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Significance of Biofertilizers for Sustainable Agriculture, Food Safety and Food Security: A Review

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ABSTRACT

Agriculture remains central to the global economy, with over 60% of the population dependent on it for livelihood and sustenance. As the world grapples with challenges such as population growth, environmental degradation, and the overuse of agrochemicals, there is an urgent need for sustainable agricultural practices that safeguard food safety and ensure long-term food security. Biofertilizers, as microbial-based inputs, offer an eco-friendly and cost-effective alternative to chemical fertilizers by enhancing soil fertility, promoting plant growth, and reducing environmental pollution. This review aims to examine the role of biofertilizers in sustainable agriculture, with a particular emphasis on their contribution to food security and safety. Key aspects analyzed include the types, mechanisms, formulation techniques, benefits, and limitations of biofertilizers, supported by empirical data. The findings highlight that biofertilizers can significantly improve crop productivity, boost soil health, and reduce the dependency on synthetic inputs. However, variability in field performance, lack of farmer awareness, and formulation challenges hinder their widespread adoption. The review underscores the need for integrated strategies, policy support, and continued research to unlock the full potential of biofertilizers in promoting a sustainable, resilient, and food-secure future.

Keywords: Chemical fertilizers, Eco-friendly agriculture, Organic farming, Soil fertility, food safety

1. INTRODUCTION

The global agricultural sector is facing major challenges, including soil degradation, declining productivity, environmental pollution, and the growing demand for food. However, intensive agricultural practices based on the extensive use of synthetic fertilizers and pesticides have contributed to the depletion of natural resources, loss of soil fertility, and ecosystem degradation [1]. The excessive application of agrochemicals led to nutrient imbalances, soil acidification, reduced microbial diversity, and contamination of water resources through runoff and leaching [2]. In addition, these inputs pose potential risks to human health and food safety, highlighting the needs for more sustainable agricultural approaches[2]. Consequently, the transition toward environmentally friendly farming systems has become essential for ensuring both food security and environmental sustainability.

Organic farming has emerged as a promising alternative to conventional agriculture. By utilizing natural resources and biological processes, it enhances soil fertility and crop productivity while minimizing environmental impacts. This farming system combines traditional knowledge with modern scientific principles to promote sustainable agricultural development [3]. Among its various components, biofertilizers have gained considerable attention as effective substitutes for chemical fertilizers.

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Biofertilizers are preparations containing beneficial microorganisms that improve nutrient availability in the rhizosphere and stimulate plant growth. They contribute to nitrogen fixation, phosphate solubilization, potassium mobilization, and the production of growth-promoting compounds [4-5].

Despite their advantages, the widespread adoption of biofertilizers remains constrained by inconsistent field performance, limited farmer awareness, and challenges related to formulation, storage, and distribution [6]. Addressing these limitations requires a better understanding of their mechanisms, applications, and effectiveness under diverse agricultural conditions.

This review examines various aspects of biofertilizers, including their types, formulations, applications, and contributions to sustainable agriculture and food security. Particular emphasis was placed on literature describing the mechanisms through which biofertilizers enhance nutrient availability, improve soil fertility, and increase crop productivity. In addition, studies addressing the challenges associated with their adoption, as well as strategies for improving their effectiveness and wider utilization, were critically evaluated.

A systematic approach was employed to ensure the inclusion of reliable, relevant, and up-to-date scientific evidence. This methodology facilitated a comprehensive and balanced assessment of the current status of biofertilizer research and its significance in promoting sustainable agricultural production, food security, and environmental sustainability.

2. Significance of Biofertilizers

The increasing global demand for food has driven the extensive use of synthetic fertilizers to enhance agricultural productivity. While these inputs have contributed substantially to crop yields, their prolonged and excessive application has resulted in several environmental and agronomic problems, including soil acidification, nutrient leaching, groundwater contamination, and the disruption of beneficial soil microbial communities [7]. Furthermore, intensive dependence on chemical fertilizers can reduce nutrient-use efficiency, impair root development, and increase crop susceptibility to pests and diseases [8]. These concerns have highlighted the need for environmentally sustainable nutrient management strategies.

Biofertilizers have emerged as an effective alternative and complementary approach to conventional fertilization. They contain beneficial microorganisms, including nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, arbuscular mycorrhizal fungi (AMF), and plant growth-promoting rhizobacteria (PGPR), which enhance nutrient availability and support plant growth through natural biological processes [9]. In addition to improving nutrient cycling, biofertilizers contribute to soil health, environmental sustainability, and agricultural productivity.

2.1. Sustainable Nutrient Management

Unlike synthetic fertilizers that supply nutrients in concentrated inorganic forms, biofertilizers improve nutrient availability through biological nitrogen fixation, phosphate solubilization, potassium mobilization, and other microbial activities [10]. These processes enhance nutrient-use efficiency while reducing nutrient losses through leaching and runoff. Consequently, biofertilizers help maintain long-term soil fertility, reduce environmental pollution, and lower greenhouse gas emissions associated with fertilizer production and use [11]. Although they may not completely replace chemical fertilizers in all cropping systems, biofertilizers can significantly reduce dependence on synthetic inputs when integrated into sustainable nutrient management programs [12].

2.2. Enhancement of Crop Growth and Productivity

Numerous studies have demonstrated the positive effects of biofertilizers on crop growth and yield. Yield increases ranging from 10% to 40% have been reported when biofertilizers are applied either independently or in combination with reduced levels of chemical fertilizers [10].

Recent investigations further indicate that biofertilizers can sustain agricultural productivity while reducing chemical fertilizer requirements [13-15]. Positive responses have been observed in major crops such as rice, wheat, and maize, where biofertilizer application improved yield, nutrient uptake, and soil quality [16-18]. However, their effectiveness may vary depending on crop species, soil properties, climatic conditions, and the compatibility between microbial strains and host plants. Consequently, site-specific application strategies are essential to maximize their benefits [19].

2.3. Improvement of Plant Stress Tolerance

Biofertilizers also play an important role in enhancing plant resilience to abiotic stresses, including drought, salinity, and temperature extremes. Beneficial microorganisms improve water and nutrient acquisition, stimulate antioxidant defence systems, and regulate the production of stress-responsive phytohormones [20-21].

2.4. Economic and Environmental Advantages

The use of biofertilizers offers significant economic and environmental benefits. They can be produced using relatively inexpensive raw materials and are often more affordable than synthetic fertilizers, making them particularly attractive to smallholder and resource-limited farmers [10]. Moreover, biofertilizers support environmentally responsible agriculture by reducing the carbon footprint of crop production and promoting the recycling of biological resources in accordance with circular bioeconomy principles [22].

2.5. Contribution to Food Safety and Soil Health

The extensive use of synthetic fertilizers and pesticides can lead to the accumulation of chemical residues in soils and agricultural produce, raising concerns regarding food safety, environmental quality, and human health. In contrast, biofertilizers provide an environmentally friendly and residue-free approach to nutrient management, thereby supporting the production of safer food while minimizing ecological risks [23].

Beyond their role in nutrient supply, biofertilizers contribute significantly to soil health. Beneficial microorganisms enhance soil biological activity, increase microbial biomass, stimulate enzymatic processes, and improve organic matter dynamics, leading to better soil structure and fertility [6]. These improvements support efficient nutrient cycling and create favorable conditions for sustained crop growth.

Recent studies have demonstrated that biofertilizers can maintain or enhance crop productivity while preserving soil quality, particularly when used alone or in combination with reduced amounts of chemical fertilizers [24-25]. Such integrated nutrient management approaches offer a practical strategy for balancing agricultural productivity with environmental sustainability. However, their effectiveness is influenced by several factors, including crop species, soil properties, climatic conditions, and the compatibility between microbial strains and host plants. Consequently, inconsistent or neutral responses may occur when biofertilizers are applied under unsuitable conditions or when soils already possess adequate nutrient levels [26].

Overall, biofertilizers play a critical role in promoting soil health, improving food safety, and supporting sustainable agricultural production. Their successful implementation requires site-specific management practices that optimize microbial performance while maintaining productivity and environmental integrity.

Biofertilizers are grouped into different types on the basis of their functions and mode of action. Figure 1 shows the main types of biofertilizers which are commonly used in organic farming. Despite their numerous benefits, the widespread adoption of biofertilizers remains constrained by several challenges, including inconsistent performance under field conditions, limited shelf life, and the lack of standardized formulations and quality control systems [28-29]. Variability in environmental conditions, soil characteristics, and microbial survival can influence the effectiveness of biofertilizers, leading to inconsistent outcomes

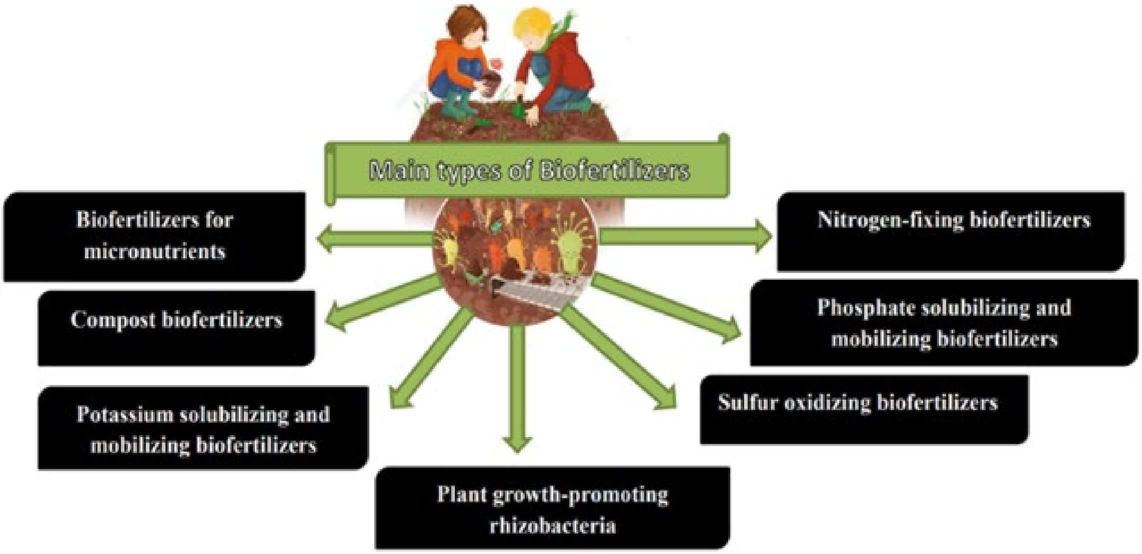

Figure 1. Main types of biofertilizers [27]

Addressing these limitations through continued research, technological innovation, and improved regulatory frameworks is essential to enhance their reliability and promote their broader use in sustainable agriculture.

3. Formulation and Application of Biofertilizers

The effectiveness of biofertilizers largely depends on their formulation, which is designed to maintain the viability and activity of beneficial microorganisms during production, storage, transportation, and field application. Biofertilizer formulations typically consist of selected microbial strains combined with suitable additives and carrier materials that protect microbial cells and ensure their survival under varying environmental conditions. An effective formulation facilitates the delivery of a sufficient number of viable microorganisms to the rhizosphere, where they can colonize plant roots and perform their beneficial functions.

As mentioned by Nosheen et al., (2021) the appropriate formulations not only improve the survival of microorganisms during storage but also enhance their establishment and activity in soil following application [2]. Consequently, the development of improved formulations is a critical step in the commercialization of biofertilizers, as it contributes to greater product stability, efficacy, and quality. Currently, biofertilizers are available in several formulation types, including peat-based, liquid, granular, and dry powder formulations. Each formulation possesses distinct advantages and limitations with respect to storage stability, ease of application, microbial survival, and cost. The comparative advantages and disadvantages of these formulations are summarized in Table 1.

3.1. Carrier Materials in Biofertilizer Formulations

Carrier materials play a fundamental role in biofertilizer production, serving as vehicles for transporting living microorganisms from the manufacturing facility to the field. An ideal carrier maintains microbial viability and physiological activity during storage while providing temporary protection and support after application to the soil. Carrier materials can create favorable microenvironments by supplying nutrients, retaining moisture, and providing physical protection through pore spaces and surface attachment sites [30].

The incorporation of microorganisms into suitable carrier materials has been shown to improve storage life, facilitate handling and transportation, and enhance the overall effectiveness of biofertilizer products. The selection of an appropriate carrier depends on factors such as the microbial species involved, the intended application method, and the desired shelf life of the product. Since different microorganisms have varying physiological requirements, no single carrier material is universally suitable for all biofertilizer formulations. Organic, inorganic, and synthetic materials have therefore been explored as carriers for different biofertilizer products. Research evidences [31] clearly explained the characteristics of an ideal carrier material, include;

•Non-toxic to both microorganisms and plants.
•Good pH-buffering capacity.
•Available in sufficient quantities and at reasonable cost.
•Easy to sterilize, process, and handle.
•Free from contaminants and lump-forming materials.
•High moisture-retention capacity.
•Capable of maintaining microbial viability during storage.
•Cost-effective for large-scale production and application.

Table 1. Advantages and disadvantages of major types of formulations in biofertilizers;

Types of formulation	Advantages	Disadvantages	References
Granules	The rate of application can be easily controlled Handling is comparatively easier They are not applied in direct contact with the chemicals or pesticides which are toxic for the microbes. They are less dusty	Their bulkier size makes the transport and storage expensive. The rate of application has to be increased to attain anticipated outcome.	[32-33]
Liquid formulations	Handling and application procedures are easy either on seeds or in soil They have high cell concentrations and enable for the use of a smaller amount for the same efficiency. They allow manufacturers to insert enough amounts of nutrients and cell protectants to boost performance more than solid based carriers Lesser contamination Longer shelf life Better protection against environmental challenges Higher field efficacy. Greater compatibility with farm machineries.	No carrier protection Rapidly lose viability on seed.	[34]
Peat formulations	Cost-effectiveness High adsorption ability	Release of Toxic compounds can be	[35]

	It creates a nutrient-rich and protective atmosphere for a range of microbes to flourish and form micro colonies.	occurred during sterilization Complications in getting consistent quality and results in the farm	
Dried powder	Easily attached to the seed surfaces Longer survival of microbes.	Shorter shelf life More chances for contamination Poor moisture and retention capacity Takes more time for quality control Dosage contradictory to farmers.	[13]

4. Limitations

Although biofertilizers have demonstrated considerable potential in enhancing soil fertility, crop productivity, and sustainable agricultural practices over the past several decades, their widespread adoption remains limited. Despite encouraging research findings and successful applications in various cropping systems, the commercialization and large-scale utilization of biofertilizers have not progressed as rapidly as anticipated [6].

Several technical, environmental, economic, and regulatory challenges hinder the effective implementation of biofertilizer technology. Factors such as inconsistent field performance, limited shelf life, inadequate quality control measures, variability in environmental conditions, and low farmer awareness can significantly affect their effectiveness and acceptance. In addition, challenges associated with production, storage, transportation, and distribution often constrain the commercial viability of biofertilizer products.

Addressing these limitations is essential to improve the reliability, accessibility, and adoption of biofertilizers in modern agriculture. The major constraints affecting their large-scale application and commercialization are summarized in Table 2.

Table 2. Limitations associated with the production and usage of biofertilizers

Classifications	Limitations
Technical limitations	• Shortage for the trained workers in the production units. • Inaccessibility of appropriate carrier materials. • Low level of awareness to the farmers.
Infrastructure limitations	• Shortage of power supply. • Unavailability of essential application equipment. • Limited resource generation and lower investment for the production of biofertilizers.
Production limitations	• Inaccessibility of appropriate facilities for the production. • Inadequate facilities for quality control. • Unavailability of suitable and efficient strains. • Mutation of microbial strains during fermentation.
Field level limitations	• Adverse soil and climatic factors. • Poor crop management. • Usage of substandard inoculants. • Competitive effect from native microbial population.

	• Faulty inoculation techniques. • Lack of knowledge and training to the farmers in this area.
Marketing limitations	• Lack of regulation and standards for biofertilizer products. • Lack of strong promotion and insufficient publicity. • Lack of quality assurance. • Inadequate transportation and storage facilities. • Seasonal and uncertain demand for the biofertilizers. • Poor and incomplete labeling of biofertilizer products
Biological limitations	• Unavailability of right inoculant at the right place at the right time.
Financial limitations	• Unavailability of adequate funding from government and private bodies. • Uneasiness in getting bank loans.

(Sources; [6, 22, 36]

5. The Way Forward

Although biofertilizers are widely promoted as a cornerstone of sustainable and organic agriculture, their practical contribution to mainstream farming systems remains limited. This gap between potential and actual performance is largely driven by biological variability, inconsistent field responses, weak commercialization pathways, and insufficient integration into conventional nutrient management systems. As a result, biofertilizers are still often treated as supplementary inputs rather than core components of crop production strategies.

Bridging this gap requires moving beyond laboratory-scale efficacy studies toward a more realistic understanding of field-level constraints. In many cases, inconsistent performance is not solely a biological limitation but also reflects inadequate formulation quality, poor strain–environment compatibility, and weak delivery systems. Therefore, future progress depends on reframing biofertilizers not just as microbial products, but as context-dependent technologies requiring site-specific optimization.

Effective advancement will require coordinated institutional engagement across research, policy, and extension systems. However, current efforts are often fragmented, with limited translation of research outputs into scalable agricultural technologies. Strengthening the research-to-field pipeline—from controlled experiments to long-term, multi-location validation and commercial deployment—is essential for improving reliability and farmer confidence. In parallel, integration strategies combining biofertilizers with reduced chemical inputs must be empirically optimized rather than assumed to be universally effective.

A more critical shift is also needed in research design itself. Instead of focusing primarily on isolated strain performance, future studies should emphasize ecological interactions, soil variability, and socio-economic feasibility. This requires interdisciplinary collaboration among agronomists, soil microbiologists, plant pathologists, breeders, and agricultural economists, supported by structured short-, medium-, and long-term research frameworks.

From a development perspective, several persistent bottlenecks require targeted intervention:

- Formulation constraints: Limited stability of current carrier systems highlights the need for scientifically optimized, cost-effective materials that ensure microbial viability under real storage and field conditions.
- Strain limitations: Many existing products rely on narrow-spectrum or poorly competitive strains, reducing effectiveness across diverse soils and crops.
- Lack of standardization: Absence of uniform protocols for dosage, application timing, and crop-specific recommendations continues to undermine consistency.
- Field variability: Performance remains highly sensitive to soil properties, climate, and native microbial communities, yet these factors

are often insufficiently accounted for in product development.

- Weak regulatory systems: Inadequate quality control, certification mechanisms, and labeling standards reduce trust and limit large-scale adoption.
- Poor knowledge transfer: Extension systems remain underutilized, resulting in limited farmer understanding and suboptimal application practices.

At the same time, scaling biofertilizer use requires stronger institutional and economic support mechanisms. Investment in production infrastructure, regulatory enforcement, and farmer training is as critical as scientific innovation. Without these enabling systems, technological improvements alone are unlikely to translate into widespread adoption.

Recent advances in molecular biology, microbial genomics, nanotechnology, and synthetic biology offer promising avenues for improving strain efficiency and formulation stability. However, these innovations remain unevenly translated into field-ready products, largely due to gaps in applied research and weak commercialization frameworks. Consequently, the sector remains in a transitional stage where scientific potential exceeds implementation capacity.

Overall, the future of biofertilizers depends not only on developing better microbial formulations but also on addressing systemic weaknesses in validation, regulation, and adoption pathways. A deeper, more integrated understanding of soil–microbe–plant–environment interactions, supported by robust field evidence and enabling policy structures, is essential for transforming biofertilizers from promising inputs into reliable components of sustainable agricultural systems.

Conflicts of interest: The authors declare no conflict of interest

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