



## Biofertilizers for Crop Production and Soil Fertility

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**B**iofertilizers—A key component of sustainable agricultural intensification is the use of living microbial inoculants that increase plant growth and nutrient availability. Biofertilizers can increase yields while lowering dependency on synthetic inputs by generating phytohormones, mobilizing nitrogen, phosphorus, and other nutrients, and enhancing soil health. The main functional groups (nitrogen fixers, phosphate-solubilizers, potassium and zinc mobilizers, mycorrhizae, cyanobacteria, and multifunctional PGPR) are reviewed in this article along with their mechanisms of action, effects on soil fertility and crop productivity, formulation and quality control, field application techniques, and integration within integrated plant nutrient management (IPNM). Constraints, risk management, and policy/market factors are also examined. Research shows that using biofertilizer in the right context enhances crop production, soil ecosystem functioning, and nutrient usage efficiency across a variety of agroecologies. Next-generation consortiums, improvements in carriers and encapsulation, digital decision support, and robust standards for efficacy and quality assurance.

### Introduction

Biologically based inputs are receiving more attention due to the worldwide need to improve food security while reducing environmental externalities. Over-reliance on synthetic fertilizers can lower biodiversity, deteriorate soil quality, and increase greenhouse gas emissions and water eutrophication. Beneficial bacteria applied to seeds, soil, or plants, known as biofertilizers, provide an environmentally sound strategy to maintain production, improve soil functionality, and lower input intensity (Vessey, 2003; Lugtenberg & Kamilova, 2009; Bhattacharyya & Jha, 2012). Direct nutrient transformations (such as N<sub>2</sub> fixation and P solubilization), plant growth promotion through phytohormones and signaling, disease suppression through niche occupation and induced systemic resistance (ISR), and changes to soil structure are the main sources of their agronomic usefulness. Biofertilizers are powerful supplements that can enhance fertilizer use efficiency and long-term soil health, but they are neither a cure-all nor a direct substitute for mineral fertilizers (Adesemoye & Kloepper, 2009; Bashan et al., 2014).

### Major Macro- and Micro-Nutrients and Their Roles in Plants

(Based on Devi and Sumathy, 2017)

| Element   | Symbol | mg/kg Soil | % in Soil | Type  | Major Functions/Application                          | Deficiency Symptoms                                 |
|-----------|--------|------------|-----------|-------|------------------------------------------------------|-----------------------------------------------------|
| Nitrogen  | N      | 15,000     | 1.5       | Macro | Leaf and stem growth                                 | Yellowing of leaves; short stalk growth             |
| Potassium | K      | 10,000     | 1.0       | Macro | Maintains stomatal turgor; growth; enzyme activation | Stunted growth; leaf necrosis; reduced gas exchange |

|            |    |       |     |       |                                                                        |                                                                                            |
|------------|----|-------|-----|-------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Calcium    | Ca | 5,000 | 0.5 | Macro | Acid-base regulation; enzyme catalyst                                  | Poor meristem growth; blossom end rot                                                      |
| Magnesium  | Mg | 2,000 | 0.2 | Macro | Activates ATP/ADP metabolism; photosynthesis; respiration              | Necrosis of lower mature leaves                                                            |
| Phosphorus | P  | 2,000 | 0.2 | Macro | Plant growth; fruit ripening                                           | Reduced flowering and poor plant growth                                                    |
| Sulphur    | S  | 1,000 | 0.1 | Macro | Protein formation and structure                                        | Poor growth of young leaves; thin brittle stems                                            |
| Chlorine   | Cl | 100   | —   | Micro | Respiration; maintenance of cell turgor                                | Wilting; stunted growth                                                                    |
| Iron       | Fe | 100   | —   | Micro | Enzyme catalyst; chlorophyll synthesis; protein synthesis; respiration | Necrosis of young leaves                                                                   |
| Boron      | B  | 20    | —   | Micro | Metabolism of calcium and potassium                                    | Poor growth; blackening of roots and shoots                                                |
| Manganese  | Mn | 50    | —   | Micro | Carbohydrate metabolism                                                | Necrotic spots on leaves; leaf shedding                                                    |
| Zinc       | Zn | 20    | —   | Micro | Enzyme activator                                                       | Stunted growth                                                                             |
| Copper     | Cu | 6     | —   | Micro | Chlorophyll formation                                                  | Stunted growth; tip death; twisted leaves; blue-green coloration; necrosis; loss of turgor |
| Molybdenum | Mo | 0.1   | —   | Micro | Nitrogen and carbohydrate metabolism                                   | Interveinal necrosis; mottling; inward folding of older leaves                             |

## Definitions and Scope

When applied to seed, plant surfaces, or soil, preparations containing live microorganisms that improve nutrient availability or uptake and promote plant growth are commonly referred to as "biofertilizer" in agricultural practice. This comprises:

- Bacteria that fix nitrogen, such as *Rhizobium*, *Bradyrhizobium*, *Azotobacter*, and *Azospirillum*.
- Phosphate-solubilizing microorganisms (PSM), which include fungus like *Aspergillus* and bacteria like *Pseudomonas* and *Bacillus*.
- Mycorrhizal fungi, particularly AMF (arbuscular mycorrhizal fungi).
- Cyanobacteria, particularly in rice paddies.
- Plant growth-promoting rhizobacteria (PGPR), which has advantages for several traits. In fact, goods may combine functions, however some definitions distinguish "biostimulants" (non-nutritional growth enhancers) from biofertilizers (Mahanty et al., 2017; Glick, 2012).

## Functional Groups and Mechanisms of Action

### Biological Nitrogen Fixation (BNF)

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**Phosphorus Solubilization and Mobilization**

Due to fixation with Ca, Fe, and Al, phosphorus is often limiting. Organic acids (gluconic and citric), chelators, and phosphatases that liberate labile P from insoluble sources are released by phosphate-solubilizing bacteria and fungi. Mycorrhizae increase P uptake efficiency and frequently improve micronutrient acquisition by extending hyphal networks beyond of the P depletion zone (Richardson et al., 2009). These processes can enhance residual P usage and lessen the requirement for high P fertilizer rates.

**Potassium and Micronutrient Mobilization**

Through siderophore synthesis, acidity, and chelation, certain microorganisms weather K-bearing minerals and mobilize Zn, Fe, and other micronutrients. Increased micronutrient availability complements macronutrient supply by influencing photosynthesis, enzyme activity, and grain quality.

**Phytohormone Production and Stress Modulation**

PGPR produces gibberellins, cytokinins, and indole-3-acetic acid (IAA), which encourage root growth and nutrient seeking. Under stress, ACC deaminase-rich strains reduce ethylene levels, promoting resistance to drought, salt, and temporary nutritional shortages (Glick, 2012; Bhattacharyya & Jha, 2012).

**Biocontrol, ISR, and Rhizosphere Engineering**

By suppressing root infections through niche competition, antibiosis, lytic enzymes, and elicitation of ISR, inoculants can indirectly increase plant vigor and nutrient uptake. In addition to stabilizing soil aggregates, biofilm development and exopolysaccharide synthesis improve water dynamics and aeration.

**Impacts on Crop Production****Yield and Nutrient Use Efficiency (NUE)**

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**Context Dependence and Variability**

Microbial strain, host genotype, soil chemistry, climate, and management all affect responses. Efficacy may be decreased by subpar inoculant quality, poor carrier survival, antagonistic native microbiota, or a mismatch with soil pH/moisture. Local adaptability, formulation robustness, and suitable application windows are critical for field-scale success (Bashan et al., 2014).

**Contributions to Soil Fertility and Health****Nutrient Cycling and Soil Organic Matter**

In addition to increasing root biomass and rhizodeposition, biofertilizers speed up the cycling of nutrients (N, P, K, and micronutrients), which indirectly promotes the accumulation of organic matter in the soil. They can eventually increase cation exchange capacity and affect aggregate stability by enhancing root systems and microbial activity.

**Soil Structure, Aggregation, and Water Relations**

Exopolysaccharides and other microbial exudates promote aggregation, which lowers bulk density and increases porosity. Improved structure protects crops from dry spells and supports microbial communities that sustain nutrient conversions by increasing infiltration and water-holding capacity.

**Biodiversity and Ecosystem Function**

Inoculants can diversify functional guilds in the rhizosphere, reinforcing redundancy and resilience. In long-term systems, biological inputs are associated with higher soil biota richness and activity (Mäder et al., 2002).

## Product Types, Formulation, and Quality Control

### Delivery Systems and Carriers

Peat, lignite, vermiculite, composted materials, and sterilized soil-based carriers are common carriers; liquid inoculants and encapsulated beads (alginate) increase shelf life and desiccation resistance. For seed and granule formulations, coating methods provide accurate rhizosphere distribution.

### Label Claims, Purity, and Viability

The presence of impurities, strain identity, and viable cell counts determine quality. Labels should list the target crop, suggested rates, storage conditions, and concentration (e.g., CFU per gram or mL). Independent certification and quality verification initiatives safeguard farmers and lessen market volatility.

### Storage and Shelf Life

Viability is deteriorated by temperature, moisture, and UV radiation. Shelf life is extended by cold-chain or cool, dry storage. When compared to simple carriers, liquid formulations containing protectants and encapsulated medicines frequently show better stability.

### Best Practices and Application Strategies

Inoculation of Seeds Propagules and developing roots have close contact thanks to seed coating and slurries. To preserve viability, use appropriate adhesives, steer clear of high-salt fertilizers in the coating, and plant as soon as possible following treatment.

### Soil Application and In-furrow

In-furrow liquids or grains are helpful in automated systems because they localize bacteria close to roots. Because AMF has limited saprophytic development, positioning close to the seed/root zone is essential.

### Treatments for Transplants and Root Dips

Root dips are beneficial for vegetable and orchard crops right before transplanting because they create early symbiosis and reduce transplant shock.

### Combining Programs for Fertilizer

Mineral nutrients are complemented by biofertilizers, however they are not usually completely replaced. Strip trials can be used to assess stepwise replacement (e.g., 20–40% N or P decrease depending on crop–soil context). Micronutrient and N:P:K balance supply ensures that microbial benefits translate into yield.

### Soil Conditions, Timing, and Compatibility

Avoid using strong agrochemicals during or soon after application, and apply when soil moisture and temperature encourage microbial activity. Antagonism is avoided by testing for compatibility with starting fertilizers and seed treatments (fungicides and insecticides).

## Limitations, Dangers, and Reduction

### Context Sensitivity and Variability

The main limitation is heterogeneous field reactions. Employ robust formulations, regionally verified strains, and agronomic techniques that promote microbial establishment (e.g., residue retention, less excessive tillage).

### Inaccurate Labeling and Poor Products

Poor quality items may be permitted by lax regulations. Check production and expiration dates, look for extension or agronomic advice, and choose verified suppliers.

### Non-target Effects and Biosafety

Although biofertilizers used in agriculture are usually thought to be safe, it is nevertheless crucial to follow registration regulations and environmental evaluations, especially for new strains and consortia.

## Integration with Sustainable Intensification and IPNM

When biofertilizers are included into integrated plant nutrition management, the most consistent benefits occur:

- Incorporate site-specific nutrient management and soil testing.

- To support the soil food web, keep organic amendments (composts, residues) in place.
- When necessary, use gypsum or liming to optimize pH for microbial activity and P availability.
- To expand microbial habitats, use cover crops and crop rotations. These systems increase resilience, decrease losses, and improve nutrient circularity (Richardson et al., 2009; Mäder et al., 2002).

## Markets, Policy, and Extension

Enabling settings necessitate:

- Explicit standards, definitions, and labeling specifications.
- Independent monitoring and verification of quality.
- Encourage the manufacture of biofertilizer locally using ethical manufacturing techniques.
- Public-private collaborations for validation on farms.
- Digital advising tools for connecting crops, products, and soil. Reliable performance statistics, farmer education, and risk-sharing arrangements are essential for scaling success.

## Prospective Paths

Among the innovations are:

- Multi-strain, functionally complementary consortia that are adapted to crop and soil restrictions, such as N fixers + PSB + AMF.
- Next-generation encapsulation and carriers (such as nanocellulose and protective polymers) to increase field ruggedness and shelf life.
- Precision delivery (smart coatings, seed-applied microgranules).
- Selection of strains for stress-prone situations based on metabolomics and genomics.
- Adoption-guiding decision-support systems that incorporate soil testing, weather, and product features.
- More robust stewardship and regulatory frameworks to preserve efficacy and confidence.

## Conclusion

Long-term soil fertility, crop yield, and nutrient usage efficiency may all be enhanced using biofertilizers, which are a significant and sustainable solution. Biofertilizers increase nutrient availability, promote plant growth, improve soil structure, and fortify resistance to environmental stresses by employing beneficial microorganisms like nitrogen-fixing bacteria, phosphate-solubilizing microbes, mycorrhizal fungi, cyanobacteria, and multifunctional PGPR. Their incorporation into agricultural systems promotes ecosystem stability and environmental preservation while lowering reliance on artificial fertilizers. However, the quality of microbial strains, soil conditions, crop variety, climate, and appropriate application techniques all have a significant impact on how successful biofertilizers are. High-quality formulations, appropriate handling and storage, region-specific advice, and integration with balanced nutrient management techniques like Integrated Plant Nutrient Management (IPNM) are therefore necessary for effective adoption. Future developments in microbial consortia, carrier technologies, encapsulation techniques, genomics, and precision agricultural instruments should increase the dependability and effectiveness of biofertilizers. Biofertilizers may play a significant part in attaining sustainable agricultural intensification, restoring soil health, and guaranteeing global food security in an ecologically responsible way with the help of strict regulations, farmer awareness, research support, and efficient extension services.

## In-text Citations

Citations in the text follow the author–year format, for example: (Vessey, 2003), (Richardson et al., 2009), (Bashan et al., 2014), (Mäder et al., 2002), (Bhattacharyya & Jha, 2012), (Lugtenberg & Kamilova, 2009), (Glick, 2012), (Adesemoye & Kloepper, 2009).

## References

1. Adesemoye, A. O., & Kloepper, J. W. (2009). Plant–microbes interactions in enhanced fertilizer-use efficiency: A review. *Applied Microbiology and Biotechnology*, 85, 1–12.
2. Bashan, Y., de-Bashan, L. E., Prabhu, S. R., & Hernandez, J.-P. (2014). Advances in plant growth-promoting bacterial inoculants and inoculation technology. *Plant and Soil*, 378, 1–33.
3. Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. *World Journal of Microbiology and Biotechnology*, 28, 1327–1350.
4. Glick, B. R. (2012). Plant growth-promoting bacteria: Mechanisms and applications. *Scientifica*, 2012, 963401.
5. Lugtenberg, B., & Kamilova, F. (2009). Plant growth-promoting rhizobacteria. *Annual Review of Microbiology*, 63, 541–556.
6. Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, 296(5573), 1694–1697.
7. Mahanty, T., Bhattacharjee, S., et al. (2017). Biofertilizers: A sustainable approach for plant and soil health. *Journal of Plant Growth Regulation*, 36, 1–20.
8. Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, 255, 571–586. <https://doi.org/10.1023/A:1026037216893>
9. Richardson, A. E., Barea, J.-M., McNeill, A. M., & Prigent-Combaret, C. (2009). Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant and Soil*, 321, 305–339. <https://doi.org/10.1007/s11104-009-9895-2>
10. Bashan, Y., de-Bashan, L. E., Prabhu, S. R., & Hernandez, J.-P. (2014). Advances in plant growth-promoting bacterial inoculant technology: Formulations and practical perspectives (1998–2013). *Plant and Soil*, 378, 1–33. <https://doi.org/10.1007/s11104-013-1956-x>
11. Bhardwaj, D., Ansari, M. W., Sahoo, R. K., & Tuteja, N. (2014). Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. *Microbial Cell Factories*, 13, 66. <https://doi.org/10.1186/1475-2859-13-66>
12. Hayat, R., Ali, S., Amara, U., Khalid, R., & Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth promotion: A review. *Annals of Microbiology*, 60, 579–598. <https://doi.org/10.1007/s13213-010-0117-1>
13. Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. *Annual Review of Microbiology*, 63, 541–556. <https://doi.org/10.1146/annurev.micro.62.081307.162918>
14. Malusá, E., & Vassilev, N. (2014). A contribution to set a legal framework for biofertilisers. *Applied Microbiology and Biotechnology*, 98, 6599–6607. <https://doi.org/10.1007/s00253-014-5751-6>
15. Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., Subramanian, S., & Smith, D. L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science*, 9, 1473. <https://doi.org/10.3389/fpls.2018.01473>
16. Calvo, P., Nelson, L., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. *Plant and Soil*, 383, 3–41. <https://doi.org/10.1007/s11104-014-2131-8>
17. Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus*, 2, 587. <https://doi.org/10.1186/2193-1801-2-587>
18. Herridge, D. F., Peoples, M. B., & Boddey, R. M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil*, 311, 1–18. <https://doi.org/10.1007/s11104-008-9668-3>

19. Smith, S. E., & Read, D. J. (2008). *Mycorrhizal Symbiosis* (3rd ed.). Academic Press. <https://doi.org/10.1016/B978-012370526-6.50001-2>
20. Sessitsch, A., Brader, G., Pfaffenbichler, N., Gusenbauer, D., Mitter, B. (2018). The contribution of plant microbiota to economy growth. *Microbial Biotechnology*, 11, 801–805. <https://doi.org/10.1111/1751-7915.13209>
21. Singh, J. S., Pandey, V. C., & Singh, D. P. (2011). Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. *Agriculture, Ecosystems & Environment*, 140, 339–353. <https://doi.org/10.1016/j.agee.2011.01.017>
22. Raklami, A., Bechtaoui, N., Tahiri, A. I., Anli, M., Meddich, A., & Oufdou, K. (2019). Use of rhizobacteria and mycorrhizae consortium in the open field as a strategy for improving crop nutrition, productivity and soil fertility. *Frontiers in Microbiology*, 10, 1106. <https://doi.org/10.3389/fmicb.2019.01106>
23. Wang, X., Wang, M., Xie, X., Guo, S., Zhou, Y., Zhang, X., & Wang, G. (2020). Plant growth promotion by phosphate-solubilizing bacteria: Attributes and future challenges. *Journal of Advanced Research*, 26, 7–14. <https://doi.org/10.1016/j.jare.2020.03.002>
24. Verma, M., Mishra, J., & Arora, N. K. (2019). Plant growth-promoting rhizobacteria: Diversity and applications. In N. K. Arora (Ed.), *PGPR Amelioration in Sustainable Agriculture* (pp. 129–160). Woodhead Publishing. <https://doi.org/10.1016/B978-0-12-815879-1.00006-3>
25. Xu, X., Li, S., & Cui, S. (2020). Effects of biofertilizers on soil microbial community structure in different cropping systems: A review. *Journal of Soils and Sediments*, 20, 4474–4489. <https://doi.org/10.1007/s11368-020-02746-3>
26. Basu, A., Prasad, P., Das, S. N., Kalam, S., Sayyed, R. Z., Reddy, M. S., & El Enshasy, H. (2021). Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: Recent developments, constraints, and prospects. *Sustainability*, 13, 1140. <https://doi.org/10.3390/su13031140>
27. Zaidi, A., Khan, M. S., Ahemad, M., & Oves, M. (2009). Plant growth promotion by phosphate solubilizing bacteria. *Acta Microbiologica et Immunologica Hungarica*, 56, 263–284. <https://doi.org/10.1556/AMicr.56.2009.3.6>
28. Zhang, Y., Li, T., Liu, Y., Li, X., & Zhang, C. (2019). The effects of biofertilizers on crop yield: A meta-analysis. *Agronomy for Sustainable Development*, 39, 1–13. <https://doi.org/10.1007/s13593-019-0589-3>
29. Chen, J., Liu, X., Zheng, J., Zhang, B., Lu, H., Chi, Z., Pan, G., Li, L., & Smith, P. (2018). Biochar soil amendment increased non-flooded paddy rice yield by changing nitrogen cycling. *Soil Science Society of America Journal*, 82, 1279–1290. <https://doi.org/10.2136/sssaj2018.04.0132> (note: if your scope is strictly biofertilizers, you may omit this)