
Green Agriculture - The Role of Beneficial Microorganisms in Crop Production

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ABSTRACT

Green agriculture aims to increase agricultural productivity while protecting the environment and the health of the land. Beneficial microorganisms are critical for sustainable agricultural production, as they enhance nutrient availability, stimulate plant growth, promote root formation and help plants to tolerate environmental stresses. Rhizobium, Azotobacter, Azospirillum, phosphate-solubilising bacteria, plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi, cyanobacteria, and Trichoderma are all microorganisms that are involved in the functions of nutrient cycling, biological nitrogen fixation, soil fertility, and the natural suppression of disease. Using chemical fertilisers and pesticides as biocontrol agents and biofertilizers, it is possible to decrease the extent of dependency on these compounds. Using beneficial microorganisms along with crop rotation, balanced fertilisation, organic manures and other sustainable farming practices can increase the quality of soil and vigorous crop growth. Therefore, beneficial microorganisms are important biological resources for developing profitable, climate-resilient, and ecologically sustainable agricultural systems.

INTRODUCTION

"Agriculture is vital to global food security, rural livelihoods and economic development. However, with the rise in population, climate change, soil degradation, water scarcity and the excessive use of synthetic fertilisers and pesticides, sustainable food production has become challenging. Overuse of agrochemicals can negatively impact soil fertility, microbial diversity, water quality and ecosystems. Therefore, there is a requirement of productive, environmentally sustainable and resource-efficient agricultural systems (Vessey, 2003; Bhattacharyya & Jha, 2012; Kour et al., 2019; Singh, 2020).

Green agriculture is sustainable agricultural production, which supports soil health, biological nutrient cycling, protection of biodiversity, resource use efficiency and reduction in the use of ecologically hazardous inputs. The beneficial microorganisms are now gaining importance because of their potential to improve nutrient availability, plant development, soil fertility and health of the plant.

There are many bacteria, fungi, archaea, actinomycetes and other micro-organisms in the soil and rhizosphere. The rhizosphere is an active zone where plant roots exchange exudates and metabolites for microorganisms. These interactions modulate nutrient cycling, root development, plant growth and reactions to the environment (Berendsen et al., 2012; Mendes, 2013; Philippot, 2013; Trivedi, 2020). Recent studies have revealed that the plant microbiome can enhance agricultural productivity and resistance to environmental perturbations.

Plant growth-promoting rhizobacteria (PGPR) are important microorganisms. Plant development is promoted by biological nitrogen fixation, phosphate solubilisation, potassium mobilisation, siderophore synthesis, phytohormone control, nutrient acquisition and pathogen suppression. PGPR have been used in climate-resilient agriculture for improving plant responses to abiotic stresses such as drought, salinity, and nutrient deficits (Kumawat et al., 2023; Aloo, 2023).

Biofertilizers containing *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilising bacteria, cyanobacteria and mycorrhizal fungi improve nutrient availability and use efficiency. Rhizobia fix nitrogen and phosphate-solubilising bacteria mobilise resources for sustainable nutrient management. In suitable settings, arbuscular mycorrhizal fungi enhance plant nutrition and water uptake through their large hyphal networks (Smith & Read, 2008; Begum et al., 2019). Helpful bacteria help control biological illnesses. *Trichoderma*, *Bacillus* and *Pseudomonas* suppress plant diseases through competition, antibiosis, manufacture of extracellular enzymes, parasitism and induction of plant defence systems. Therefore, microbial biocontrol agents and biofertilizers can improve integrated nutrition and pest management and reduce chemical inputs. Recent research shows that microbial inoculants can enhance plant growth and soil health.

Microbial aid important in climate stress. Environmental conditions such as drought, salt, extreme temperature and others can severely impact crop growth and production. Beneficial bacteria enhance root development, nutrition and water acquisition, phytohormone control, osmolyte production, antioxidant activity and plant defence responses, leading to increased stress tolerance. Recent research demonstrated that drought-tolerant PGPR can enhance crop resilience and soil health.

Our knowledge of plant-microbe interactions has been improved by microbiome, genomics, metagenomics, transcriptomics, proteomics and metabolomics. These technologies are assisting researchers to identify microbial populations, functional traits and consortia relevant for sustainable agriculture. Microbiome-based technologies and multifunctional microbial inoculants have an essential purpose in crop production (de Souza et al., 2020; Compant, 2025).

Microbial technologies have a great potential, but their performance in the field may vary depending on soil conditions, crop genotype, climate, microbial strain, quality of the inoculum and interactions with the local microbial community. Successful use of this type of biostimulant needs strain selection, formulation, quality control, field validation and integration with other agronomic practises (Backer et al., 2018; Kour et al., 2019; Compant, 2025). “Recent assessments also emphasise the need to incorporate microbial inoculants into soil and crop management practices rather than applying them as synthetic inputs.

Thus, beneficial bacteria hold the key to profitable, sustainable and climate-resilient agriculture. They play a role in green agriculture through nutrient cycling, biological nitrogen fixation, plant growth stimulation, disease management, soil health and stress tolerance improvement. This overview discusses major families of beneficial bacteria, mechanisms of action, biofertilizer and biocontrol uses, soil health and stress management, microbial consortia, and existing restrictions and future potential for sustainable crop production

2. BENEFICIAL MICROORGANISMS AND THEIR ROLE IN GREEN AGRICULTURE

Beneficial microorganisms are **eco-friendly bacteria, fungi, cyanobacteria and other useful microbes** that live in soil, around plant roots or within plant tissues. They contribute to plant growth, nutrient cycling and crop health. These microorganisms can improve soil fertility, increase nutrient availability, promote root development and help protect plants from certain diseases and pests. Therefore, beneficial microorganisms are increasingly considered important biological tools for reducing excessive dependence on synthetic fertilizers and pesticides and promoting sustainable crop production (Vessey, 2003; Bhattacharyya & Jha, 2012; Kour et al., 2019; Compant et al., 2025).

2.1. NITROGEN-FIXING BACTERIA: Nitrogen-fixing microorganisms convert atmospheric nitrogen into forms that plants can utilize. *Rhizobium* forms symbiotic associations with leguminous plants, while *Azotobacter* and *Azospirillum* contribute to nitrogen nutrition and plant growth in several crops. Their activities improve nitrogen availability and support efficient nutrient management (Lugtenberg & Kamilova, 2009; Glick, 2012; Kour et al., 2019).

2.2. PHOSPHATE-SOLUBILIZING MICROORGANISMS: Phosphorus is essential for plant growth, but a large proportion of soil phosphorus may occur in forms that are not readily available to plants. Phosphate-solubilising bacteria and fungi, including species of *Bacillus* and *Pseudomonas*, can release organic acids and other compounds that increase phosphorus availability in the rhizosphere. This process can improve root development and plant nutrient uptake (Richardson et al., 2009; Alori et al., 2017; Khan et al., 2023).

2.3. MYCORRHIZAL FUNGI: Arbuscular mycorrhizal fungi form beneficial associations with plant roots. Their fungal hyphae extend into the surrounding soil and increase the area explored

by the root system. This association can improve the uptake of phosphorus, micronutrients and water and may enhance plant performance under suitable environmental conditions (Smith & Read, 2008; Begum et al., 2019).

2.4. BIOCONTROL MICROORGANISMS: Beneficial microorganisms can protect crops against several plant pathogens. *Trichoderma* species can suppress harmful fungi through competition, mycoparasitism, antimicrobial compounds and stimulation of plant defence responses. Certain bacterial groups, particularly *Bacillus* and *Pseudomonas*, can also contribute to biological disease suppression (Compant et al., 2005; Harman et al., 2004; Harman, 2006).

2.5 MAJOR BENEFITS FOR GREEN AGRICULTURE

1. Improved Nutrient Efficiency: Beneficial microorganisms contribute to the availability and uptake of important nutrients such as **nitrogen, phosphorus and potassium**. Nitrogen-fixing bacteria contribute biologically available nitrogen, phosphate-solubilising microorganisms improve phosphorus availability, and some microorganisms help mobilise potassium from soil minerals. These activities can improve nutrient-use efficiency and reduce excessive dependence on chemical fertilisers (Vessey, 2003; Richardson et al., 2009; Alori et al., 2017; Kour et al., 2019).

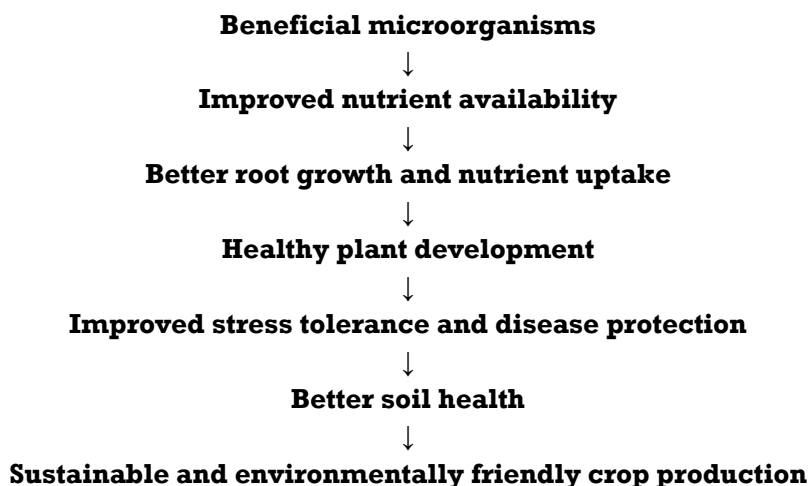
2. Promotion of Plant Growth: Many beneficial microorganisms promote plant growth through nutrient mobilisation, production or regulation of plant-growth substances, improvement of root development and enhanced nutrient uptake. Plant growth-promoting rhizobacteria (PGPR) are particularly important because they can influence root architecture and improve overall plant vigour (Glick, 2012; Bhattacharyya & Jha, 2012; Backer et al., 2018).

3. Improved Stress Tolerance: Beneficial microorganisms can help plants tolerate **drought, salinity, high temperature and other environmental stresses**. They may improve root growth, water and nutrient acquisition, osmotic adjustment, antioxidant activity and plant defence responses. Therefore, microbial inoculants have potential for developing climate-resilient cropping systems (Nadeem et al., 2014; Vurukonda et al., 2016; Kumawat et al., 2023).

4. Improvement of Soil Health: Microorganisms are essential components of healthy soil. They participate in **organic matter decomposition, nutrient cycling, carbon transformation and soil aggregation**. Mycorrhizal fungi and other beneficial microorganisms can contribute to soil aggregation and biological activity, while diverse microbial communities support important processes in the rhizosphere (van der Heijden et al., 2008; Berendsen et al., 2012; Mendes et al., 2013).

5. Natural Disease Suppression: Beneficial microorganisms can reduce the activity of certain plant pathogens through **competition, antibiosis, enzyme production, mycoparasitism and induction of plant defence mechanisms**. Microbial biocontrol agents can therefore complement integrated pest and disease management and help reduce excessive dependence on synthetic pesticides (Compant et al., 2005; Harman et al., 2004; Harman, 2006).

6. Support for Sustainable Crop Production: The overall contribution of beneficial microorganisms to green agriculture can be summarised as:



Thus, beneficial microorganisms are important biological partners in **green agriculture**. Their integration with organic manures, balanced fertilisation, crop rotation, proper irrigation and integrated pest management can contribute to productive, healthy and environmentally sustainable farming systems (Trivedi et al., 2020; Rigobelo et al., 2023; Compant et al., 2025).

3. ROLE OF BENEFICIAL MICROORGANISMS IN CROP PRODUCTION

Beneficial microorganisms generally enhance agricultural production by enhancing the availability of nutrients, root development, plant growth and soil health. In general, their main functions are as follows.

1. Fixation of Nitrogen: Some microbes, including *Rhizobium*, *Azotobacter* and *Azospirillum*, transform air nitrogen into forms that can be used by plants. *Rhizobium* has a symbiotic relationship with legume roots and fixes nitrogen inside root nodules. This enhances the nutrition of nitrogen and decreases the dependency on synthetic nitrogen fertilisers (Vessey, 2003; Bhattacharyya & Jha, 2012; Glick, 2012).

2. Phosphate Solubilisation: Most of the soil phosphorus is in a form that plants cannot use. Phosphate solubilising bacteria such as species of *Bacillus* and *Pseudomonas* create organic acids and other compounds that convert unavailable phosphorus to soluble forms. This results in improved phosphorus availability to plant roots and healthy growth (Richardson et al., 2009; Alori et al., 2017).

3. Mobilisation of potassium: Plants need potassium to flourish; however, some of the potassium in the soil is bound up in minerals and is not readily available for the plants to use. Some microbes can mobilise potassium from mineral sources, making it more available to plants. This can boost plant nutrition and promote crop development (Meena et al., 2016).

4. Root Growth Stimulation: Plant growth-promoting microorganisms (PGPMs) can promote root growth by producing and/or regulating plant growth chemicals such as auxins, cytokinins and gibberellins. They can promote the development of more lateral roots and root hairs, hence bigger and healthier root system (Glick, 2012; Vejan et al., 2016).

5. Better Nutrient Absorption: Helpful bacteria improve the capacity of plants to get nutrients from the soil. For example, mycorrhizal fungi develop broad fungal hyphae that explore soil beyond the immediate root zone and assist plants absorb phosphate, nitrogen, micronutrients and water. This enhances plant growth and nutrient-use efficiency (Smith & Read, 2008; Begum et al., 2019).

6. Plant growth stimulation: The combined action of nitrogen fixation and mobilisation, stimulation of root growth and improved nutrient uptake leads to better plant growth and crop vitality. PGPR and other beneficial bacteria can also generate siderophores, enzymes and other chemicals that aid plant development and aid plants in tolerating environmental stress (Bhattacharyya & Jha, 2012; Backer et al., 2018; Trivedi et al., 2020).

4. BIOFERTILIZERS

Biofertilizers are preparations containing **living beneficial microorganisms** that improve the availability of nutrients to plants and support healthy crop growth. Unlike synthetic fertilizers, biofertilizers work mainly through natural biological processes such as nitrogen fixation, nutrient solubilization and nutrient mobilization. They can improve nutrient-use efficiency, soil fertility and plant growth and are therefore important components of sustainable and green agriculture (Vessey, 2003; Bhattacharyya & Jha, 2012).

TYPES OF MICROBIAL BIOFERTILIZERS

1. Nitrogen-Fixing Biofertilizers: Nitrogen-fixing microorganisms convert atmospheric nitrogen into forms that plants can utilise.

- **Rhizobium:** Forms root nodules mainly in leguminous plants and fixes atmospheric nitrogen through symbiosis.
- **Azotobacter:** A free-living nitrogen-fixing bacterium that is commonly associated with non-leguminous crops.
- **Azospirillum:** Associates closely with plant roots and contributes to nitrogen nutrition and plant growth.
- **Cyanobacteria:** Blue-green algae such as *Anabaena* and *Nostoc* fix atmospheric nitrogen and are particularly useful in wetland and rice-growing systems.

These microorganisms improve nitrogen availability and can reduce the requirement for excessive nitrogen fertilisers (Vessey, 2003; Glick, 2012; Kour et al., 2019).

2. Phosphate-Solubilizing Microorganisms: Phosphorus is essential for root development, energy transfer and other plant processes, but much of the phosphorus in soil is present in poorly available forms. Phosphate-solubilising bacteria and fungi, including species of *Bacillus*, *Pseudomonas* and *Aspergillus*, help release phosphorus into soluble forms that can be absorbed by plant roots (Richardson et al., 2009; Alori et al., 2017).

3. Potassium-Mobilizing Microorganisms: Some soil microorganisms can release potassium from minerals and make it available to plants. Potassium is important for water balance, enzyme activity, photosynthesis and overall plant strength. Potassium-mobilising microorganisms can therefore improve potassium nutrition and contribute to healthy crop development (Meena et al., 2016).

4. Mycorrhizal Biofertilizers: Mycorrhiza is a beneficial association between fungi and plant roots. Arbuscular mycorrhizal fungi develop a network of hyphae around and within roots, extending the area through which plants can obtain nutrients and water. They are particularly effective in improving phosphorus uptake and can also contribute to soil aggregation and plant tolerance to environmental stresses (Smith & Read, 2008; Begum et al., 2019).

BENEFITS OF BIOFERTILIZERS TO CROPS: Biofertilizers provide several important benefits:

- **Improve nutrient availability**, particularly nitrogen, phosphorus and potassium.
- **Promote root development** and improve nutrient and water uptake.
- **Increase plant growth and crop vigour.**
- **Improve soil biological activity and fertility.**
- **Support better nutrient-use efficiency.**
- **Help plants tolerate drought, salinity and other environmental stresses.**
- **Reduce excessive dependence on synthetic fertilizers.**
- **Support environmentally friendly and sustainable crop production** (Backer et al., 2018; Kour et al., 2019).

5. BENEFICIAL MICROORGANISMS AND SOIL HEALTH

Microorganisms that enhance nutrient availability, plant growth, soil health and disease control support agricultural production. Briefly, their functions are as follows.

1. *Bacillus amyloliquefaciens*: Solubilises phosphate and potassium and produces siderophores and other plant growth-promoting compounds (Kumar et al., 2012; Shafi, 2017).
2. *Bacillus licheniformis*: increases phosphate and zinc availability and stimulates plant growth via several beneficial activities (Goswami et al., 2016).
3. Phosphate solubilisation is a feature of *Bacillus megaterium*. It can generate organic acids and other chemicals that benefit plant growth by increasing phosphorus (Alori et al., 2017).
4. *Bacillus subtilis* enhances plant growth and nutrient availability. It competes with harmful microorganisms around the roots of the plants and secretes antibiotic compounds (Kloepper et al., 2004; Shafi, 2017).
5. *Trichoderma atroviride*: Enhances seed germination, root development and plant growth and induces systemic resistance (ISR), which helps plants to fend off infections (Harman et al., 2004; Contreras-Cornejo, 2009).
6. *Trichoderma harzianum* : A well-studied fungi for biological control. It decreases Fusarium, Rhizoctonia and Pythium by competition, mycoparasitism and cell wall-destroying enzymes. It can stimulate plant growth and nitrogen cycling (Benítez et al., 2004; Harman et al., 2004).
7. *Saccharomyces cerevisiae* is a yeast that is also a plant biostimulator. Metabolites and plant growth-boosting compounds released can help in root development, nutrient acquisition and plant vigour (El-Tarabily & Sivasithamparam, 2006; Lonhienne et al., 2021). The shared benefits of these advantageous bacteria.

These microbes can have multiple benefits:

1. **Nutrient mobilisation:** Microorganisms can solubilise or mobilise nutrients such as phosphorus, potassium, iron and zinc for plant roots (Richardson et al., 2009; Alori, 2017).

2. Growth of plants/roots: Beneficial microbes can produce or influence plant-growth compounds such as IAA, cytokinins, and other metabolites that promote plant health and root development (Glick, 2012; Vejan et al., 2016).

3. Disease Control: Beneficial micro-organisms can compete with pathogens for resources and can produce antimicrobials and enzymes. Biocontrol bacteria such as *Trichoderma* and *Bacillus* are important (Harman et al., 2004; Shafi, 2017).

4. Systemic Opposition: Beneficial bacteria help plants fight back, inducing systemic resistance. This can enhance plant resilience to diseases (Pieterse et al., 2014).

5. Tolerance of Stress: Beneficial bacteria impact root growth, water uptake, osmotic adjustment and antioxidant reactions, leading to increased plant tolerance to drought, salinity, heat and other environmental stresses (Vurukonda et al., 2016; Nadeem, 2014).

6. Decomposition of Organic Matter and Soil Health: Microbial enzymes break down organic material and plant debris, recycling nutrients. Microbial and fungal hyphae can also coalesce, become porous and hold water (Rillig & Mummey, 2006; Trivedi et al., 2020).

6. ROLE IN PLANT DISEASE MANAGEMENT

Beneficial microorganisms are important biological tools for **reducing plant diseases and maintaining crop health**. They can suppress harmful pathogens around plant roots and may also stimulate the plant's natural defence system. Among the most widely studied microbial biocontrol agents are *Trichoderma*, *Bacillus* and *Pseudomonas* species (Harman et al., 2004; Compant et al., 2005).

1. *Trichoderma*: *Trichoderma* is a beneficial soil fungus widely used for biological control of plant diseases. It can suppress pathogenic fungi through **competition for nutrients and space, mycoparasitism and production of antimicrobial compounds and cell-wall-degrading enzymes**. It can also stimulate plant defence responses and promote root growth (Harman et al., 2004; Benítez et al., 2004).

2. *Bacillus* species are useful bacterial biocontrol agents because they can survive in soil and form resistant spores. They produce several antimicrobial substances that inhibit plant pathogens. They can also colonise root surfaces and stimulate plant defence mechanisms, thereby supporting plant health (Kloepper et al., 2004; Shafi et al., 2017).

3. *Pseudomonas*: Beneficial *Pseudomonas* species, particularly fluorescent pseudomonads, are important rhizosphere bacteria. They can suppress pathogens through **competition, siderophore production, antimicrobial compounds and stimulation of induced systemic resistance (ISR)**. Their ability to colonise plant roots makes them useful for biological disease management (Haas & Défago, 2005; Weller, 2007).

7. ROLE IN ABIOTIC STRESS TOLERANCE

Beneficial microbes help plants to cope with abiotic stress

Plants are frequently subjected to drought, salinity, excessive temperature and nutrient deficiency which can limit plant growth and food production. Beneficial micro-organisms associated with plant roots might improve the ability of plants to withstand these stresses through improvement of water and nutrient uptake, stimulation of root growth, modulation of plant hormones and boosting their antioxidant defence mechanisms (Vurukonda et al., 2016; Nadeem et al., 2014).

1. Drought Stress

When plants don't get enough water from drought, root growth, photosynthesis, and nutrient uptake are all hampered. Good bacteria for plants such as PGPR and mycorrhizal fungus can help roots grow and absorb more water. They also may enhance the efficacy of antioxidants and assist plants to maintain water homeostasis under drought conditions (Vurukonda et al., 2016; Nadeem et al., 2014).

Simple to understand:

Good microbes for plants mean improved root growth, better uptake of water, and better drought resistance.

2. Salt stress: Too much salt can affect plants' ability to take in water and upset the balance of ions. Good bacteria help roots grow, plants take up nutrients better, manage water better. Some PGPR also modulate hormones that induce stress and antioxidant systems reducing the adverse effects of salinity (Glick, 2012; Vejan et al., 2016).

Easy to follow: Good bacteria means better water interactions, better nutritional balance and less salt stress.

3. Strains of Hot Temperatures: High temperatures can damage cell membranes, interfere with photosynthesis and lead to the production of more reactive oxygen species (ROS). Beneficial bacteria improve the antioxidant defence mechanisms, promote the plant growth and uptake of water and nutrients, therefore increasing their tolerance to heat stress (Dimkpa et al., 2009; Nadeem et al., 2014).

Easy to read. Good bacteria → More antioxidant defence → Less cell damage → Better heat handling abilities

4. Absence of nutrition: Plants may have trouble growing with a lack of nourishment, especially nitrogen, phosphorus, potassium and micronutrients. Helpful microbes improve the availability of nutrients by fixing nitrogen, solubilising phosphorus and cycling mineral minerals. Mycorrhizal fungi also aid roots access nutrients by increasing the area explored in the soil (Richardson et al., 2009; Alori et al., 2017).

8. FUTURE PERSPECTIVES

Beneficial Microorganisms have great potential for the establishment of sustainable climate-resilient and environment-friendly agriculture. Future research should emphasise on the improvement of microbial formulations, compatible combinations of microorganisms, and reliable uses of microbial products in the field.

Improved microbial formulations: Improved formulations can enhance microbial survivability, shelf life and efficacy under field settings (Bashan et al., 2014).

Microbial consortia: Application of several beneficial microbes in combination may provide multiple benefits such as nutrient mobilisation, plant growth stimulation and disease control (Woo & Pepe, 2018).

Plant microbiome studies Modern microbiome studies can aid in identification of helpful microbes and comprehend their interaction with crops and soil (Trivedi et al., 2020).

Climate-resilient microorganisms: Selection of drought-, salinity- and high temperature-performing microbes can assist climate-resilient crop production (Nadeem et al. , 2014).

Precision agriculture: Microbial applications could be used in precision agriculture for the application of suitable microorganisms according to the need of crop and soil.

More field research needed: In an effort to prove efficacy, stability and economic advantages of microbial products under various agricultural circumstances, long-term field experiments are required (Backer et al., 2018).

CONCLUSION

Green agriculture provides a sustainable approach to crop production by combining **higher productivity with environmental protection**. Beneficial microorganisms play an important role in this approach by improving nutrient availability, promoting plant growth, supporting soil health and helping plants tolerate diseases and environmental stresses. Their use can reduce excessive dependence on chemical fertilizers and pesticides while improving the efficient use of soil, water and other natural resources. Integrating microbial technologies with organic resources, balanced nutrient management and biological pest control can contribute to **healthy soils, resilient crops and sustainable food production**. Therefore, beneficial microorganisms represent an important biological tool for developing **productive, eco-friendly and climate-resilient agricultural systems**.