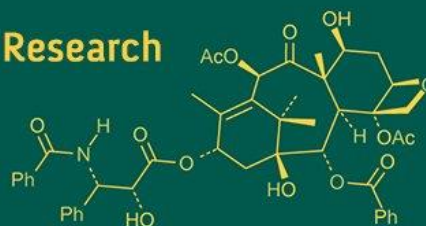
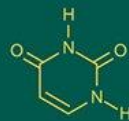
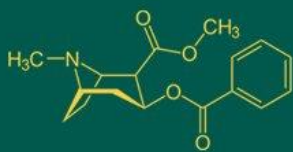


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Biofertilizers and microbial amendments for soil fertility enhancement

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Abstract

Biofertilizers and microbial additions are environmentally friendly alternatives to synthetic fertilizers that make use of beneficial soil microbes to improve soil fertility, nutrient availability and crop yield. This thorough overview summarizes the developments in biofertilizer research and practice. We describe the mechanisms of microbial enhancement of soil fertility including nitrogen fixation (symbiotic and free living), solubilization of soil phosphorus and potassium, chelation of micronutrients (via siderophores and organic acids), synthesis of plant hormones and suppression of pathogens through competition or antibiotic production. The main types of biofertilizers are rhizobia (symbiotic with legumes), free living diazotrophs (*Azotobacter*, *Azospirillum*), phosphate solubilizers (*Bacillus*, *Pseudomonas*, fungi like *Penicillium*), arbuscular mycorrhizal fungi (*Glomus*, *Rhizophagus* spp.), cyanobacteria (*Anabaena* in *Azolla*), PGPR (*Pseudomonas*, *Bacillus*, *Serratia*, *Azospirillum*) and engineered consortia. Formulation and manufacturing options are reviewed, from carrier based (peat, charcoal, vermicompost) inoculants to liquid broths and advanced polymer/nanoparticle encapsulation, with discussion of viability, shelf life and quality control. Application methods (seed coating, soil drench, root dipping, foliar sprays and integrative practices) are surveyed along with environmental and agronomic impacts. Multiple Meta analyses and field trials demonstrate yield improvements (often 10-30%) and enhanced nutrient use efficiency, especially under nutrient limited or arid conditions, as well as benefits to soil organic matter and structure. We discuss regulatory aspects (eg Indian FCO, EU fertilizer regulation), safety aspects (strain selection to exclude pathogens, routine testing), and social aspects of adoption (farmer awareness, extension help, market access). Finally, gaps in knowledge are identified (e.g. variability in field performance, understanding of microbe-plant specificity, effect of life cycle) and directions for future research are suggested, including advanced microbial screening (genomics, synthetic biology), tailored consortia and integration with sustainable farming systems. This analytical analysis highlights the potential of biofertilizers as a contributor to sustainable soil fertility management but also highlights problems that need to be overcome.

Keywords: *Azolla*, PSPP, bio fertilizer, yield, legumes

Introduction

Soil fertility is a key factor that determines agricultural output and has been historically maintained by using synthetic fertilizers. Chemical fertilizers, however, have poor usage efficiency, cause environmental contamination (eutrophication of water bodies, greenhouse gas emissions) and destroy soil biota over time ^[1]. On the other hand biofertilizers live preparations of helpful microorganisms provide an environmentally friendly technique to increase nutrient availability and soil health. These include nitrogen fixing bacteria (symbiotic or free living), phosphate solubilizing microorganisms, mycorrhizal fungi, cyanobacteria and other plant growth promoting rhizobacteria (PGPR) ^[2]. Applied to seeds, soils or organic amendments, these inoculants colonize plant roots or soil niches and induce natural processes such as fixing atmospheric N₂ into plant usable ammonia, solubilizing insoluble phosphates and mineral compounds, mobilizing potassium and micronutrients, producing phytohormones (IAA, gibberellins) and improving plant stress tolerance. Biofertilizers may replace certain chemical inputs and increase yields (particularly when inputs are minimal), and help to making agriculture more sustainable and climate resilient by enhancing the soil microbiome. The present study synthesizes available information on history, methods, kinds, manufacture, use and effects of biofertilizers ^[3].

Biofertilizers are the combination of traditional knowledge and current science. Early agriculture accidentally utilized biofertility by using crop rotations and manures. Evidence points to the adoption of legume-cereal rotations thousands of years ago to boost yields, suggesting nitrogen replenishment in soils. Systematic knowledge started in the 19th century: chemist Jean Baptiste Boussingault, in 1838, found that legume-rich soils improved crop growth, indicating atmospheric N₂ supply [4]. In 1886, key tests by Hermann Hellriegel and Hermann Wilfarth showed that legume root nodules fixed atmospheric nitrogen and maintained plant development without supplemental fertilizer. Beijerinck (1888) isolated the root nodule bacterium (later called *Rhizobium*) and proved it to be the microbial agent [5]. The first peat based *Rhizobium* inoculant “Nitragin” was launched by German business Nobbe & Hiltner in 1896, which gave birth to biofertilizer technology. By the turn of 20th century several strains of *Rhizobium* were found for different legumes and free living diazotrophs such *Azotobacter chroococcum* were discovered (Beijerinck, 1901) as possible non symbiotic N fixers [6].

Mechanisms of Soil Fertility Enhancement

Beneficial microbes improve soil fertility through multiple, often complementary mechanisms:

Biological Nitrogen Fixation (BNF): Some bacteria can convert atmospheric N₂ to ammonia. *Rhizobium* (and other species such as *Bradyrhizobium*, *Mesorhizobium*) colonize nodules on legume roots in symbiosis and fix high amounts of N₂ (usually 50-300 kg N/ha season). Free dwelling diazotrophs (e.g. *Azotobacter*, *Azospirillum*, *Gluconacetobacter*, *Frankia* and cyanobacteria such as *Nostoc*) fix nitrogen without nodules, although generally at lower rates (10-50 kg N/ha). They use an enzyme (nitrogenase) that has high energy to make NH₃ that adds to plant nitrogen feeding [7, 8].

Phosphorus Solubilization: Many biofertilizer bacteria produce organic acids (gluconic, citric, oxalic acid) or enzymes (phosphatases) which solubilize bound soil phosphates. For example, *Bacillus megaterium*, *Pseudomonas fluorescens*, *Enterobacter*, *Aspergillus* and *Penicillium* species may solubilize rock phosphate and other insoluble P compounds to soluble orthophosphate. This improves the availability of P and typically leads to considerable savings of chemical P fertilizers (studies show that PSB may replace ~30-50 kg P₂O₅/ha) [9].

Potassium Mobilization: Plant micronutrients like iron, zinc, copper and manganese may be chelated in insoluble forms. Iron (and other Metals) are chelated by siderophores (Fe chelating compounds) produced by rhizosphere bacteria making them more accessible to plants. For example, *Pseudomonas putida* secretes pyoverdine which enhances Fe absorption while bacterial organic acids may mobilize Zn and Mn. Enzymatic oxidation may also liberate Zn, Cu, S from organic or mineral compounds via microbial action [10].

Micronutrient Chelation: Many PGPR produce plant hormones such as indole 3 acetic acid (IAA), gibberellins, cytokinins and abscisic acid analogs. These hormones encourage root elongation, branching and root hair formation to help take up water and nutrients. For example,

Azospirillum brasilense secretes potent auxins and results in a well developed root system. Smaller roots or more early growth might lead into larger harvests [11].

Phytohormone Production: Many PGPR produce plant hormones such as indole 3 acetic acid (IAA), gibberellins, cytokinins and abscisic acid analogs. These hormones promote root formation and branching, and the growth of root hairs, hence improving the absorption of water and nutrients. One example is *Azospirillum brasilense*, a species recognized for its robust auxin production, resulting to denser root systems. This may result in increased yields from smaller roots, or quicker early development [12].

Enzymatic Nutrient Cycling: Soil bacteria catalyse the degradation of organic materials, mineralising nutrients (ammonification, nitrification, sulphur oxidation). Enzymes like nitrogenase (for N₂), urease, proteases, phosphatases and cellulases result from microbial Metabolism. Biofertilizer bacteria accelerate cycling of organic nitrogen and release ammonium and nitrate, thereby increasing the amount of N accessible to plants. Likewise, microbial phosphatases mineralize organic P molecules [13].

Biocontrol and Stress Alleviation: Indirectly, biofertilizers enhance plant health by inhibiting soil diseases and pests. Some strains emit antibiotics (2,4 diacetylphloroglucinol by *Pseudomonas*, lipopeptides by *Bacillus*, etc.) or volatile chemicals (hydrogen cyanide by *Pseudomonas*, *Bacillus*) that inhibit soil borne fungus and bacteria. Others generate systemic resistance in plants, predisposing them for disease. Furthermore, the enhanced root vigor (via hormones or mycorrhizal symbiosis) assists plants in tolerating abiotic challenges (drought, salinity) by improving water and nutrient absorption [14].

Soil Structure Improvement: The action of microbes improves soil aggregation and porosity. Mycorrhizal fungus add glomalin (a glycoprotein) that cements soil particles and increases aggregate stability. Bacterial biofilms and fungal hyphae produce channels in soil and enhance aeration and water penetration. These impacts may enhance the organic carbon of the soil and its overall fertility over time [15].

Collectively, these strategies provide a more productive, biologically active soil environment. For example, inoculation with rhizobia not only contributes N but also has favorable side effects: rhizobia create siderophores and phytohormones, and cause nodulated plants to fix N year after year, improving soil N pools. Likewise, phosphate solubilizing microorganisms turn the normally lost rock phosphate into plant nutrition, therefore increasing fertilizer usage [16]. In consortia microorganisms may function additively or synergistically. E.g. a bacterial consortium of N fixer + PSB + mycorrhizal fungus can frequently out perform any single strain. Importantly, biofertilizers minimize the requirement for high chemical fertilizer rates, therefore reducing greenhouse gas emissions (reduced N₂O from fertilizer) and reducing leaching losses that contribute to eutrophication [17].

Types of Microbial Biofertilizers

Biofertilizers are categorized by the beneficial traits and microbial taxa involved. Major types include symbiotic nitrogen fixing bacteria, free living diazotrophs, phosphate

solubilizers, mycorrhizal fungi, cyanobacteria, and other PGPR. Each type is briefly described below, with representative organisms and functions ^[18].



Fig 1: Root nodules (pinkish bumps) on clover roots formed by nitrogen fixing *Rhizobium* bacteria

Rhizobia (Legume symbionts): Rhizobia are Gram negative bacteria (*Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Mesorhizobium*, etc.) that establish mutualistic partnerships with legumes (beans, peas, clover, alfalfa, peanut, soybean). Most legume species need a suitable strain of *Rhizobium* ^[19]. They infect root hairs and generate nodules, specialized organs in which the rhizobia fix N₂ upon inoculation. The plant provides the bacteria with carbohydrates and gets ammonia in exchange. Rhizobial inoculants may provide 50-300 kg N ha⁻¹ to legume crops hence greatly lowering fertilizer N demands. In addition to N fixation, certain rhizobia generate auxins or siderophores ^[20]. Certain strains show mild biocontrol properties. Effective rhizobial inoculants are commonly employed for pulses (chickpea, pigeon pea, lentil), oilseed legumes (soybean, peanut) and forage legumes (alfalfa, clover) ^[21].

Free Living Diazotrophs (*Azotobacter*, *Azospirillum*, etc.): These bacteria do not need plants to fix nitrogen.

Azotobacter spp. (aerobic, motile rods) found in neutral to alkaline soils; fix 20-40 kg N/ha in the rhizosphere of non-legumes (wheat, maize, vegetables); also create growth hormones and antibiotics that inhibit fungi. *Azospirillum* species are microaerophilic, spiral shaped bacteria (e.g. *Azospirillum brasilense*, *A. lipoferum*) that colonise the roots of cereals and grasses (maize, sorghum, millets) ^[22]. They provide a little quantity of N (10-30 kg/ha), but are appreciated for their ability to stimulate root development via the production of phytohormones (auxins, gibberellins) and improve water and nutrient absorption. Other free living N fixing organisms include *Gluconacetobacter diazotrophicus* (sugarcane endophyte) and *Clostridium* (anaerobic N fixers) ^[23].

Phosphate Solubilizing Microorganisms (PSMs): These include bacteria and fungi which may release phosphorus from insoluble phosphates. Common bacterial genera include *Bacillus* (e.g. *B. megaterium*, *B. circulans*), *Pseudomonas* (e.g. *P. striata*), *Enterobacter*, *Serratia*, and *Burkholderia*. certain fungal solubilizers include *Aspergillus niger*, *Penicillium bilaiae*, and certain *Streptomyces* ^[25]. PSMs release organic acids (gluconate, malate, oxalate) to chelate Ca/Mg and acidify the microenvironment to dissolve rock phosphates or bound soil P. Plants may double the efficiency with which they take up phosphorus; production increases (typically 10-20%) are observed in crops such as wheat, maize and legumes when P solubilizers are administered. Other formulations combine PSBs with N fixers for multi-nutrient advantages ^[26].

Arbuscular Mycorrhizal Fungi (AMF): AMF (phylum *Glomeromycota*; e.g. *Glomus intraradices*, *Rhizophagus irregularis*) develop symbioses with ~80% of terrestrial plants. Fungal hyphae invade the root cells of the cortex to create arbuscules (branched feeding structures) and vesicles (storage) ^[27]. These interactions increase the effective root system and enhance the absorption of immobile nutrients (in particular phosphorus, but also Zn, Cu, S) and water. AMF may provide 5-20% of plant P in low P soils. They are obligate biotrophs (cannot be cultivated readily in pure culture). Commercial inoculants usually incorporate soil/peat with spores. Farmers employ AMF inoculants in horticulture, forestry and sustainable agriculture. Effects on production are frequently site dependant but consistently increase soil structure and long term fertility ^[28].

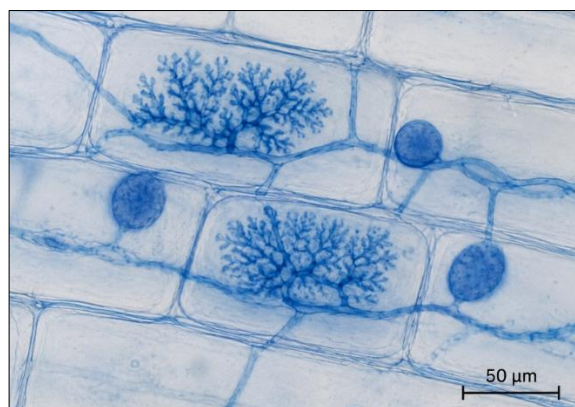


Fig 2: Microscopic image of arbuscular mycorrhizal structures (blue) inside plant root cells.

Other Plant Growth-Promoting Rhizobacteria (PGPR): This large group comprises non nodulating bacteria that colonize the rhizosphere and promote growth by different ways. Important genera include *Bacillus*, *Pseudomonas*, *Enterobacter*, *Burkholderia*, *Serratia* and *Acetobacter*. For example, *Bacillus subtilis* and *Bacillus licheniformis* may solubilize phosphate, generate IAA and release lytic enzymes to control the infections [29]. *Pseudomonas fluorescens* strains are known to produce siderophores and compounds with antibiotic activity. Some N may be contributed by *Enterobacter* and *Klebsiella* (diazotrophs). Fungal PGPR *Trichoderma harzianum* (biocontrol fungus, also stimulates roots) PGPR inoculants may typically boost seed germination, nutrient absorption and stress tolerance in a variety of crops (vegetables, cereals, fruits) [30].

Cyanobacteria and Algal Biofertilizers: Cyanobacteria (blue green algae) as *Anabaena*, *Nostoc* and *Oscillatoria* are employed mainly in wetland rice. Strains fix 20-30 kg N/ha

and excrete it into flooded soils, and create growth hormones. Cyanobacterial inoculation by straw or algal sludge (e.g., *Anabaena azollae* in *Azolla* ferns that grow on water surfaces) is well known in rice fields in Asia. *Azolla* (a fern with endophytic *Anabaena*) may be used as green manure and can provide up to 60 kg N/ha when added before transplantation [31].

Biofertilizer Consortia: It is realised that no single strain can meet all the requirements of a plant and so the biofertilizers of today often include mixed cultures. For example, an inoculant may include a *Rhizobium*, a PSB and a mycorrhizal fungus to provide N, P and micronutrients together [32]. Formulations may also be a combination of PGPR and organic amendments (vermicompost enhanced with microorganisms) or employ seed coatings with various bacteria. These consortia may have additive effects, e.g., maize yield may rise higher with an *Azospirillum* +PSB combination than with either alone [33].

Table 1: Microbial taxa and their beneficial functions [34, 35, 36, 37, 38, 39]

Microbe (Genus/Species)	Functions and Benefits
<i>Rhizobium</i> (e.g. <i>R. leguminosarum</i>)	Symbiotic N ₂ fixation in legumes (root nodule formation, ~50-250 kg N/ha). Contributes to legume N nutrition and soil N.
<i>Bradyrhizobium</i> (e.g. <i>B. japonicum</i>)	Legume symbionts for soybean, peanut etc. Efficient N ₂ fixation; some strains solubilize phosphate.
<i>Azotobacter chroococcum</i>	Free living N ₂ fixation (~20-40 kg N/ha); produces antibiotics; promotes cereals, pulses.
<i>Azospirillum brasilense</i>	Associative N ₂ fixation (10-20 kg N/ha) and phytohormone (IAA) production; enhances root growth in cereals (maize, sorghum).
<i>Frankia</i> (e.g. <i>F. alni</i>)	Symbiotic N ₂ fixation in actinorhizal plants (e.g. alder trees), ~100-200 kg N/ha benefit.
<i>Gluconacetobacter diazotrophicus</i>	Endophytic N ₂ fixer in sugarcane and other crops; 10-30 kg N/ha. Also produces vitamins.
<i>Bacillus megaterium</i>	Solubilizes phosphorus (and zinc); produces growth hormones. Enhances P uptake in cereals/legumes.
<i>Pseudomonas fluorescens</i>	Phosphate solubilizer, siderophore producer (Fe chelation), antifungal antibiotics. Biocontrol agent in many crops.
<i>Bacillus subtilis</i>	Produces lytic enzymes, antibiotics (biocontrol), IAA; some strains fix N ₂ and solubilize phosphate. Used on vegetables.
<i>Pseudomonas putida</i>	Siderophore mediated Fe uptake, phosphate solubilization, biocontrol against pathogens (e.g. <i>Fusarium</i>).
<i>Penicillium bilaiae</i>	Fungal phosphate solubilizer; enhances P availability in alkaline soils, especially for soybean, corn.
<i>Glomus/Rhizophagus intraradices</i>	Arbuscular mycorrhizal fungus; extends root for increased P, Zn uptake (~10-30% more P), improves drought resistance.
<i>Nostoc/Anabaena</i>	Cyanobacteria (rice paddies); fix N ₂ (20-30 kg N/ha) and release ammonia; also produce growth regulators.
<i>Bacillus thuringiensis</i> (non Bt)	Although known as a biopesticide, some Bt strains can promote plant growth via enzyme secretion (not primary N fixer).
<i>Trichoderma harzianum</i>	Fungal PGPB; suppresses soil pathogens via antibiosis; induces plant resistance; enhances root growth.
<i>Serratia marcescens</i>	Produces IAA, solubilizes P, and biocontrol Metabolites; benefits rice, legumes.

Formulation and Production of Biofertilizers

Producing an effective biofertilizer requires culturing beneficial microbes and formulating them into stable products. Key steps and methods include:

Culture and Fermentation: Microbial strains are being cultured under sterile or regulated circumstances. Nitrogen fixing organisms such as *Rhizobium* and *Azotobacter* may be mass cultured on specified medium (usually yeast extract mannitol broth) including carbon sources (sucrose, mannitol). The active strains of phosphate solubilizers may be selected in medium containing insoluble phosphate [40]. Liquid fermentation produces a high cell density broth (10⁸ -10⁹ CFU/mL) that may be condensed or blended with carriers. Solid state fermentation involves growing microorganisms on a solid substrate (peat, sawdust, charcoal) and is beneficial for fungi such as *Trichoderma* and AMF (cultured with host roots

or spores). After culture, bacteria are mixed with carriers to make inoculant formulations [41].

Carriers and Dry Formulations Typical carriers include peat moss (high cation exchange), lignite (coal), vermiculite, perlite, charcoal or compost. A typical peat carrier inoculant contains 80-90% moisture to facilitate life of microbes [42]. Microbes are absorbed or blended with the carrier, e.g. a peat based *Rhizobium* inoculant is created by mixing peat with a *Rhizobium* broth to obtain ~10⁸ CFU/g. Other carriers are utilized for the preparation of dry powders: diatomaceous earth, talc powder, zeolites. Dry formulations have a lengthy shelf life if kept wet and cold (typically 9-24 months at 4-25°C) [43].

Liquid and Granular Products. The majority of current biofertilizers are liquid formulations (broths with stabilizers). They are simple to apply but have a limited shelf life (6-12

months) if preservatives/glycerol are not added. Slow release of microorganisms in soil from granular (polymer or clay beads) Seed coating adhesives (gum Arabic, molasses) are used to attach bacteria to seeds in seed applied inoculants [44].

Microencapsulation and Nanoformulations: Progress includes encapsulation of microorganisms in biopolymers (alginate beads, polysaccharide matrices) to protect against desiccation and for progressive release. Nanobiofertilizers are microorganisms or nutrients encapsulated in nano carriers (such as silver or chitosan nanoparticles) for improving stability and adhesion. These new carriers have the potential to increase viability and field effectiveness, but they will need rigorous testing for safety [45, 46].

Quality Control Parameters: QC is performed to verify effectiveness and safety. Important factors include the number of live cells (generally $\geq 10^8$ CFU / g for solid inoculants, $\geq 10^6 - 10^9$ CFU / mL for liquid), no impurities (no pathogens), pH (usually neutral to slightly alkaline), moisture content (commonly 20-35% in solids) and shelf life under specified storage conditions [47]. For symbiotic inoculants, tests “Nodule forming ability” are used to verify that the strain is still nodulating the host plant. Minimum CFU and shelf life are defined by international standards (ISO 17088) and national regulations (Fertilizer Control Order (FCO) of India) (e.g. *Rhizobium* inoculants should have $\geq 10^9$ CFU/g and be viable for ≥ 1 year) [48].

Application Methods

Implementing biofertilizers in the field involves delivering the microbes to the plant or soil environment. Common application strategies include:

Seed Inoculation (Coating): Biofertilizer is coated on seeds soon before sowing. Peat based powders or liquid inoculants (sometimes with sticker agents) attach bacteria to seed surface. This approach is often employed with legumes (*Rhizobium*) and grains. It ensures rapid root colonization.

Soybeans, for example, are routinely inoculated with *Rhizobium* before planting, generally in combination with a carboxymethyl cellulose or gum arabic sticker. It's easy, but timing is critical (apply inoculant to dried seed so bacteria don't germinate prematurely) and equipment is needed to guarantee even coverage [49].

Soil/Root Application: Application of microbial inoculant (liquid or solid) directly to soil. Liquid formulations may be applied by in furrow drench or with the irrigation water. This is typical for veggies, horticulture and tree nurseries. A microbial slurry is used as root-dip for transplanted seedlings (e.g., rice seedlings or roots of pepper plant as root-dip in suspension of *Azospirillum* before transplanting). Soil drenches may also be applied at certain development phases (e.g. blossoming) [50].

Foliar Sprays: Certain biofertilizer and biostimulant (microalgae suspensions, PGPR in sprays) are sprayed to foliage, although this is less traditional. Foliar inoculation may reduce foliar infections and occasionally improve nutrient absorption (e.g. foliar treatment of algal extracts for micronutrients, or *Bacillus subtilis* to develop systemic resistance) [51].

Co composting/Organic Amendment: Microorganisms are added to composts, manures, or organic granules. While mixing the biofertilizer organisms with the vermicompost or organic slurry, the material becomes decomposed, which gives a slow release. This is the case of organic farming, where the combination of microbial inoculants with farmyard manure or compost brings dual advantages of nutrients and helpful microorganisms [52].

Pellet/Tablet Delivery: Some new products encapsulate microorganisms in alginate or other matrices to create pellets or capsules that may be put in proximity to roots. This delayed release formulation may enhance survivability in tough soils [53].

Table 2: Common biofertilizer formulations and application characteristics [54, 55, 56, 57, 58, 59]

Formulation/Product Type	Key Microbes	Form and Carrier	Target Crops
Peat based <i>Rhizobium</i> inoculant	<i>Rhizobium leguminosarum</i> , others	Powder on peat	Legumes (beans, peas, lentils, alfalfa, clover)
Liquid <i>Azospirillum</i> inoculum	<i>Azospirillum brasilense</i>	Liquid broth	Maize, wheat, sorghum, millet
Charcoal based <i>Azotobacter</i> powder	<i>Azotobacter chroococcum</i>	Dried charcoal/loam	Cucurbits, vegetables, cereals
Phosphate solubilizer (<i>Bacillus</i>)	<i>Bacillus megaterium</i> , <i>B. subtilis</i>	Granules/powder	All crops (especially maize, wheat, legumes)
Mycorrhiza granules	<i>Glomus intraradices</i> (spores)	Vermiculite granules	Vegetables, trees, ornamentals
Phosphobacterin (fertilizer + PSMs)	<i>Pseudomonas</i> , <i>Bacillus</i> spp.	Powder (charcoal/peat)	Wheat, rice, corn
Biofilm coated seeds	Consortium (N_2 fix + PSB + PGPR)	Polymeric film	Maize, rice, soybean
Blended NPK biofertilizer	Mixed rhizo bacteria, <i>Azolla</i> granules	Mixed organo mineral	Rice, wheat
<i>Trichoderma</i> powder granules	<i>Trichoderma harzianum</i>	Rice bran/loam	Nursery seedlings, vegetables
Algal broth for foliar spray	Cyanobacteria (<i>Anabaena</i> , <i>Nostoc</i>)	Liquid	Rice paddies, some vegetables
Microalgae solution (<i>Spirulina</i>)	<i>Spirulina platensis</i> (as biostimulant)	Liquid	Horticultural crops, rice
Nano encapsulated inoculant	<i>Bacillus</i> , <i>Rhizobium</i> , etc.	Nano polymer particles	High value crops (experimental)
<i>Azolla</i> biomass (green manure)	Water fern with <i>Anabaena azollae</i>	Fresh biomass (wet)	Lowland rice

Efficacy Factors

Despite demonstrated benefits, biofertilizer performance can be variable. Factors influencing efficacy include:

Soil Conditions: Microbial survival is influenced by soil pH, texture, moisture and organic matter concentration. Rhizobia like neutral to slightly acid soils, alkaline soils may need limestone AMF are more effective in neutral soils than in

flooded areas. Dry soils may kill the inoculants, whereas excessively moist soils may prefer diseases over the introduced bacteria. Nutrient levels are also important, and ironically, if there is too much accessible P or N, the plant may lose its drive to maintain the symbiosis with the microbes. High soil P may inhibit mycorrhizal colonization or render P solubilizers unnecessary^[60, 61].

Environmental Stress: Microbial activity is affected by temperature and climate. Most of the biofertilizer strains perform well at mild settings (20 - 30 °C). Extremes (cold, intense heat) destroy sensitive cells. Soil application is a key mortality risk due to dessication. Seed coating microbes need enough soil moisture for a short period after planting. Matching inoculant strains to local climate is so crucial. Spore making *Bacillus* may be more adapted to live in hot temperatures; cyanobacteria or aquatic *Azolla* are adapted to tropical flooded fields^[62].

Crop Microbe Compatibility: Each plant species or variety may behave differently to a particular microbe. The legume-*Rhizobium* symbiosis is very particular; a given *Rhizobium* species may nodulate certain legumes but not others. Also, certain PGPR may be more effective on specific cultivars. The inoculant strain must be shown to be compatible with the target crop^[63].

Microbial Strain Quality: The strength of the strain itself is critical. High performing strains (from robust plants or chosen in laboratories) have fixed more N or solubilized more P than local soil strains. Quality control guarantees that the product has right strains (genuine and uncontaminated). For example, if the label states that the inoculant is *Bradyrhizobium japonicum*, it must be the strain specified otherwise no nodulation would happen^[64].

Formulation and Storage: The formulation of the carrier and product may increase or decrease the vitality of microbes. Even a superb microorganism may perish if maintained incorrectly or if the carrier (e.g. excessive ammonia) is harmful. Dessication tolerance may be increased using adjuvants like trehalose (protective sugar) or skim milk. Often improper storage (high temperature, humidity) leads to low CFU counts upon sale, decreasing effectiveness^[65].

Method of Application and Dose: Dose should be sufficient to reach the rhizosphere. If you take too little you won't have much impact. Overdose (extremely uncommon) does not provide any advantage beyond saturation. Uniform application guarantees all plants to benefit. Double inoculation (seed treatment + soil application) may promote nodulation notably in unfavorable soils^[66].

Agronomic Practices: Soil fumigation, pesticides and intensive use of mineral fertilizers might destroy beneficial inoculants. Microbe dispersion is also affected by tillage and irrigation. Best methods include biofertilizers, moderate chemical usage (e.g. 50-70% of required N or P with inoculant), low soil disturbance and no bactericidal sprays around the time of planting^[67].

Environmental and Agronomic Impacts

Field research shows that biofertilizers can significantly affect crop performance and soil health:

Yield and productivity: Meta-analyses and studies show consistent yield benefits with the usage of biofertilizers. Global studies show that crop yields improve around 10 to 30 percent on average above uninoculated controls^[68]. Key discoveries include rice with ~10-20% yield increase by inoculation with *Azolla* or *Rhizobium* (for legumes cultivated in rotation), maize with 5-15% increase with *Azospirillum* + N fertilizer, and wheat with up to 10% with *Azotobacter* or PSB. Vegetable crops frequently show bigger relative growth because of low starting fertility^[69]. These yield impacts result in greater nutrient usage efficiency: plants recover a larger proportion of administered N and P. One Meta study for example indicated that biofertilizers increased nitrogen utilization efficiency (N absorption per unit N applied) by ~20%. Biofertilizer advantages are especially bigger in low input (poor soils, drought) or stressed situations. In high production systems with good fertilization, the marginal benefit is reduced since nutrients are no longer limiting^[70].

Crop Quality: Biofertilizers increase quality indices of crops in many circumstances. Legume crops tend to have greater protein content because of increased N. Sometimes, fruit and vegetables seeded with PGPR show an increased content of sugars or vitamins, perhaps due to an improved absorption of micronutrients. For example, there are reports of enhanced production of tomatoes and soluble solids after *Rhizobium*+PSB therapy. Some biofertilizers (e.g. *Trichoderma*) may enhance plant phytoalexins, therefore boosting the disease resistance and post harvest quality^[71].

Soil Health: Regular application of biofertilizer improves soil fertility. Nitrogen fixing bacteria increase organic N in soils over time. Mycorrhizal networks deposit glomalin, increasing soil organic matter. One research reported combined usage of biofertilizers and organic amendments with a ~0.1-0.3% per year increase in soil organic carbon (SOC)^[72]. Improved soil aggregation and porosity leads to better water retention and less erosion. Microbial variety is typically increased: injected soils have more diverse bacterial and fungal communities, which may further help maintain fertility. One Chinese Meta study indicated biofertilizers boosted soil organic matter by ~16%. Healthy soils also recycle nutrients better, completing the circle of sustainability^[73].

Use less fertilizer: Biofertilizers may dramatically cut fertilizer use. Full nodulation of legumes by *Rhizobium* may address all the N demands of a crop, removing the need for synthetic N on certain crops, is often said. *Azospirillum* + 50 - 70% of the typical N rate may replace 100% of the N treatments in yield. In cereal systems. In certain experiments, phosphate solubilizing biofertilizers have been demonstrated to lower P fertilizer requirements by 20 - 50%. Finally, the integrated nutrient management (INM) using biofertilizers and decreased chemical fertilizers is a significant technique for maintaining yields while reducing costs and environmental effect^[74].

Environmental Benefits: Biofertilizers may substitute for certain synthetic fertilizers, therefore reducing greenhouse gas emissions. For example, one estimate is that the use of 30 kilogram urea equivalent via biological N fixation saves ~60 kg CO₂ equivalent per hectare (since N fertilizer manufacture and subsequent field N₂O emissions are significant). Less

leaching of nitrates and phosphates, hence less water contamination. Moreover, many PGPR also contribute moderately to climate mitigation via sequestration of carbon in soil (biomass) ^[75, 76].

Limitations and variability: Field results aren't always favorable. Some experiments show no substantial production impact, particularly in already rich soils or under poor

environmental circumstances. Biofertilizer effects were dependent on environment and soil in Meta analyses: most production improvements were in dry climates and at moderate (not severely low) soil nutrient levels. Therefore, biofertilizers are not a magic wand but an element of a systems approach. Farmers that use these strategies should monitor outcomes in the field and change their procedures accordingly ^[77, 78].

Table 3: Field trial outcomes of biofertilizer application across crops and regions ^[79, 80, 81, 82, 83, 84]

Crop	Region/Country	Biofertilizer Applied	Outcome (Yield increase or effect)
Rice	Philippines	<i>Azolla fern (Anabaena inoculum)</i>	+15-30% yield; supplied ~20-30 kg N/ha
Soybean	Brazil	<i>Bradyrhizobium japonicum</i> inoculant	+18% yield; grain protein +5%
Maize	India (semi arid)	<i>Azospirillum brasilense</i>	+12% grain yield; improved root biomass
Wheat	Iran (arid)	<i>Azotobacter chroococcum</i> + PSB	+10% yield; N fertilizer use reduced by 30%
Tomato	Spain	<i>Bacillus subtilis</i> + PGPR consortia	+20% yield; increased fruit weight and TSS (sugars)
Potato	Netherlands	<i>Pseudomonas fluorescens</i> seed coat	+8% tuber yield; lower bacterial wilt incidence
Cotton	Pakistan	<i>Azospirillum</i> + Phosphate solubilizer	+15% lint yield; soil N/P levels higher
Legume (Peanut)	Senegal	<i>Rhizobium sp.</i> inoculant	+25% pod yield; significant reduction in N fertilizer needed
Cucumber	USA	<i>Trichoderma harzianum</i> root dip	+18% yield; reduced fungal disease symptoms

Conclusion

Biofertilizers and microbiological supplements are an important step towards sustainable agriculture. They boost soil health by microbes and minimize dependence on chemical fertilizers and improve nutrient harnessing by natural capacity of soil availability. Our analysis indicates that biofertilizers, when appropriately applied, may substantially enhance crop yields and nutrient usage efficiency (typically 10-30%) and provide long-term environmental advantages, including increased soil organic matter and decreased greenhouse gas emissions. Critical success criteria are selection of the correct microbial inoculant for the crop and environment; high quality formulations; and biofertilizers as part of good agronomic practices. There is potential, but there are also hurdles. Without knowledge of local soil-climate settings, performance in the field may be variable. Further study into microbial ecology, better formulation and end-user education is required. But the worldwide trends (regulatory support, environmental concerns, precision farming) are clearly in favor of an increased usage of biofertilizers. We see breakthroughs such as multi strain consortia, gene edited beneficial bacteria and custom manufactured biofertilizers for particular soils/crops to move the field ahead. In conclusion, biofertilizers and microbial supplements provide an evidence-based and environmentally acceptable approach to restore soil fertility. With concentrated efforts in research, regulation and extension, these living fertilizers may make a considerable contribution to food security and agro ecosystem resilience in the next decades.

References

- Chen J, Luo YQ, Groenigen VKJ, Hungate BA, Cao JJ, Zhou XH, *et al.* A keystone microbial enzyme for nitrogen control of soil carbon storage. *Sci Adv.* 2018;4:eaq1689.
- Gomiero T, David P, Paoletti MG. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Crit Rev Plant Sci.* 2011;30:95-124.
- Kour D, Rana KL, Yadav AN, Yadav N, Kumar M, Kumar V, *et al.* Microbial biofertilizers: bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatal Agric Biotechnol.* 2020;23:101487.
- Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A, *et al.* Biofertilizers: a potential approach for sustainable agriculture development. *Environ Sci Pollut Res.* 2017;24:3315-3335.
- Assainar SK, Abbott LK, Mickan BS, Whiteley AS, Siddique KHM, Solaiman ZM. Response of wheat to a multiple species microbial inoculant compared to fertilizer application. *Front Plant Sci.* 2018;9:1601.
- Mazzola M, Frelich S. Prospects for biological soilborne disease control: application of indigenous versus synthetic microbiomes. *Phytopathology.* 2017;107:256-263.
- Niu B, Wang WX, Yuan ZB, Sederoff RR, Sederoff H, Chiang VL, *et al.* Microbial interactions within multiple strain biological control agents impact soil-borne plant disease. *Front Microbiol.* 2020;11:585404.
- Prajval V, Krishnamoorthi A, Thakur R, Ruchitha T, Kapoor M, Singh A, *et al.* From code to crop: how bioinformatics is transforming crop genomics in modern agriculture and bettering environment. *J Adv Biol Biotechnol.* 2024;27(4):27-49.
- Anushi SS, Krishnamoorthi A, Kumar S, Pareta P, Kalaiselvi P, Sinha G, *et al.* Biotech bounty on verge: GM (genetically modified) crops and the science of sustainable agriculture and horticulture.
- Anushi FD, Krishnamoorthi A, Singh V. Enhancing sustainable food systems through the cultivation of nutrient-rich crops: millets.
- Vejan P, Abdullah R, Khadiran T, Ismail S, Boyce AN. Role of plant growth-promoting rhizobacteria in agricultural sustainability: a review. *Molecules.* 2016;21:573.
- Chamkhi I, Cheto S, Geistlinger J, Zeroual Y, Kouisni L, Bargaz A, *et al.* Legume-based intercropping systems promote beneficial rhizobacterial community and crop yield under stressing conditions. *Ind Crops Prod.* 2022;183:114958.
- Varghese EM, Kour B, Ramya S, Krishna PD, Nazla KA, Sudheer K, *et al.* Rice in acid sulphate soils: role of

- microbial interactions in crop and soil health management. *Appl Soil Ecol.* 2024;196:105309.
14. Ali S, Li DC, Jing H, Ahmed W, Abbas M, Qaswar M, *et al.* Soil microbial biomass and extracellular enzymes regulate nitrogen mineralization in a wheat-maize cropping system after three decades of fertilization in a Chinese Ferrosol. *J Soils Sediments.* 2021;21:281-294.
 15. Mei PY, Dou T, Song XH, Li LY. Control of *Coptis* root rot by combination of *Bacillus cereus* isolate Y9 and other antagonistic microorganisms. *J Plant Pathol.* 2024;106:1295-1309.
 16. Thomas L, Singh I. Microbe-mediated biotic stress signaling and resistance mechanisms in plants. In: Giri B, Sharma MP, editors. *Plant Stress Biology: Strategies and Trends.* Singapore: Springer; 2020. p. 297-334.
 17. Cao MY, Narayanan M, Shi XJ, Chen XP, Li ZL, Ma Y. Optimistic contributions of plant growth-promoting bacteria for sustainable agriculture and climate stress alleviation. *Environ Res.* 2023;217:114924.
 18. Pérez Rodríguez MM, Piccoli P, Anzuay MS, Baraldi R, Neri L, Taurian T, *et al.* Native bacteria isolated from roots and rhizosphere of *Solanum lycopersicum* L. increase tomato seedling growth under a reduced fertilization regime. *Sci Rep.* 2020;10:15642.
 19. Pešaković M, Karaklajić Stajić Ž, Milenković S, Mitrović O. Biofertilizer affecting yield-related characteristics of strawberry (*Fragaria* × *ananassa* Duch.) and soil microorganisms. *Sci Hortic.* 2013;150:238-243.
 20. Singh A, Labanya GSR. Exploring the role of hydrogen in agriculture for machinery, biomass and reducing carbon footprints. *Plant Arch.* 2025;25(1):2852-2863.
 21. Debnath P, Raj R. Optimizing functional genomics and application of root wounding and immersion for enhanced virus-induced gene silencing in plants: a comprehensive review. *Plant Arch.* 2025;25(1):3115-3126.
 22. Krishnamoorthi A, Chaurasia J, Baidya BK, Singh A, Kumar V, Singh A. A comprehensive review on evolution, challenges of models, opportunities in urban farming practices in the world. *J Sci Res Rep.* 2024;30(6):136-156.
 23. Raghuvanshi HR, Kalaiselvi P, Ravindra NR, Kumar V. Biotechnological breakthroughs: paving the path to cleaner and more productive agriculture through bioremediation. *J Adv Biol Biotechnol.* 2024;27(4):119-142.
 24. Bhardwaj R, Kumar M, Kaushal N, Kamboj AD, Krishnamoorthi A, Singh A, *et al.* From lab to bouquet: the biotechnological frontier in modern floriculture for sustainable and resilient flower farming. *J Adv Biol Biotechnol.* 2024;27(2):119-137.
 25. Jain S, Ranganna G, Jadhav PS, Shrivastava U, Sood A, Prasad L, *et al.* Cultivating tomorrow: harnessing gene editing and silencing for precision horticulture. *J Adv Biol Biotechnol.* 2024;27(1):147-160.
 26. Krishnamoorthi A, Salam NK, Kalaiselvi D, KB C, Kumar S, Kumar V, *et al.* Digital sequencing information in agricultural crops: a comprehensive review. *Int J.* 2024;8(8):1404-1412.
 27. Zhang J, Zhuang MH, Shan N, Zhao Q, Li H, Wang LG. Substituting organic manure for compound fertilizer increases yield and decreases NH₃ and N₂O emissions in an intensive vegetable production system. *Sci Total Environ.* 2019;670:1184-1194.
 28. Zhao QY, Ran W, Wang H, Li X, Shen QRR, Shen S, *et al.* Biocontrol of *Fusarium* wilt disease in muskmelon with *Bacillus subtilis* Y-IVI. *BioControl.* 2013;58:283-292.
 29. Sun B, Gu LK, Bao LJ, Zhang SW, Wei YX, Bai ZH, *et al.* Application of biofertilizer containing *Bacillus subtilis* reduced the nitrogen loss in agricultural soil. *Soil Biol Biochem.* 2020;148:107911.
 30. Jin N, Jin L, Wang SY, Li JW, Liu FH, Liu ZC, *et al.* Reduced chemical fertilizer combined with bio-organic fertilizer affects the soil microbial community and yield and quality of lettuce. *Front Microbiol.* 2022;13:863325.
 31. Xiong W, Guo S, Jousset A, Zhao QY, Wu HS, Li R, *et al.* Biofertilizer application induces soil suppressiveness against *Fusarium* wilt disease by reshaping the soil microbiome. *Soil Biol Biochem.* 2017;114:238-247.
 32. Tao CY, Li R, Xiong W, Shen ZZ, Liu SS, Wang BB, *et al.* Bio-organic fertilizers stimulate indigenous soil *Pseudomonas* populations to enhance plant disease suppression. *Microbiome.* 2020;8:137.
 33. Subiramani S, Ramalingam S, Muthu T, Nile SH, Venkidasamy B. Development of abiotic stress tolerance in crops by plant growth-promoting rhizobacteria (PGPR). In: Kumar M, Kumar V, Prasad R, editors. *Phyto Microbiome in Stress Regulation.* Singapore: Springer; 2020. p. 125-145.
 34. Cao Y, Zhang ZH, Ling N, Yuan YJ, Zheng XY, Shen B, *et al.* *Bacillus subtilis* SQR9 can control *Fusarium* wilt in cucumber by colonizing plant roots. *Biol Fert Soils.* 2011;47:495-506.
 35. Rimpika, Anushi, Manasa S, Anusha KN, Sharma S, Thakur A, *et al.* An overview of precision farming. *Int J Environ Clim Change.* 2023;13(12):441-456.
 36. Jain S, Bhujel S, Shrivastava U, Mohapatra A, Mishra G. Advancements in drone technology for fruit crop management: A comprehensive review. 2023.
 37. Liu QM, Meng XH, Li T, Raza W, Liu DY, Shen QR. The growth promotion of peppers (*Capsicum annuum* L.) by *Trichoderma guizhouense* NJAU4742-based biological organic fertilizer: Possible role of increasing nutrient availabilities. *Microorganisms.* 2020;8:1296.
 38. Zhang SS, Raza W, Yang XM, Hu J, Huang QW, Xu YC, *et al.* Control of *Fusarium* wilt disease of cucumber plants with the application of a bio-organic fertilizer. *Biol Fert Soils.* 2008;44:1073-1080.
 39. Guo S, Xiong W, Hang XN, Gao ZL, Jiao ZX, Liu HJ, *et al.* Protists as main indicators and determinants of plant performance. *Microbiome.* 2021;9:64.
 40. Zhang Y, Wang X, Pang G, Cai F, Zhang J, Shen ZZ, *et al.* Two-step genomic sequence comparison strategy to design *Trichoderma* strain-specific primers for quantitative PCR. *AMB Express.* 2019;9:179.
 41. Allende Montalbán R, San Juan Heras R, Martín Lammerding D, Delgado MDM, Albarrán MDM, Gabriel JL. The soil sample conservation method and its potential impact on ammonium, nitrate and total mineral nitrogen measurements. *Geoderma.* 2024;448:116963.
 42. Rao BKR, John B, Wingwafi RW. Comparison of three digestion methods for total soil potassium estimation in soils of Papua New Guinea derived from varying parent materials. *Commun Soil Sci Plant Anal.* 2011;42:1259-1265.

43. Bolyen E, Rideout JR, Dillon MR, Bokulich NA, Abnet CC, Al-Ghalith GA, Alexander H, Alm EJ, Arumugam M, Asnicar F, *et al.* Reproducible, interactive, scalable and extensible microbiome data science using QIIME 2. *Nat Biotechnol.* 2019;37:852-857.
44. Callahan BJ, McMurdie PJ, Rosen MJ, Han AW, Johnson AJA, Holmes SP. DADA2: High-resolution sample inference from Illumina amplicon data. *Nat Methods.* 2016;13:581-583.
45. Quast C, Pruesse E, Yilmaz P, Gerken J, Schweer T, Yarza P, *et al.* The SILVA ribosomal RNA gene database project: Improved data processing and web-based tools. *Nucleic Acids Res.* 2013;41:D590-D596.
46. Kõljalg U, Nilsson RH, Abarenkov K, Tedersoo L, Taylor AFS, Bahram M, *et al.* Towards a unified paradigm for sequence-based identification of fungi. *Mol Ecol.* 2013;22:5271-5277.
47. Hu XJ, Liu JJ, Liang AZ, Li LJ, Yao Q, Yu ZH, Li YS, Jin J, Liu XB, Wang GH. Conventional and conservation tillage practices affect soil microbial co-occurrence patterns and are associated with crop yields. *Agric Ecosyst Environ.* 2021;319:107534.
48. Fan YL, Liu JJ, Liu ZX, Hu XJ, Yu ZH, Li YS, *et al.* Chitin amendments eliminate the negative impacts of continuous cropping obstacles on soil properties and microbial assemblage. *Front Plant Sci.* 2022;13:1067618.
49. Schroder JL, Zhang HL, Girma K, Raun WR, Penn CJ, Payton ME. Soil acidification from long-term use of nitrogen fertilizers on winter wheat. *Soil Sci Soc Am J.* 2011;75:957-964.
50. Ahn S, Cho M, Sadowsky MJ, Jang J. Dissimilatory nitrate reductions in soil *NeoBacillus* and *Bacillus* strains under aerobic condition. *J Microbiol.* 2025;63:e2411019.
51. Mpanga IK, Ludewig U, Dapaah HK, Neumann G. Acquisition of rock phosphate by combined application of ammonium fertilizers and *Bacillus amyloliquefaciens* FZB42 in maize as affected by soil pH. *J Appl Microbiol.* 2020;129:947-957.
52. Mi WH, Sun Y, Xia SQ, Zhao HT, Mi WT, Brookes PC, *et al.* Effect of inorganic fertilizers with organic amendments on soil chemical properties and rice yield in a low-productivity paddy soil. *Geoderma.* 2018;320:23-29.
53. Fan KK, Delgado-Baquerizo M, Guo XS, Wang DZ, Zhu YG, Chu HY. Biodiversity of keystone phylotypes determines crop production in a four-decade fertilization experiment. *ISME J.* 2021;15:550-561.
54. Masunga RH, Uzokwe VN, Mlay PD, Odeh I, Singh A, Buchan D, *et al.* Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. *Appl Soil Ecol.* 2016;101:185-193.
55. Zeng QX, Peñuelas J, Sardans J, Zhang QF, Zhou JC, Yue K, *et al.* Keystone bacterial functional module activates phosphorus-mineralizing genes to enhance enzymatic hydrolysis of organic phosphorus in a subtropical forest soil with five-year nitrogen addition. *Soil Biol Biochem.* 2024;192:109383.
56. Rawat P, Das S, Shankhdhar D, Shankhdhar SC. Phosphate-solubilizing microorganisms: Mechanism and their role in phosphate solubilization and uptake. *J Soil Sci Plant Nutr.* 2021;21:49-68.
57. Guo S, Jiao ZX, Yan ZG, Yan XY, Deng XH, Xiong W, *et al.* Predatory protists reduce bacterial wilt disease incidence in tomato plants. *Nat Commun.* 2024;15:829.
58. Ma YW, Zuohereguli K, Zhang LS, Kang YL, Shi LW, Xu H, *et al.* Soil microbial mechanisms to improve pear seedling growth by applying *Bacillus* and *Trichoderma*-amended biofertilizers. *Plant Cell Environ.* 2025;48:3968-3980.
59. Kumar A, Singh J. Biofilms-forming microbes: Diversity and potential application in plant-microbe interaction and plant growth. In: Kumar M, Kumar V, Prasad R, editors. *Plant Microbiomes for Sustainable Agriculture*. Cham: Springer International Publishing; 2020. p. 173-197.
60. Gu Y, Wei Z, Wang XQ, Friman VP, Huang JF, Wang XF, *et al.* Pathogen invasion indirectly changes the composition of soil microbiome via shifts in root exudation profile. *Biol Fert Soils.* 2016;52:997-1005.
61. Ge JQ, Li D, Ding JX, Xiao X, Liang YT. Microbial coexistence in the rhizosphere and the promotion of plant stress resistance: A review. *Environ Res.* 2023;222:115298.
62. Mukherjee PK, Mendoza-Mendoza A, Zeilinger S, Horwitz BA. Mycoparasitism as a mechanism of *Trichoderma*-mediated suppression of plant diseases. *Fungal Biol Rev.* 2022;39:15-33.
63. Xiao ZY, Zhao QQ, Li W, Gao LW, Liu GD. Strain improvement of *Trichoderma harzianum* for enhanced biocontrol capacity: Strategies and prospects. *Front Microbiol.* 2023;14:1146210.
64. Monteiro RA, Balsanelli E, Wassem R, Marin AM, Brusamarello-Santos LCC, Schmidt MA, *et al.* *Herbaspirillum*-plant interactions: Microscopical, histological and molecular aspects. *Plant Soil.* 2012;356:175-196.
65. Sun SL, Yang WL, Fang WW, Zhao YX, Guo L, Dai YJ. The plant growth-promoting rhizobacterium *Variovorax boronicumulans* CGMCC 4969 regulates the level of indole-3-acetic acid synthesized from indole-3-acetonitrile. *Appl Environ Microbiol.* 2018;84:e01817.
66. Maxton A, Masih SA. *Variovorax*-soil-mediated growth amelioration and abiotic stress alleviation in *Capsicum annum*. *Res J Biotechnol.* 2024;19:79-86.
67. Dogra T, Priyadarshini A, Kanika, Kumar A, Singh NK. Identification of genes involved in salt tolerance and symbiotic nitrogen fixation in chickpea *Mesorhizobium ciceri* Ca181. *Symbiosis.* 2013;61:135-143.
68. Liswadiratanakul S, Yamamoto K, Matsutani M, Wattanasaree V, Kihara S, Shiwa Y, *et al.* Replacement of water yam (*Dioscorea alata* L.) indigenous root endophytes and rhizosphere bacterial communities via inoculation with a synthetic bacterial community of dominant nitrogen-fixing bacteria. *Front Microbiol.* 2023;14:1060239.
69. Lin SY, Hamed A, Huang H, Young CC. *AlloRhizobium terrae* sp. nov., isolated from paddy soil, and reclassification of *Rhizobium oryzae*. *Int J Syst Evol Microbiol.* 2020;70:397-405.
70. Ahmad I, Narayan S, Shukla J, Shirke PA, Kumar M. Endofungal *Rhizobium* species enhance arsenic tolerance in colonized host plants under arsenic stress. *Arch Microbiol.* 2022;204:375.
71. Feng Y, Kang Y, Wang ZB, Du CY, Tan J, Zhao XY, *et al.* *Ralstonia solanacearum* infection induces tobacco

- roots to secrete chemoattractants to recruit antagonistic bacteria and defensive compounds to inhibit pathogen. *Pest Manag Sci.* 2025;81:1817-1828.
72. Cagide C. Identification of plant compounds involved in microbe-plant communication during the coinoculation of soybean with *Bradyrhizobium elkanii* and *Delftia* sp. strain JD2. *Mol Plant Microbe Interact.* 2018;31:1192-1199.
73. Han JG, Sun L, Dong XZ, Cai ZQ, Sun XL, Yang HL, *et al.* Characterization of a novel plant growth-promoting bacterium, *Delftia tsuruhatensis* HR4, as a diazotroph and potential biocontrol agent against various plant pathogens. *Syst Appl Microbiol.* 2005;28:66-76.
74. Lv HH, Ji CC, Zhang L, Jiang CC, Cai HM. Zinc application promotes nitrogen transformation in rice rhizosphere soil by modifying microbial communities and gene expression levels. *Sci Total Environ.* 2022;849:157858.
75. Wani SH, Anand S, Singh B, Bohra A, Joshi R. WRKY transcription factors and plant defense responses: Latest discoveries and future prospects. *Plant Cell Rep.* 2021;40:1071-1085.
76. Khan AL, Waqas M, Kang SM, Al-Harrasi AA, Hussain J, Al-Rawahi AA, *et al.* Bacterial endophyte *Sphingomonas* sp. LK11 produces gibberellins and indole-3-acetic acid and promotes tomato plant growth. *J Microbiol.* 2014;52:689-695.
77. Wang F, Wei YL, Yin TZ, Wang CC, Chao YH, Jia MY, *et al.* *Sphingomonas* sp. Hbc6 alters physiological Metabolism and recruits beneficial rhizosphere bacteria to improve plant growth and drought tolerance. *Front Plant Sci.* 2022;13:1002772.
78. Ali A, Mohanta TK, Asaf S, Rehman N, Al-Housni S, Al-Harrasi A, *et al.* Biotransformation of benzoin by *Sphingomonas* sp. LK11 and ameliorative effects on growth of *Cucumis sativus*. *Arch Microbiol.* 2019;201:591-601.
79. Ghadamgahi F, Tarighi S, Taheri P, Saripella GV, Anzalone A, Kalyandurg PB, *et al.* Plant growth-promoting activity of *Pseudomonas aeruginosa* FG106 and its ability to act as a biocontrol agent against potato, tomato and taro pathogens. *Biology.* 2022;11:140.
80. Biessy A, Fillion M. Phenazines in plant-beneficial *Pseudomonas* spp.: Biosynthesis, regulation, function and genomics. *Environ Microbiol.* 2018;20:3905-3917.
81. Yang ZY, Liu TB, Fan JQ, Chen YQ, Wu SL, Li JJ, *et al.* Biocontrol agents modulate phyllosphere microbiota interactions against pathogen *Pseudomonas syringae*. *Environ Sci Ecotechnol.* 2024;21:100431.
82. Macey MC, Pratscher J, Crombie AT, Murrell JC. Impact of plants on the diversity and activity of methylotrophs in soil. *Microbiome.* 2020;8:31.
83. Kim DY, Kim J, Lee YM, Lee JS, Shin D, Ku B, *et al.* Identification and characterization of a novel cold-adapted D-xylobiose- and D-xylose-releasing endo- β -1,4-xylanase from an Antarctic soil bacterium, *Duganella* sp. *Biomolecules.* 2021;11:680.
84. Haack FS, Poehlein A, Kröger C, Voigt CA, Piepenbring M, Bode HB, *et al.* Molecular keys to the *Janthinobacterium* and *Duganella* spp. interaction with the plant pathogen *Fusarium graminearum*. *Front Microbiol.* 2016;7:1668.