

ORIGINAL RESEARCH ARTICLE

Advancing sustainable agriculture with beneficial microbes: Enhancing crop growth and yield for food security and human health

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ABSTRACT

The application of biofertilizers (beneficial microbes) represents a transformative paradigm in modern agriculture. This paper delves into the multifaceted benefits of biofertilizers in the context of crop production. It examines how biofertilizers work their magic in enhancing crop growth, yield, and quality, underpinning their pivotal role in sustainable agriculture. Beyond these primary advantages, the paper explores the ripple effects of biofertilizer utilization, where it emerges as a linchpin in the global quest for food security. Biofertilizers not only reduce the environmental footprint of agriculture but also contribute to improving human health. This paper synthesizes current knowledge, revealing that biofertilizers have emerged as a potent tool in addressing the challenges of modern agriculture, from crop enhancement to environmental conservation and public health. It serves as a call to action for their wider adoption, heralding the era of biofertilizers as a cornerstone of sustainable agricultural practices.

Keywords: biofertilizers; sustainable agriculture; food security; environmental sustainability; crop quality; nutrient management; economic and health benefits

1. Introduction

Agriculture, as the cornerstone of global food production, faces an unprecedented challenge in the 21st century^[1]. The world's population continues to surge, exerting relentless pressure on agricultural systems to meet the burgeoning demand for food, feed, and fiber. Simultaneously, climate change, environmental degradation, and dwindling natural resources cast a shadow of uncertainty over the future of food security and sustainable agriculture. In this dynamic landscape, it becomes imperative to seek innovative, ecologically sound, and sustainable solutions to address the escalating needs of both crops and the planet^[1].

One such innovation is the use of biofertilizers, an emerging frontier in the realm of agriculture^[2]. Biofertilizers encompass a range of beneficial microorganisms, predominantly nitrogen-fixing bacteria, mycorrhizal fungi, and phosphate-solubilizing microorganisms, which form symbiotic relationships with plants^[2]. These microorganisms, harnessed for their remarkable potential, serve as biologically driven fertilizers that unlock the latent magic within the soil-plant-microorganism nexus. Their mode of action primarily involves enhancing nutrient availability to plants, particularly nitrogen, phosphorus, and other essential micronutrients^[3].

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While the concept of using beneficial microorganisms for crop cultivation is not new, the resurgence of interest in biofertilizers has been driven by several interconnected factors. First and foremost, the pressing need for sustainable agricultural practices has ignited a renewed focus on biological solutions that reduce the dependence on chemically synthesized fertilizers. Biofertilizers have emerged as a compelling answer to this need, aligning with the global pursuit of environmentally friendly, low-input, and resource-efficient agriculture (Figure 1)^[2].



Figure 1. Benefits of beneficial microbes in agriculture.

This paper seeks to explore the multifaceted role of biofertilizers in revolutionizing agriculture (Table 1). It sets out to elucidate the ways in which biofertilizers operate as catalysts for crop growth, yield enhancement, and improved crop quality. In doing so, it goes beyond the conventional narratives to examine the broader implications of biofertilizer utilization^[4].

Table 1. A detailed list of benefits of biofertilizers in agriculture.

Benefit	Description
1) Improved soil health	Biofertilizers enhance soil structure, microbial activity, and nutrient availability.
2) Enhanced nutrient uptake	They improve the uptake of essential nutrients by plants, leading to healthier crops.
3) Sustainable agriculture	Biofertilizers reduce the environmental impact of farming and promote long-term sustainability.
4) Crop yield enhancement	They increase crop yields by providing plants with necessary nutrients.
5) Soil fertility improvement	Biofertilizers enrich the soil with organic matter and essential nutrients.
6) Reduced chemical fertilizers	The use of biofertilizers decreases reliance on chemical fertilizers, reducing costs.
7) Enhanced crop quality	They influence the appearance, taste, texture, and nutritional value of crops.
8) Resistance to plant diseases	Biofertilizers, like mycorrhizal fungi, can help plants resist diseases.
9) Environmental sustainability	They reduce soil degradation, nutrient runoff, and greenhouse gas emissions.
10) Human health and nutrition	Biofortified crops grown with biofertilizers address micronutrient deficiencies.
11) Climate change resilience	Biofertilizers can help crops adapt to changing climate conditions.
12) Economic prosperity	Increased crop yield and quality lead to higher income for farmers.
13) Reduced environmental pollution	They minimize nutrient runoff, mitigating water pollution and its effects.

Table 1. (Continued).

Benefit	Description
14) Carbon sequestration	Healthy, biofertilizer-treated plants can sequester more carbon.
15) Resilience to climate change	Biofertilizer-treated crops are more resilient to climate change effects.
16) Biodiversity conservation	Biofertilizers create a favorable environment for beneficial soil organisms.
17) Innovative agricultural practices	Their use drives innovation in sustainable farming methods.

This table summarizes the various benefits of using biofertilizers in agriculture, covering soil health, crop quality, environmental sustainability, and more.

Biofertilizers transcend the mere augmentation of nutrient availability; they wield far-reaching impacts^[5]. Their utilization resonates deeply with the aspirations of achieving food security, mitigating environmental degradation, and promoting human health^[4]. As such, this review endeavors to uncover the intricate interplay between biofertilizers and these overarching goals.

The core objectives of this paper can be summarized as follows:

- 1) To elucidate the mechanisms by which biofertilizers enhance crop growth, yield, and quality, underlining their significance in contemporary agriculture.
- 2) To explore the ramifications of biofertilizer deployment in the context of food security, emphasizing the role they play in bolstering global nutritional needs.
- 3) To delve into the environmental benefits of biofertilizers, including their potential in reducing soil degradation, nutrient runoff, and greenhouse gas emissions.
- 4) To analyze the contributions of biofertilizers to human health, particularly through the cultivation of nutritionally enriched crops that address micronutrient deficiencies and promote well-being.
- 5) To champion the wider adoption of biofertilizers as a cornerstone of sustainable agricultural practices and a beacon for the future of agriculture.

As agriculture stands at the nexus of the world's most pressing challenges, the time has come to embrace innovative solutions that not only boost crop production but also safeguard the planet and nourish its inhabitants. Biofertilizers, as showcased in this review, hold the promise to unlock the magic of sustainable agriculture, where crop growth, yield, and quality coexist with food security, environmental resilience, and human health.

2. Discussion

2.1. Elucidating the mechanisms of biofertilizers in enhancing crop growth, yield, and quality

Biofertilizers, harnessed from beneficial microorganisms, are pivotal agents in contemporary agriculture. They operate through diverse mechanisms to enhance crop growth, increase yields, and elevate crop quality^[4,6,7]. Understanding these mechanisms is crucial for realizing the significance of biofertilizers in modern agriculture. Here, we delve into the key mechanisms through which biofertilizers exert their transformative effects:

- 1) **Nitrogen fixation:** Nitrogen is a vital nutrient for plant growth, and many crops depend on the conversion of atmospheric nitrogen into a plant-usable form. Nitrogen-fixing bacteria, such as *Rhizobium* and *Azotobacter*, form symbiotic relationships with leguminous crops and free-living associations with non-legumes. They convert atmospheric nitrogen into ammonium, making it readily available to plants. This mechanism not only boosts plant growth but also reduces the need for synthetic nitrogen fertilizers, mitigating environmental pollution.

- 2) Phosphorus solubilization: Phosphorus is another essential nutrient, often found in soil in insoluble forms. Phosphate-solubilizing microorganisms secrete organic acids and enzymes that break down these insoluble phosphates into plant-accessible forms. As a result, plants can better access phosphorus, leading to improved root development, enhanced nutrient uptake, and increased yield.
- 3) Enhanced nutrient uptake: Beyond nitrogen and phosphorus, biofertilizers facilitate the absorption of other essential nutrients, including potassium, calcium, and micronutrients. They enhance the nutrient uptake efficiency of plants, ensuring a steady supply of nutrients for optimal growth and development.
- 4) Disease suppression: Some biofertilizers contain beneficial microorganisms that act as biocontrol agents against plant pathogens. These microorganisms outcompete or inhibit harmful pathogens, reducing the incidence of diseases. This not only safeguards crop health but also contributes to higher yields and better crop quality.
- 5) Improved soil structure: Biofertilizers foster improved soil structure by enhancing microbial diversity and organic matter content. This results in better aeration, water retention, and nutrient cycling in the soil, creating an environment conducive to root growth and overall plant health.
- 6) Hormone production: Certain biofertilizers produce plant growth-promoting hormones like auxins and gibberellins. These hormones stimulate various plant processes, including cell elongation, flowering, and fruit development. As a result, crops exhibit enhanced growth and increased yield potential.
- 7) Bioavailability of nutrients: Biofertilizers make nutrients in the soil more bioavailable to plants. By releasing enzymes and chelating compounds, they break down nutrients into forms that plants can readily absorb. This bioavailability ensures that crops receive a consistent supply of essential nutrients throughout their growth cycle.
- 8) Improved photosynthesis: The interactions between plants and biofertilizers lead to enhanced photosynthetic efficiency. This increased photosynthesis results in greater carbohydrate production, which is essential for crop growth and development.

The significance of these mechanisms cannot be overstated in the context of contemporary agriculture. Biofertilizers offer a sustainable and environmentally friendly approach to enhancing crop growth, boosting yields, and improving crop quality. By promoting these mechanisms, biofertilizers contribute not only to agricultural productivity but also to the broader goals of sustainable food production and ecological resilience.

2.2. Exploring the ramifications of biofertilizer deployment for food security

Food security, the universal goal of ensuring that all people have access to safe and nutritious food, has become an increasingly complex and pressing global issue^[1]. Biofertilizers, with their multifaceted contributions, are emerging as key players in the quest to bolster global nutritional needs and address the challenges of food security^[8-10]. Here, we delve into the ramifications of biofertilizer deployment in this context, emphasizing their pivotal role:

- 1) Enhanced crop yield: Biofertilizers, by promoting efficient nutrient uptake and growth mechanisms, significantly enhance crop yield. This augmented agricultural productivity is instrumental in mitigating food scarcity, especially in regions where crop yields are traditionally low.
- 2) Crop diversification and resilience: Biofertilizers enable farmers to diversify their crop choices and experiment with a wider range of food crops. This diversification not only ensures a more varied diet but also enhances the resilience of agriculture against climate change and environmental shocks.
- 3) Nutrient-enriched crops: Biofertilizers contribute to nutrient-dense crop production. This enrichment is particularly crucial in addressing micronutrient deficiencies that lead to hidden hunger. Crops fortified with essential nutrients like iron, zinc, and vitamin A are vital for improving public health and reducing malnutrition.

- 4) **Reduced post-harvest losses:** By boosting crop quality and reducing susceptibility to diseases, biofertilizers can help reduce post-harvest losses. This preservation of crops ensures a more stable food supply and reduces food waste, contributing to food security.
- 5) **Lower input costs:** Biofertilizers offer an economically viable alternative to chemical fertilizers, making agriculture more accessible to resource-constrained smallholder farmers. Reduced input costs enable farmers to invest in other aspects of food production and distribution, increasing food availability.
- 6) **Environmental sustainability:** Biofertilizers contribute to sustainable agriculture by reducing the environmental footprint of farming. Sustainable practices help maintain ecosystems and ensure the long-term availability of resources necessary for food production.
- 7) **Global nutritional needs:** In a world where the demand for nutritious food is ever-increasing, biofertilizers facilitate the production of crops that not only meet calorific needs but also address the nutritional requirements of a growing population. They help ensure that global nutritional needs are met in a sustainable manner.
- 8) **Human health:** By improving the quality and nutritional content of crops, biofertilizers play a direct role in human health. They help combat diet-related diseases and promote overall well-being by ensuring that the food supply is rich in essential nutrients.
- 9) **Poverty alleviation:** Enhanced crop production resulting from biofertilizer use can uplift the economic status of smallholder farmers. Increased income, combined with access to nutritious food, contributes to poverty alleviation and improves the food security of vulnerable communities.

The consequences of biofertilizer deployment in the context of food security are far-reaching. Biofertilizers act as enablers, driving agricultural practices that not only increase food production but also fortify it with essential nutrients. Their role in addressing global nutritional needs, supporting smallholder farmers, and fostering sustainable agriculture positions them as integral components of the solution to the ever-growing challenge of food security.

2.3. Delving into the environmental benefits of biofertilizers

The environmental advantages of biofertilizers are a crucial dimension of their role in modern agriculture. These natural alternatives offer sustainable and eco-friendly solutions that not only enhance crop growth but also mitigate the detrimental impacts of conventional farming practices^[11-14]. Here, we explore the environmental benefits of biofertilizers, emphasizing their potential to address soil degradation, nutrient runoff, and greenhouse gas emissions:

- 1) **Soil health and structure:** Biofertilizers foster improved soil health by enhancing its microbial diversity and organic matter content. This results in better soil structure, which is more resistant to erosion and compaction. Healthy soils are more productive and resilient, reducing the need for intensive soil management practices that contribute to soil degradation.
- 2) **Reduced soil erosion:** The improved soil structure promoted by biofertilizers leads to reduced soil erosion. This, in turn, safeguards topsoil, which is rich in organic matter and essential nutrients. By preventing erosion, biofertilizers help maintain soil fertility and prevent land degradation.
- 3) **Nutrient retention:** Conventional chemical fertilizers often leach nutrients into water bodies, leading to nutrient runoff and water pollution. Biofertilizers, by contrast, enhance nutrient retention in the soil. They work in synergy with the plant's root system to reduce the loss of nutrients, ensuring that they remain available for plant uptake rather than contributing to environmental pollution.
- 4) **Mitigation of nutrient runoff:** The reduction in nutrient runoff is a significant environmental benefit of biofertilizers. By keeping nutrients in the soil, they prevent the contamination of water bodies with excessive nitrogen and phosphorus, which can lead to harmful algal blooms and aquatic ecosystem

disruption.

- 5) Greenhouse gas reduction: Biofertilizers play a role in mitigating greenhouse gas emissions. Conventional farming practices, such as the excessive use of chemical fertilizers, release nitrous oxide, a potent greenhouse gas. Biofertilizers, by improving nutrient use efficiency and reducing the need for synthetic fertilizers, lower the carbon footprint of agriculture.
- 6) Reduced chemical residues: The reduced reliance on chemical pesticides and fertilizers in biofertilizer-based agriculture leads to fewer chemical residues in soil and water. This reduces the risk of soil and water contamination and the associated environmental and health impacts.
- 7) Preservation of biodiversity: Biofertilizers create a more favorable environment for beneficial soil organisms. This fosters soil biodiversity and a healthier ecosystem, reducing the need for chemical inputs that can harm non-target species.
- 8) Sustainable agricultural practices: Biofertilizers align with the principles of sustainable agriculture. By reducing the environmental impact of farming, they contribute to the long-term sustainability of agricultural practices.
- 9) Erosion control: Healthy plants with strong root systems, fostered by biofertilizers, help control erosion. They bind soil particles together, reducing the likelihood of soil erosion during heavy rainfall or windy conditions.
- 10) Eco-friendly nutrient management: Biofertilizers offer a more eco-friendly approach to nutrient management. They minimize the environmental drawbacks of synthetic fertilizers while ensuring that crops receive the nutrients they need for optimal growth.

The environmental benefits of biofertilizers are intertwined with their contributions to sustainable agriculture. By addressing soil degradation, nutrient runoff, and greenhouse gas emissions, biofertilizers offer a promising pathway towards environmentally responsible and ecologically sustainable food production systems. Their role in preserving soil and water quality, reducing agricultural emissions, and fostering biodiversity positions them as essential components of a sustainable and environmentally conscious agriculture.

2.4. Analyzing the contributions of biofertilizers to human health

Biofertilizers, in their role as promoters of nutrient-dense crop production, have significant implications for human health^[15-18]. They offer a sustainable and eco-friendly approach to agriculture that can address the issue of malnutrition and improve overall well-being. Here, we analyze the contributions of biofertilizers to human health, particularly through the cultivation of nutritionally enriched crops:

- 1) Micronutrient enrichment: Biofertilizers play a critical role in enhancing the micronutrient content of crops. Crops fortified with essential micronutrients like iron, zinc, and vitamin A address the problem of hidden hunger, which is characterized by a lack of vital micronutrients in the diet. By reducing micronutrient deficiencies, biofertilizers directly contribute to improved health outcomes.
- 2) Prevention of diet-related diseases: Biofortified crops cultivated with the assistance of biofertilizers can help prevent diet-related diseases. Iron-rich crops combat anemia, while zinc-fortified crops enhance the immune system and promote wound healing. Vitamin A-enriched crops improve eye health and reduce the risk of blindness. These contributions to human health are a result of the nutritional quality of biofortified crops.
- 3) Reduced malnutrition: By ensuring that crops are rich in essential nutrients, biofertilizers can help reduce the prevalence of malnutrition, particularly in vulnerable populations. This reduction in malnutrition has wide-ranging health benefits, from improved child development to stronger immune systems in adults.
- 4) Nutrient accessibility: Biofertilizers not only enhance nutrient content in crops but also improve nutrient

accessibility. Nutrients in biofortified crops are often in a form that is more readily absorbed by the human body. This increased bioavailability ensures that the nutrients are efficiently utilized, further improving health outcomes.

- 5) **Public health impact:** The wide-scale adoption of biofertilizers for the cultivation of nutrient-dense crops can have a profound impact on public health. Reduced rates of malnutrition, anemia, and other diet-related health issues can lead to improved public health indicators and a lower burden on healthcare systems.
- 6) **Community well-being:** Healthy communities are essential for overall well-being. Biofertilizers contribute to community well-being by reducing the prevalence of diseases related to nutrient deficiencies. This, in turn, leads to healthier and more productive communities with improved quality of life.
- 7) **Enhanced immune system:** Crops fortified with micronutrients like zinc and vitamin C, cultivated with the help of biofertilizers, boost the immune system. A strong immune system is vital for protecting against infections and diseases, enhancing overall health and well-being.
- 8) **Cognitive development:** In children, proper nutrition, including the consumption of biofortified crops, is crucial for cognitive development. Adequate intake of essential micronutrients supports brain development and can improve learning outcomes and cognitive abilities.
- 9) **Maternal and child health:** Biofertilizers contribute to maternal and child health by reducing the risk of complications during pregnancy and childbirth. Ensuring that women have access to nutrient-rich foods during pregnancy is essential for the health of both mothers and their children.
- 10) **Healthy aging:** Improved nutrition from biofortified crops can lead to healthier aging. The prevention of diet-related diseases ensures a higher quality of life in old age, with reduced healthcare costs and a lower burden on healthcare systems.

Biofertilizers offer a sustainable and ecologically responsible solution to the complex issue of human health and nutrition. By enhancing the nutritional quality of crops and reducing the prevalence of micronutrient deficiencies, they directly contribute to improved health outcomes, healthier communities, and overall well-being. Their potential to address diet-related diseases and prevent malnutrition underscores their vital role in public health and human development.

2.5. Championing the wider adoption of biofertilizers

Biofertilizers have emerged as a beacon for the future of agriculture, offering a sustainable and eco-friendly alternative to conventional farming practices. Their potential to transform agriculture and contribute to sustainable food production makes a strong case for their wider adoption^[19-25]. Here, we champion the broader use of biofertilizers as a cornerstone of sustainable agricultural practices:

- 1) **Environmental sustainability:** Biofertilizers are environmentally sustainable. By reducing the reliance on chemical fertilizers, they mitigate the adverse environmental impacts associated with synthetic nutrient inputs. This includes lower greenhouse gas emissions, reduced soil and water pollution, and the preservation of biodiversity.
- 2) **Soil health:** The use of biofertilizers fosters improved soil health. They enhance soil microbial diversity and organic matter content, contributing to better soil structure and nutrient retention. Healthy soils are the foundation of sustainable agriculture.
- 3) **Nutrient efficiency:** Biofertilizers promote nutrient use efficiency. They enhance the availability and accessibility of nutrients to plants, reducing waste and nutrient runoff. This not only benefits crop growth but also conserves resources.
- 4) **Reduced chemical residues:** With biofertilizers, there is a reduced need for chemical pesticides and synthetic fertilizers. This leads to fewer chemical residues in soil and water, contributing to a safer and

healthier environment.

- 5) Food security: Biofertilizers play a crucial role in food security. By enhancing crop yields and nutritional quality, they contribute to a stable food supply. Their ability to address hidden hunger and malnutrition aligns with the goal of nourishing a growing global population.
- 6) Human health: The nutritional quality of biofortified crops directly impacts human health. By addressing diet-related diseases and deficiencies, biofertilizers have the potential to reduce healthcare costs and improve public health indicators.
- 7) Innovative agriculture: The adoption of biofertilizers encourages innovation in agriculture. This includes the development of biofortified crop varieties, precision nutrient management, and sustainable farming practices. These innovations are essential for the future of agriculture.
- 8) Economic benefits: Biofertilizers can lead to increased economic returns for farmers. By improving crop yields and quality, they enhance farm profitability and contribute to the economic well-being of farming communities.
- 9) Climate resilience: The sustainable practices associated with biofertilizers enhance the resilience of agriculture to climate change. They promote practices that are adaptable to changing environmental conditions.
- 10) Global sustainability goals: Biofertilizers align with global sustainability goals, including those outlined in the United Nations' Sustainable Development Goals (SDGs). They contribute to responsible consumption and production, clean water and sanitation, and zero hunger, among others.
- 11) Educational and outreach opportunities: The promotion of biofertilizers provides opportunities for education and outreach in sustainable agriculture. It empowers farmers with knowledge and resources for environmentally responsible practices.
- 12) Community well-being: Wider adoption of biofertilizers can lead to healthier and more resilient communities. Improved public health and economic well-being contribute to the overall well-being of communities.
- 13) Reduced environmental impact: The reduction in the environmental impact of agriculture is a critical driver of the adoption of biofertilizers. As the world faces increasing environmental challenges, sustainable practices like biofertilizers have become imperative.

Championing the broader adoption of biofertilizers is not only a sound agricultural strategy but also a response to the environmental and food security challenges of our time. Their multifaceted contributions to sustainable agriculture, environmental preservation, and human well-being underscore their importance in shaping the future of agriculture. By integrating biofertilizers into mainstream agricultural practices, we can work towards a more sustainable, resilient, and food-secure future.

3. Conclusions

The journey of exploring biofertilizers and their multifaceted contributions to agriculture, food security, the environment, and human health has led to several compelling conclusions:

- 1) Sustainable agriculture: Biofertilizers offer a sustainable alternative to conventional farming practices, reducing the environmental impact of agriculture. Their ability to enhance soil health, increase nutrient use efficiency, and minimize chemical inputs supports the long-term sustainability of farming.
- 2) Nutrient-dense crops: The use of biofertilizers results in the cultivation of nutrient-dense crops. These crops address hidden hunger, reduce diet-related diseases, and contribute to improved public health outcomes.
- 3) Environmental stewardship: Biofertilizers play a vital role in environmental stewardship. They reduce nutrient runoff, soil degradation, and greenhouse gas emissions, contributing to a healthier planet.

- 4) Resilience to climate change: The sustainable practices associated with biofertilizers make agriculture more resilient to the challenges of climate change. Their adoption can help farming systems adapt to changing environmental conditions.
- 5) Economic prosperity: Biofertilizers not only benefit the environment and public health but also enhance the economic prosperity of farming communities. By improving crop yields and quality, they contribute to increased income for farmers.
- 6) Global sustainability: The adoption of biofertilizers aligns with global sustainability goals, including those outlined in the United Nations' Sustainable Development Goals (SDGs). These goals encompass responsible production and consumption, zero hunger, and clean water and sanitation, among others.

4. Future recommendations

As we conclude this exploration of biofertilizers, several recommendations emerge for their wider adoption and integration into global agricultural systems:

- 1) Promote awareness and education: Initiatives should be developed to raise awareness about the benefits of biofertilizers among farmers, policymakers, and consumers. Educational programs can play a crucial role in advocating for their adoption.
- 2) Research and innovation: Continued research is essential to develop new strains of biofertilizers that are tailored to specific crops and environmental conditions. Innovations in biofertilizer technology can further enhance their effectiveness.
- 3) Policy support: Governments and agricultural authorities should provide policy support and incentives for the adoption of biofertilizers. This can include subsidies, training programs, and regulatory frameworks that encourage their use.
- 4) Collaborative efforts: Collaboration between governments, non-governmental organizations, agricultural institutions, and the private sector can facilitate the production and distribution of biofertilizers. Partnerships can help make biofertilizers more accessible to farmers.
- 5) Scaling up production: Efforts should be made to scale up the production of biofertilizers to meet the growing demand. This includes investing in the infrastructure needed for large-scale production.
- 6) Consumer awareness: Consumers should be educated about the health benefits of biofortified crops. This can lead to increased demand for such crops in the market.
- 7) Monitoring and evaluation: Systems for monitoring the impact of biofertilizers on crop production, environmental sustainability, and public health should be established. Regular evaluations can help fine-tune their application.
- 8) Adaptation to local contexts: Biofertilizers should be adapted to local environmental conditions and specific crop requirements. Tailoring their use to local contexts enhances their effectiveness.
- 9) Integrated farming practices: Biofertilizers are most effective when integrated into broader sustainable farming practices. Encouraging farmers to adopt comprehensive and sustainable farming systems can maximize their impact.
- 10) Research into climate-resilient varieties: Given the importance of climate resilience, research into biofortified crop varieties that can thrive under changing climate conditions is vital.

In conclusion, biofertilizers represent a promising avenue for addressing the complex challenges of modern agriculture, from sustainability and food security to environmental preservation and public health (**Figure 2**). Their wider adoption and integration into global agricultural systems require a concerted effort from all stakeholders. As we look to the future, the transformative potential of biofertilizers in shaping a more sustainable and nourished world remains a beacon of hope and progress.

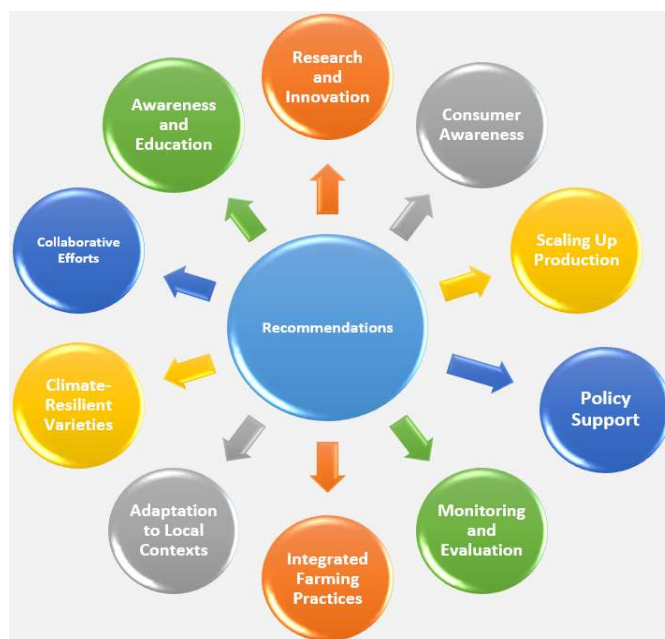


Figure 2. Biofertilizers recommendations in modern agriculture.

Author contributions

Conceptualization, methodology, software and validation, A and UK; formal analysis, investigation, resources, data curation, UK; writing—original draft preparation, A; writing—review and editing, and visualization, UK; supervision, project administration, and funding acquisition, A. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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