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Plant-Microbe Interactions in Soil Health and Plant Growth

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Abstract
Plant and microbe interactions play a major role in maintaining the health of the soil, the productive State of crops and environmental harmony. This paper summarizes insights on the contributions of two important types of microorganisms, arbuscular mycorrhizal fungi (AMF) and nitrogen-fixing bacteria (NFB) to increasing plant nutrient uptake, water use and the plant resistance to abiotic and biotic stresses. AMF also increase the surface area of roots due to their large networks of hyphae which facilitate effective phosphorus (P), zinc (Zn) and other micronutrient acquisition, as well as increasing aggregation of soils by producing glomalin. NFB fix atmospheric nitrogen N_2 into ammonium (NH_4^+) thus decreasing the use of synthetic fertilizers which are highly dependent on the roots by producing phytohormones. There is a synergistic effect between AMF and NFB that leads to better soil structure, increased nutrient-use efficiency, and resistance to stress. Incorporation of such microbes in the bio-fertilizer and microbial integrated pest management (IPM) type systems decreases the utilization of the chemical input, alleviates the greenhouse gases and sustains the biodiversity. The review points to field evidence to indicate that co-inoculation methods can be used to sustain or even improve yields that have a lower environmental impact. Although their advantage is evident, the effects of AMF and NFB performance are dependent on the soil type, climatic conditions, plant species, and strain specificity of microbes, which is the reason to develop specific studies. Utilizing such interactions provides a sustainable nature-based approach to attain sustainable intensification of agriculture at scale.

Introduction
The population of bacteria, fungi, archaea and other microbes that inhabit the soil is a heterogeneous mix, typically referred to as soil microbiomes, and is an essential part of functioning ecosystems. These communities of microorganisms form a part of the soil health and govern nutrient cycling, decomposition of organic matters, and soil structures (De Mandal et al., 2021). With the help of these processes, plant productivity and resilience can be greatly affected directly by soil microbiomes hence becoming the foundation of sustainable agriculture. The mycorrhizal fungi and nitrogen-fixing bacteria have been reported as some of the positive members of soil microbiome with well-established symbiotic relationship with plants. The mycorrhizal fungi increase root surface and allow the uptake of phosphorus, nitrogen, and micronutrients in the body in addition to ameliorating the water relations of the plant (Dhiman et al., 2024). Genera such as Rhizobium and Azotobacter are nitrogen-fixing bacteria which convert nitrogen in the atmosphere into available forms thus making nitrogen fertilizer less necessary (U. Kumar et al., 2023). In addition to strengthening nutrition in the plants, these symbioses also heighten resistance to abiotic stresses which include drought, salinity, and heavy metal toxicity (D. Sharma et al., 2020). Soil microbiomes have been found not only to provide ecological benefit through the health of a plant, but they can also offer an ecological advantage by benefiting the plant population. Microbial symbionts can aid nutrient-use efficiency, which can help to minimize overdose application of chemical fertilizers,

decreasing the chances of nutrient loss due to runoff and causing eutrophication; (Nazli et al., 2020). Equally, the co-occurrence of positive microbes has been known to inhibit soil-borne pathogens by way of competitive exclusion, generation of antibiotics, or activation of the systemic resistance in plants (Ahmad & Zaib, 2020). These are natural plant defence mechanisms that help in the reduction of pesticide use which further made the environment sustainable. With progress in molecular biology, metagenomics, and high-throughput sequencing, recent years have provided a sea-change in our perspectives on soil microbial diversity and its functionality (A. Kumar & Verma, 2019). Researchers have found that microbiomes in soil are sensitive to land-use, climate change, and cropping management regimes. An example is intensive tillage, monoculture cropping, and overuse of agrochemicals that have been revealed to have a disturbing effect on microbial diversity and damage ecosystem services (Vishwakarma et al., 2020). On the other hand, conservation agriculture interventions which include less tillage, crop rotation, and organic manure will promote varied and functional microbial communities that would boost the vitality of the soil as well as crop yield(Tharanath et al., 2024). Soil microbiome has received a lot of attention with regard to sustainable production, and food security. With ever-increasing world populations and arable land forced to drive to higher plant yields with fewer ecosystem consequences, plant-microbe interaction optimisation is a promising means to achieve both targets. The use of biotic forces that perform positive microbial activities (i.e., the use of bio fertilizers, inoculation with beneficial strains, and engineering the microbiome) could help the agricultural sector minimise usage of non-renewable inputs and counter-balance the environmental impact of farming (Schirawski & Perlin, 2018).

Microbiomes and Plant Health in Soil

Mycorrhizal Fungi

To conduct the exchange, AMF invade the innermost cortex of the roots and form arbuscules, specialised structures of exchange. In this instance, phosphorus (P) and other minerals are exchanged against carbohydrates of the plant so the plants provide us with carbohydrates (Fig. 1). According to the meta-analysis data, AMF will enhance under drought stress the shoot P content by 34%, the root biomass by 25 %, and the antioxidant enzymes (SOD and CAT) activities by 40% (Rosier et al., 2018). In addition, AMF hyphae also releases the glycoprotein glomalin, which increases soil particle binding and enhances aggregation and 15 % increase in water-holding capacity (Morris et al., 2019).

Bacteria Fixers of Nitrogen

Root colonization starts with secretion of Nod factors by nitrogen-fixing bacteria like Rhizobium spp. that induce curling of root hairs resulting in nodule formation. Within these nodules, nitrogenase enzyme complex (nifH gene) fix the atmospheric (N_2) into plant-available ammonium (NH_4^+). According to the results of field studies, N inputs vary from 70 to 200 kg ha 1 yr 1, which in turn increases grain yields by 1.3 t ha 1 (Soumare et al., 2020). Several diazotrophs are also producers of indole-3-acetic acid (IAA), a growth regulator that promotes lateral root growth (Fig. 1), increasing nutrient foraging capacity again.

Mechanisms of Interaction

Table 1. Comparative mechanisms of AMF and NFB in promoting plant performance

Process	AMF	NFB	Reference
Nutrient acquisition	Hyphal P & Zn uptake	Biological N_2 fixation	Smith & Read (2022)
Stress tolerance	Osmolyte accumulation, enhanced CAT	ACC-deaminase lowers ethylene	Bender et al. (2023)

Soil health	Glomalin-mediated aggregation	Exopolysaccharides improve tilth	Rillig & Mummey (2020)

The individual benefits of AMF and NFB are different and supplementary: AMF lengthen root absorption regions of untranslocated nutrients that include phosphorus and zinc whereas NFB provide limited nitrogen. They both increase tolerance to stressors--AMF through the accumulation of osmolytes and NFB through ethylene. Glomalin and NFB, produced by AMF and NFB, respectively, are part of the soil structure which enhances aeration and retention of water.

Farming that cares Three Eco-friendly Farming

Empirical evidence reveals that there is the potential of yield stability to achieve stability without increasing dependency with inoculants of AMF and NFB together. As an example, co-inoculation of soybean with Rhizobium and AMF achieved 45 % reduction of urea consumption with no yield penalty (Xu et al., 2025). Bio fertilizers in commerce have Glomus intraradices and Brady rhizobium japonicum and are able to reduce greenhouse-gas emissions in 0.8 t CO2-e ha-1 yearly (Chandrasekaran, 2024). Such techniques are in line with the principles of regenerative agriculture, which are reducing the cost of production and the environmental burden.

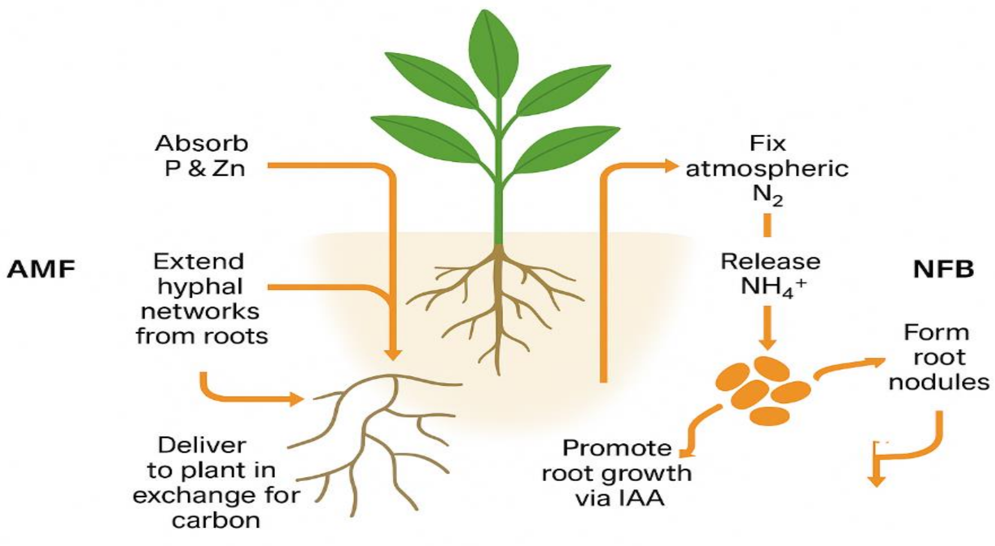


Fig. 1. Simplified interaction pathways of AMF and NFB

The specific pairing of arbuscular mycorrhizal fungi (AMF) and nitrogen-fixing bacteria (NFB) is presented in figure 1, to show their part in the growth of plants and nutrient cycling. AMF networks their hyphal bodies on the left into the surrounding soil, augmenting the root surface area and allowing the critical mineral absorption of phosphorus (P), and zinc (Zn). These nutrients are transported to the plant in the form of a trade offering carbon compounds made during the process of photosynthesis. NFB grow root nodules on the right where they aerobically fix atmospheric nitrogen (N_2) into ammonium (NH_4^+) by the nitrogenise enzyme complex. This fixed nitrogen is made readily accessible to the plant and in combination with the bacteria produced indole-3-acetic acid (IAA) stimulates root growth as well as branching. In combination, these processes also enhance plant nutrition, root architecture and resilience, and alleviate the need for synthetic fertilizers. Fulfilling the synergistic potential of AMF and NFB is one possible route to sustainable intensification. Such symbioses can both optimize the efficiency of nutrient use, resilience of plants and soil health and reduce the emissions of greenhouse- gases all at once. Integration of precise microbial inoculation mixes can therefore serve to bring about sustained agricultural payoffs and environmental sustainability.

Mechanisms of Interaction

Sustainable agriculture is based on the interplay between plants and the beneficial soil microbes including mycorrhizal fungi (AMF) and nitrogen- fixing bacteria (NFB). The organisms establish mutualistic interactions with roots and boost the absorption of nutrients, the tolerance of stresses, and soil health (Smith & Read, 2010).

Nutrient Acquisition

The mycorrhizal fungi increase the nutrient uptake by growing their hyphae that pervade deeply in soil matrix. This effectively expands the area of absorption of the root to what would not have been done by the roots alone. The mobilization of phosphorus (P) is of especial concern to AMF because P, the other micronutrients, including zinc (Zn), and copper (Cu), contain low mobility in soils (Hartman et al., 2023). Fungal hyphae absorb such nutrients and deliver them to the host plant in exchange of carbon compounds which are formed through photosynthesis. Biological nitrogen fixation (BNF) occurs in nitrogen-fixing bacteria, the most important of which are Rhizobium, Bradyrhizobium and Azotobacter spp. This is a form of converting atmospheric nitrogen (N_2) to ammonia (NH3) through the nitrogenase enzyme complex. This ammonia is again protonated to become ammonium (NH_4^+) which could be straight transitioned by the plants into amino acids and proteins (Hoosein et al., 2023). With a combination of the AMF and the NFB, plants obtain a balance between the supply of macro and micronutrients without relying too much on synthetic fertilizers.

Stress Tolerance

Useful microbes play an exceptional role in the resistance of plants to stress. Another role of AMF in enhancing water status of plants through osmotic adjustment is by accumulating stress incompatible solutes (osmolytes) like proline and glycine betaine that could help in maintaining plant cell turgor under drought or saline circumstances (Wang et al., 2022). AMF also trigger antioxidant defence processes, increasing the actions of catalysts such as superoxide dismutase (SOD) and catalase (CAT), which attenuate the effects of oxidative damage in the abiotic stresses. NFB has the ability to build up tolerability to stress by balancing hormones. Numerous diazotrophs secrete 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which reduces the amount of ethylene, a plant hormone that, at its excessive levels, can block the growth of roots during stressful periods (Zhou et al., 2022). Moreover, NFB tend to synthesize plant growth hormones like indole-3-acetic acid (IAA) that enhance lateral root formation and enhances the nutrient and water uptake under unfavourable conditions.

Dead nodules, root exudates and microbial biomass are compliments of soil organic carbon pools.

AMF and NFB both add to long-term soil fertility and soil structure. Thereby, AMF can release glomalin glycoprotein that strengthens soil particles into stable aggregates, decreasing erosion and enhancing structure aeration (Ghorui et al., 2025). This raises the water holding capacity of the soil and the soil compaction resistance. NFB enhances the quality of the soil by increasing organic materials. The pools of soil organic carbon include compliments of dead nodules, and root exudates, and the microbial biomass. A large number of NFB also synthesize exopolysaccharides (EPS) that aid in several processes such as binding soils particles, enhancing their porosity and promoting the growth of other beneficial microorganisms, enriching microbial diversity (Dietrich et al., 2020). The overall impact is a healthier ecosystem in the soil resulting in increased biologically activity of the soil and less reliance on chemical fertilizers.

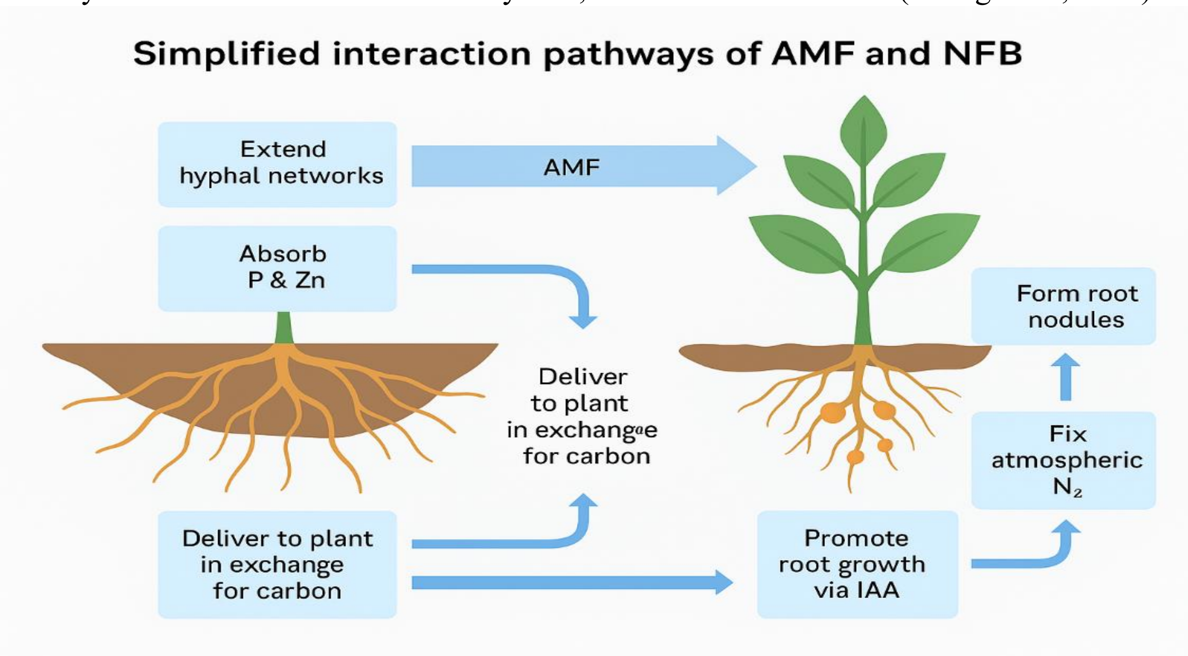
Table 2. Comparative roles of AMF and NFB in plant–soil systems

Function	AMF Contribution	NFB Contribution
Nutrient acquisition	P, Zn, Cu uptake via hyphae	N_2 fixation to NH_4^+
Stress tolerance	Osmolyte accumulation, antioxidant activation	ACC deaminase lowers ethylene, IAA promotes root growth
Soil health	Glomalin-mediated soil aggregation	EPS improves tilth and organic matter

The table 2 shows the comparative, non-redundant functions arbuscular mycorrhizal fungi (AMF) and nitrogen-fixing bacteria (NFB) in plant soil systems. The proportionately less mobile P, Zn and Cu are utilized more through AMF, making them more accessible by extending their mycelial nets, and NFb provide N, breaking down atmospheric N_2 gas into plant-accessible (NH_4^+) (Bi et al., 2022; Hassan, 2025). In case of stress, AMF enrich the plants with osmolyte buildups and promote antioxidant involvement, and NFB diminish ethylene presences by using ACC deaminase and improve root formation using indole-3-acetic acid (IAA). Soil health wise, AMF produce glomalin glycoprotein that initiates aggregation of soil and increases soil tilth and organicmatter sul Homicidal and NFB also increase soil tilth and the amount of organicmatter secretion of exopolysaccharides (EPS). These functions enhance soil ecosystem sustainability and together, they increase plant productivity.

Integrated Benefits

In AMF - NFB co-inoculation of a plant system, the additive effects of both inoculants may be falling short of their individual effects. Such as, the phosphorus supply may be enhanced by AMF that supports the energy-consuming nitrogen fixation by NFB. In the meantime, additional nitrogen can elicit root growth provided by NFB, which would facilitate increasing the colonization of AMF. Co-inoculation reduces the application of nitrogen fertilizer in field tests by 40-50% and does not decrease yields, or even increases those (Zhang et al., 2024).



Complimentary relationship between arbuscular mycorrhizal fungi (AMF) and nitrogen-fixing bacteria (NFB) in plant support is described in figure 2. On their left side, AMF propound their hyphal networks deep in the soil that augmented the nutrient absorption surface area of the root. Such hyphae can take up vital minerals, including phosphorus (P) and zinc (Zn), and carry them to the plant in exchange of carbon derived in the process of photosynthesis. NFB on the right develop root nodules in which they fix nitrogen in the atmosphere (N_2) and produce ammonium (NH_4^+) that is available to plants. This fixed state of nitrogen also provides the protein and chlorophyll requirements of the plant and, when added to microbial synthesis of indole-3-acetic acid (IAA), results in increased root growth. The combination of the processes increases the nutrient availability, stimulates healthy root structure, and makes plants healthier as well as more productive without the need to depend on synthetically based fertilizers.

Sustainable Agricultural Practices

Sustainable agriculture tries to reconcile all three aspects: crop productivity, the health of the environment and economic feasibility by simultaneously decreasing the reliance on synthetic inputs and at least sustaining or making yields increase. Such aims are twofold concerning the use of biofertilizers and bioinoculants as well as incorporation of useful microorganisms into the pest control ecosystems.

1. Glomalin is a glycoprotein secreted by the AMF that includes the staying of soil particles into an intact mass bonded to their compact agglomerates that increase water holding capacity and erosion reduction. Bio-fertilizers include preparations of living microorganisms, namely arbuscular mycorrhizal fungi (AMF), nitrogen-fixing bacteria (NFB), phosphate-solubilizing bacteria (PSB), and plant growth-promoting rhizo-bacteria (PGPR) whose application either on seeds, soil, or the surface of a plant becomes its rhizosphere or root interior to enhance plant growth (Debnath et al., 2019). Microbial products used to manage plant health and soil quality including consortia of several beneficial microbes are often abbreviated as bio-inoculants though this term commonly has a broader meaning. The first benefit of such products is that they enhance availability of nutrients. As an illustration, AMF hyphae can increase the effective absorptive surface area of plant roots to enable the take-up of relatively immobile nutrients, including phosphorus (P) and zinc (Zn) (Bhantana et al., 2021). In the same way, NFB, including Rhizobiums and Bradyrhizobiums, fix atmospheric nitrogen (N_2) into ammonium (NH_4^+), a crucial nutriment to plants that prevents the need to use synthetic fertilizer energy to provide plants with the nutrient (Wahab et al., 2023). With a range of benefits beyond nutrient acquisition, the biofertilizers can improve soil health and its architecture. In the case of soybean, co-inoculation with AMF (Glomus intraradices) and NFB (Bradyrhizobium japonicum) not only led to a 45 percent decrease in the urea input; it culminated in an increase or equivalent yield. Certain bacterial bio- inoculants produce exopolysaccharides (EPS) and this enhances the tilth, porosity and microbial diversity in soil. Some of the studies note their potential of increasing the yield. Beneficial Bugs Integrated Pest Management (IPM) in the same manner, wheat inoculated with PGPR and AMF had an increased grain protein content and biomass in comparison with chemical fertilizer-only treatments (Ebbisa, 2022). Environmentally: bio-fertilizers reduce the emission of greenhouse gases by decreasing the amount of synthetic fertilizers that are required; these fertilizers are energy-rich to produce and are easily lost by volatilization and leaching of their nutrients. As an example, the substitution of a part of the nitrogen fertilizers with microbial inoculants resulted in up to 0.8 t ha 1 of carbon dioxide equivalent emissions avoided per year at field scale (Thangavel et al., 2022).

2. Beneficial microbes form one of the most significant strategies of the biological control component of IPM and act as the natural antagonist to plant pathologies and pests.

Another long-lasting sustainable approach is the integrated pest management (IPM) which integrates the biological, cultural, physical and chemicals strategies to control pests in a manner that any damage caused by the pest is minimum whilst the risks posed the health of the human beings or the environment is also minimized (Collins, 2023).

- Antibiosis: Excretion of anti-microbial substance and this contains antibiotics, lipo-peptides and volatile organic compounds (VOC) (Etesami et al., 2021).
- Some types of bio inoculants contain biocontrol agents like Trichoderma spp., Bacillus subtilis, Pseudomonas fluorescens, and others that prevent the disease by their various mechanisms:
- Construction of the rhizosphere: the competition of space and nutrients, out-competition of pathogens.
- This minimises chances of polluting the environment and the development of pests with insane resistance to the reputed effects of pesticides.
- Mycoparasitism or direct infection of pathogenic fungi by other fungi such as Trichoderma, and breaking down their frames of hyphae.

The induced systemic resistance (ISR), where plant defensive reactions occur as the result of a plant defence-causing agent, or beneficial microbe that initiates jasmonic acid (JA)- and ethylene-mediated defensive signalling pathways, leading to plant enhancement of an overall preparedness to combat most pathogens (Clark & Zeto, 2000). One of the successful IPM using microbials is the implementation of Bacillus thuringiensis (Bt) that manufactures a crystal (Cry) proteins that are fatal to certain insect larvae, but not lethal to humans and useful species. On the same note, there is a control of bacterial wilt and root-knot nematode in vegetables by the use of Pseudomonas fluorescens formulations (Neumann & George, 2010). With the advantages microbes offer to IPM, the use of chemical pesticides can be lessened significantly. As an example, the application of Trichoderma harzianum and Pseudomonas fluorescens during cultivating rice resulted in a 40-50 % limited application of the fungicide without a drop in the yield (N. Sharma et al., 2025). The microbial IPM along with Biofertilizer

Synergy between Bio-fertilizers and Microbial IPM.

Environmental and Economic consequences Improvement in disease resistance may also be achieved by use of microbes that improve plant nutrition through enhancement of plant vigor, or microbes with biocontrol technology that may improve nutrient cycling processes by inhibition of pathogens that otherwise would weaken roots (disease). To take a specific example of Azospirillum brasilense (a nitrogen-fixing PGPR), not only does it fix (N_2), but also produces siderophores, which bind iron, making it unavailable to some fungal pathogens (Prasad, 2022). Co-application of Rhizobium spp., AMF, and Trichoderma spp. have been demonstrated to increase the yield of chickpeas by 25 % when compared with control treatments besides also decreasing the occurrence of soil-borne diseases by 35 %. The multifunctional optimization in this method makes the input to be efficient and the trade-offs minimal to the environment.

Environment Economics Footing

Not only can microbial-based strategies be adopted to provide sustainability in several ways:

- Decreased use of chemical input, reduction of cost of production.
- Reduce the environmental impact such as less nutrient discharge, and pesticides transfer.
- Better soil biodiversity, which enhances a sustainable self-resilient agroecosystem.
- Better quality crops, superior nutrient levels and a drop in chemical residues.

Economically, it is seen that the cost of bio-fertilizers and biocontrol products differs but compared to the returns on investment in the long run, they perform well with the limiting contact of fertilizers and pesticides and increased yield and high market value of the crop produced through sustainable agriculture.

Table 3. Functions of Biofertilizers and IPM Microbes

Function	Biofertilizer Contribution	IPM Microbial Contribution
Nutrient acquisition	P, Zn uptake (AMF), N_2 fixation (NFB)	Indirect via healthier plants
Stress tolerance	Osmolyte accumulation, antioxidant activation	ISR induction, ACC deaminase activity
Soil health	Glomalin/EPS improve structure & fertility	Supports beneficial microbe diversity
Pest/disease control	Not primary role	Antibiosis, mycoparasitism, competition

Bio-fertilizers and IPM microbes are in accord concerning the sustainable agriculture (Bio-fertilizer IpMm, Table 3). In nutrient acquisition, the bio-fertilizers have direct effects by making plants access phosphorus (P) and zinc (Zn) with the help of arbuscular mycorrhizal fungi (AMF) and atmospheric nitrogen N_2 with the help of nitrogen-fixing bacteria (NFB), whereas the IPM microbes have an indirect effect by improving the health of the plant and root system. In terms of stress tolerance, biofertilizer boosts osmolyte build-up and stimulates antioxidant pathways, and IPM microorganisms induce an induced systemic resistance (ISR) and express ACC deaminase, reducing the level of stress-generated ethylene. Biofertilizers also produce glomalin and exopolysaccharides (EPS) in the soil to enhance the soil structure and fertility whereas a diverse and balanced microbial community is ensured with the assistance of IPM microbes in soil health. Biofertilizers do not play any direct role in pest and disease control, albeit that IPM microbes act against pathogens by means of antibiosis, mycoparasitism, and competition. Relatively, the table brings out the synchronicity of nutrient-based biofertilizers and pest-repressive IPM microbials in developing robust agricultural behemoths.

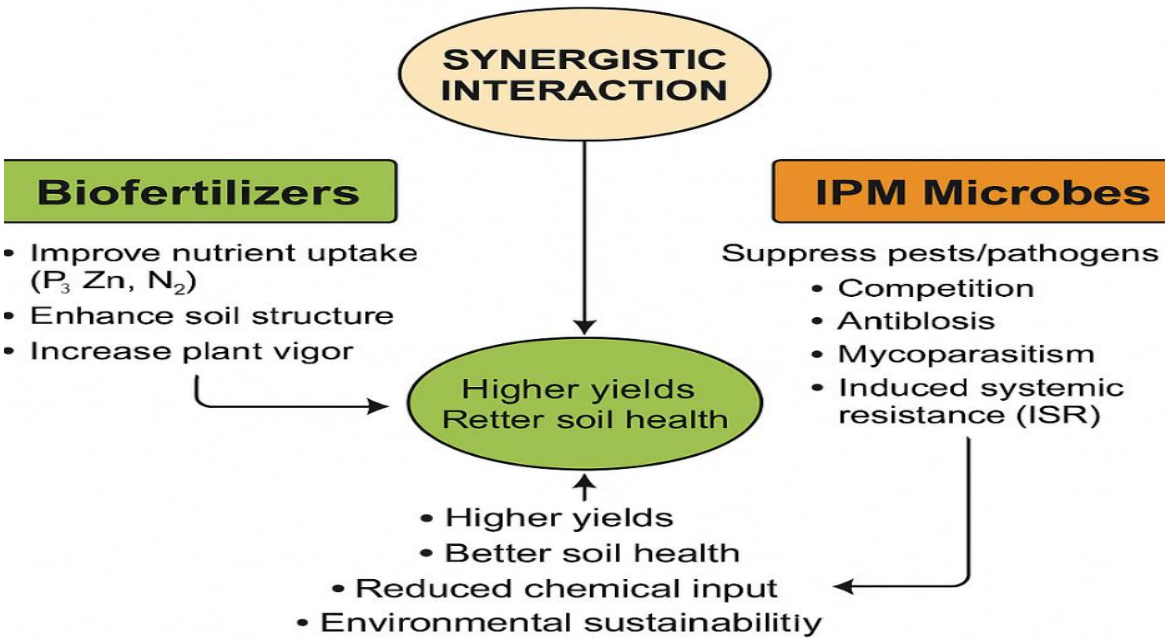


Figure 3: Interactions of Biofertilizers and IPM Microbes in Sustainable Agriculture

Figure 3 shows the functionality of the biofertilizers and IPM (Integrated Pest Management) microbes in nurturing sustainable farming. The biofertilizers also enhance nutrient absorption (especially phosphorus (P), zinc (Zn) and nitrogen (N_2), soil structure and general plant vigor on the left side. IPM microbes on the right side- suppress pests and pathogens by way of a competition, antibiosis, mycoparasitism and induced systemic resistance (ISR). The two systems play off each other to provide better yields and healthier soils which translate into less chemical input requirement and enhanced environmental sustainability. The figure shows that the overall impact of the combination of these practices will be more than the sum of the individual contributions, which makes them the complementary methods to achieve the long-term resilience in agriculture.

Conclusion

Plant- microbe interactions constitute the major building block of healthy and productive agro-involving systems, which are critical in soil health and agriculture production. Among them, amber-like mycorrhizal fungi (AMF) and nitrogen-transforming bacteria (NFB) attract with their ability to increase the intake of nutrients, absorption of water, and resistance to environment conditions. AMF increase root surface area by vast hyphal networks enhancing the access of the immobile nutrients like phosphorus and zinc as well as the soil aggregates by the production of glomalin. NFB add biologically fixed nitrogen deferring the use of synthetic fertilizers although in process boosting the vegetative growth of roots through phytohormones such as indole-3-acetic acid (IAA). These interactions are not in itself, but they synergize to give positive effects to the crop, soil, and ecosystem health. Their incorporation into sustainable farming systems--included in description of bio fertilizers, microbial inoculants and microbial aspects of integrated pest management (IPM) provides a nature-based means of lessening the exposure of chemicals, reducing greenhouse emissions, as well as conserving biodiversity.

Nevertheless, the mechanisms are rather complicated, and the overall effect is still unclear; the process requires the specificity of the soil type, climate, plant species, and the exact strains of microorganisms. Improvements in research and field trial are needed, and microbial formulations should be optimized, the efficacy of colonization optimized, and the uniformity of performance needs to be maintained in changing farm environments. Through a better understanding and implementation of these insights we are able to create cost effective, scalable solutions to use plant microbe symbiosis to increase global availability of food in a sustainable way that protects the environment. With such an approach, AMF and NFB will stay key figures in the move toward an ultimately sustainable agriculture.

Future Research Directions

Future research should focus on elucidating the molecular mechanisms of plant-microbe interactions and identifying key microbial species and strains that can be used as bio fertilizers and bio inoculants. Additionally, studies should explore the potential of these interactions in mitigating climate change and promoting ecosystem resilience. By understanding and harnessing the power of plant-microbe interactions, we can develop sustainable agricultural practices that enhance crop productivity, improve soil health, and protect the environment for future generations

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