil 10: 87-115.
10. Yadav A, Ashok A (2014) Effect of dual inoculation of AM fungi and Pseudomonas with phosphorus fertilizer rates on growth performance, nutrient uptake and yield of soybean. Researcher 6: 5-13.
11. Smith SE, Read DJ (2008) Mycorrhizal Symbiosis. Elsevier Science, UK.
12. Saia S, Aissa E, Luziatelli F, Ruzzi M, Colla G (2020) Growth-promoting bacteria and arbuscular mycorrhizal fungi differentially benefit tomato and corn depending upon the supplied form of phosphorus. Mycorrhiza 30: 133-147.
13. Casieri L, Lahmidi NA, Doidy J, Veneault-Fourrey C, Migeon A (2013) Biotrophic transportome in mutualistic plant-fungal interactions. Mycorrhiza 23: 597-625.
14. Lehmann A, Rillig MC (2015) Arbuscular mycorrhizal contribution to copper, manganese and iron nutrient concentrations in crops- a meta-analysis. Soil Biol Biochem 81: 147-158.
15. Kuila D, Ghosh S (2015) Aspects, problems and utilization of Arbuscular Mycorrhizal (AM) application as bio-fertilizer in sustainable agriculture. Curr Res Microb Sci 3: 100107.

16. Begum N, Qin C, Ahanger MA, Raza S, Khan MI, et al. (2019) Role of arbuscular mycorrhizal fungi in plant growth regulation: implications in abiotic stress tolerance. Front Plant Sci 10: 1068.

17. Thirkell TJ, Charters MD, Elliott AJ, Sait SM, Field KJ (2017) Are mycorrhizal fungi our sustainable saviours? Considerations for achieving food security. J Ecol 105: 921-929.

18. Sbrana C, Avio L, Giovannetti M (2014) Beneficial mycorrhizal symbionts affecting the production of health-promoting phytochemicals. Electrophoresis 35: 1535-1546.

19. Sangwan S, Prasanna R (2022) Mycorrhizae helper bacteria: unlocking their potential as bioenhancers of plant-arbuscular mycorrhizal fungal associations. Microbiol Ecol 84: 1-10.

20. Gupta MM, Chourasiya D, Sharma MP (2019) Diversity of arbuscular mycorrhizal fungi in relation to sustainable plant production systems. Microbial Diversity in Ecosystem Sustainability and Biotechnological Applications: 167-186.

21. Agnolucci M, Palla M, Cristani C, Cavallo N, Giovannetti M, et al. (2019) Beneficial plant microorganisms affect the endophytic bacterial communities of durum wheat roots as detected by different molecular approaches. Front Microbiol 10: 2500.

22. Wahid F, Sharif M, Fahad S, Adnan M, Khan IA, et al. (2019) Arbuscular mycorrhizal fungi improve the growth and phosphorus uptake of mung bean plants fertilized with composted rock phosphate fed dung in alkaline soil environment. J Plant Nut 42: 1760-1769.

23. Hildebrandt U, Ouziad F, Marner FJ, Bothe H (2006) The bacterium *Paenibacillus* validus stimulates growth of the arbuscular mycorrhizal fungus Glomus intraradices up to the formation of fertile spores. FEMS Microbiol Lett 254: 258-267.

24. Bidondo LF, Silvani V, Colombo R, Pérgola M, Bompadre J, et al. (2011) Pre-symbiotic and symbiotic interactions between Glomus intraradices and two *Paenibacillus* species isolated from AM propagules: In vitro and in vivo assays with soybean (AG043RG) as plant host, Soil Biol Biochem 43: 1866-1872.

25. Turrini A, Avio L, Giovannetti M, Agnolucci M (2018) Functional complementarity of Arbuscular Mycorrhizal Fungi and Associated Microbiota: The Challenge of Translational Research. Front Plant Sci 9: 1407.

26. Deveau A, Labbé J (2016) Mycorrhiza helper bacteria. John Wiley & Sons Inc, USA.

27. Barea JM, Toro M, Orozco MO, Campos E, Azcón R (2002) The application of isotopic (32P and 15N) dilution techniques to evaluate the interactive effect of phosphate-solubilizing rhizobacteria, mycorrhizal fungi and Rhizobium to improve the agronomic efficiency of rock phosphate for legume crops. Nutr Cycling Agroecosyst 63: 35-42.

28. Etesami H, Glick BR (2020) Halotolerant plant growth–promoting bacteria: prospects for alleviating salinity stress in plants. Environ Exp Bot 178: 104124.

29. Artursson V, Finlay RD, Jansson JK (2006) Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. Environ Microbiol 8: 1-10.

30. Chanway CP, Holl FB (1991) Biomass increase and associative nitrogen fixation of mycorrhizal Pinus contorta seedlings inoculated with a plant growth promoting Bacillus strain. Can J Bot 69: 507-511.

31. Hoseinzade H, Ardakani MR, Shahdi A, Rahmani HA, Noormohammadi G, et al. (2016) Rice (*Oryza sativa* L.) nutrient management using mycorrhizal fungi and endophytic Herbaspirillum seropedicae. J Integr Agric 15: 1385-1394.

32. Balakrishna N, Lakshmipathy R, Bagyaraj DJ, Ashwin R (2017) Influence of alley copping system on AM fungi, microbial biomass C and yield of finger millet, peanut and pigeon pea. Agroforest Syst 91: 487-493.

33. Bona E, Cantamessa S, Massa N, Manassero P, Marsano F, et al. (2016) Arbuscular mycorrhizal fungi and plant growth-promoting pseudomonads improve yield, quality and nutritional value of tomato: a field study. Mycorrhiza 27: 1-11.

34. Berdeni D, Cotton TEA, Daniell TJ, Bidartondo MI, Cameron DD, et al. (2018) The effects of arbuscular mycorrhizal fungal colonisation on nutrient status, growth, productivity, and canker resistance of apple (*Malus pumila*). Front Microbiol 9: 1461.

35. Wang Y, Wang M, Li Y, Wu A, Huang J (2018) Effects of arbuscular mycorrhizal fungi on growth and nitrogen uptake of Chrysanthemum morifolium under salt stress. PLoS One 13: 0196408.

36. Farjad M, Rigault M, Pateyron S, Martin-Magniette ML, Krapp A, et al. (2018) Nitrogen limitation alters the response of specific genes to biotic stress. Int J Mol Sci 19: 3364.

37. Kong L, Zhang Y, Du W, Xia H, Fan S, et al. (2021) Signalling responses to N starvation: focusing on wheat and filling the putative gaps with findings obtained in other plants. Front Plant Sci 12: 656696.

38. Kobae Y, Kawachi M, Saito K, Kikuchi Y, Ezawa T, et al. (2015) Up-regulation of genes involved in N-acetylglucosamine uptake and metabolism suggests a recycling mode of chitin in intraradical mycelium of arbuscular mycorrhizal fungi. Mycorrhiza 25: 411-417.

39. Park BS, Yao T, Seo JS, Wong ECC, Mitsuda N, et al. (2018) Arabidopsis nitrogen limitation adaptation regulates ORE1 homeostasis during senescence induced by nitrogen deficiency. Nat Plants 4: 898-903.

40. Kobae Y (2018) Dynamic phosphate uptake in arbuscular mycorrhizal roots under field conditions. Front Environ Sci 6: 159.

41. Liu Z, Li M, Liu J, Wang J, Lin X, et al. (2022) Higher diversity and contribution of soil arbuscular mycorrhizal fungi at an optimal P-input level. Agric Ecosyst Environ 337: 108053.

42. Marschner H, Rimmington G (1998) Mineral nutrition of higher plants. Plant Cell Environ 11: 147-148.

43. Sharif M, Claassen N (2011) Action mechanisms of arbuscular mycorrhizal fungi in phosphorus uptake by *Capsicum annuum* L. Pedosphere 21: 502-511.

44. Nouri E, Surve R, Bapaume L, Stumpe M, Chen M, et al. (2021) Phosphate suppression of arbuscular mycorrhizal symbiosis involves gibberellic acid signalling. Plant Cell Physiol 62: 959-970.

45. Klugh KR, Cumming JR (2007) Variations in organic acid exudation and aluminum resistance among arbuscular mycorrhizal species colonizing Liriodendron tulipifera, Tree Physiol 27: 1103-1112.

46. Emran M, Rashad M, Gispert M, Pardini G (2017) Increasing soil nutrients availability and sustainability by glomalin in alkaline soils. Agric Biosyst Eng 2: 74-84.

47. Johri AK, Oelmüller R, Dua M, Yadav V, Kumar M, et al. (2015) Fungal association and utilization of phosphate by plants: success, limitations, and future prospects. Front Microbiol 6: 984.

48. Benedetto A, Magurno F, Bonfante P, Lanfranco L (2005) Expression profiles of a phosphate transporter gene (GmosPT) from the endomycorrhizal fungus Glomus mosseae. Mycorrhiza 15: 620-627.

49. Ravi RK, Balachandar M, Yuvarani S, Anaswara S, Pavithra L, et al. (2021) Arbuscular mycorrhiza in sustainable plant nitrogen nutrition: mechanisms and impact. Soil Nitr Ecol 10: 407-436.

50. Govindarajulu M, Pfefer PE, Jin HR, Abubaker J, Douds DD, et al. (2005) Nitrogen transfer in the arbuscuslar mycorrhizal symbiosis. Nature 435: 819-823.

51. Johnson NC (2010) Resource stoichiometry elucidates the structure and function of arbuscular mycorrhizas across scales. New Phytol 185: 631-647.

52. Hachiya T, Sakakibara H (2017) Interactions between nitrate and ammonium in their uptake, allocation, assimilation, and signalling in plants. J Exp Bot 68: 2501-2512.

53. Leigh J, Fitter AH, Hodge A (2011) Growth and symbiotic effectiveness of an arbuscular mycorrhizal fungus in organic matter in competition with soil bacteria. FEMS Microbiol Ecol 76: 428-438.

54. Belmondo S, Fiorilli V, Pérez-Tienda J, Ferrol N, Marmeisse R, et al. (2014) A dipeptide transporter from the arbuscular mycorrhizal fungus Rhizophagus irregularis is upregulated in the intraradical phase. Front Plant Sci 5: 436.

55. Hodge A, Storer K (2015) Arbuscular mycorrhiza and nitrogen: implications for individual plants through to ecosystems. Plant Soil 386: 1-19.

56. Jones SL, French K (2021) Soil nutrients differentially influence root colonisation patterns of AMF and DSE in Australian plant species. Symbiosis 83: 209-223.

57. Gutjahr C (2014) Phytohormone signaling in arbuscular mycorhiza development. Curr Opin Plant Biol 20: 26-34.

58. Rozmos M, Bukovska P, Hrselova H, Kotianova M, Dudas M, et al. (2021) Organic nitrogen utilisation by an arbuscular mycorrhizal fungus is mediated by specific soil bacteria and a protist. The ISME Journal 16: 676-685.

59. Battini F, Grønlund M, Agnolucci M, Giovannetti M, Jakobsen I (2017) Facilitation of phosphorus uptake in maize plants by mycorrhizosphere bacteria. Sci Rep 7: 4686.

60. Hawkins HJ, Johansen A, George E (2000) Uptake and transport of organic and inorganic nitrogen by arbuscular mycorrhizal fungi. Plant Soil 226: 275-85.

61. Jansa J, Forczek ST, Rozmoš M, Püschel D, Bukovská P, et al. (2019) Arbuscular mycorrhiza and soil organic nitrogen: network of players and interactions. Chem Biol Technol Agric 6: 10.

62. Miransari M (2010) Contribution of arbuscular mycorrhizal symbiosis to plant growth under different types of soil stress. Plant Biol 12: 563-569.

63. Püschel D, Janoušková M, Voříšková A, Gryndlerová H, Vosátka M, et al. (2017) Arbuscular mycorrhiza stimulates biological nitrogen fixation in two medicago spp. through improved phosphorus acquisition. Front Plant Sci 8: 390.

64. Ngosong C, Tatah BN, Olougou MNE, Suh C, Nkongho RN, et al. (2022) Inoculating plant growth-promoting bacteria and arbuscular mycorrhiza fungi modulates rhizosphere acid phosphatase and nodulation activities and enhance the productivity of soybean (Glycine max). Front Plant Sci 13: 934339.

65. Fernandez CW, Koide RT (2012) The role of chitin in the decomposition of ectomycorrhizal fungal litter. Ecol 93: 24-28.

66. Bukovská P, Bonkowski M, Konvalinková T, Beskid O, Hujslová M, et al. (2018) Utilization of organic nitrogen by arbuscular mycorrhizal fungi-is there a specific role for protists and ammonia oxidizers? Mycorrhiza 28: 269-83.

67. Tisserant E, Malbreil M, Kuo A, Kohler A, Symeonidi A, et al. (2013) Genome of an arbuscular mycorrhizal fungus provides insight into the oldest plant symbiosis. Proc Natl Acad Sci 110: 20117-20122.

68. Ingraffia R, Amato G, Frenda AS, Giambalvo D (2019) Impacts of arbuscular mycorrhizal fungi on nutrient uptake, N2 fixation, N transfer, and growth in a wheat/faba bean intercropping system. PLoS One 14: 0213672.

69. Nadal M, Sawers R, Naseem S, Bassin B, Kulicke C, et al. (2017) An N-acetylglucosamine transporter required for arbuscular mycorrhizal symbioses in rice and maize. Nat Plants 3: 17073.

70. Balestrini R, Brunetti C, Chitarra W, Nerva L (2020) Photosynthetic Traits and Nitrogen Uptake in Crops: Which Is the Role of Arbuscular Mycorrhizal Fungi? Plants 9: 1105.

71. Frey-Klett P, Garbaye J (2005) Mycorrhiza helper bacteria: a promising model for the genomic analysis of fungal–bacterial interactions. New Phytol 168: 4-8.

72. Zhang L, Fan J, Ding X, He X, Zhang F, et al. (2014) Hyphosphere interactions between an arbuscular mycorrhizal fungus and a phosphate solubilizing bacterium promote phytate mineralization in soil. Soil Biol Biochem 74: 177-183.

73. Patel DK, Archana G, Kumar GN (2007) Variation in the nature of organic acid secretion and mineral phosphate solubilization by Citrobacter sp. DHRSS in the presence of different sugars. Curr Microbiol 56: 168-174.

74. Wahid F, Sharif M, Steinkellner S, Khan MA, Marwat KB, et al. (2016) Inoculation of arbuscular mycorrhizal fungi and phosphate solubilizing bacteria in the presence of rock phosphate improves phosphorus uptake and growth of maize. Pak J Bot 48: 739-747.

75. Jones DE, Oburger E (2011) Solubilisation of Phosphorus by Soil Microorganisms. Phosphorus in Action: 169-198.

76. Whitelaw MA (1999) Growth promotion of plants inoculated with phosphate solubilizing fungi. Adv Agronomy 69: 99-151.

77. Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA (2013) Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus 2: 587.

78. Stamford NP, dos Santos PR, de Moura AMMF, Santos CERS, de Freitas ADS (2003) Biofertilzers with natural phosphate, sulphur and Acidithiobacillus in a soil with low available-P. Sci Agric 60: 767-773.

79. Ahmed E, Holmström SJM (2014) Siderophores in environmental research: roles and applications. Microb Biotechnol 7: 196-208.

80. Karimzadeh J, Alikhani HA, Etesami H, Pourbabaei AA (2020) Improved phosphorus uptake by wheat plant (*Triticum aestivum* L.) with rhizosphere fluorescent pseudomonads strains under water-deficit stress. J Plant Growth Regul 40: 162-178.

81. Richardson AE, Barea LM, Mcneill AM, Prigent-Combaret C (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant Soil 321: 305-339.

82. Emami S, Alikhani HA, Pourbabaei AA, Etesami AA, Sarmadian F, et al. (2019) Effect of rhizospheric and endophytic bacteria with multiple plant growth promoting traits on wheat growth. Environ Sci Pollut Res Int 26: 19804-19813.

83. Hayat R, Ali S, Amara U, Khalid R, Ahmed I (2010) Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol 60: 579-598.

84. Dakora FD, Phillips DA (2002) Root exudates as mediators of mineral acquisition in low-nutrient environments. Plant Soil 245: 35-47.

85. Jones D, Dennis P, Owen A, van Hees PAW (2003) Organic acid behaviour in soils–misconceptions and knowledge gaps. Plant Soil 248: 31-41.

86. Etesami H, Maheshwari DK (2018) Use of plant growth promoting rhizobacteria (PGPRs) with multiple plant growth promoting traits in stress agriculture: action mechanisms and future prospects. Ecotoxicol Environ Saf 156: 225-246.

87. Ramasamy K, Joe MM, Kim KY, Lee SM, Shagol CC, et al. (2011) Synergistic effects of arbuscular mycorrhizal fungi and plant growth promoting rhizobacteria for sustainable agricultural production. Korean J Soil 44: 637-649.

88. Tarafdar JC, Yadav RS, Meena SC (2001) Comparative efficiency of acid phosphatase originated from plant and fungal sources. J Plant Nutr Soil Sci 164: 279-282.

89. Wang Y, Lambers H (2020) Root-released organic anions in response to low phosphorus availability: recent progress, challenges and future perspectives. Plant Soil 447: 135-156.

90. Guidry MW, Mackenzie MT (2003) Experimental study of igneous and sedimentary apatite dissolution: control of pH, distance from equilibrium, and temperature on dissolution rates. Geochim Cosmochim Acta 67: 2949-2963.

91. Antoun H, Prévost D (2005) Ecology of plant growth promoting rhizobacteria. Biocontrol and Biofertilization: 1-38.

92. Baskaran P, Hyvonen R, Berglund SL, Clemmensen KE, Agren GI, et al. (2017) Modelling the influence of ectomycorrhizal decomposition on plant nutrition and soil carbon sequestration in boreal forest ecosystems. New Phytol 213: 1452-65.

93. Oliveira ALM, Stoffels M, Schmid M, Reis VM, Baldani JI, et al. (2009) Colonization of sugarcane plantlets by mixed inoculations with diazotrophic bacteria. Eur J Soil Biol 45: 106-113.

94. Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255: 571-586.

95. Pal SS (1998) Interactions of an acid tolerant strain of phosphate solubilizing bacteria with a few acids tolerant crops. Plant Soil 198: 169-177.

96. Srinath J, Bagyaraj DJ, Satyanarayana BN (2003) Enhanced growth and nutrition of micropropagated Ficus benjamina to Glomus mosseae co-inoculated with Trichoderma harzianum and Bacillus coagulans. World J Microbiol Biotechnol 19: 69-72.

97. Kumar V, Narula N (1999) Solubilization of inorganic phosphates and growth emergence of wheat as affected by Azotobacter chroococcum mutants. Biol Fert Soils 28: 301-305.

98. Singh S, Kapoor KK (1999) Inoculation with phosphate-solubilizing microorganisms and a vesicular-arbuscular mycorrhizal fungus improves dry matter yield and nutrient uptake by wheat grown in a sandy soil. Biol Fertil Soils 29: 139-144.

99. Kim KY, Jordan D, McDonald GA (1997) Effect of phosphate-solubilizing bacteria and vesicular-arbuscular mycorrhizae on tomato growth and soil microbial activity. Biol Fertil Soils 26: 79-87.

100. Egamberdiyeva D (2007) The effect of plant growth promoting bacteria on growth and nutrient uptake of maize in two different soils. Appl Soil Ecol 36: 184-189.

101. Parihar M, Meena VS, Mishra PK, Rakshit A, Choudhary M, et al. (2019) Arbuscular mycorrhiza: a viable strategy for soil nutrient loss reduction. Arch Microbiol 201: 723-735.

102. Vuolo F, Novello G, Bona E, Gorrasi S, Gamalero E (2022) Impact of Plant-Beneficial Bacterial Inocula on the Resident Bacteriome: Current Knowledge and Future Perspectives. Microorganisms 10: 2462.

103. Wang F, Feng G (2020) Arbuscular mycorrhizal fungi interactions in the rhizosphere. Rhizosphere Biology: Interactions Between Microbes and Plants: 217-235.

104. Toro M, Azcón R, Barea JM (1997) Improvement of arbuscular mycorrhiza development by inoculation of soil with phosphate solubilizing rhizobacteria to improve rock phosphate bioavailability (P32) and nutrient cycling. Appl Environ Microbiol 63: 4408-4412.

105. Pons S, Fournier S, Chervin C, Bécard G, Rochange S, et al. (2020) Phytohormone production by the arbuscular mycorrhizal fungus *Rhizophagus irregularis*. PLoS One 15: 0240886.

106. Nuccio EE, Hodge A, Pett-Ridge J, Herman DJ, Weber PK, et al. (2013) An arbuscular mycorrhizal fungus significantly modifies the soil bacterial community and nitrogen cycling during litter decomposition. Environ Microbiol 15: 1870-1881.

107. Herman DJ, Firestone MK, Nuccio E, Hodge A (2012) Interactions between an arbuscular mycorrhizal fungus and a soil microbial community mediating litter decomposition. FEMS Microb Ecol 80: 236-247.

108. Schrey SD, Hartmann A, Hampp R (2014) Rhizosphere interactions. Ecological Biochemistry: Environmental and Interspecies Interactions: 292-311.

109. Agnolucci M, Battini F, Cristani C, Giovannetti M (2015) Diverse bacterial communities are recruited on spores of different arbuscular mycorrhizal fungal isolates. Biol Fertil Soils 51: 379-389.

110. Ordoñez YM, Fernandez BR, Lara LS, Rodriguez A, Uribe-Vélez D, et al. (2016) Bacteria with phosphate solubilizing capacity alters mycorrhizal fungal growth both inside and outside the root and in the presence of native microbial communities. PLoS One 11: 0154438.

111. Bao X, Zou J, Zhang B, Wu L, Yang T, et al. (2022) Arbuscular mycorrhizal fungi and microbes interaction in rice mycorrhizosphere. Agronomy 12: 1277.

112. Ren W, Guo Y, Han X, Sun Y, Li Q, et al. (2022) Indigenous microorganisms offset arbuscular mycorrhizal fungi-induced plant growth and nutrient acquisition through negatively modulating the genes of phosphorus transport and nitrogen assimilation. Front Plant Sci 13: 880181.

113. Scheublin TR, Sanders IR, Keel C, van der Meer JR (2010) Characterisation of microbial communities colonising the hyphal surfaces of arbuscular mycorrhizal fungi. ISME J 4: 752-763.

114. Wu S, Shi Z, Chen X, Gao J, Wang X (2022) Arbuscular mycorrhizal fungi increase crop yields by improving biomass under rainfed condition: a meta-analysis. Peer J 10: 12861.

115. Zhu Y, Lv GC, Chen YL, Gong XF, Peng YN, et al. (2017) Inoculation of arbuscular mycorrhizal fungi with plastic mulching in rainfed wheat: A promising farming strategy. Field Crops Res 204: 229-241.

116. Espidkar Z, Yarnia M, Ansari MH, Mirshekari B, Asadi Rahmani H (2017) Differences in nitrogen and phosphorus uptake and yield components between barley cultivars grown under arbuscular mycorrhizal fungus and Pseudomonas strains Co-Inoculation in rainfed condition. Appl Ecol Environ Res 15: 195-216.

117. Suri VK, Choudhary AK (2013) Effects of vesicular arbuscular mycorrhizae and applied phosphorus through targeted yield precision model on root morphology, productivity, and nutrient dynamics in soybean in an acid alfisol. Commun Soil Sci Plant Anal 44: 2587-2604.

118. Erman M, Demir S, Ocak E, Tüfenkçi S, Oĝuz F, et al. (2011) Effects of Rhizobium, arbuscular mycorrhiza and whey applications on some properties in chickpea (*Cicer arietinum* L.) under irrigated and rainfed conditions 1-Yield, yield components, nodulation and AMF colonization. Field Crops Res 122: 14-24.

119. Sharma V, Sharma S, Sharma S, Kumar V (2019) Synergistic effect of bio-inoculants on yield, nodulation and nutrient uptake of chickpea (*Cicer arietinum* L) under rainfed conditions. J Plant Nutri 42: 374-383.

120. Rezaie MA, Pasari B, Mohammadi K, Rokhzadi A, Karami E (2020) Study the effect of mycorrizal fungi, chitosan and cycocel on agronomic characteristics of rainfed chickpea. Legume Res 43: 546-551.

121. Agnolucci M, Avio L, Palla M, Sbrana C, Turrini A, et al. (2020) Health-promoting properties of plant products: the role of mycorrhizal fungi and associated bacteria. Agronomy 10: 1864.

122. Eke P, Adamou S, Fokom R, Nya VD, Fokou PVT, et al. (2020) Arbuscular mycorrhizal fungi alter antifungal potential of lemongrass essential oil against Fusarium solani, causing root rot in common bean (*Phaseolus vulgaris* L.). Heliyon 6: 05737.

123. Veresoglou SD, Sen R, Mamolos AP, Veresoglou DS (2011) Plant species identity and arbuscular mycorrhizal status modulate potential nitrification rates in nitrogen-limited grassland soils. J Ecol 99: 1339-1349.

124. Seguel A, Meier F, Azcón R, Valentine A, Meriño-Gergichevich C, et al. (2020) Showing their mettle: extraradical mycelia of arbuscular mycorrhizae form a metal filter to improve host Al tolerance and P nutrition. J Sci Food Agric 100: 803-810.

HERALD

Advances In Industrial Biotechnology | ISSN: 2639-5665
Advances In Microbiology Research | ISSN: 2689-694X
Archives Of Surgery And Surgical Education | ISSN: 2689-3126
Archives Of Urology
Archives Of Zoological Studies | ISSN: 2640-7779
Current Trends Medical And Biological Engineering
International Journal Of Case Reports And Therapeutic Studies | ISSN: 2689-310X
Journal Of Addiction & Addictive Disorders | ISSN: 2578-7276
Journal Of Agronomy & Agricultural Science | ISSN: 2689-8292
Journal Of AIDS Clinical Research & STDs | ISSN: 2572-7370
Journal Of Alcoholism Drug Abuse & Substance Dependence | ISSN: 2572-9594
Journal Of Allergy Disorders & Therapy | ISSN: 2470-749X
Journal Of Alternative Complementary & Integrative Medicine | ISSN: 2470-7562
Journal Of Alzheimers & Neurodegenerative Diseases | ISSN: 2572-9608
Journal Of Anesthesia & Clinical Care | ISSN: 2378-8879
Journal Of Angiology & Vascular Surgery | ISSN: 2572-7397
Journal Of Animal Research & Veterinary Science | ISSN: 2639-3751
Journal Of Aquaculture & Fisheries | ISSN: 2576-5523
Journal Of Atmospheric & Earth Sciences | ISSN: 2689-8780
Journal Of Biotech Research & Biochemistry
Journal Of Brain & Neuroscience Research
Journal Of Cancer Biology & Treatment | ISSN: 2470-7546
Journal Of Cardiology Study & Research | ISSN: 2640-768X
Journal Of Cell Biology & Cell Metabolism | ISSN: 2381-1943
Journal Of Clinical Dermatology & Therapy | ISSN: 2378-8771
Journal Of Clinical Immunology & Immunotherapy | ISSN: 2378-8844
Journal Of Clinical Studies & Medical Case Reports | ISSN: 2378-8801
Journal Of Community Medicine & Public Health Care | ISSN: 2381-1978
Journal Of Cytology & Tissue Biology | ISSN: 2378-9107
Journal Of Dairy Research & Technology | ISSN: 2688-9315
Journal Of Dentistry Oral Health & Cosmesis | ISSN: 2473-6783
Journal Of Diabetes & Metabolic Disorders | ISSN: 2381-201X
Journal Of Emergency Medicine Trauma & Surgical Care | ISSN: 2378-8798
Journal Of Environmental Science Current Research | ISSN: 2643-5020
Journal Of Food Science & Nutrition | ISSN: 2470-1076
Journal Of Forensic Legal & Investigative Sciences | ISSN: 2473-733X
Journal Of Gastroenterology & Hepatology Research | ISSN: 2574-2566
Journal Of Genetics & Genomic Sciences | ISSN: 2574-2485
Journal Of Gerontology & Geriatric Medicine | ISSN: 2381-8662
Journal Of Hematology Blood Transfusion & Disorders | ISSN: 2572-2999
Journal Of Hospice & Palliative Medical Care
Journal Of Human Endocrinology | ISSN: 2572-9640
Journal Of Infectious & Non Infectious Diseases | ISSN: 2381-8654
Journal Of Internal Medicine & Primary Healthcare | ISSN: 2574-2493
Journal Of Light & Laser Current Trends
Journal Of Medicine Study & Research | ISSN: 2639-5657
Journal Of Modern Chemical Sciences
Journal Of Nanotechnology Nanomedicine & Nanobiotechnology | ISSN: 2381-2044
Journal Of Neonatology & Clinical Pediatrics | ISSN: 2378-878X
Journal Of Nephrology & Renal Therapy | ISSN: 2473-7313
Journal Of Non Invasive Vascular Investigation | ISSN: 2572-7400
Journal Of Nuclear Medicine Radiology & Radiation Therapy | ISSN: 2572-7419
Journal Of Obesity & Weight Loss | ISSN: 2473-7372
Journal Of Ophthalmology & Clinical Research | ISSN: 2378-8887
Journal Of Orthopedic Research & Physiotherapy | ISSN: 2381-2052
Journal Of Otolaryngology Head & Neck Surgery | ISSN: 2573-010X
Journal Of Pathology Clinical & Medical Research
Journal Of Pharmacology Pharmaceutics & Pharmacovigilance | ISSN: 2639-5649
Journal Of Physical Medicine Rehabilitation & Disabilities | ISSN: 2381-8670
Journal Of Plant Science Current Research | ISSN: 2639-3743
Journal Of Practical & Professional Nursing | ISSN: 2639-5681
Journal Of Protein Research & Bioinformatics
Journal Of Psychiatry Depression & Anxiety | ISSN: 2573-0150
Journal Of Pulmonary Medicine & Respiratory Research | ISSN: 2573-0177
Journal Of Reproductive Medicine Gynaecology & Obstetrics | ISSN: 2574-2574
Journal Of Stem Cells Research Development & Therapy | ISSN: 2381-2060
Journal Of Surgery Current Trends & Innovations | ISSN: 2578-7284
Journal Of Toxicology Current Research | ISSN: 2639-3735
Journal Of Translational Science And Research
Journal Of Vaccines Research & Vaccination | ISSN: 2573-0193
Journal Of Virology & Antivirals
Sports Medicine And Injury Care Journal | ISSN: 2689-8829
Trends In Anatomy & Physiology | ISSN: 2640-7752

Submit Your Manuscript: https://www.heraldopenaccess.us/submit-manuscript

Herald Scholarly Open Access, 2561 Cornelia Rd, #205, Herndon, VA 20171, USA.
Tel: +1 202-499-9679; E-mail: info@heraldsopenaccess.us
http://www.heraldopenaccess.us/