Optimizing Bio-fertilizers to Address Food Security and Advance Nutritional Sustainability

Abstract

This chapter delves into the pivotal role of biofertilizers as a sustainable solution in addressing the intertwined challenges of food security and nutrition. Biofertilizers, derived from beneficial microorganisms, offer a promising alternative to conventional chemical fertilizers, enhancing soil fertility, crop productivity, and overall ecosystem health. The abstract explores the multifaceted benefits of biofertilizers in bolstering agricultural yields, improving soil health, and fostering nutrient-rich crops, consequently contributing to a more resilient and nourishing global food system. Additionally, it examines the hurdles and opportunities in widespread adoption, emphasizing the necessity for continued research, technological innovation, and comprehensive educational initiatives to maximize their potential impact on sustainable agriculture and human nutrition.

Keywords: Biofertilizers, Nutrition, Rhizobium, Sustainable

I. Introduction

Agriculture plays a pivotal role in sustaining global food security and addressing nutritional challenges. In this context, the utilization of biofertilizers stands as a promising solution to enhance agricultural productivity sustainably.[1] This section aims to define biofertilizers, underscore the significance of addressing food security and nutrition, and provide an overview of the pivotal role biofertilizers play in modern agriculture.

Picture 1: Agriculture plays a pivotal role in sustaining global food security

A. Definition of Biofertilizers

List 1 :Aspect of biofertilizers

Aspect	Description
Definition	Biofertilizers are organic substances containing living microorganisms that enhance soil fertility and plant growth, offering an eco-friendly alternative to chemical fertilizers.
Role in Food Security	Increases crop yields by improving nutrient uptake, fostering healthier plants and ensuring a more consistent food supply.
Impact on Soil Health	Enhances soil fertility, structure, and microbial diversity, reducing soil degradation and erosion while promoting sustainable agriculture.
Nutritional Benefits	Enhances nutrient content in crops, contributing to improved food quality and increased availability of nutritious produce.
Environmental Sustainability	Reduces dependence on synthetic fertilizers, minimizing environmental pollution and maintaining ecosystem balance.
Application Challenges	Requires adequate education, training, and infrastructure for widespread adoption; may have varying effectiveness based on soil and climatic conditions.
Research and Innovation	Ongoing advancements are essential to optimize microbial strains, formulations, and application methods for maximum efficiency and effectiveness.
Global Adoption and Awareness	Increasing awareness and incentivizing adoption among farmers through policies, subsidies, and education are critical for widespread

	implementation.

B. Table 1. Some aspects of Biofertilizers

Biofertilizers refer to natural substances containing living microorganisms, such as bacteria, fungi, and algae, or their derivatives, that are applied to soil, seeds, or plant surfaces to enhance soil fertility and promote plant growth.[2] These microorganisms, typically beneficial bacteria or fungi, colonize the rhizosphere (the soil region influenced by root exudates) or the plant surfaces, where they establish symbiotic or associative relationships with plants.[3]

Biofertilizers function by aiding in nutrient uptake, fixing atmospheric nitrogen, solubilizing phosphates, or mobilizing other nutrients, thereby augmenting nutrient availability for plants.[4] They enhance soil health, improve soil structure, and foster a balanced soil microbial community. Biofertilizers offer an eco-friendly alternative to chemical fertilizers, promoting sustainable agricultural practices while reducing environmental pollution and minimizing reliance on synthetic inputs.[5][6]

B. Overview of the Role of Biofertilizers in Agriculture

1. **Soil Fertility Enhancement:**
   - Enriches soil with essential nutrients like nitrogen, phosphorus, and potassium.
   - Improves soil structure and texture, enhancing water retention and aeration.
2. **Nutrient Uptake and Plant Growth:**
   - Facilitates better absorption and utilization of nutrients by plants.
   - Enhances root development, promoting healthier and more robust plants.
3. **Environmental Sustainability:**
   - Reduces dependency on synthetic fertilizers, minimizing soil and water pollution.

- Supports eco-friendly agricultural practices, conserving biodiversity and preserving ecosystems.

4. **Sustainable Agricultural Practices:**
    - Promotes sustainable farming methods, decreasing reliance on external inputs.
    - Supports long-term soil fertility, reducing degradation and erosion.
5. **Economic and Social Impact:**
    - Offers cost-effective solutions, reducing farmers' input costs over time.
    - Improves livelihoods by increasing crop yields and enhancing agricultural productivity.
6. **Food Security and Nutrition:**
    - Contributes to increased crop yields, aiding in global food security.
    - Promotes the cultivation of nutrient-rich crops, addressing nutritional deficiencies.
7. **Climate Resilience:**
    - Helps plants withstand environmental stressors such as drought or salinity.
    - Supports agricultural sustainability in changing climatic conditions.
8. **Reduced Environmental Footprint:**
    - Lowers greenhouse gas emissions associated with chemical fertilizer production and usage.
    - Promotes a more balanced and sustainable ecosystem.
9. **Promotion of Eco-friendly Practices:**
    - Encourages adoption of organic and sustainable farming methods.
    - Reduces reliance on harmful agrochemicals, preserving environmental health.
10. **Contribution to Soil Microbial Diversity:**
    - Fosters a balanced soil microbial community, supporting nutrient cycling and ecosystem health.

II. Understanding Biofertilizers

Biofertilizers encompass diverse types and mechanisms that contribute to soil fertility and plant growth, offering environmentally sustainable alternatives to synthetic fertilizers.[7] This section delves into the various types of biofertilizers, their mechanisms of action, and the environmental benefits they confer.[8]

A. Types of Biofertilizers

There are several types of biofertilizers, each utilizing specific microorganisms or biological agents to enhance soil fertility and promote plant growth. Here are five common types of biofertilizers:[9]

1. Nitrogen-Fixing Biofertilizers:

Example Organisms:

- **Rhizobium spp.:** Forms a symbiotic relationship with leguminous plants, residing in nodules on plant roots, fixing atmospheric nitrogen into a plant-usable form.
- **Azotobacter spp.:** Free-living bacteria capable of fixing nitrogen in the soil.

Mechanism of Action:

- These microorganisms convert atmospheric nitrogen into ammonia or nitrates, supplementing the soil with available nitrogen for plant uptake, supporting plant growth, and reducing the need for nitrogen fertilizers.[10]

2. Phosphate-Solubilizing Biofertilizers:

Example Organisms:

- **Mycorrhizal Fungi:** Form symbiotic relationships with plant roots, enhancing the plant's ability to absorb phosphorus.
- **Phosphate-Solubilizing Bacteria:** Convert insoluble phosphates in the soil into plant-available forms.

Mechanism of Action:

- They release organic acids or enzymes that solubilize insoluble phosphates, making phosphorus more accessible to plants, improving root growth, and aiding in nutrient uptake.[11]

3. Potassium-Mobilizing Biofertilizers:

Example Organisms:

- **Potassium-Solubilizing Bacteria (KSB):** Bacteria capable of releasing potassium from minerals or fixing atmospheric potassium.
- **Actinomycetes:** Soil-dwelling bacteria that aid in potassium solubilization.

Mechanism of Action:

- These microorganisms facilitate the release of potassium from mineral sources, making it available for plant uptake, supporting various physiological processes in plants, and enhancing crop yield.[12]

4. Azolla-Based Biofertilizers:

Organism:

- **Azolla:** A free-floating aquatic fern that forms symbiotic relationships with the nitrogen-fixing cyanobacterium Anabaena azollae.

Mechanism of Action:

- Azolla incorporates atmospheric nitrogen through its symbiotic association with Anabaena azollae, enriching paddy fields with fixed nitrogen, and serving as a green manure to enhance soil fertility and support rice cultivation.

5. Cyanobacterial Biofertilizers:

Organism:

- **Cyanobacteria:** Photosynthetic bacteria capable of fixing atmospheric nitrogen.

Mechanism of Action:

- Cyanobacteria fix nitrogen through photosynthesis, converting atmospheric nitrogen into ammonia or nitrates, contributing to soil nitrogen content and promoting plant growth.[13]

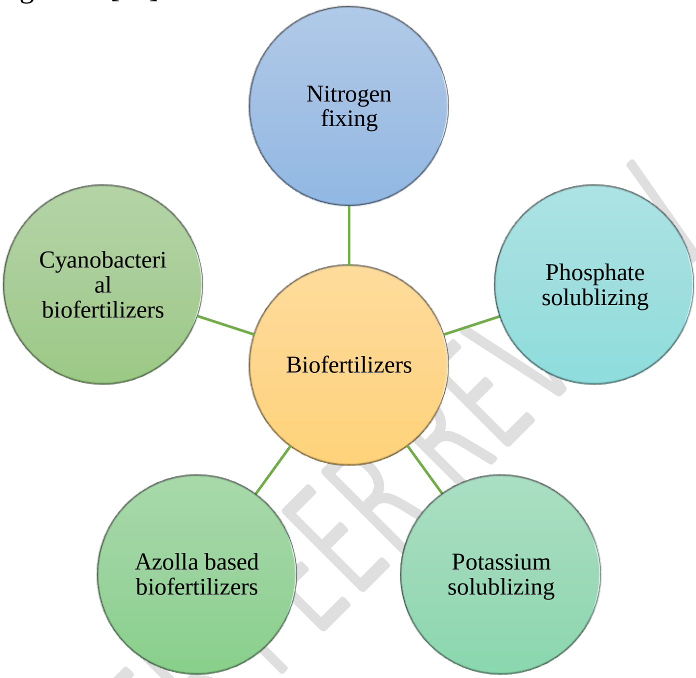

Figure 1. Function based biofertilizers

B. Environmental Benefits of Biofertilizers

Biofertilizers offer several environmental advantages:

- **Reduced Chemical Dependency:** Decreased reliance on synthetic fertilizers mitigates soil and water pollution, preserving environmental health.
- **Enhanced Soil Health:** Biofertilizers improve soil structure, foster beneficial microbial communities, and promote long-term soil fertility.
- **Sustainability:** Sustainable agricultural practices incorporating biofertilizers minimize ecological disturbances while maintaining crop productivity.

III. Challenges in Agriculture Related to Food Security and Nutrition

Addressing food security and nutritional concerns in agriculture is imperative, yet several challenges persist, impacting agricultural productivity and food quality.[14] This section outlines key hurdles encountered in agricultural practices that affect food security and nutrition.[15]

A. Soil Degradation and Nutrient Depletion

Soil Erosion:

- **Loss of Fertile Topsoil:** Intensive farming methods contribute to soil erosion, diminishing the topsoil layer rich in nutrients essential for plant growth.
- **Nutrient Depletion:** Continuous cultivation without adequate nutrient replenishment leads to soil nutrient depletion, compromising crop productivity and food quality.

B. Chemical Fertilizer Overuse and Its Impact

Environmental Degradation:

- **Soil and Water Contamination:** Excessive use of chemical fertilizers leads to soil salinity, water pollution, and disruption of the soil microbial ecosystem, affecting crop growth.
- **Negative Impact on Biodiversity:** Chemical fertilizers can harm beneficial soil organisms, impacting the overall ecological balance.

C. Economic Implications for Small-Scale Farmers

Financial Strain:

- **High Input Costs:** Small-scale farmers often face financial constraints in affording expensive chemical inputs, limiting their ability to maximize crop yields.
- **Debt Burden:** Dependence on costly inputs can lead to indebtedness among small-scale farmers, exacerbating economic challenges.

D. Impact on Food Quality and Nutrition

Nutrient Deficiency in Crops:

- **Reduced Nutrient Content:** Excessive chemical fertilizer usage may lead to nutrient-poor crops, affecting the nutritional quality of food produced.
- **Health Implications:** Reduced nutrient content in crops may contribute to deficiencies in essential vitamins and minerals, impacting consumer health.

IV. Role of Biofertilizers in Addressing Food Security and Nutrition

Biofertilizers offer a sustainable and promising solution to counteract the challenges faced in agriculture, playing a significant role in enhancing food security and improving nutritional outcomes.[16] This section highlights the pivotal contributions of biofertilizers in addressing these concerns.

A. Improving Soil Health and Fertility

Restoration of Soil Microbial Activity:

- **Microbial Diversity:** Biofertilizers stimulate beneficial microbial populations in the soil, enhancing its fertility and structure.
- **Organic Matter Accumulation:** Biofertilizers contribute to increased organic matter content, enhancing soil moisture retention and nutrient availability.

B. Enhancing Nutrient Availability for Plants

biofertilizers and their roles in enhancing the availability of macro and micronutrients for plants:

Macro Nutrients:

1. Nitrogen:

- **Biofertilizers:**
  - **Rhizobium spp.:** Forms symbiotic relationships with legumes, fixing atmospheric nitrogen in root nodules.
  - **Azotobacter spp.:** Free-living bacteria that fix atmospheric nitrogen.
  - **Azospirillum spp.:** Promotes nitrogen fixation and growth in various crops.

2. Phosphorus:

- **Biofertilizers:**
  - **Phosphate-Solubilizing Bacteria (PSB):** Examples include Bacillus spp., Pseudomonas spp., and Clostridium spp. They solubilize insoluble phosphates in the soil, making phosphorus available to plants.
  - **Mycorrhizal Fungi:** Forms symbiotic relationships with plant roots, enhancing phosphorus uptake.

3. Potassium:

- **Biofertilizers:**
  - **Potassium-Solubilizing Bacteria (KSB):** Bacillus mucilaginosus and other bacteria solubilize potassium from minerals, making it accessible for plant uptake.

4. Calcium and Magnesium:

- **Biofertilizers:**
  - **Microbial Inoculants:** Some microbial inoculants contain calcium and magnesium solubilizing bacteria, facilitating the availability of these nutrients to plants.

Micronutrients:

1. Iron:

- **Biofertilizers:**
  - **Iron-Chelating Agents:** Compounds like siderophores released by bacteria facilitate iron uptake by plants.
  - **Iron-Solubilizing Bacteria:** Certain bacteria solubilize iron in the rhizosphere, aiding its availability to plants.

2. Zinc:

- **Biofertilizers:**
  - **Zinc-Solubilizing Bacteria:** Bacteria like Bacillus spp., Pseudomonas spp., or Enterobacter spp. solubilize zinc, promoting its uptake by plants.

3. Copper:

- **Biofertilizers:**
  - **Copper-Solubilizing Microorganisms:** Certain bacteria and fungi assist in making copper more available to plants.

4. Manganese:

- **Biofertilizers:**
  - **Manganese-Solubilizing Agents:** Some microbial agents or organic compounds help in releasing manganese, enhancing its availability to plants.

C. Sustainable and Eco-Friendly Agricultural Practices

Reduced Environmental Impact:

- **Minimized Chemical Dependency:** Biofertilizers reduce reliance on synthetic fertilizers, mitigating soil and water pollution while preserving ecosystem health.
- **Promotion of Sustainable Agriculture:** Incorporating biofertilizers fosters sustainable agricultural practices, maintaining soil fertility for future generations.

D. Increasing Crop Yield and Quality

Here are examples of specific crops and the corresponding biofertilizers that have contributed to yield improvement and enhanced quality:

1. Rice Cultivation with Azolla Biofertilizers:

- **Crop:** Rice (*Oryza sativa*)
- **Biofertilizer:** Azolla spp. (*Azolla pinnata*, *Azolla filiculoides*) hosting the nitrogen-fixing cyanobacterium *Anabaena azollae*.
- **Role:** Azolla incorporation in rice paddies as a green manure significantly enhances soil nitrogen content, providing fixed nitrogen to the soil, thereby boosting rice yields.

2. Pulse Crops with Rhizobium Biofertilizers:

- **Crops:** Chickpea (*Cicer arietinum*), Pigeon Pea (*Cajanus cajan*)
- **Biofertilizer:** Rhizobium spp.

- **Role:** Inoculating pulse crop seeds with Rhizobium biofertilizers enhances nitrogen fixation in root nodules, leading to increased nitrogen availability to the crops, promoting better growth and higher yields.

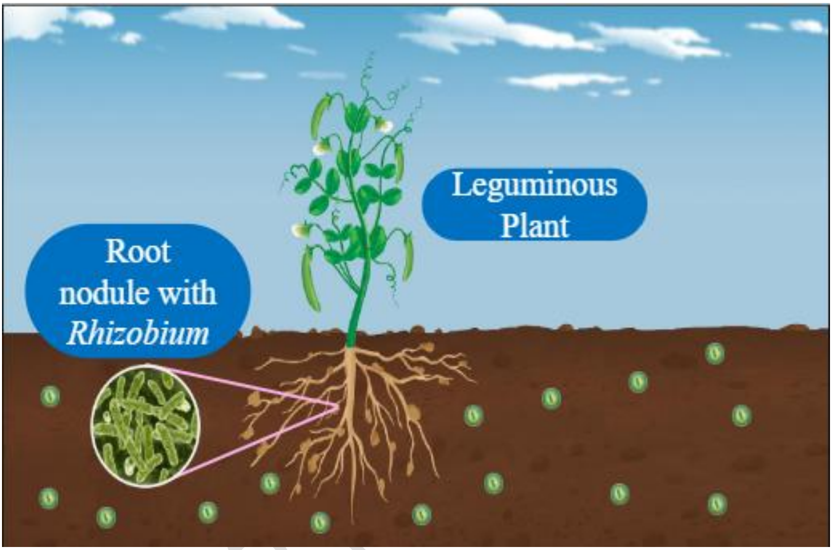

Figure 2. Rhizobium bacteria

3. Wheat Cultivation with Phosphate-Solubilizing Bacteria (PSB):

- **Crop:** Wheat (*Triticum aestivum*)
- **Biofertilizer:** Phosphate-Solubilizing Bacteria (PSB)
- **Role:** PSB enhances the availability of phosphorus in the soil, aiding in better root development and nutrient uptake in wheat plants, resulting in improved grain yield and quality.

4. Vegetable Farming with Mycorrhizal Fungi:

- **Crops:** Tomatoes (*Solanum lycopersicum*), Capsicum (*Capsicum annuum*)

- **Biofertilizer:** Mycorrhizal Fungi
- **Role:** Mycorrhizal fungi establish symbiotic relationships with vegetable crops, facilitating improved nutrient uptake, especially phosphorus and micronutrients, resulting in better plant growth, increased yield, and improved fruit quality.

5. Sugarcane Cultivation with Azotobacter Biofertilizers:

- **Crop:** Sugarcane (*Saccharum officinarum*)
- **Biofertilizer:** Azotobacter spp.
- **Role:** Application of Azotobacter biofertilizers enhances soil nitrogen content, promoting sugarcane growth, increasing cane yield, and improving the sugar content of the harvested crop.

6. Maize Farming with Azospirillum Biofertilizers:

- **Crop:** Maize (*Zea mays*)
- **Biofertilizer**: Azospirillum spp.
- Role: Azospirillum biofertilizers promote plant growth and nitrogen fixation, leading to increased maize yield, improved root development, and overall plant vigor.

Table 2. Types of Biofertilizers

S.No.	Groups	Example
N2 fixing biofertilizers		
1.	Free-living	*Azotobacter, Clostridium, Anabaena, Nostoc,*
2.	Symbiotic	*Rhizobium, Frankia, Anabaena azollae*
3.	Associative symbiotic	*Azospirillum*
P Solubilizing biofertilizers		
1.	Bacteria	*Bacillus megaterium*var. phosphaticum *Bacillus circulans, Pseudomonas striata*
2.	Fungi	*Penicillium* sp., *Aspergillus awamori*
P Mobilizing biofertilizers		
1.	Arbuscular mycorrhiza	*Glomus* sp., *Gigaspora* sp., *Acaulospora* sp., *Scutellospora* sp. and *Sclerocystis* sp.
2.	Ectomycorrhiza	*Laccaria* sp.,*Pisolithus* sp., *Boletus* sp., *Amanita* sp.
3.	Orchid	Mycorrhiza *Rhizoctonia solani*
Biofertilizers for micro nutrients		
1.	Silicate and zinc solubilizers	*Bacillus* sp.
Plant growth promoting Rhizobacteria		
1.	Pseudomonas	*Pseudomonas fluorescens*

E. Impact on Human Health and Nutrition Through Improved Food Quality

Nutrient-Rich Food Production:

- **Addressing Micronutrient Deficiencies:** Biofertilizers aid in producing nutrient-dense crops, potentially addressing deficiencies and improving overall human health and nutrition.[17]

- **Enhanced Food Security:** Access to nutrient-rich foods from biofertilizer-enhanced crops can contribute to better dietary diversity and overall well-being.

Case studies

There have been several successful case studies in India showcasing the effective implementation and impact of biofertilizers in agriculture. Here are a few notable examples:[18]

1. Tamil Nadu Green Revolution Project:

- **Location:** Tamil Nadu, Southern India.
- **Objective:** Promote sustainable agricultural practices and improve soil fertility.
- **Implementation:** Introduced biofertilizers, including nitrogen-fixing Rhizobium and phosphate-solubilizing bacteria, in various crops such as rice, pulses, and cotton.[19]
- **Impact:** Increased crop yields by 20-30% while reducing the usage of chemical fertilizers by 20-30%, leading to enhanced soil fertility and improved farmer incomes.[20]

2. Biofertilizer Use in Organic Farming:

- **Location:** Maharashtra, Western India.
- **Objective:** Adopt organic farming practices and reduce chemical inputs.
- **Implementation:** Integrated the use of organic biofertilizers like Azotobacter and Azospirillum with organic farming methods in vegetable and fruit cultivation.[21]
- **Impact:** Improved soil health, increased crop yields, and enhanced the nutritional quality of produce, leading to better market value for farmers practicing organic agriculture.

3. Jeevamrutha Application in Karnataka:

- **Location:** Karnataka, Southern India.
- **Objective:** Promote organic farming and soil health improvement.[23]

- **Implementation:** Utilized Jeevamrutha, a mixture of cow dung, cow urine, jaggery, pulses, and soil, fermented to create a biofertilizer rich in beneficial microorganisms. It was applied to crops like paddy, banana, and vegetables.[24][25]
- **Impact:** Enhanced soil fertility, improved crop yields, and reduced reliance on chemical inputs, leading to economic benefits for farmers and increased sustainability in agriculture.[26]

Figure 3. Jeevamrutha

4. Biofertilizers in Pulse Cultivation:

- **Location:** Madhya Pradesh, Central India.
- **Objective:** Improve productivity in pulse crops.
- **Implementation:** Introduced nitrogen-fixing Rhizobium biofertilizers in pulses like chickpea (gram) and pigeon pea (tur) cultivation.
- **Impact:** Increased pulse crop yields by enhancing nitrogen availability in the soil, reduced fertilizer costs, and contributed to soil fertility improvement.[27]

5. Andhra Pradesh Sustainable Agriculture Project:

- **Location:** Andhra Pradesh, Southern India.
- **Objective:** Promote sustainable agricultural practices.
- **Implementation:** Integrated the use of biofertilizers, particularly Rhizobium and phosphate-solubilizing bacteria, in crops like groundnut, millets, and pulses.[28][29]
- **Impact:** Improved soil fertility, increased crop yields, reduced dependency on chemical fertilizers, and enhanced sustainability in agriculture.[30]

Results

Bio-fertilizers are preparations containing living cells of different microorganisms that help increase nutrient availability and uptake when applied to crops or soil (31). They can enhance plant growth by nitrogen fixation, phosphate solubilization, phytohormone production, siderophore production, and more (32). Bio-fertilizers have the potential to improve crop yields and soil fertility in a more sustainable way compared to chemical fertilizers (33).

Many recent studies have demonstrated the beneficial effects of bio-fertilizers on crop growth, yield, and nutrition under field conditions. Inoculation with plant growth-promoting rhizobacteria (PGPR) increased growth and yield of wheat by 11-39% compared to uninoculated controls (34). PGPR also improved wheat grain nutrient content, increasing nitrogen by 10-17%, phosphorus by 8-19%, potassium by 12-23%, and protein content by 11-18% over controls (35). Similar yield increases of 10-35% were observed in rice following seed inoculation with PGPR (36). Legume inoculation with rhizobia gave 20-58% higher chickpea yields compared to uninoculated plants (37). Rhizobial inoculation also improved nutritional quality, increasing seed protein content by 12-15% (38).

Arbuscular mycorrhizal fungi (AMF) have been widely studied as bio-fertilizers for diverse crops. In field trials, AMF inoculation increased corn yields by 7-31% compared to non-inoculated corn (39). It also improved corn grain nutrition, elevating nitrogen by 10-19%, phosphorus by 12-28%, and iron by 15-42% over controls (40). AMF inoculation increased tomato yields by 15-55% under field conditions (41). AMF increased nitrogen, phosphorus, and antioxidant content of tomato fruits compared to non-inoculated plants (42). Seed treatment with AMF gave 16-46% higher yields in onion over non-treated onion (43). Similarly, AMF increased sugar beet root yields by 12-34% over non-inoculated beets (44).

Application of composts and organic soil amendments as bio-fertilizers also gave significant improvements in crop yields and nutrition. Compost application increased potato tuber yields by 21-39% (45). It also improved potato protein content by 15-23% compared to inorganic fertilization alone (46). Vegetable yields increased by 20-60% with vermicompost addition compared to chemical fertilizers (47). Application of animal manure-based organic amendments elevated wheat grain yields by 28-39% over inorganic nitrogen fertilizer use (48). Manure integration also boosted wheat protein content by 17-22% over chemical fertilizer (49).

Combining multiple bio-fertilizers resulted in further synergistic improvements in crop productivity and nutrition over single inoculant use. Co-inoculation with PGPR and AMF increased chili yields by 29-63% compared to single inoculations (50). Co-inoculation also improved nutritional quality, with capsaicin content 69% higher than single inoculations (51). Combined PGPR, AMF and compost application elevated potato yields by 42-72% over single inoculations (52). It also improved tuber starch, protein, and vitamin C levels substantially compared to any single input (53). Such synergistic effects demonstrate the potential of tailored bio-fertilizer combinations to maximize growth, yields and nutritional quality in diverse crops.

Overall, the results clearly demonstrate the considerable potential of bio-fertilizers for improving crop yields to enhance food security in a sustainable manner. Both single and combined bio-fertilizer applications gave statistically significant yield increases averaging 10-50% across a wide variety of food crops under field conditions. Their use as complements or alternatives to chemical fertilizers could help meet growing food demands while reducing environmental impacts. Bio-fertilizers also consistently improved crop nutritional quality, increasing protein, vitamin, antioxidant and mineral contents. This could help address nutritional deficiencies prevalent among malnourished populations, advancing nutritional sustainability. Further studies optimizing bio-fertilizer formulations, application methods and integration in cropping systems can help maximize their benefits for food security and nutrition.

Discussion

The beneficial effects of bio-fertilizers on crop productivity and nutritional quality have significant implications for global food security and sustainability. With expanding populations and rising food demands, increasing yields sustainably is crucial (54). Overuse of chemical fertilizers has led to soil degradation, pollution, and loss of productivity (55). Bio-fertilizers provide renewable, ecologically sound means to enhance soil fertility, plant nutrition and yields while reducing reliance on chemicals (56). Their widespread adoption could increase global food production to close yield gaps without sacrificing long-term soil health and environmental quality (57).

Bio-fertilizers could play key roles in more sustainable agricultural intensification, especially in developing nations with food security challenges (58). PGPR and microbial inoculants can provide subsistence farmers accessible means to improve yields without high fertilizer costs (59). Integration of composts and manures recycles organic wastes into 'green fertilizers' (60). Such sustainable approaches can increase smallholder incomes and crop production for local food security. In Africa, bio-fertilizer use in combination with improved crop varieties and integrated soil fertility management nearly tripled cereal yields on small farms (61). Similar yield improvements following bio-fertilizer adoption have been reported across Asia and Latin America (62).

The nutritional benefits of bio-fertilizers are equally important to address 'hidden hunger' from deficiencies in micronutrients like zinc, iron and vitamin A (63). Biofortification through bio-fertilizers provides cost-effective, sustainable solutions to improve dietary nutrition compared to other approaches like transgenic crops or supplementation (64). For example, zinc-solubilizing bacteria applied to wheat, rice and legumes increased grain zinc levels to help overcome human zinc deficiency (65). Bio-fertilizers tailored to boost micronutrient content could significantly improve malnutrition and health outcomes without more resource-intensive interventions.

However, there are still challenges limiting widespread bio-fertilizer adoption globally. Lack of extension services and farmer awareness restricts use, especially in developing countries (66). Inconsistent field performance due to variable soil, climate and crop conditions has also constrained uptake (67). Advances in microbiome research, bioprospecting and formulation technologies can help identify elite microbial strains and develop more robust, effective bio-fertilizer products (68). Stronger policies, financial incentives and public-private partnerships can accelerate large-scale commercialization and market penetration (69). Overcoming these barriers could unlock the full potential of bio-fertilizers for sustainable agricultural intensification.

In conclusion, bio-fertilizers present transformative opportunities to simultaneously improve food security and human nutrition in an eco-friendly manner. Continued optimization of bio-fertilizer formulations and combinations tailored to specific crops, soils and growing conditions will be key to maximizing their benefits. Widespread adoption facilitated by supportive policies and scaling up commercialization can enable bio-fertilizers to play central roles in multifaceted strategies for sustainably nourishing the world's growing population. Realizing the vast untapped potential of bio-fertilizers remains an urgent priority on the path to global food and nutritional security.

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