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Multiple Functions of Microbes to Improve Food and Soil Nutrition in Support of Environment Management to Maintain Global Agricultural Practices

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Abstract

Plant-microbe interactions are interesting phenomena Soil microbial biomass is considered the living part of the soil organic matter, which acts as an agent of transformation of organic matter and is a source of available nutrients. Activities of soil microbes can change the soil environment rapidly and influence the rate of nutrient cycling. Soil microbes also play a significant role in the formation of macro aggregates. The potential of soil microorganisms has been recognized widely for the improvement of soil quality, soil formation, aggregation, and revegetation. Soil microbes are involved in various ecosystem processes, such as litter decomposition, phosphate solubilization, nitrogen fixation, oxidation of various inorganic components of soil or mineralization of inorganic components, and mycorrhizal symbiosis. Implications of plants and their symbionts like mycorrhizal fungi, nitrogen-fixing bacteria, and free-living rhizosphere populations of bacteria promote plant establishment and growth. Therefore, active soil microbial biomass is an essential component for long-term soil fertility. The application of microbial technology which we can refer to as green technology has become an integral element of forestry as well as agriculture and has substantially contributed to forest and agricultural productivity and ensuring the ecosystem's sustainability. This article reviews some of the important aspects of microbial applications in agriculture and forestry and discusses different facets of microbial functions, their interaction with plants and soil, and their role in the sustainability of natural resources, forests, and agroecosystems.

Keywords: Ecosystem Sustainability; Forest productivity; Green technology; Microbes; Organic Nutrients

Abbreviations: AMF: Arbuscular Mycorrhizal Fungi; PGPR: Plant Growth Promoting Rhizobacteria; RSC: Rice Straw Compost; GVC: Gliricidia Vermicompost.

Introduction

Microbes and plants share a very special relationship, which is referred to as symbiosis, where both partners mutually co-exist and benefit each other in various ways. Microbes being ubiquitous in nature are natural constituents of soil and play a very significant role in the composition, functioning, stability, and sustainability of the ecosystem. Soil-plant-microbes interaction has been considered the basis of the ecological functioning the terrestrial ecosystems, be it natural forests, planted forests, or agri-ecological systems. As far as nutrient availability to plants is concerned, rhizospheric microbial activity is of great importance. Due to the Rhizospheric activity of microbes, the root exudates are released by plants, which are rich sources of carbon, thus carbon fluxes in soil are crucial determinants of rhizosphere function. The release of root exudates and decaying plant material provide sources of carbon compounds for the heterotrophic soil biota, in the form of either growth substrates or structural material for root-associated microbial flora [1]. Nitrogen-fixing microbes can exist as free-living organisms in associations with different degrees of complexity with other microbes and plants. The most abundant element (N) in the atmosphere is very often the limiting element for the growth of most organisms. To overcome this limitation, numerous soil organisms interact with each other. The combination of nitrogen-fixing organisms ensures the fixing of atmospheric nitrogen in the soil and its availability to the plants. Recently, Prasad, et al. [2] reported positive effects of *Rhizobium* inoculation in combination with species of *Azotobacter*, *Pseudomonas, Fraturia,* Arbuscular Mycorrhizal Fungi (AMF), and *Azospirillum* inoculants for different plant species.

Symbiosis is a biological phenomenon involving dynamic changes in the genome metabolism and signalling network [3]. Most of the legumes possess two types of microbial symbionts namely mycorrhizal fungi and nitrogen-fixing bacteria, thereby establishing the triple association, capable of supplying N and P contents to the plants [4-6]. Both, mycorrhizal fungi and *Rhizobium* act as microbial biofertilizers and have the unique ability to convert nutritionally important elements from unavailable to available forms through the biological process [7,8]. For improving the quality of microbial biofertilizers, a depth study of microbial characteristics, effectiveness, consistency, and limitations are required, not only at the laboratory and production level but also at the field level. The microbial biofertilizers are 100% natural, low cost, require eco-friendly organic inputs, and could act as supplementary to chemical fertilizers. The best quality organic fertilizers are known to provide all the nutrients required by plants and help to improve the quality of soil in a natural microbial environment. The uniqueness of microbes and their often-unpredictable nature and biosynthetic capabilities, given a specific set of environmental conditions, has made them likely candidates for solving particularly difficult problems in the biological sciences and other fields as well. Over the past 50 years, to advance medical technology, human and animal health, food processing, food safety, genetic engineering, ecological protection, agricultural biotechnology, and more efficient treatment of agricultural and municipal waste. Microorganisms have been used in a variety of ways. This is the most impressive achievement. However, in recent years, microbial technology has been applied to various agricultural and environmental problems with great success. Microbes are effective only when they are treated with suitable and optimum conditions for metabolizing their substrates, including available water, oxygen, pH, and temperature in their environment.

Microbes are usable in different post-harvest agricultural processes, in manure production, or even in the control of pest diseases. The extraction of costly minerals from poor or left-over mines or the production of raw materials for the production of chemicals of immense utility or even the production of fuel gases like methane or hydrogen are all modern achievements in the field of microbial research. Possibly thousands of other technologies may be waiting behind the screen for their release in development programmers for green technologies in the future. Microbes are useful in eliminating problems associated with the use of chemical fertilizers and pesticides; they are now widely applied in natural farming and organic agriculture [9,10]. Environmental pollution caused by excessive soil erosion and the consequent deposition of sediments into surface and ground waters, transport of chemical fertilizers and pesticides, and improper disposal of human and animal waste is a serious environmental problem worldwide and causing social problem. Often scientist's groups have attempted to solve these problems using established chemical and physical methods. Nevertheless, they have usually found that such problems cannot be solved without using microbial methods and technologies in coordination with agricultural production [11,12]. Soil microbiologists and microbial ecologists have tended to differentiate soil microbes as beneficial or harmful according to their functions viz., affect soil quality, plant growth, yield, and plant health. In the present article, various aspects of microbial inputs application in forestry and agriculture and their role in ecosystem sustainability and economic importance for sustainable development have been discussed and reviewed.

Integrities of Natural Ecosystems and the Application of Positive and Active Microbes

The mismanagement and extreme use of chemical fertilizers and pesticides have often adversely affected the environment and created food safety and human and animal health issues. Consequently, there has been a growing interest in natural and organic agriculture by consumers, microbiologists, and ecologists, as possible alternatives to chemical-based conventional agriculture. Agricultural systems that follow natural ecosystem principles are currently attracting significant attention in both developed and developing countries. For alternative and sustainable agriculture, soil quality improvement, integrated pest, and nutrient management, and beneficial microorganisms are being explored by agricultural research establishments [12,13]. Although these concepts and related methods are promising, they also have limitations. The main limitation of using microbial inoculants is the problem of reproducibility and lack of consistent results. Unfortunately, certain microbial cultures have been promoted by their suppliers as being effective for controlling a wide range of soil-borne pathogens when in fact they were effective only on specific pathogens under very specific conditions. Some suppliers have suggested that their particular microbial inoculant is similar to a pesticide that would suppress the general soil microbial population while increasing the population of a specific beneficial microorganism. The use of consortium cultures of beneficial microbes as soil inoculants is based on the principles of natural ecosystems which are sustained by their constituents; that is, by the quality and quantity of their inhabitants and specific ecological parameters, i.e., the greater the diversity and number of the inhabitants, the higher the order of their interaction, the more stable the ecosystem. The consortium culture approach is simply an effort to apply these principles to agricultural soils, and to shift the biological equilibrium in Favor of increased plant growth, productivity, and disease protection [12].

Soil Microflora for Optimum Crop Production and Protection

The new horizons in the development of biological sciences have enabled us to use microbial flora as inoculants, and organic amendments in agricultural management practices to create a more favorable soil biological environment for optimum productivity, and simultaneously protection of the forest and agriculture resources. The increasing trend of using biofertilizers and bio-pesticides is obvious and gaining importance as ecologically safe technologies. For a century, microbiologists have known that organic wastes and residues including animal manures, crop residues, green manures, and municipal wastes contain their own indigenous populations of microorganisms often with broad physiological capabilities. It is also known that organic wastes and residues are applied to soils many of these introduced microorganisms can function as biocontrol agents by controlling or suppressing soil-borne pathogens through their competitive and antagonistic activities. In actual practice, the results have been unpredictable and inconsistent, and the role of specific microbes has not been well defined.

The diversity and population factors associated with soil microbiota have prevented scientists from supervising research to develop control approaches. Many believe that, even when beneficial microbes are cultured and inoculated into soils, their number is relatively small compared with the indigenous soil inhabitants, and they would likely be rapidly overwhelmed by the established soil microflora. Subsequently, many would argue that the application of beneficial microbes is successful under laboratory conditions. It would be virtually impossible to achieve the same success under actual field conditions. Such thinking still exists today and serves as a principal constraint to the concept of controlling the soil micro flora [14], but currently, scientists, ecologists, and microbiologists agree to achieve after uses of bio inoculants in laboratories and nurseries as well as field conditions and found positive results more overall agricultural crops.

Microbial Technology for Restoration of Degraded Ecosystems

The soils of disturbed sites are low in available nutrients and lack the nitrogen-fixing bacteria and mycorrhizal fungi usually associated with root rhizospheres. As such, land restoration in tropical, sub-tropical, and semi-arid areas faces a number of constraints related to soil degradation and water shortage. As mycorrhizae may enhance the ability of the plant to cope with water stress associated with nutrient deficiency and drought. The use of arbuscular mycorrhizal fungi (AMF) can also increase the establishment rate of desired vegetation by reducing the amount of fertilizer required for vegetation establishment and stimulating the expansion of useful microbes in the rhizosphere. Soil inoculation with a consortium of AMF and Plant growth promoting rhizobacteria (PGPR) has significantly enhanced plant growth and biomass production in degraded lands. The consortium of beneficial bacterial and arbuscular mycorrhizal inoculants accelerates nitrogen fixation and phosphatase enzyme activity in the rhizosphere of plants which ensures the supply of nitrogen and phosphorus in the soil. Thus, the potential of soil microorganisms has been recognized widely in the improvement of soil quality, soil formation, aggregation, and revegetation through their activities in litter decomposition and nutrient cycling. Microbial activities such as phosphate solubilization, nitrogen fixation, oxidation of various inorganic components of soil, mineralization of inorganic components, and mycorrhizal symbiosis are major beneficial activities that play a very important role in soil system functioning. An active soil microbial biomass is an essential factor in the long-term fertility of soils.

Microorganisms improve the nutrient status and texture with the addition of organic matter [15]. Microorganisms alter the pH of the habitat making it suitable for the establishment of higher plants. These microbes alter the soil pH by acidifying their surrounding environments acidic, allowing them to complete with other microbes. Fungi, on the other hand, are more common in forest acidic soils because they prefer at least slightly acidic pH conditions [16]. The pH alteration among the various microorganisms, vesicular and arbuscular mycorrhizal fungi, nitrogen fixers, and phosphate solubilizers are very important for all plants. Phosphorus is an important plant nutrient next to nitrogen for plant growth. The most important aspect of the phosphorus cycle is microbial mineralization, solubilization, and immobilization besides the chemical fixation of phosphorus in the soil. Phosphorus solubilizing microorganisms convert insoluble inorganic phosphate compounds into soluble forms. Significantly high concentrations of phosphate-soluble bacteria are often found in rhizosphere soils. Fungal genera with this ability also include *Penicillium* and *Aspergillus* [17]. *Pseudomonas* is a typical plant growth-promoting rhizobacteria and their interactions with AM fungi mutually enhance each other's colonization and achieve additive plant growth enhancement [18]. Another mechanism of activity of PGPR on plant development is the generation of siderophores. Siderophores are produced by most fungi and bacteria, including *Pseudomonas*, *Rhizobacteria*, and *Azotobacter* [19]. AM fungi which are an important group of soil-borne microorganisms; contribute substantially to the establishment, productivity, and longevity of natural or man-made ecosystems. Some of the microorganisms are being applied as biofertilizers and have proved promising agents for the recovery of wastelands. The plantation supplemented with beneficial microbial inoculants has a greater influence on the natural regeneration process of degraded wastelands.

Microbes and Agro-Ecosystem's Sustainability

Microbes are necessary for the soil for improving productivity and soil health. Microbiologists and foresters use naturally occurring organisms to develop biofertilizers, bio-pesticides, bio-herbicides, bio-insecticide, and bio-nematicides to assist plant growth, survival, and control weeds, pests, and diseases (Figure 1). Microbes that live in the soil actually help plants to absorb more nutrients. Plants and friendly microbes are involved in nutrient recycling. In return, plants donate their waste by-products for the microbes to use as food. Scientists use these friendly microbes to develop biofertilizers. Phosphate, nitrogen, and potash are important macronutrients for plant development [20-22]. These compounds exist actually within the environment, but plants have a constrained capacity to extricate them. Phosphate plays an imperative part in trim push resistance, development, quality, and specifically or by implication, in nitrogen obsession.

Species of *Pseudomonas* and *Penicillium* help to unlock phosphate from the soil. *Rhizobium* is a bacteria used to make bio fertilizers. This bacterium lives on the plant's roots called nodules. The nodules are biological factories that can take atmospheric nitrogen and convert it into an organic form that the plant can use. Potassium is an essential macronutrient that plays a vital role in the growth, metabolism, and development of plants. With a large population of friendly bacteria on the root's rhizosphere, the legume can use naturally occurring nitrogen instead of the expensive traditional nitrogen fertilizer. Moreover, biofertilizers help plants use all resources available in the soil and air, thus permitting farmers to reduce the number of chemical fertilizers. Important applications of microbes in agro ecosystems are given below:

Figure 1: Systematic sketch for application of microbes for sustainable agriculture.

As Bio Fertilizers

Bio fertilizers are the source of microbial inoculants, which have confidence supported by many countries both economically and environmentally. Therefore, in developing countries like India, microbial biofertilizers can solve problems of high input cost of chemical fertilizers, and thus may save the economy of the country [23]. Microbial bio fertilizers directly provide nutrition to crop plants. These are cultures of microbes (bacteria and fungi) packed in liquid formulations or in the carriers as wettable powder formulations. Thus, the critical input in biofertilizers is the microbes. They help plants indirectly through better uptake of macro and micronutrients and improving nutrient availability in the soil ecosystems. Microbial biofertilizers can be defined as microbial inoculants containing live colony-forming units (cells) or spores of selected strains of nitrogen-fixing, phosphate and zinc solubilizing, potassium mobilizing microbes, applied to seed, soil, or compost to accelerate certain microbial processes; thus, augmenting the availability of nutrients in an easily assailable form to plants. Soil bacteria, nitrogen fixing soil bacteria, cyanobacterium, phosphate solubilizing soil bacteria, molds, and fungi are some of the most common biological fertilizers [24].

Biological Nitrogen Fixation (BNF)

Several bacterial species belonging to genera *Acetobacter*, *Acinetobacter Azotobacter*, *Azospirillum*, *Flavobacterium*, *Erwinia*, *Burkholderia*, *Alcaligenes*, *Arthrobacter*, *Enterobacter*, *Rhizobium*, *Bradyrhizobium*, and *Serratia* are associated with the plant rhizosphere and can exert a positive effect on plant development [20,21]. Plants play a significant role in selecting and enriching particular types of bacteria through the constituents of their root exudates. Hence, the bacterial community within the rhizosphere is created depending on the nature and concentrations of natural constituents of exudates, and the comparing capacity of the microscopic organisms to utilize these as sources of vitality [25]. There is a continuum of bacterial communities in the soil rhizosphere, rhizoplane and inside the plant tissues [25]. Rhizosphere bacterial communities however have efficient systems for uptake and catabolism of organic compounds present in root exudates [26]. Several bacteria help to derive maximum benefit from root exudates by their ability to attach to the root rhizoplane.

Since associative interactions of plants and microbes must have come into existence as a result of co-evolution, the utilization of the last-mentioned gather as bio inoculants must be preadapted so that it fits into a long-term maintainable agricultural system. PGPRs are commonly used as bioinoculants for improving the growth and yield of crops and offer an attractive way to replace chemical fertilizers, pesticides, and supplements [27]. The use of biofertilizer, bio enhancer BNF bacteria, and beneficial microbes can reduce chemical fertilizer and consequently lower production costs. Application of PGPR to increase productivity may be a viable alternative to organic fertilizers which also helps in reducing pollution and preserving the environment in the spirit of ecological agriculture [28]. Thus, rhizospheric bacteria can be a promising tool for promoting plant growth in agro ecosystems [29]. Moreover, PGPR or combinations of PGPR and AMF can improve the nutrient use efficiency of fertilizers and allow reduced application rates of chemical fertilizers [30-32].

Symbiotic Nitrogen Fixer (SNF) Bio Fertilizer

Two groups of nitrogen-fixing bacteria (NFB) have been studied extensively, which include *Frankia* and *Rhizobia. Frankia* forms root nodules on more than 280 species of woody plants from 8 different families [33]. However, its symbiotic relationship is not as well understood. *Frankia* is known to form an effective symbiosis with the species of *Alnus* and *Casuarina* [1,34,35]. Several individual species may improve plant nutrition by releasing plant growth regulators, siderophores, and hydrogen cyanide or may increase phosphate availability [36]. An increase in rhizosphere populations has been reported after crop rotation with non-legumes [37]. With abundance benefiting subsequent crops [26,38]. In rhizobial taxonomy, thirteen genera (viz., *Azorhizobium*, *Bradyrhizobium, Mesorhizobiumm*, *Methylobacterium, Rhizobium,* and *Phyllo bacterium, Microvigra, Ochrobacterium, Devosia, Shinella, Burkholderia* and *Sinorhizobium*) are derived, based on the polyphasic taxonomic methodology. Under different agro-climatic conditions, legumes of economic importance are grown in India, and the presence of native rhizobia has therefore been anticipated. *Rhizobium* and *Bradyrhizobium* are the most important NFBs used in developing countries.

Rhizobium

Rhizobium is a gram-negative nitrogen-fixing bacteria (BFB). The genus is capable of enhancing the ability of legumes to fix atmospheric nitrogen into ammonia and acts as a natural biofertilizer for leguminous crops. *Rhizobium* forms a symbiotic association with leguminous crops to develop nitrogen-fixing nodules in the roots of host crops such as lentils, beans, lupine, cowpea, pea, mung bean, red gram, soybean, alfalfa, beans, leguminous trees, etc., thereby, playing a vital role in agriculture [39-43]. The name rhizobia refer to *Rhizobium*, *Bradyshzodium*, *Sinorhizobium*, *Azorhizobium*, and *Mesorhizobium*. They can exert direct or indirect influence on plant hormones or decrease the inhibitory effect of pathogens by way of nitrogen fixation [44]. Different strains are found to be active in arranging a continuous supply of nitrogen to the plants. Strains are cultured as mass inoculum production under aseptic artificial conditions. Culture broth is applied as liquid formulation or mixed in definite strength with carrier materials such as charcoal, fly ash, talc powder, and molasses as wettable powder formulation.

The liquid and wettable powder formulations packed in sterilized bottles and/ or aluminum packets are marketed for application in the case of the specific crop either by treatment of the seeds of the legumes or sometimes by drenching of the base of the plants. Nodules formed in the roots of leguminous plants after the association of root and inoculum culture. These nodules are the active sites of nitrogen fixation. They help in increasing the productivity of pulses by assimilating atmospheric nitrogen and fixing it in the root nodule. Active nodules contain a red pigment called leghaemoglobin. Leghaemoglobin pigment regulates oxygen diffusion within the nodule. Intensities of nitrogen fixation are directly proportional to the amount of haemoglobin present in nodules [45]. They fix atmospheric nitrogen and thus not only increase the production of the inoculated crops but also leave a fair amount of nitrogen in the soil, which benefits the subsequent crops. *Rhizobium* is the best biofertilizer for leguminous crops in the worldwide ecosystem. *Rhizobium* can fix approximately 50-230 Kg N ha^{-1} and improve by 10-35% crop productivity. Numerous studies have demonstrated that a variety of free-living rhizospheric and endophytes can promote nodulation and nitrogen fixation of various rhizobium strains, leading to increased plant leguminous plant growth (Table 1).

Rhizobia species	Co-Inoculation	Host Plants	References
R. tropici CIAT899	Paenibacillus polymyxa (DSM 36)	Phaseolus vulgaris	[46]
R. tropici CIAT899	Pseudomonas fluorescens YsS6	Phaseolus vulgaris	[47]
Rhizobium spp.	Bacillus aryabhattai Sb	Trifolium repens	[48]
Rhizobium leguminosarum bv. Tri foli	Bacillus insolutis, Bacillus brevis Agrobacterium rhizogene	Trifolium pratense	[49]
Rhizobium	Bacillus subtilis OSU-142	Phaseolus vulgari	[50]
Rhizobium leguminosarum PR1	Bacillus thuringiensis KR1	Pisum sativum; Lens culinaris	[51]
Bradyrhizobium japonicum	B. subtilis NEB4 and NEB5 B. thuringiensis NEB1	Glycine max	[52]
B. japonicum	Nonomuraea rubra	Glycine ma	[53]
Sinorhizobium melilot	Exiguobacterium sp. M2N2c and B1N2b	Trigonella foenum-graecum	[54]
E. adhaerens	Paenibacillus taichungensis M10 Paenibacillus	Vigna radiata	[55]
Mesohizobium spp. Ca181 and Ca313	Pseudomonas sp. CRP55b and CRS68	Cicer arietinum	[56]
Cupriavidus taiwanensis	Pseudomonas fluorescens	Mimosa pudica	[57]
Mesorhizobium ciceri	Anabaena	Cicer arietinum	[58]
Ensifer (Sinorhizobium) medicae	Pseudomonas fluorescens	Medicago truncatula	[59]
Rhizobium etli	Paenibacillus polymyxa	Phaseolus vulgaris	[60]

Table 1: Beneficial interactions between consortia of rhizobia and non-rhizobial bacteria and their positive effects in the symbiosis with leguminous plants.

It is well known that nitrogen plays a very significant role in plant growth and crop productivity. Apart from symbiotic nitrogen fixation, non-symbiotic nitrogen fixation has great significance in agricultural development but one main limitation that it faces is the availability of carbon and energy sources for the energy-intensive nitrogen fixation process. However, this limitation can be compensated by moving closer to or inside the plants, viz, in diazotrophs present in the rhizosphere, rhizoplane, or those growing endophytically.

Plant Growth Promoting Rhizobacteria (PGPR)

The PGPR, a group of beneficial plant bacteria is potentially useful for stimulating plant growth and increasing crop productivity. It is frequently used successfully in field crops for increasing productivity through improved nutrient uptake [61]. Commercial applications of PGPR are being tested and are successful; however, a better understanding of the microbial interactions that result in improving plant growth will greatly increase the success rate of field applications [62]. PGPR, a root-colonizing bacterium, is known to influence plant growth through a variety of direct and indirect mechanisms. Some chemical changes in soil are associated with PGPR. Some bacterial strains directly regulate plant physiology by mimicking the synthesis of plant hormones, whereas others increase mineral and nitrogen availability in the soil as a way to augment growth. The isolates could exhibit more than two or three PGPR trials, which may promote plant growth directly or indirectly, or synergistically [63].

The plant growth stimulating effect of bacterial inoculants is influenced by soil nutritional status. Bacterial inoculation has a much better stimulatory effect on plant growth in nutrient-deficient soil than in nutrient-rich soil [21]. The diazotroph bacterial inoculation significantly increases the seed cotton yield, plant height, and microbial population in soil [64]. Bacteria isolated from composts such as agricultural waste compost (FWC), rice straw compost (RSC), Gliricidia vermicompost (GVC), and FWC-associated macrofauna exhibit synergistic effects on millet growth when used in combination with compost [65]. The use of PGPR with P-enriched compost in an integrated manner improves the growth, yield, and nodulation in chickpeas [66]. Useful bacteria can contribute to maintain plant's intrinsic resistance to these challenges; therefore, the inoculation of bacterial consortium into crops can reduce the negative influence of biotic or abiotic stress conditions on plants [67] (Table 2).

Consortium Inoculum	Crop	Stress	Outcome	References
Pseudomonas fluorescens and Azospirillum	Cotton	Rhizoctonia bataticola	Increased seed cotton yield, Decreased root rot incidence	[68]
Pseudomonas aeruginosa PHU094 and Mesorhizobium sp. RL091	Chickpea	Sclerotium rolfsii	Plant growth promotion (increased shoot length and total biomass	[69]
Pseudomonas spp.	Potato	Phytophthora infestans	Reduction of mycelial growth Decreased release of zoospores induced systemic resistance (ISR) activation (reduced the number of pathogen spores)	[70]
Xanthomonas sp.Stenotrophomonas sp, and Microbacterium sp	Arabidopsis thaliana	Hyaloperonospora arabidopsidis	Plant growth promotion, ISR activation (peroxidase (PO), polyphenol oxidase (PPO), phenylalanine ammonia-lyase	[71]
Pseudomonas putida CRN-09 and Bacillus subtilis CRN-16	Mung bean	Macrophomina phaseolina	Plant growth promotion (increased shoot and root length, shoot and root fresh weight)	[72]
Ochrobactrum pseudogrignonense RJ12, Pseudomonas sp. RJ15, and Bacillus subtilis RJ46	Black gram and Pea	Drought	Plant growth promotion (increased seed germination percentage, root length, shoot length, and dry weight) Elevated production of ROS scavenging enzymes and cellular osmolytes Higher leaf chlorophyll content	[73]
Bacillus cereus AR156, Bacillus subtilis SM21, and Serratia sp. XY21	Cucumber	Drought	Increased the leaf proline content Significantly enhanced the superoxide dismutase (SOD) activity	[74]
Brevibacillus fluminis, Brevibacillus agri, and Bacillus paralicheniformis	Brinjal, potato, tomato, and chilli	Salinity	Increased germination percentage Plant growth promotion (an increase in shoot length, root length, dry and fresh weight	[75]
B. megaterium CAM12 and P. agglomerans CAH6	Mung bean	Aluminum and drought	Reduced Al uptake in plants Plant growth promotion (increased plant biomass) Higher content of carotenoids, chlorophyll	[76]

Table 2: Bacterial consortia and their beneficial effects on crop plants under biotic and abiotic stresses.

However, novel methods are needed to explore bacterial-microbe and plant-microbe interactions under abiotic and biotic stress conditions to identify potential bacteria that are resistant to stress or stress tolerance bacteria to improve plant growth and 0 [77].

Phosphate Solubilizing Bacteria (PSB)

Phosphorus is the second most important key element after nitrogen as a mineral nutrient in terms of quantitative plant requirements. The improvement of soil fertility is one of the most common strategies to increase agricultural productivity. In addition to BNF, Phosphate solubilization is equally important for crop efficiency and soil health. Phosphorus is an essential macronutrient important for the growth and development of living organisms. Microorganisms offer a biological rescue system capable of solubilizing the insoluble inorganic P of soil and making it available to plants. PSB is capable of converting insoluble inorganic phosphorus into an available soluble form by producing organic acids and acid phosphatases which play a major role in the mineralization of organic phosphorus. The rhizospheric phosphate utilizing bacteria could be a promising source for PGPR in agriculture [28]. Several studies have reported that the PGPR inoculants increase P uptake by plants [78,79].

Among the heterogeneous and naturally abundant microbes inhabiting the rhizosphere, the phosphate solubilizing microbes (PSM) including bacteria have provided an alternative biotechnological solution in sustainable agriculture to meet the P demands of plants. These organisms not only supply phosphorus to plants, but also promote plant growth through other mechanisms. Current developments in our understanding of the functional diversity, rhizosphere colonizing ability, mode of actions, and careful application are likely to facilitate their use as reliable components in the management of sustainable agricultural systems [31,80]. The most proficient PSM belong to genera *Bacillus, Rhizobium,* and *Pseudomonas,* amongst bacteria, and *Aspergillus* and *Penicillium,* amongst fungi. Within rhizobia, two species modulating chickpea, *Mesorhizobiumm ciceri,* and *Mesorhizobiumm editerraneum*, are known as good phosphate solubilizers [81]. Identification and characterization of soil PSB for effective plant growth promotion broadens the spectrum of phosphate solubilizers available for field application. Moreover, the application of PSM and PGPR together can reduce chemical P by up to 50% without any significant reduction of grain yield in corn [45]. It also enhances vegetative growth and fruit quality, in addition to the reduction in the pollution of the environment [82].

Potash Mobilizing Bacteria (PMB)

Potassium is the third most essential macronutrient that plays a dynamic role in regulating the opening and closing of stomata and enhancing CO_2 uptake of Adenosine Triphosphate (ATP). ATP is the main molecule for storing and transferring energy within cells. ATP is produced in mitochondria and chloroplast crystals. The cell wall also bonds with another cell wall to form the structure of the plant. ATP is an important energy source for the growth metabolism and development of plants. It can be used to store energy for future reactions or be withdrawn to pay for reactions when energy is required by the plant cells. Although our soils are rich in potassium, the availability of potassium for absorption by plants is very low. PMB plays a vital role in the formation of amino acids and proteins from ammonium ions, which are absorbed by roots, from the soil. It also plays a role in transporting carbohydrates and proteins from the ground to the roots. PMB also plays an energetic role in the uptakes of other elements, particularly nitrogen, phosphorus, and calcium, and regulates the permeability of the cellular membrane.

Arbuscular Mycorrhizal Fungi (AM Fungi)

Mycorrhiza literally means 'fungus root'. The term was coined a century ago to describe the symbiotic association of plant roots and certain fungi. There are several types of mycorrhizal fungi, orchids and ericaceous plants have their particular brand but those fungi which colonize in vivo, and in vitro commodities are referred to as AM fungi. AM fungi have been colonizing the root system of most native land plants essentially ever since plants have grown on land. The fungal hyphae extend from root surfaces like tiny conduits out into the soil, greatly enhancing the absorptive surface area of the root system. Under natural conditions, most plants live in a close beneficial association with soil microorganisms like AM fungi. The AM fungi colonize plants' roots form an essential link between the plant and its soil environment, and work as an effective biological tool for creating a healthy ecosystem [83,84].

According to Prasad [10], approximately 90% of all plant species form an association with AM fungi. These plant species constitute a broad range of agro-forestry and horticultural crops, vegetables, oilseeds, grains crops, millets, and ornamental and forage crops [85]. The roots of most plant species form a symbiotic association with specialized fungi (*Glomus, Gigaspora, Acaulospora, Enterophospora*, and *Sclerocystis*) known as mycorrhiza. AMF is the most abundant kind of mycorrhizal fungi described as universal plant symbioses. Studies on AMF conducted during the last few decades envisaged their occurrence in a wide variety of hosts, and different habitats, and have reported variability in their quality and quantity [24,85,86]. Prasad and Kaushik [87] have described the ecology, physiology, biochemistry, and taxonomy of mycorrhizal fungi. During the last few decades, mycorrhizae have been frequently applied in many trees, crops, and ornamental plants worldwide. Mycorrhiza increases by 20-50% yield and enhances the uptake of especially P, K, Zn, S, Fe, Cu, and water. Even, it can survive in harsh conditions in soil ecosystems. AMF is usually inoculated to seedlings, coated on seeds as well as directly applied to the soil. Moreover, AMF is applied for re-vegetating wasteland, and for the management of plant diseases and pests [88,89].

Arbuscular Mycorrhizal Fungi										
Beneficial Relationships	**Aculospora scrobiculata**	**Rhizophagus intraradices**	**Rhizophagus fasciculatum**	**Glomusetunicatum**	**Glomus aggregatum**	**Gigaspora margarita**	**Gigaspora decipiens**	**Funneliformis geosporus**	**Funneliformis mosseae**	**Scutellospora heterogana**
Plant Nutrition Attributes										
Increased Phosphorus (P) uptake	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increased Nitrogen (N) uptake	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Access Organic forms of N and P	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increased Potassium (K) uptake	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N, P, Ca, K, Mg, Fe, Mn, maximum accumulation in root & Shoot	Yes	Yes	Yes	Yes	-	Yes	-	Yes	Yes	-
Zn maximum accumulation in root	-	Yes	Yes	Yes	Yes	-	-	Yes	Yes	-
Increased Micronutrient (Fe, Zn, Ca, Mn, Cu, S, Mg, B) uptake	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increase P, N, Zn, B maximum uptake in the shoot	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increase photosynthetic activity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
High levels of Enzyme Activity Benefiting Nutrient and Micronutrient Acquisition	Yes	Yes	-	Yes	-	Yes	-	Yes	Yes	Yes
Tolerant of High Fertility Levels	-	Yes	Yes	-	Yes	-	Yes	Yes	-	-
Extracts minerals from long distances from the root systems (beyond 8 cm)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increases Mineral Uptake	Yes	Yes	Yes	Yes	-	Yes	-	Yes	-	-
Effective Root Colonization with time-release Fertilizers	-	Yes	Yes	-	Yes	-	Yes	-	Yes	Yes
Plant Growth and Its Establishment										
Increased Feeder Root Systems	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Improved Plant Establishment	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes
Increased Immune power of the Crop	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Increases Production of Vegetable Crops	Yes	Yes	Yes	-	-	-	-	-	Yes	Yes
Increases Crop Yields	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Very Effective in Agricultural soils	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes
Improved Growth of Grain Crops	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	-
Improved Growth of Tropical and Sub-tropical Fruits	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Improved Performance of Woody Perennials	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes
Increases Fruiting and Flowering	Yes	Yes		Yes		Yes	Yes	Yes	Yes	Yes
Improves Plant Performance in Sandy Soils	-	-	-	-	Yes	-	-	-	-	-
Improves Performance of Palms and Fruit Trees	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes	-	-

Improves Growth and Performance of Turf Grasses, Agricultural Crops and Nursery Stock	-	Yes	Yes	Yes	-	-	Yes	-	Yes	Yes
Well-adapted to a Wide Variety of Plants and Soil Conditions	Yes	Yes	Yes	-	-	-	-	-	Yes	Yes
Enhances Crops product Quality	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes
Enhance Seed's minerals and Vitamins	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes
Suppression of plant pathogens and root diseases										
Stimulates Root Development	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes
Keeps Root Systems Healthier	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes	Yes
Nematode Protection of Roots	-	Yes	-	Yes	-	-	-	-	Yes	Yes
Promotes Disease Suppression	Yes	Yes	Yes	Yes	-	Yes	Yes	Yes	Yes	Yes
Effectively Suppressed Verticillium wilt	-	-	Yes	Yes	-	-	-	-	Yes	-
Heat and Drought Tolerance										
Active during periods of low water availability	Yes	Yes	Yes	Yes		-	Yes	Yes	Yes	Yes
Greatly improves drought tolerance	Yes	Yes	Yes	Yes		-	Yes	Yes	Yes	Yes
Drought protection of crops	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes
Soil Physical and Chemical Conditions										
Protects Against Heavy Metal Toxicity	-	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes
Effective in Mine Reclamation	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes
Salt Tolerance	Yes	Yes	Yes	Yes		-	-	Yes	Yes	Yes
Tolerance in Plants Growing on Cr Contaminated Soils	-	Yes	Yes	Yes			-	Yes	Yes	Yes

Table 3: AM fungi Potential Attributed and Their Beneficial Relationship with Land Plants.

Mycorrhizae for Plant Growth

Mycorrhizae play a positive role in phosphate uptake by plants (Table1). In most soils, a large part of P is held in mineral lattices and therefore, is not immediately exchangeable with ions in soil solution. The massive synthesis of cytoplasm is proportional to the increase in plasmalemma area in the arbuscular region. Roots of mycorrhizae-inoculated plants generally uptake more P from soil. When a phosphate threshold is reached, only mycorrhizal roots are able to absorb P from soil [33,35,81,90,91]. However mycorrhizal plants do not gain access to insoluble P in soil. Currently, it has been made clear that replenishment of the supply of P from distant soil (beyond the 8 cm distance from roots) to root surfaces being low, the mycorrhizal hyphae, having an organic connection with the root, extend to this distance and absorb P [35].

This arbuscular mycorrhizae-mediated phosphate transport takes place in three phases namely uptake by fungal hyphae in soil, movement to hyphae inside the root cortex, and release in the host plant. Usually, the fungus uptake P from the soil in the form of orthophosphate ions from the labile pool, and its translocation to the root is believed to take place mainly by cytoplasmic streaming of polyphosphate granules in the vacuoles of the mycorrhizal fungus. Whereas, examining the role of AMF to utilize various less available P sources, such as rock phosphate, several studies [92], have reported that possibly due to greater physical contact between phosphate particles and hyphae, than between host roots and these particles, more P become available to mycorrhizal plants [93-98]. Currently, mycorrhizae are being considered a system of diverse importance in agriculture. Their effects in causing shifts in chlorophyll and plant hormone gradients, resistance to water stress, and decreased leakage of electrolytes from injured or diseased cells are gaining importance and drawing the attention of scientists [99-103]. Scientists observed enhanced and improved productivity for various crops when infected with different species of AMF. Moreover, the rotation of crops influences the stability of mycorrhizal flora in soil ecosystems.

The importance of AMF as a tool for improving growth and productivity in diverse groups of plants was recognized only after the work of Baylis [104] and Mosse [105]. However, during the last five decades, a lot of information has been gathered about the taxonomy, ecology, physiology, and anatomy of AM fungi and their relationship with the hosts, especially with reference to the uptake of water, phosphorous and other macro and micronutrients, hormone production, wasteland management, and control of diseases [29,30,106-111]. Currently, attempts are being made to cultivate them in culture and use them in different plant production systems [75,112-115].

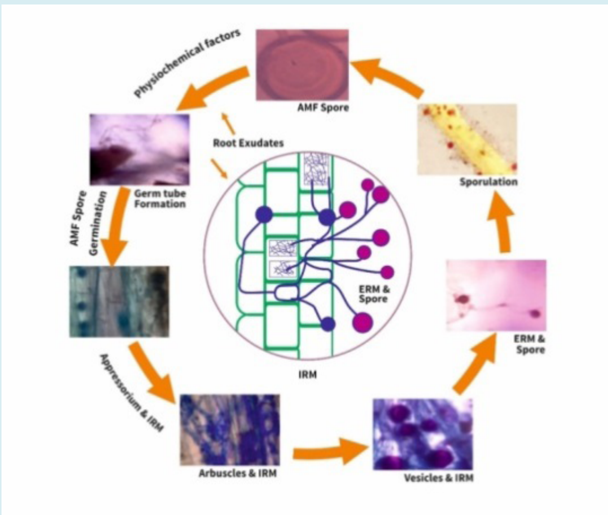

Figure 2: Structural characterization and development of AM Fungal infection within the host cell and their life cycle in the soil ecosystem.

As Bio Pesticides

Biopesticides are certain types of pesticides derived from natural organisms, such as bacteria, fungi, viruses, or protozoans. Microbes are the active ingredient of biopesticides. Biological pesticides can control many different types of pests, but the individual active ingredients are relatively specific to the target pest. Microbes found in the soil are not so friendly to plants. These pathogens can cause disease and damage plants. Biopesticides are generally inherently less toxic than traditional pesticides. They usually only affect organisms closely related to the target pest. Biopesticides are effective in very small quantities and decompose quickly, resulting in lower exposures, and largely avoiding pollution problems. They critically reduce the use of conventional pesticides, and crop yields are high after the application of biopesticides. The major group of microbes used as biopesticides include bacteria genera, *Chromobacterium, Pseudomonas,* and *Yersinia*, fungal genera *Beauveria, Paecilomyces, Verticillium, Hirsutella, Metarhizium*, and *Lecanicillium* and nematodes belonging to the genera *Steinernema* and *Heterorhabditis* [116-118].

As Bio Herbicides

Weeds are a problem for humans, animals, and the environment. Not only do they compete with crops for water, nutrients, sunlight, and space, but they also act as a breeding ground for insects and pests, clog irrigation and drainage systems, affect crop quality, and store weed seeds in crops. Bioherbicides are an environment-friendly alternative to harmful and chemical pesticides. The microbial population of herbicides is defined as bioherbicides that can control weeds. Bioherbicides are another way of controlling weeds without the environmental hazards posed by synthetic herbicides. In this approach, indigenous plant pathogens isolated from weeds are cultured to produce a large number of infected propagules which are applied at a rate that could cause a high level of infection leading to suppression of the target weed. It is estimated that there are over 100 plant pathogens that have or are under evaluation for their potential as bioherbicides. These include fungi and bacteria that cause foliar diseases, soilborne fungi, bacterial pathogens, and deleterious rhizobacteria. Bio herbicide compounds are derived from microbes such as bacteria, protozoa, fungi, mites, and other biological agents to kill weeds, insects, and pathogens. Biological herbicides are available in the form of some suspensions which are biodegradable and show no effect on the environment. Microorganisms have invasive genes that attack the weed's defense genes, allowing them to kill the weed. The benefit of using bioherbicides is that they can survive in the environment long enough for the next growing season when there will be more weeds to infect. Because they are cheaper than synthetic pesticides, they have the potential to significantly reduce agricultural costs. Bioherbicides are not harmful to the environment compared to conventional herbicides.

As Bio insecticides: Presently, the world population heavily depends on the agricultural production of plants and animals for daily food needs. Without this food source, many of us would not be able to survive. Pests are common in agriculture, and we use special substances called pesticides to control or kill them. Bioinsecticides are made from natural living microorganisms (bacteria, fungi viruses, etc.) found in nature. Insect pests are most dangerous for agricultural crops and lead to a reduction in crop productivity. Bioinsecticides can help in developing alternative controls to synthetic insecticides to fight against insect pests. There are microbes in the soil that attack fungi, viruses, or bacteria, which cause root diseases. Bioinsecticide coatings on the seed which carry these beneficial organisms can be developed to protect the plants during the critical seedling stage. Biological pesticides do not persist long in the environment and have a short shelf life. It is effective in small quantities, and safer for humans and animals compared to synthetic insecticides. They are highly specific, often affecting only a single species of insect, have a highly specific mode of action, act slowly, and the timing of their application is relatively critical. Fermentation technology is used for the mass production of bioinsecticide. Spores are harvested and packaged as liquid and suitable A powder that can be sprayed after being combined with water to create a suspension is referred to as a wettable powder formulation for application of insect-ridden fields. After spores are applied, they use enzymes to break through the outer surface of the insects' bodies. Once inside the body, they begin to multiply and eventually lead to death. Bioinsecticides have the best potential for long-term insect control compared to conventional insecticides. Such as *Bacillus thuringiensis*, *B. sphaericus* is the potent bioinsecticide [119].

As Bionematicides: Crops are severely damaged by root nematodes, causing significant economic losses worldwide. Nematodes infection is one of the major problems in agriculture and horticulture crops including vegetables. Nematodes cause severe damage to the plant roots, thereby reducing water and nutrient absorption which leads to a decline in crop productivity. Also, the infested plant becomes more susceptible to other stress factors such as heat, water shortage, nutritional deficiencies and plant diseases. It has been observed that the nematode control becomes difficult with the application of common chemical pesticides, therefore biological nematicides have been suggested as the better option for the control of plant pathogenic nematode pests that infects agricultural crops*. Pasteuria pentrans* [120] *Bacillus subtilis, B. cereus, B. pasteurii, B. amyloliquefaciens, B. mycoides, B. pumilus, B. sphaericus, P. fluorescence, Rhizobium leguminosarum, P. putida, S. marcescens can provoke ISR* [121]. Important fungi that parasitize nematodes and reduce their population include *Aspergillus niger, Paecilomyces lilacinus, Trichoderma harzianum, Arthrobotryso ligospora, and Paecilomyces lilacinus* [122].

The term bio-compost means plant matter (waste of the sugar industry) that has been decomposed and recycled as a fertilizer or manure. Bio-compost is considered a key ingredient in organic farming. It is very rich in nutrients. The process of bio-composting is done by simply piling up waste in the field or any outdoor place and then leaving it undisturbed for three to six months or more. The modern-day bio-composting process has many steps like monitoring the composting at regular intervals. The plant waste is decomposed using several human and plant-friendly bacteria and fungi. It is usually done by shredding the plant matter, adding sufficient water to maintain proper moisture level, and then regularly turning the mixture to provide better aeration. The addition of worms and fungi helps in the process of decomposition. They break up the complex compounds into simpler ones and during the process, lots of heat, carbon dioxide, and ammonium are produced. This ammonium is recycled by microorganisms and made available to plants as nitrite and nitrate. Bio compost consists of nitrogen, phosphate-solubilizing bacteria, and plenty of useful decomposing fungi. This biofertilizer helps the farmers to improve the physical structure, enriches the soil with helpful microbes, increases soil fertility, and improves water holding capacity, thereby increasing the crop's growth, shoot and root biomass, and productivity. Soil-borne pathogens are observed to be suppressed after the application of organic amendments. Moreover, bio-compost in the ecosystems is very useful for controlling soil erosion, constructing wetlands, and using them as landfill cover.

Beneficial and Effective Microorganisms: A New Dimension for Green Technology

Generally, microbiologists consider that the number of soil microbes can be improved by applying organic amendments to the soil. It is commonly true because most soil microbes are heterotrophic. They require complex organic molecules of carbon and nitrogen for metabolism and biosynthesis [123]. Applications of organic inputs (seaweed, microbes, organic fertilizers, fish meal, crushed crab shells, etc.) not only help to balance the micronutrient content in soil but also increase the population of beneficial antibiotic-producing actinomycetes. It changes the soil to a disease-suppressive condition within a relatively short period. Beneficial microbes are predominant in organic farming or natural farming methods; however, their function will depend on the ecosystem and environmental conditions. It can take several hundred years for various species of higher and lower plants to interact and develop into a definable and stable ecosystem [27,124]. The ultimate goal is to select microorganisms that are physiologically and ecologically compatible with each other and that can be introduced as consortium cultures into the soil where their beneficial effects can be realized [14].

Conclusion and Future Prospective

The soil microbial community functions in several biogeochemical processes that are fundamental to soil development and plant growth. With an extensive literature assessment, it can be concluded that the microbes are utilized in agriculture and forestry for various purposes. A significant consideration in the application of useful microbes to soil is the optimization of their synergistic properties. Beneficial microbes become effective after inoculation into the soil, their initial populations must be maintained at a certain critical threshold level. The highest reliable approach is to inoculate the soil with favourable microorganisms as part of a mixed culture, at a sufficiently high inoculum density to maximize the potential for modification to environmental and environmental conditions. There is an increasing global trend of organic farming which encourages the application of biofertilizers and bio-pesticides to assist plant growth and control weeds, pests, and diseases. Amidst the growing concerns of environmental deterioration, going green is probably the only way out for environment-friendly sustainable agriculture and maintaining the natural properties of the soil. Optimizing the application of microbial fertilizers or inoculants is possibly the pertinent strategy for the efficient utilization of natural resources ensuring the sustainability of the natural resources and ecosystems. This approach will be suitable for agriculturalists, forestry practitioners, and organic nutritive crop growers with their low-input farming practices and simultaneously help to improve soil health and preserve the environment for the present and future generations.

Conflict of Interest

Authors have no conflict of interest.

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