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Review Article

The Role of Microbial Biotechnology in Advancing Sustainable Agriculture

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Abstract

Agricultural systems increasingly rely on biotechnological approaches to enhance food production while maintaining environmental sustainability. As the global population continues to grow and climatic variability intensifies, conventional agricultural practices are becoming increasingly inadequate to meet the rising demand for food. Modern biotechnological interventions, including genetic engineering and genome-editing technologies such as CRISPR, have facilitated the development of crop varieties with improved tolerance to drought, enhanced resistance to insect pests and superior nutritional quality. These advances also contribute to reducing the dependence on chemical fertilizers and pesticides, thereby minimizing their adverse environmental impacts. In addition, beneficial microorganisms have emerged as promising tools for sustainable agriculture by improving soil fertility, promoting plant growth, enhancing nutrient availability and increasing crop resilience against biotic and abiotic stresses. The integration of microbial biotechnology with precision agricultural technologies further optimizes the efficient use of water and nutrients, reduces agricultural waste and supports long-term soil health. Furthermore, plant tissue culture techniques enable the large-scale production of disease-free planting materials, while genetic engineering facilitates the development of crops with desirable agronomic traits and novel plant-derived products. Despite these significant advances, concerns regarding biosafety, environmental impacts and public acceptance continue to influence the widespread adoption of biotechnology-based agricultural practices. Microbial biotechnology is expected to play a pivotal role in improving crop productivity, mitigating the impacts of drought and heat stress and promoting environmentally sustainable farming systems. However, successful implementation will require appropriate regulatory frameworks, interdisciplinary collaboration, continuous scientific innovation and greater public awareness to translate these technological advances into practical and sustainable agricultural solutions.

Keywords: Biotechnology, CRISPR, Microbial biotechnology, Plant-microbe interactions, Sustainable agriculture

Introduction

Microorganisms are ubiquitous and inhabit diverse plant tissues, including the phyllosphere, endosphere and rhizosphere. Among these habitats, the rhizosphere, the narrow region of soil surrounding plant roots, represents one of the most biologically active environments, where complex interactions occur between plant roots and microbial communities. Root exudates provide essential nutrients that support microbial colonization, while microorganisms contribute to nutrient acquisition, plant growth and stress tolerance, thereby establishing a mutually beneficial relationship (Berg *et al.*, 2020).

The intricate network formed by plant roots and their associated microorganisms constitutes the plant-root microbiome, a dynamic and diverse biological system that plays a fundamental role in plant development, nutrient cycling and adaptation to environmental stresses. Owing to its remarkable complexity, understanding the plant

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microbiome requires an integrated approach rather than the study of individual microbial components in isolation. Plant-microbiome interactions influence microbial community assembly, nutrient cycling, plant immunity and overall ecosystem functioning, making them fundamental to sustainable agricultural production (Trivedi *et al.*, 2020). In addition to bacteria and fungi, other soil organisms, including nematodes and various microfauna, influence microbial interactions and collectively contribute to plant health and ecosystem functioning (Backer *et al.*, 2018).

Recent advances in genomics, transcriptomics, proteomics and other high-throughput molecular techniques have considerably improved our understanding of plant-microbe interactions. These technological developments have revealed the molecular mechanisms governing microbial colonization, communication and their beneficial effects on plant growth and productivity. Consequently, manipulation of the plant microbiome has emerged as a promising strategy for improving agricultural sustainability and crop resilience under changing environmental conditions.

The composition and activity of rhizosphere microbial communities are influenced by plant genotype, soil characteristics, climatic conditions and agricultural management practices. These microbial communities regulate nutrient availability, enhance resistance to biotic and abiotic stresses and contribute significantly to maintaining soil fertility and ecosystem stability (dos Reis *et al.*, 2024). Understanding the factors that shape rhizosphere microbial communities is therefore essential for developing sustainable agricultural practices that minimize environmental degradation while maintaining crop productivity.

Although microorganisms associated with aerial plant tissues also contribute to plant health, the rhizosphere remains the primary site of plant-microbe interactions and has consequently received considerable scientific attention. Continued investigation of microbial diversity, colonization dynamics and functional interactions within the rhizosphere will facilitate the development of innovative microbial technologies for sustainable agriculture (Aguilar-Paredes *et al.*, 2020). This review discusses the role of microbial biotechnology in sustainable agriculture, with particular emphasis on plant-microbe interactions, microbial mechanisms underlying plant protection and growth promotion, recent biotechnological advances, current challenges and future prospects for enhancing agricultural sustainability.

Comparing Standard Farming with Sustainable Practices

Conventional agriculture has played a significant role in increasing global food production through the extensive use of mechanization, synthetic fertilizers, chemical pesticides and intensive cultivation practices. These production systems are primarily designed to maximize crop yield and economic returns. Typical features of conventional farming include repeated tillage, continuous monocropping, heavy application of synthetic fertilizers and limited incorporation of organic amendments such as compost or farmyard manure (Durán *et al.*, 2021). Although these practices have substantially improved agricultural productivity, they have also contributed to soil degradation, biodiversity loss, environmental pollution and declining ecosystem resilience.

The primary objective of conventional agriculture is to achieve maximum production per unit area by utilizing high-yielding crop varieties, chemical inputs and modern agricultural machinery. While this approach has successfully supported global food security for several decades, its long-term sustainability has become increasingly challenging due to climate change, soil degradation, declining water quality, increasing pest and disease outbreaks and the depletion of natural resources (Ferreira *et al.*, 2024; Francioli *et al.*, 2025). These challenges have prompted researchers and policymakers to explore more sustainable agricultural production systems.

Sustainable agriculture aims to maintain agricultural productivity while conserving natural resources, protecting biodiversity and minimizing adverse environmental impacts. Unlike conventional farming, which primarily emphasizes maximum yield, sustainable farming adopts a holistic approach that integrates environmental protection, economic viability and social responsibility. However, sustainability remains a multidimensional concept and its interpretation often varies depending on ecological, economic and social perspectives (Bathaei and Štreimikienė, 2023).

Different approaches to sustainable agriculture have been proposed. Some emphasize improving the efficiency of conventional farming practices through reduced chemical inputs and better resource management, whereas others advocate more transformative agricultural systems based on ecological principles, biodiversity conservation and ecosystem restoration (Aamir *et al.*, 2020). Regardless of the approach adopted, the common objective is to ensure long-term agricultural productivity while preserving environmental quality.

One of the major distinctions between conventional and sustainable agriculture lies in their environmental impacts. Conventional farming frequently relies on intensive applications of synthetic fertilizers and pesticides, which may contribute to soil degradation, nutrient leaching, water contamination, greenhouse gas emissions and the decline of beneficial soil microorganisms. Continuous monocropping and intensive tillage further reduce soil organic matter and accelerate soil erosion (Fatima *et al.*, 2025).

In contrast, sustainable agricultural practices seek to minimize these adverse effects through the adoption of environmentally friendly management strategies. These include crop rotation, conservation tillage, organic farming, integrated nutrient management, the application of organic manures and biofertilizers and biological pest management. Such practices improve soil fertility, enhance soil microbial diversity, increase water-use efficiency and promote long-term ecosystem stability. Sustainable farming also encourages diversified cropping systems, including intercropping, cover cropping and the conservation of beneficial insects and other natural enemies that contribute to biological pest control.

Although conventional agriculture generally provides higher short-term productivity, sustainable agriculture offers substantial long-term environmental and ecological benefits. By improving soil health, conserving biodiversity, reducing dependence on synthetic agrochemicals and enhancing ecosystem resilience, sustainable farming provides a viable pathway toward maintaining agricultural productivity while ensuring environmental sustainability for future generations.

Protective Mechanisms of Microbes

Plant-associated microorganisms play a dual role in agricultural ecosystems, acting either as plant pathogens or as beneficial microorganisms that promote plant growth and protect crops from various biotic stresses. Several bacterial pathogens, including *Pseudomonas syringae*, *Erwinia amylovora*, *Xanthomonas* spp., *Ralstonia solanacearum* and *Xylella fastidiosa*, are responsible for economically important diseases affecting tomato, tobacco, olive, bean, apple, banana and potato crops. The severity of these diseases depends on multiple factors, including pathogen population density, environmental conditions, host susceptibility and interactions within the surrounding microbial community (Naylor *et al.*, 2020).

In contrast, beneficial microorganisms residing in the rhizosphere, phyllosphere or plant endosphere enhance plant defense through a wide range of biological mechanisms. These microorganisms suppress plant pathogens by competing for nutrients and ecological niches, thereby limiting pathogen establishment and proliferation. Many beneficial microbes also produce antimicrobial compounds, hydrolytic enzymes, volatile organic compounds and siderophores that inhibit the growth and activity of phytopathogens. Consequently, the use of beneficial microorganisms has emerged as an environmentally friendly alternative to the excessive application of synthetic pesticides for crop protection (Ray *et al.*, 2020). Recent studies have further demonstrated the effectiveness of plant- and microbial-based disease management strategies in reducing the reliance on synthetic fungicides while improving crop health and environmental sustainability (Alimzhanova *et al.*, 2025).

An important mechanism employed by beneficial microorganisms is the activation of the plant's innate defense system through induced systemic resistance (ISR). The rhizosphere therefore functions as an important biological interface where beneficial microorganisms regulate plant immunity and suppress soil-borne diseases through complex ecological interactions (Pieterse *et al.*, 2016). Following successful colonization of plant roots, these microorganisms stimulate complex signaling pathways involving phytohormones such as jasmonic acid and ethylene, resulting in enhanced resistance against a broad spectrum of pathogens and insect pests. Rapid colonization of the rhizosphere further restricts the availability of space and nutrients for pathogenic microorganisms, thereby reducing their ability to establish infection (Shree *et al.*, 2024).

Several bacterial and fungal groups contribute significantly to biological disease suppression in agricultural soils. Members of the phyla *Firmicutes*, *Actinobacteria* and *Acidobacteria* have been reported to suppress soil-borne diseases such as *Fusarium* wilt by producing antimicrobial metabolites and promoting disease-suppressive soil conditions. Similarly, endophytic bacteria belonging to the genera *Serratia* and *Enterobacter* have demonstrated protective effects against take-all disease in cereal crops through multiple biocontrol mechanisms (Ray *et al.*, 2020).

In addition to pathogen suppression, beneficial microorganisms influence plant physiological processes by regulating phytohormone production, improving nutrient acquisition, enhancing root development and increasing tolerance to abiotic stresses. These multiple mechanisms collectively improve plant health, strengthen natural defense systems and contribute to sustainable crop production. Consequently, microbial-based disease management has become an important component of environmentally sustainable agricultural practices and an effective alternative to conventional chemical-based crop protection strategies (Shree *et al.*, 2024).

Figure 1 provides a schematic overview of the principal mechanisms employed by beneficial microorganisms to enhance plant growth, improve nutrient acquisition, induce systemic resistance, suppress plant pathogens and ultimately contribute to sustainable agricultural production.

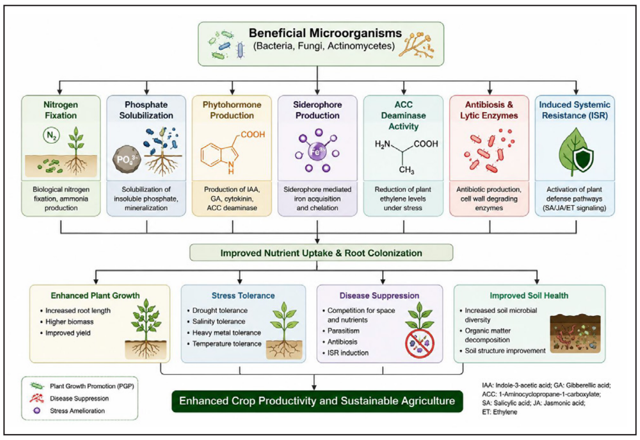


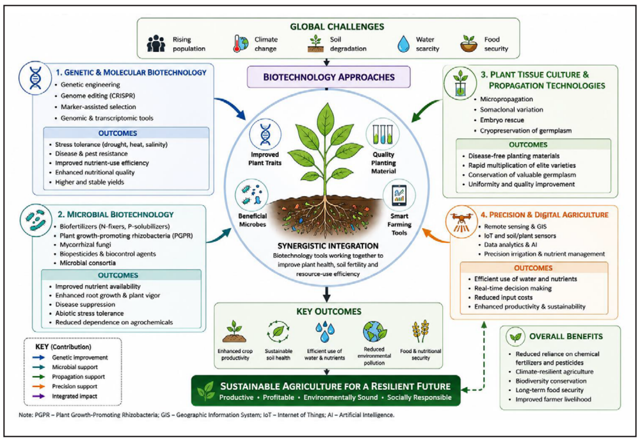
Figure 1: Mechanisms of plant growth promotion and disease suppression by beneficial microorganisms

Role of Biotechnology in Achieving Sustainable Agricultural Practice

Rapid population growth, shrinking arable land, depletion of natural resources and increasing climatic uncertainties have posed significant challenges to global agricultural production. These challenges necessitate the development of innovative and sustainable agricultural practices capable of ensuring food security while minimizing environmental degradation (Singh *et al.*, 2019). In this context, biotechnology has emerged as an indispensable tool for improving crop productivity, enhancing resource-use efficiency and promoting sustainable agricultural development.

Modern biotechnology encompasses a wide range of techniques, including genetic engineering, genome editing, molecular breeding, tissue culture and microbial biotechnology. These approaches have enabled the development of crop varieties with improved resistance to insect pests and diseases, enhanced tolerance to drought, salinity and heat stress and superior nutritional quality. Consequently, biotechnology contributes to reducing dependence on chemical fertilizers and pesticides while promoting environmentally sustainable crop production (Spooren *et al.*, 2024).

Advances in molecular biology have significantly improved our understanding of the genetic, physiological and biochemical mechanisms underlying plant growth, development and stress adaptation. Such knowledge has facilitated the identification of desirable genes and molecular pathways that can be manipulated to improve agronomic traits in crops and livestock (Malkawi and Kapiel, 2024). Figure 2 illustrates the integrated role of microbial biotechnology and plant genetic improvement in promoting sustainable agricultural practices.



Note: PGPR – Plant Growth-Promoting Rhizobacteria; GIS – Geographic Information System; IoT – Internet of Things; AI – Artificial Intelligence.

Figure 2: Integrated role of modern biotechnological approaches in sustainable agriculture

Genetic engineering and genome-editing technologies, particularly CRISPR-based approaches, have considerably accelerated crop improvement compared with conventional breeding methods. These technologies enable precise modification of target genes, facilitating the development of crop varieties with enhanced resistance to biotic and abiotic stresses, improved nutrient-use efficiency and increased nutritional value. In addition, biotechnology has contributed to the development of crops capable of maintaining productivity under nutrient-deficient, saline and drought-prone conditions, thereby supporting sustainable agricultural production.

Plant tissue culture techniques have further strengthened agricultural biotechnology by enabling the rapid multiplication of elite cultivars and the large-scale production of disease-free planting materials. These techniques also contribute to the conservation of valuable genetic resources and facilitate the propagation of commercially important crops (Suresh *et al.*, 2025).

Microbial biotechnology has become an integral component of sustainable agriculture through the development of biofertilizers, biopesticides and plant growth-promoting microorganisms. These biological inputs improve nutrient availability, stimulate root development, enhance soil fertility and increase plant resilience against environmental stresses. When integrated with modern agricultural technologies, microbial biotechnology contributes to more efficient utilization of water and nutrients, reduced environmental pollution and improved long-term agricultural sustainability (Yarzábal and Chica, 2021; Díaz-Rodríguez *et al.*, 2025).

Overall, biotechnology has transformed modern agriculture by providing precise, efficient and environmentally sustainable alternatives to conventional agricultural practices. Continued advances in molecular genetics, microbial biotechnology and precision agriculture are expected to further enhance crop productivity, resource-use efficiency and resilience under changing climatic conditions.

Microbial-based Ecology, Biotechnological and Sustainable Farming Approach

Sustainable agriculture requires innovative strategies that enhance crop productivity while minimizing environmental degradation and reducing dependence on synthetic agrochemicals. In recent years, microbial biotechnology has emerged as a promising approach for achieving these objectives through the utilization of beneficial microorganisms that improve plant growth, nutrient availability and resistance to both biotic and abiotic stresses. These microorganisms play a crucial role in maintaining soil health, promoting ecosystem stability and supporting environmentally sustainable agricultural production.

Advances in microbial ecology have significantly improved our understanding of the complex interactions between plants and their associated microbial communities. Beneficial microorganisms colonize the rhizosphere, phyllosphere and endosphere, where they establish dynamic associations with plants that influence growth, nutrient acquisition and stress adaptation. Consequently, microbial biotechnology has evolved from laboratory-based research to practical field applications, with microbial inoculants increasingly being incorporated into sustainable crop production systems (Nazarova *et al.*, 2024). Microbial inoculants have become increasingly important components of sustainable crop production owing to their ability to improve nutrient availability, stimulate plant growth and enhance resistance to environmental stresses (Díaz-Rodríguez *et al.*, 2025).

The successful application of microbial biotechnology is largely based on the natural symbiotic relationships that have evolved between plants and microorganisms over millions of years. Among these interactions, biological nitrogen fixation represents one of the most significant contributions of beneficial microorganisms to sustainable agriculture. Nitrogen-fixing bacteria convert atmospheric nitrogen into forms readily available to plants, thereby reducing dependence on synthetic nitrogen fertilizers and improving soil fertility (Suman *et al.*, 2022). Similarly, mycorrhizal fungi enhance phosphorus uptake, improve water-use efficiency and increase plant tolerance to environmental stresses through mutually beneficial associations with plant roots. Recent evidence also highlights the important role of beneficial microorganisms in enhancing drought tolerance through improved water-use efficiency, osmotic adjustment and modulation of plant physiological responses (Mikiciuk *et al.*, 2024). Microbial biotechnology has also demonstrated considerable potential for recycling agricultural wastes and improving sustainable phosphorus management through enhanced nutrient recovery and bioavailability (Oubohssaine *et al.*, 2025).

Microbial diversity also plays an essential role in maintaining soil ecosystem functions. The composition of microbial communities is influenced by plant genotype, soil characteristics, climatic conditions and agricultural management practices. Variations in microbial diversity affect nutrient cycling, organic matter decomposition, disease suppression and overall soil productivity. Consequently, understanding microbial ecology is fundamental for developing efficient microbial inoculants capable of improving crop performance under diverse environmental conditions.

The application of microbial inoculants has expanded considerably in recent years. Biofertilizers, biopesticides and plant growth-promoting microorganisms contribute to sustainable crop production by enhancing nutrient availability, producing phytohormones, suppressing plant pathogens and improving plant tolerance to drought, salinity and other environmental stresses. Table 1 summarizes representative microbial inoculants, their mechanisms of action and their applications in different crop species.

Recent advances in molecular biology and next-generation

Table 1: Representative microbial inoculants and their applications in selected crops

Microbial Inoculant	Type	Application Strategy	Major Mechanisms	Effect on Plant Growth	Effect on Plant Defense	Representative Crops
Azospirillum brasilense	Bacteria (PGPR)	Single	N_2 fixation, IAA production	Increased root length, biomass	Enhanced tolerance to abiotic stress	Rice, wheat, maize
Rhizobium spp.	Bacteria (Symbiotic)	Single	Biological N fixation	Improved nodulation, yield	Indirect defense via improved vigor	Legumes
Bacillus subtilis	Bacteria (PGPR)	Single	Phosphate solubilization, ISR induction	Improved nutrient uptake	Activation of JA/ET-mediated ISR	Rice, tomato
Pseudomonas fluorescens	Bacteria (PGPR)	Single	Siderophore, antibiotics, ISR	Enhanced shoot/root growth	Suppression of soil-borne pathogens	Wheat, rice
Trichoderma harzianum	Fungus (Biocontrol)	Single	Mycoparasitism, phytohormones	Enhanced root growth	Systemic resistance, pathogen suppression	Tomato, maize
Glomus spp. (AMF)	Fungus (Mycorrhiza)	Single	Improved P uptake, water use	Increased biomass, yield	Enhanced resistance to root pathogens	Rice, wheat
Azospirillum + *Azotobacter*	Bacterial consortium	Consortium	Complementary N fixation, hormones	Synergistic growth enhancement	Improved stress tolerance	Rice, maize
Bacillus + *Pseudomonas*	Bacterial consortium	Consortium	ISR, nutrient mobilization	Higher yield than single inoculant	Stronger pathogen suppression	Wheat, vegetables
AMF + PGPR (*Glomus* + Bacillus)	Fungal-bacterial consortium	Consortium	Improved nutrient uptake + ISR	Enhanced root-shoot ratio	Reduced disease severity	Rice, legumes
Trichoderma + PGPR	Fungal-bacterial consortium	Consortium	Biocontrol + hormone signaling	Vigorous growth	Strong systemic resistance	Tomato, chilli
Endophytic bacteria (*Enterobacter, Serratia*)	Endophytes	Single/ Consortium	Colonization, ISR, antibiosis	Improved nutrient efficiency	Suppression of vascular pathogens	Cereals

sequencing technologies have further strengthened microbial biotechnology by facilitating the characterization of complex plant-associated microbial communities. Recent molecular studies have demonstrated that plant genotypes can influence the composition of root-associated microbial communities, thereby affecting nutrient-use efficiency and plant performance under field conditions (Zhang *et al.*, 2019). Metagenomic approaches enable researchers to identify beneficial microorganisms, investigate microbial community dynamics and understand functional interactions among microbial populations under different environmental conditions. Advances in microbiome engineering have further expanded opportunities to enhance biological control, nutrient acquisition and plant growth-promoting mechanisms through targeted manipulation of beneficial microbial communities (Orozco-Mosqueda *et al.*, 2018). Such knowledge is essential for designing efficient microbial consortia capable of improving nutrient acquisition and enhancing crop resilience under field conditions.

Several studies have demonstrated that microbial consortia often perform more effectively than single microbial inoculants because different microorganisms contribute complementary functions within the rhizosphere. The application of multifunctional microbial consortia has received increasing attention because synergistic interactions among different microbial species enhance nutrient cycling, stress tolerance and overall crop productivity under diverse environmental conditions (Kumar *et al.*, 2025). For example, nitrogen-fixing bacteria can function synergistically with phosphate-solubilizing microorganisms and arbuscular mycorrhizal fungi, resulting in improved nutrient uptake, enhanced plant growth and greater resistance to environmental stresses. These synergistic interactions have considerable potential for improving the efficiency and stability of microbial-based agricultural technologies.

The principal microbial technologies currently employed in sustainable agriculture, along with their major advantages, limitations and representative agricultural applications, are summarized in table 2.

Despite these promising developments, several ecological and genetic challenges remain. The successful establishment of introduced microorganisms depends on their ability to survive, colonize plant tissues, compete with indigenous microbial communities and adapt to varying environmental conditions. Furthermore, certain microbial genera, including *Bacillus*, *Burkholderia*, *Enterobacter*, *Escherichia*, *Klebsiella*, *Salmonella* and *Staphylococcus*, contain both beneficial and potentially pathogenic strains. Therefore, comprehensive characterization of microbial inoculants is essential to ensure their efficacy and biosafety before large-scale agricultural application.

A deeper understanding of plant-microbe interactions, microbial community assembly and ecological processes will facilitate the development of next-generation microbial technologies for sustainable agriculture. Integrating microbial ecology with modern biotechnological approaches will contribute to improving crop productivity, maintaining soil health, enhancing nutrient-use efficiency and reducing dependence on synthetic agricultural inputs, thereby supporting environmentally sustainable farming systems (Nazarova *et al.*, 2024; Suman *et al.*, 2022).

Future Directions, Challenges and Constraints

Despite the considerable potential of microbial biotechnology for sustainable agriculture, several scientific, technological and practical challenges continue to limit its widespread application. One of the major constraints is the development of effective microbial formulations capable of maintaining the viability, stability and functional activity of beneficial microorganisms during storage, transportation and field application. The successful establishment of microbial inoculants depends largely on their ability to survive environmental stresses and efficiently colonize plant tissues under diverse agricultural conditions (Srivastava *et al.*, 2025).

The formulation and delivery of microbial inoculants remain critical factors influencing their field performance. Many beneficial microorganisms, particularly Gram-negative bacteria, exhibit limited shelf life because they are highly susceptible to dehydration and adverse environmental conditions. Consequently, considerable research has focused on improving microbial formulations through the incorporation of protective compounds, optimization of culture media and enhancement of extracellular polysaccharide production, which collectively improve microbial survival and persistence following application (Navarro *et al.*, 2025). Expanding access to microbial technologies among smallholder farmers through effective extension services and region-specific implementation strategies will be essential for maximizing the benefits of sustainable agriculture (Yarzábal and Chica, 2021).

Advances in form+ulation technology have also led to the development of innovative microbial delivery systems. The use of nanoparticles, polymer-based carriers, encapsulation techniques and moisture-retaining hydrogels has improved the controlled release and establishment of beneficial

Table 2: Advantages and limitations of major microbial technologies used in sustainable agriculture

Technology	Advantages	Limitations	Agricultural Application
Biofertilizers	Improved nutrient availability	Variable field performance	Nutrient management
PGPR	Root growth promotion	Host specificity	Crop productivity
Mycorrhiza	Better phosphorus uptake	Sensitive to soil disturbance	Stress tolerance
Biopesticides	Reduced pesticide use	Shelf-life limitations	Disease management
Microbial Consortia	Synergistic effects	Complex formulation	Sustainable farming

microorganisms in the rhizosphere. Similarly, the application of suitable surfactants has enhanced microbial adhesion to plant surfaces, thereby increasing colonization efficiency and improving crop responses under field conditions (Aguilar-Paredes *et al.*, 2020).

Beneficial microorganisms can be introduced into agricultural systems through various methods, including seed treatment, soil application and foliar spraying. These application strategies have demonstrated positive effects on crop growth, nutrient uptake, disease suppression and tolerance to environmental stresses in several agricultural crops (Priya *et al.*, 2023). Following successful colonization, beneficial microorganisms enhance plant performance by improving nutrient acquisition, stimulating plant defense responses, producing bioactive metabolites and forming protective biofilms that facilitate long-term persistence within plant tissues (Dissanayaka *et al.*, 2025).

Recent studies have also explored innovative approaches for improving microbial transmission between plant generations. The introduction of beneficial endophytes during the flowering stage enables microbial colonization of developing seeds, thereby allowing subsequent generations of plants to establish beneficial microbial associations from the earliest stages of growth (Badiyal *et al.*, 2024; Argentel-Martínez *et al.*, 2025). Endophytic bacteria contribute significantly to plant growth, nutrient acquisition and disease resistance while occupying internal plant tissues without causing adverse effects (Ryan *et al.*, 2008). This strategy has been successfully demonstrated through the introduction of beneficial bacteria during flowering, enabling vertical transmission of endophytic microorganisms to subsequent plant generations (Mitter *et al.*, 2017). Such strategies have considerable potential for improving the consistency and long-term effectiveness of microbial inoculation under field conditions.

The commercial adoption of microbial biotechnology has expanded rapidly owing to the increasing demand for environmentally sustainable agricultural inputs. Beneficial microorganisms such as *Azotobacter*, *Azospirillum*, *Bacillus*, *Pseudomonas*, *Burkholderia*, *Serratia* and *Rhizobium* are now widely utilized in the production of biofertilizers and biopesticides (Capozzi *et al.*, 2021). The commercialization of microbial biopesticides has increased considerably in recent years; however, regulatory approval, product standardization and market acceptance remain important challenges for their widespread adoption (Ortiz and Sansinenea, 2023). Microbial biocontrol agents have also shown considerable promise as environmentally friendly alternatives to synthetic fungicides in both preharvest and postharvest disease management systems (Sellitto *et al.*, 2021). These microbial products contribute to improved soil fertility, enhanced nutrient-use efficiency, increased crop productivity and reduced dependence on synthetic agrochemicals.

Nevertheless, several constraints continue to limit the large-scale adoption of microbial technologies. Regulatory frameworks governing the registration, commercialization and application of microbial products differ considerably among countries, creating challenges for their widespread implementation. In addition, inconsistent field performance, limited shelf life, variable environmental adaptability and difficulties associated with large-scale production remain important obstacles to commercialization. Spore-forming Gram-positive bacteria generally exhibit greater storage stability than many Gram-negative bacteria, making them more suitable for commercial formulation (Singh *et al.*, 2024).

Biosafety also represents an important consideration in the development of microbial inoculants. Although many plant-associated microorganisms promote crop growth, certain strains within genera such as *Pseudomonas* and *Burkholderia cepacia* may pose potential risks to human health under specific circumstances. Therefore, comprehensive taxonomic characterization, biosafety assessment and regulatory evaluation are essential before their large-scale agricultural application (Aamir *et al.*, 2020).

Future research should focus on developing robust microbial formulations with improved storage stability, enhanced field performance and greater ecological adaptability. Establishing regional production and distribution centers for high-quality biofertilizers and microbial inoculants, together with strengthening farmer training and extension services, would facilitate the adoption of microbial biotechnology in sustainable agriculture. Continued interdisciplinary research integrating microbial ecology, biotechnology, molecular biology and precision agriculture will further accelerate the development of reliable microbial technologies

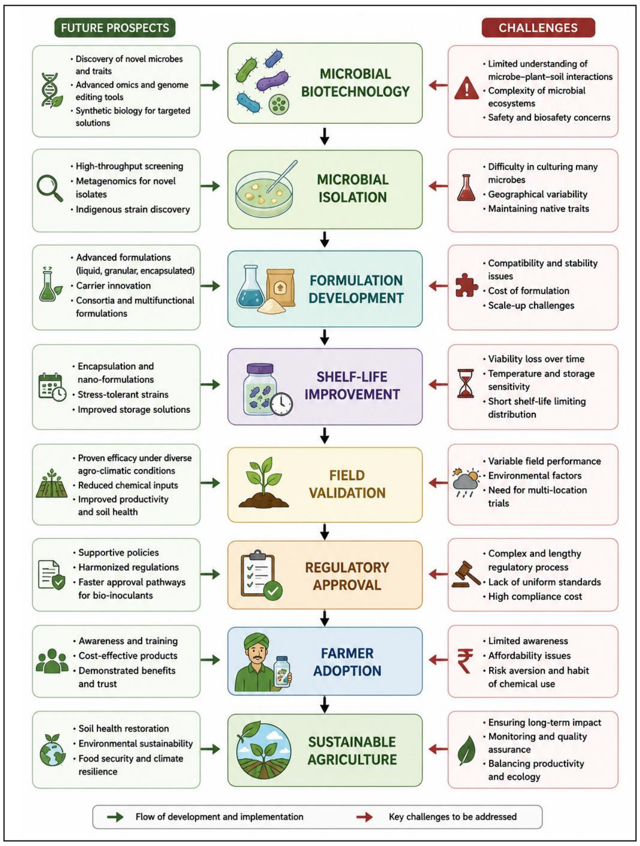


Figure 3: Future prospects and challenges in microbial biotechnology for sustainable agriculture

capable of supporting global food security while preserving environmental sustainability (Bangkele *et al.*, 2025; Hussain *et al.*, 2020).

The major challenges, technological advancements and future prospects associated with the implementation of microbial biotechnology in sustainable agriculture are summarized in figure 3.

Conclusion

Microbial biotechnology has emerged as a promising and environmentally sustainable approach for enhancing agricultural productivity while reducing dependence on synthetic fertilizers and pesticides. Beneficial microorganisms play vital roles in improving nutrient availability, promoting plant growth, suppressing plant pathogens and enhancing tolerance to both biotic and abiotic stresses. Their integration into sustainable agricultural systems not only improves soil fertility and ecosystem stability but also contributes to long-term food security and environmental conservation.

Recent advances in biotechnology, including genetic engineering, genome editing, plant tissue culture and microbial inoculant development, have significantly expanded the opportunities for developing resilient and resource-efficient agricultural systems. Furthermore, improved understanding of plant-microbe interactions and rhizosphere ecology has facilitated the development of innovative microbial technologies capable of enhancing crop productivity under changing climatic conditions.

Despite these advances, several challenges remain, including the development of stable microbial formulations, variability in field performance, commercialization constraints, biosafety considerations and regulatory limitations. Addressing these challenges will require continued interdisciplinary research, technological innovation, supportive policy frameworks and effective knowledge transfer to farming communities.

Overall, the integration of microbial biotechnology with sustainable agricultural practices offers a practical and environmentally responsible strategy for meeting future food demands while preserving natural resources. Continued research on microbial ecology, biotechnology and plant-microbe interactions will further strengthen the development of efficient, safe and economically viable microbial technologies, thereby contributing to resilient and sustainable agricultural systems.

Ethical Statement

The authors declare that no generative artificial intelligence tools were used in drafting or preparing this manuscript. The manuscript was written, interpreted and revised solely by the authors, who take full responsibility for its content.

References

Aamir, M., Rai, K.K., Zehra, A., Dubey, M.K., Kumar, S., Shukla, V., Upadhyay, R.S., 2020. Microbial bioformulation-based plant biostimulants: A plausible approach toward next generation of sustainable agriculture. In: *Microbial Endophytes: Functional Biology and Applications*. (Eds.) Kumar, A. and Radhakrishnan, E.K. Woodhead Publishing. pp. 195-225. DOI: https://doi.org/10.1016/B978-0-12-819654-0.00008-9.

Aguilar-Paredes, A., Valdés, G., Nuti, M., 2020. Ecosystem functions of microbial consortia in sustainable agriculture. *Agronomy* 10(12), 1902. DOI: https://doi.org/10.3390/agronomy10121902.

Alimzhanova, M., Meirbekov, N., Syrgabek, Y., López-Serna, R., Yegemova, S., 2025. Plant- and microbial-based organic disease management for grapevines: A review. *Agriculture* 15(9), 963. DOI: https://doi.org/10.3390/agriculture15090963.

Argentel-Martínez, L., Peñuelas-Rubio, O., Herrera-Sepúlveda, A., González-Aguilera, J., Sudheer, S., Salim, L.M., Lal, S., Pradeep, C.K., Ortiz, A., Sansinenea, E., Hathurusinghe, S.H.K., Shin, J.H., Babalola, O.O., Azizoglu, U., 2025. Biotechnological advances in plant growth-promoting rhizobacteria for sustainable agriculture. *World Journal of Microbiology and Biotechnology* 41(1), 21. DOI: https://doi.org/10.1007/s11274-024-04231-4.

Backer, R., Rokem, J.S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., Subramanian, S., Smith, D.L., 2018. Plant growth-promoting rhizobacteria: Context, mechanisms of action and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science* 9, 1473. DOI: https://doi.org/10.3389/fpls.2018.01473.

Badiyal, A., Mahajan, R., Rana, R.S., Sood, R., Walia, A., Rana, T., Manhas, S., Jayswal, D.K., 2024. Synergizing biotechnology and natural farming: Pioneering agricultural sustainability through innovative interventions. *Frontiers in Plant Science* 15, 1280846. DOI: https://doi.org/10.3389/fpls.2024.1280846.

Bangkele, L.I., Aksarah, A., Arfan., Zainal., 2025. From field to functional food integrating microbial innovation and agroindustry development for sustainable agriculture. *Journal of Agro Complex Development Society* 2(2), 40-47. DOI: https://doi.org/10.62012/agrocomplex.vi.21.

Bathaei, A., Štreimikienė, D., 2023. A systematic review of agricultural sustainability indicators. *Agriculture* 13(2), 241. DOI: https://doi.org/10.3390/agriculture13020241.

Berg, G., Rybakova, D., Fischer, D., Cernava, T., Vergès, M.C., Charles, T., Chen, X., Cocolin, L., Eversole, K., Corral, G.H., Kazou, M., Kinkel, L., Lange, L., Lima, N., Loy, A., Macklin, J.A., Maguin, E., Mauchline, T., McClure, R., Mitter, B., Ryan, M., Sarand, I., Smidt, H., Schelkle, B., Roume, H., Kiran, G.S., Selvin, J., de Souza, R.S.C., van Overbeek, L., Singh, B.K., Wagner, M., Walsh, A., Sessitsch, A., Schloter, M., 2020. Microbiome definition re-visited: Old concepts and new challenges. *Microbiome* 8, 103. DOI: https://doi.org/10.1186/s40168-020-00875-0.

Capozzi, V., Fragasso, M., Bimbo, F., 2021. Microbial resources, fermentation and reduction of negative externalities in food systems: Patterns toward sustainability and resilience. *Fermentation* 7(2), 54. DOI: https://doi.org/10.3390/fermentation7020054.

Díaz-Rodríguez, A.M., Cota, F.I.P., Chávez, L.A.C., Ortega, L.F.G., Alvarado, M.I.E., Santoyo, G., de los Santos-Villalobos, S., 2025. Microbial inoculants in sustainable agriculture: Advancements, challenges, and future directions. *Plants* 14(2), 191. DOI: https://doi.org/10.3390/plants14020191.

Dissanayaka, N.S., Udumann, S.S., Nuwarapaksha, T.D., Atapattu, A.J., 2025. Microbial partnerships in agriculture: Boosting crop health and productivity. *Circular Agricultural Systems* 5(1), e012. DOI: https://doi.org/10.48130/cas-0025-0011.

dos Reis, G.A., Martínez-Burgos, W.J., Pozzan, R., Puche, Y.P., Ocán-Torres, D., Mota, P.Q.F., Rodrigues, C., Serra, J.L., Scapini, T., Karp, S.G., Soccol, C.R., 2024. Comprehensive review of microbial inoculants: Agricultural applications, technology trends in patents and regulatory frameworks. *Sustainability* 16(19), 8720. DOI: https://doi.org/10.3390/su16198720.

Durán, P., Thiergart, T., Garrido-Oter, R., Agler, M., Kemen, E., Schulze-Lefert, P., Hacquard, S., 2021. Microbial interkingdom interactions in roots promote *Arabidopsis* survival. *Cell* 175(4), P973-983.E14. DOI: https://doi.org/10.1016/j.cell.2021.01.028.

Fatima, H., Abdul Qadeer, M.A.B., Khan, M.R., Kharal, M.A., Sajad, M., Tayyab, M., Aizaz, M., Hussain, F., Shahzad, F., 2025. Microbial biotechnology for soil health and plant nutrition: Mechanisms and future prospects. *Applied Agriculture Sciences* 3(1), 1-15. DOI: https://doi.org/10.25163/agriculture.3110307.

Ferreira, M.J., Veríssimo, A.C.S., Pinto, D.C.G.A., Sierra-Garcia, I.N., Granada, C.E., Cremades, J., Silva, H., Cunha, Â., 2024. Engineering the rhizosphere microbiome with plant growth-promoting bacteria for modulation of the plant metabolome. *Plants* 13(16), 2309. DOI: https://doi.org/10.3390/plants13162309.

Francioli, D., Kampouris, I.D., Kuhl-Nagel, T., Babin, D., Sommermann, L., Behr, J.H., Chowdhury, S.P., Zrenner, R., Moradtalab, N., Schloter, M., Geistlinger, J., Ludewig, U., Neumann, G., Smalla, K., Grosch, R., 2025. Microbial inoculants modulate the rhizosphere microbiome, alleviate plant stress responses and enhance maize growth at field scale. *Genome Biology* 26, 148. DOI: https://doi.org/10.1186/s13059-025-03621-7.

Hussain, T., Akthar, N., Aminedi, R., Danish, M., Nishat, Y., Patel, S., 2020. Role of the potent microbial based bioagents and their emerging strategies for the ecofriendly management of agricultural phytopathogens. In: *Natural Bioactive Products in Sustainable Agriculture*. (Eds.) Singh, J. and Yadav, A. Springer, Singapore. pp. 45-66. DOI: https://doi.org/10.1007/978-981-15-3024-1_4.

Kumar, P., Chitara, D., Sengupta, S., Banerjee, P., Rai, S.N., 2025. Microbial consortia in biotechnology: Applications and challenges in industrial processes. *3 Biotech* 15(11), 386. DOI: https://doi.org/10.1007/s13205-025-04558-1.

Malkawi, H.I., Kapiel, T.Y.S., 2024. Microbial biotechnology: A key tool for addressing climate change and food insecurity. *European Journal of Biology and Biotechnology* 5(2), 1-15. DOI: https://doi.org/10.24018/ejbio.2024.5.2.503.

Mikiciuk, G., Miller, T., Kisiel, A., Cembrowska-Lech, D., Mikiciuk, M., Łobodzińska, A., Bokszczanin, K., 2024. Harnessing beneficial microbes for drought tolerance: A review of ecological and agricultural innovations. *Agriculture* 14(12), 2228. DOI: https://doi.org/10.3390/agriculture14122228.

Mitter, B., Pfaffenbichler, N., Flavell, R., Compant, S., Antonielli, L., Petric, A., Berninger, T., Naveed, M., Sheibani-Tezerji, R., von Maltzahn, G., Sessitsch, A., 2017. A new approach to modify plant microbiomes and traits by introducing beneficial bacteria at flowering into progeny seeds. *Frontiers in Microbiology* 8, 00011. DOI: https://doi.org/10.3389/fmicb.2017.00011.

Navarro, B.B., Machado, M.J., Figueira, A., 2025. Nitrogen use efficiency in agriculture: Integrating biotechnology, microbiology and novel delivery systems for sustainable agriculture. *Plants* 14(19), 2974. DOI: https://doi.org/10.3390/plants14192974.

Naylor, D., DeGraaf, S., Purdom, E., Coleman-Derr, D., 2020. Drought and host selection influence bacterial community dynamics in the grass root microbiome. *The ISME Journal* 11(12), 2691-2704. DOI: https://doi.org/10.1038/ismej.2017.118.

Nazarova, N., Sazhneva, L., Sakhbieva, A., Kokhreidze, M., 2024. Biotechnology and its contribution to the agricultural economy: Using microbes for increasing crop yields. In: IX International Scientific Conference on Agricultural Science 2024. *BIO Web of Conferences* 141, 01024. DOI: https://doi.org/10.1051/bioconf/202414101024.

Orozco-Mosqueda, M.C., Rocha-Granados, M.C., Glick, B.R., Santoyo, G., 2018. Microbiome engineering to improve biocontrol and plant growth-promoting mechanisms. *Microbiological Research* 208, 25-31. DOI: https://doi.org/10.1016/j.micres.2018.01.005.

Ortiz, A., Sansinenea, E., 2023. Microbial-based biopesticides: Commercialization and regulatory perspectives. In: *Development and Commercialization of Biopesticides: Costs and Benefits*. (Ed.) Koul, O. Academic Press. pp. 103-118. DOI: https://doi.org/10.1016/B978-0-323-95290-3.00020-0.

Oubohssaine, M., Rabeh, K., Hnini, M., Aurag, J., 2025. Microbial and biotechnological approaches to harness agricultural wastes for sustainable phosphorus management in crop production. *Frontiers in Agronomy* 7, 1686198. DOI: https://doi.org/10.3389/fagro.2025.1686198.

Pieterse, C.M.J., de Jonge, R., Berendsen, R.L., 2016. The soil-borne supremacy. *Trends in Plant Science* 21(3), 171-173. DOI: https://doi.org/10.1016/j.tplants.2016.01.018.

Priya, A.K., Alagumalai, A., Balaji, D., Song, H., 2023. Bio-based agricultural products: A sustainable alternative to agrochemicals for promoting a circular economy. *RSC Sustainability* 1(4), 746-762. DOI: https://doi.org/10.1039/d3su00075c.

Ray, P., Lakshmanan, V., Labbé, J.L., Craven, K.D., 2020. Microbe to microbiome: A paradigm shift in the application of microorganisms for sustainable agriculture. *Frontiers in Microbiology* 11, 622926. DOI: https://doi.org/10.3389/fmicb.2020.622926.

Ryan, R.P., Germaine, K., Franks, A., Ryan, D.J., Dowling, D.N., 2008. Bacterial endophytes: Recent developments and applications. *FEMS Microbiology Letters* 278(1), 1-9. DOI: https://doi.org/10.1111/j.1574-6968.2007.00918.x

Sellitto, V.M., Zara, S., Fracchetti, F., Capozzi, V., Nardi, T., 2021. Microbial biocontrol as an alternative to synthetic fungicides: Boundaries between pre- and postharvest applications on vegetables and fruits. *Fermentation* 7(2), 60. DOI: https://doi.org/10.3390/fermentation7020060.

Shree, D., Khunt, N.G., Krishna, A.P., Jayasudha, S.M., 2024. Enhancing microbiome functionality and plant disease resistance through rhizosphere probiotic diversity. *International Journal of Research in Agronomy* 7(8), 767-772. DOI: https://doi.org/10.33545/2618060X.2024.v7.i8j.1396.

Singh, D., Raina, T.K., Kumar, A., Singh, J., Prasad, R., 2019. Plant microbiome: A reservoir of novel genes and metabolites. *Plant Gene* 18, 100177. DOI: https://doi.org/10.1016/j.plgene.2019.100177.

Singh, R.P., Yadav, P., Kumar, I., Kumar, A., Gupta, R.K., 2024. Precision biotechnology using beneficial microbes as a fundamental approach to the circular economy. In: *The Potential of Microbes for a Circular Economy: Developments in Applied Microbiology and Biotechnology*. (Eds.) Radhakrishnan, E.K., Kumar, A. and Aswani, R. Academic Press. pp. 73-103. DOI: https://doi.org/10.1016/B978-0-443-15924-4.00001-1.

Spooren, J., van Bentum, S., Thomashow, L.S., Pieterse, C.M.J., Weller, D.M., Berendsen, R.L., 2024. Plant-driven assembly of disease-suppressive soil microbiomes. *Annual Review of Phytopathology* 62, 1-30. DOI: https://doi.org/10.1146/annurev-phyto-021622-100127

Srivastava, A.K., Riaz, A., Jiang, J., Li, X., Uzair, M., Mishra, P., Zeb, A., Zhang, J., Singh, R.P., Luo, L., Chen, S., Yang, S., Zhao, Y., Xie, X., 2025. Advancing climate-resilient sorghum: The synergistic role of plant biotechnology and microbial interactions. *Rice* 18(1), 41. DOI: https://doi.org/10.1186/s12284-025-00796-2.

Suman, A., Govindasamy, V., Ramakrishnan, B., Aswini, K., SaiPrasad, J., Sharma, P., Pathak, D., Annapurna, K., 2022. Microbial community and function-based synthetic bioinoculants: A perspective for sustainable agriculture. *Frontiers in Microbiology* 12, 805498. DOI: https://doi.org/10.3389/fmicb.2021.805498.

Suresh, A., Ashraf, A.M., Sree, V.S., Dhas, A.K.S., Chacko, J.P., 2025. Plant-microbe interactions and rhizosphere dynamics for sustainable agriculture: A review. *Agricultural Reviews* [Online First]. DOI: https://doi.org/10.18805/ag.R-2829.

Trivedi, P., Leach, J.E., Tringe, S.G., Sa, T., Singh, B.K., 2020. Plant-microbiome interactions: From community assembly to plant health. *Nature Reviews Microbiology* 18, 607-621. DOI: https://doi.org/10.1038/s41579-020-0412-1.

Yarzábal, L.A., Chica, E.J., 2021. Microbial-based technologies for improving smallholder agriculture in the Ecuadorian Andes: Current situation, challenges and prospects. *Frontiers in Sustainable Food Systems* 5, 617444. DOI: https://doi.org/10.3389/fsufs.2021.617444.

Zhang, J., Liu, Y.X., Zhang, N., Hu, B., Jin, T., Xu, H., Qin, Y., Yan, P., Zhang, X., Guo, X., Hui, J., Cao, S., Wang, X., Wang, C., Wang, H., Qu, B., Fan, G., Yuan, L., Garrido-Oter, R., Chu, C., Bai, Y., 2019. NRT1.1B is associated with root microbiota composition and nitrogen use in field-grown rice. *Nature Biotechnology* 37, 676-684. DOI: https://doi.org/10.1038/s41587-019-0104-