AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 03 (March, 2026)
Available online at http://www.agrimagazine.in

Harnessing Microbial Inoculants for Sustainable Fruit Crop Production and Soil Health Improvement

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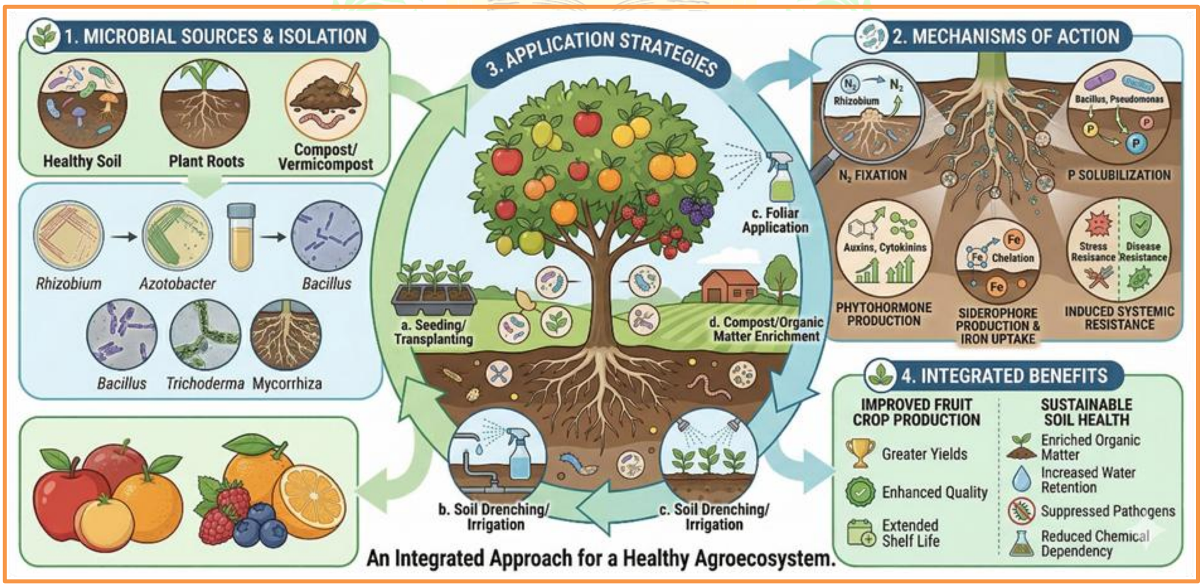
Intensive agricultural practices following the Green Revolution significantly increased crop productivity but also led to excessive dependence on chemical fertilizers. Global nitrogen use efficiency (NUE) remains below 50%, while phosphorus and potassium efficiencies often fall below 10–25% in the year of application. A large fraction of applied nutrients is lost through leaching, volatilization, runoff, or fixation in unavailable forms, resulting in economic losses and environmental degradation. Biofertilizers have emerged as a sustainable biological intervention to enhance nutrient availability and improve soil–plant interactions. Defined as carrier-based formulations containing living microorganisms capable of mobilizing nutrients from unavailable to available forms, biofertilizers function through biological nitrogen fixation, phosphate solubilization, potassium mobilization, phytohormone synthesis, and microbial antagonism. Although initially used primarily in field crops, biofertilizers are increasingly applied in fruit crops, where they contribute to improved yield, fruit quality, soil health and reduced chemical fertilizer dependence. This review aims to synthesize existing literature on the role, mechanisms and performance of biofertilizers in fruit production systems, with particular emphasis on nutrient use efficiency and sustainable horticulture.



Different types of biological fertilizers

A) Nitrogen fixing bio-fertilizer

1) Azospirillum. (Associative symbiotic)

2) Rhizobium, Anabaena azollae, Frankia (Symbiotic)
3) Azotobacter, Nostoc, Klebsiella, Clostridium, Anabaena, Beijerinkia (Free-living)

B) Phosphorus mobilizing bio-fertilizer (PMB)

1) *Rhizoctonia solani (Orchid mycorrhiza*)
2) *Amanita sp., Boletus sp., Pisolithus sp., Laccaria sp*.
3) *Ectomycorrhiza*
4) *Scutellospora sp., Gigaspora sp., Glomus sp.,*
5) *Acaulospora sp. (Arbuscular mycorrhiza)*
6) *Pezizellaericae. (Ericoid mycorrhizae)*

C) Phosphorus solubilizing bio-fertilizer (PSB)

1) *Psuedomonas striata, Bacillus megaterium var.*
2) *Bacillus circulans, B. subtilis (Bacteria)*
3) *Aspergillus awamori, Penicillium sp. (Fungi)*

D) Plant growth promoting bio-fertilizer (PGPB)

1) *Psuedomonas fluorescens (Psuedomonas)*

E) Bio-fertilizers for Micronutrients

1) Silicate and Zinc solubilizers (*Bacillus sp.*)

Role and importance of the biofertilizers

1. Biofertilizers and Nutrient Use Efficiency (NUE)

The enhancement of NUE forms the conceptual foundation of biofertilizer application. One review emphasizes that nitrogen use efficiency globally remains below 50%, and phosphorus efficiency is frequently under 25% due to fixation reactions in soil. Biofertilizers address these inefficiencies biologically rather than chemically.

Nitrogen-fixing microorganisms such as Azotobacter, Azospirillum, and Rhizobium convert atmospheric N_2 into ammonia via nitrogenase activity. Symbiotic associations can substitute 50–100 kg N ha^{-1}, reducing external nitrogen inputs. Similarly, phosphate-solubilizing bacteria (PSB) produce organic acids that chelate Ca^{2+}, Fe^{3+}, and Al^{3+}, releasing fixed phosphate into soluble forms.

2. Mechanisms of Growth Promotion in Fruit Crops

Three consistent mechanisms are identified:

a. Enhanced nutrient availability and uptake
b. Production of plant growth-promoting substances (IAA, GA_3, cytokinins)
c. Suppression of soil-borne pathogens

These mechanisms are consistently reported and align with earlier mechanistic frameworks describing increased nutrient uptake, hormone production and pathogen inhibition as central pathways. Biofertilizer performance may depend on microbial strain selection and crop-specific physiology.

3. Effects on Vegetative Growth

Consistent positive responses in vegetative parameters are reported across fruit crops:

a. Increased plant height, stem girth, leaf area, and root development in papaya and pomegranate.
b. Enhanced trunk thickness and vegetative vigor in apple with microbial consortia.
c. Improved vegetative growth in citrus through Azotobacter enrichment.

Notably, dual inoculation (e.g., AMF + Azotobacter) often outperformed single inoculations, suggesting synergistic microbial interactions.

4. Effects on Yield and Fruit Quality

a. Yield enhancement is one of the most consistently reported outcomes:
b. Banana yield increased with Azotobacter substitution of up to 50% nitrogen.
c. Strawberry yield improved by 54% with Azospirillum + nitrogen compared to nitrogen alone.
d. Mango orchards showed higher yields when biofertilizers were integrated with inorganic fertilizers.

e. Strawberry productivity and fruit quality parameters (TSS, anthocyanin) improved under combined mineral, organic, and biological fertilization.

Across studies, treatments combining 75–100% recommended fertilizer doses with biofertilizers frequently produced yields equal to or greater than 100% chemical fertilizer alone. This pattern underscores the complementary—not substitutive—role of biofertilizers.

5. Soil Health and Biological Activity

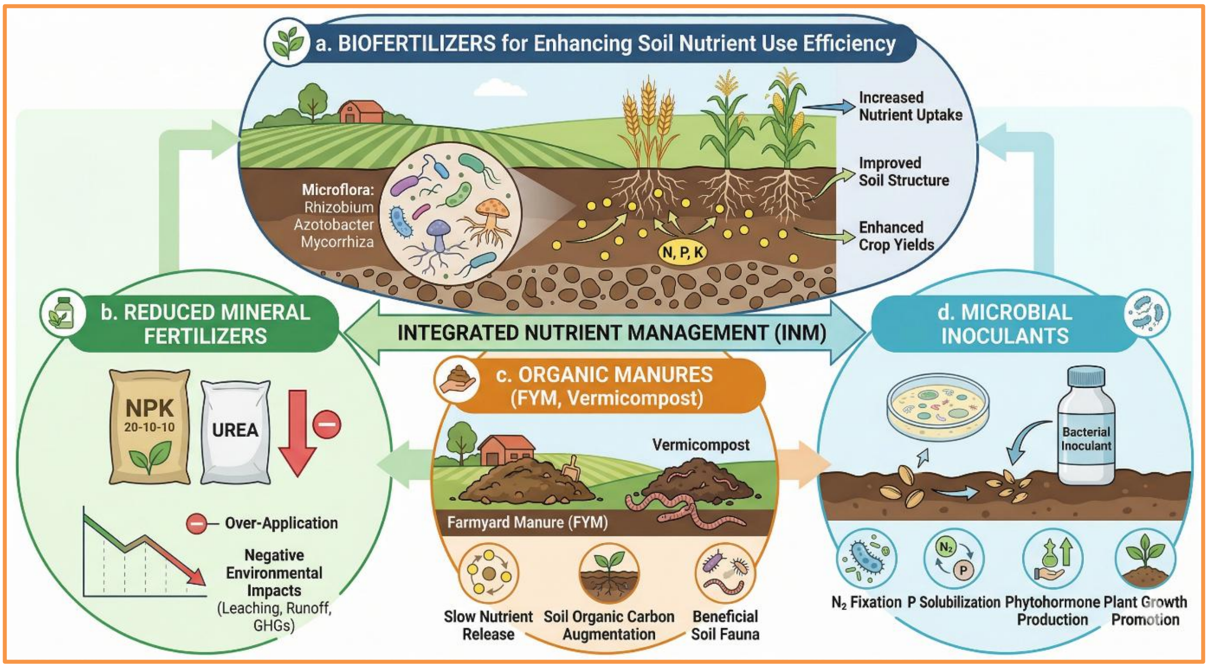
Improved soil organic carbon, microbial biomass, enzymatic activity, and nutrient status were observed under integrated biofertilizer applications. Biofertilizers also enhanced root colonization, improved nutrient cycling, and supported soil biodiversity.

Biofertilizers contribute to long-term soil fertility restoration—an aspect often neglected in purely yield-focused evaluations.

6. Integrated Nutrient Management (INM) as a Unifying Framework

A recurring conclusion across the reviews is that biofertilizers perform optimally within Integrated Nutrient Management systems. INM combines:

a. Biofertilizers for Enhancing Soil Nutrient Use Efficiency
b. Reduced mineral fertilizers
c. Organic manures (FYM, vermicompost)
d. Microbial inoculants



Evidence consistently shows that 75% RDF + biofertilizer treatments often match or surpass 100% RDF alone, enhancing both economic returns and environmental sustainability.

Constrains

- Microbial inoculants often show promising results under laboratory or controlled conditions but may perform inconsistently in field conditions due to environmental variability.
- Factors such as soil pH, temperature, moisture, and salinity significantly affect the survival and activity of introduced microorganisms.
- Introduced microbes may fail to establish themselves due to strong competition from the already existing indigenous soil microbial population.
- Many microbial inoculants have limited shelf life and require specific storage conditions, making their handling and transportation difficult.
- Ineffective or low-quality carrier materials can reduce microbial viability and limit the effectiveness of inoculants.
- Limited knowledge about the benefits, application methods, and handling of microbial inoculants restricts their widespread adoption.

- Microbial inoculants generally act slower than synthetic fertilizers, which may discourage farmers seeking immediate results.
- Some pesticides and chemical fertilizers may negatively affect the survival and efficiency of beneficial microbes.
- Not all microbial strains work equally across different crops and soil types, making it necessary to select location-specific strains.
- Lack of strict quality standards and regulation in production can lead to the availability of substandard or ineffective products in the market.

Future Thrust

Future research should prioritize:

a. Development of crop-specific microbial consortia
b. Long-term multi-location trials
c. Standardization of inoculum quality and viability
d. Molecular-level understanding of plant–microbe interactions
e. Precision biofertilizer application strategies
f. More efforts be put to fully exploit the role of biofertilizers in the farmers field by means of extension activities like field demonstration, farmer's fair and training programme.
g. The efforts are also desired in the direction of improvement of shelf life of bioinoculant in the biofertilizers during storage. Improvement of carrier material or isolation of strains which having more shelf life can help in this respect.

Integrated Nutrient Management emerges as the most effective framework, where biofertilizers complement reduced chemical fertilizer inputs to sustain high yields and economic returns. The transition toward biologically integrated nutrient management in fruit crops is not merely an alternative practice but a necessary pathway for ecological resilience, economic sustainability, and improved food quality in modern horticulture.

Conclusion

Biofertilizers represent a scientifically validated, environmentally sustainable strategy for improving nutrient use efficiency, soil health and fruit crop productivity. Through biological nitrogen fixation, phosphate solubilization, mycorrhizal associations, hormone production, and pathogen suppression, microbial inoculants enhance both plant performance and soil quality. Use of microbial inoculants is not only a low-cost technology but also it takes adequate care of soil health and environmental safety. Generally, the effect of biofertilizers on plant and yield is not as striking as that of chemical fertilizers. Since it is a living system, thus the influence is subject to environmental, biological and nutritional stresses. Moreover, the performance of the microbial inoculant depends on the quality of the inoculant and accurate specification is required to avoid poor performance of the inoculants. To become successful, this biofertilizer technology must reach to the hands of the farmers.