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MICROBIAL INNOVATIONS FOR SUSTAINABLE AGRICULTURE: A COMPREHENSIVE REVIEW

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ABSTRACT
Microbial innovations are increasingly recognized as important components of sustainable agriculture because of their potential to improve nutrient availability, soil health, crop protection and plant resilience while reducing dependence on resource-intensive agricultural inputs. This review synthesizes recent advances in agricultural microbiomes and beneficial microorganisms, with particular emphasis on plant growth-promoting rhizobacteria, endophytes, mycorrhizal fungi, actinomycetes and microbial consortia. Their roles in biological nitrogen fixation, nutrient solubilization, nutrient cycling, pathogen suppression, modulation of plant defense and enhancement of tolerance to drought, salinity and other environmental stresses are examined. The review further evaluates emerging approaches, including microbiome engineering, synthetic microbial communities, synthetic biology, multi-omics and artificial intelligence, that are enabling more targeted and function-oriented microbial interventions. Despite substantial advances, translation from laboratory and controlled-environment studies to consistent field performance remains constrained by environmental variability, poor microbial establishment and persistence, formulation and shelf-life limitations, scale-up challenges, biosafety concerns and regulatory uncertainty. An integrated crop-soil-microbiome approach, supported by ecologically adapted strains or consortia, improved delivery systems, multi-location validation, standardized quality control and data-driven microbial selection, is therefore essential for reliable field application. Future microbial technologies should be evaluated not only for biological efficacy but also for agronomic performance, economic feasibility, environmental safety and compatibility with existing crop-management practices. Such integration can strengthen the contribution of microbial biotechnology to resource-efficient, climate-resilient and environmentally sustainable agricultural production.

KEYWORDS: agricultural microbiome; biofertilizers; microbial consortia; plant-microbe interactions; biocontrol; stress tolerance; sustainable agriculture.

INTRODUCTION

Food production systems are under the dual pressure of enhancing productivity whilst conserving nature and protecting ecosystem services, making sustainability a key challenge for the agricultural sector. While yield intensification is one approach to sustainable agriculture, it is not the only one that takes into account sustainability in terms of environmental stewardship, resource-use efficiency, economic viability and long-term soil productivity (Raman, 2024). These requirements are becoming more challenging due to the growing risk of multiple climatic, environmental, economic and biological shocks and stresses that may exacerbate vulnerabilities across agricultural landscapes in the current food systems (Khatri et al., 2024). Conventional intensification has led to better agricultural production, but also poses problems with soil degradation, loss of resource efficiency and disturbance of the ecosystems due to the dependence on external inputs and intensive management (Devlet, 2021).

Current agricultural systems need to adapt to loss of soil fertility, shortage of water, climate change, new pests and diseases and the rising demand on limited natural resources. The solutions to these interrelated constraints should be able to sustain crop performance without exacerbating the environmental burden of crop production (Suchith kumar et al., 2024). The use of agrochemicals is another sustainability issue. The use of herbicides and other chemical inputs is essential for achieving intensive crop production; however, their environmental persistence, movement in soil and water, impact on nontarget organisms and possible health risks highlight the need for biologically compatible alternatives (Parven et al., 2025).

Microorganisms are biological sources of many soil–plant interface processes that are crucial for these alternatives. Beneficial bacteria, fungi and other microbial groups play a role in nutrient transformation, decomposition of organic matter, aggregation, regulation of phytohormones, suppressing pathogens and plant tolerance to environmental stress. These activities can lead to enhancement of soil qualities and plant health, and to a decrease in the reliance on resourceconsuming agricultural inputs (Ortiz & Sansinenea, 2022). This is an expansion of the concept of single beneficial strains to communities because the combined function of the microbial community has an impact on nutrient acquisition, crop productivity, stress adaptation, and ecosystem functioning. Utilization of these communities by using biofertilizers, biocontrol agents, microbial consortia and microbiome-oriented technologies is now seen as a promising way to sustainable production systems (Suman et al., 2022). Microbial processes are also found to be part of dynamic exchanges of carbon, nutrients and energy in plant–soil relationships. The relationships between the rhizosphere and plant-soil feedbacks emphasized the ecological interdependency of the contribution of microbes to agricultural functioning, with carbon belowground having the capacity to influence these processes. Belowground carbon allocation can alter plant-soil feedbacks and rhizosphere activity, revealing the ecological linkages that underlie the contribution of microbes to agricultural functioning (Prescott et al., 2020).

Although the area of microbial innovations has gained a lot of interest, the innovations are scattered in biofertilization, biological control, stress management, microbiome engineering, synthetic communities and advanced microbial delivery systems. However, microbial efficacy in the laboratory is not always replicated in the field due to factors affecting microbial establishment and function in the soil, including soil properties, crop genotype, climate, indigenous microbiota, formulation stability, and management. Thus, it is important to have an extensive synthesis to link available microbial functions to new technologies and technologies in practice used in farming.

The review is intended to critically consolidate the progress towards microbial innovations for sustainable agriculture by summarizing the diversity of microorganisms and functional mechanisms, their use in plant nutrition, soil health, crop protection, stress resistance, and the novel techniques in microbial formulations, synthetic biology, multi-omics, microbial engineering, and artificial intelligence. It also analyzes constraints to translation, ecological, regulatory and scalability issues, highlighting research priorities for sustainable and reliable agriculture based on the microbiome.

2. REVIEW METHODOLOGY

This comprehensive review integrated literature related to microbial innovations relevant to sustainable agriculture, focusing on agricultural microbiomes, soil fertility, plant nutrition, crop protection, stress tolerance, emerging microbial technologies, and implementation challenges. The scope of the themed paper was consistent with the flow of the article from microbial diversity and nutrient roles to biocontrol to advanced microbiome engineering to translation to the field. When beneficial microorganisms, plant–microbe interactions, biofertilizers, microbial consortia, synthetic communities, multi-omics, artificial intelligence, and/or commercialization barriers were included in the study, the relevant peer-reviewed studies, reviews, and/or scholarly book chapters were noted. Relevant and scientific evidence was selected and themed. The results were narratively compared, focusing on the similarities, new applications, current challenges, and future research priorities of the microbial strategies for sustainable agricultural production.

3. Agricultural Microbiomes and Functional Diversity

Agricultural microbiomes are a diverse community of bacteria, fungi, archaea and other microorganisms that live in soil and on plants. They are organized by host selection, environmental filtering, dispersal, and microbial interactions; meanwhile, they control nutrient cycling, plant development, disease suppression and ecosystem stability (Xiong & Lu, 2022). Enrichment of microbial communities in the rhizosphere is especially dynamic, as compounds produced by the roots select these microorganisms. Changes in the structure of the rhizosphere communities and nitrogen cycling processes by crop selection and management can directly link management with microbial functionality (Schmidt et al., 2019). The diversity of microbes is also found within plants, in internal tissues where the microbes form close associations with their host. These microorganisms do not cause any disease, but can aid in obtaining nutrients, growth, resistance to pathogens and adaptation to environmental stress (Adeleke & Babalola, 2021). Plant growth-promoting rhizobacteria are a case in point, which provide benefits through nitrogen fixation, nutrient solubilization, production of phytohormones and suppression of pathogens (de Andrade et al., 2023). They must be able to competitively colonize the roots, be strain-compatible, be stable for formulation and be reproducible in different heterogeneous field situations (Backer et al., 2018). Complementary functions of beneficial fungi are in close association with plant roots. Mycorrhizal Associations provide an increase in the ability of the root systems to forage for nutrients and the ability to exchange the mineral nutrients and carbon supplied by the plant. Recent progress in the study of the genomes of both fungi and plants, and in the understanding of microbial ecology, is revealing significant functional variation of mycorrhizal associations and opening the door to their potential use in crops (Martin & van der Heijden, 2024). Arbuscular mycorrhizal fungi (AMF) play a crucial role in plant health, soil aggregation, and water and phosphorus acquisition (Chen et al., 2018), but their importance is found to be different depending on the crop species, soil properties and management practices.

In addition to the above, the soils of agricultural fields possess added functional capacity from the actinomycetes due to their ability to decompose complex organic substrates, mineralize nutrients and generate antimicrobial metabolites, and antagonize soil-borne pathogens (Bhatti et al., 2017). Their contribution can reach right to the crop nutrition and productivity. In legumes, beneficial actinomycetes have been linked to increased nitrogen availability, metabolism and seed quality and productivity, while rhizosphere enrichment has been linked to increased N availability and plant metabolism (AbdElgawad et al., 2020). The multifunctional characteristics will help to establish their use as biofertilizer ingredients and biological crop-protection systems. Such coordinated biological responses are the plant–microbe interactions that combine these single microbial actions. The beneficial microorganisms can interact with the physiology of plants and influence various mechanisms such as nutrient uptake, hormonal signaling, antioxidant defense, osmotic regulation, and other mechanisms that enhance plant resistance to drought, salinity, temperature extremes and associated stresses (Kumar & Verma, 2018). Cooperation, competition, signaling, exchange of metabolites, and niche differentiation shape microbial communities all at the same time. Knowing these inter-relationships is essential to the design of microbial consortia and strategies for managing microbiomes in a way that will work in a variety of agroecological settings (Singh et al., 2017).

Agricultural microbiomes are thus not comprised of individual beneficial organisms, but of a functional biological network. Their diversity and complementary activities offer excellent ecological conditions for the development of stable microbial consortia, optimization of resource-use efficiency, and building resilience of the crops in sustainable production systems. While distinct groups of microorganisms vary in ecological niche and functional role, they all play a role in nutrient acquisition, plant protection and stress adaptation (Table 1).

Table 1. Major agricultural microbial groups and their functional roles

Microbial group	**Main habitat**	**Key function**	**Agricultural benefit**	**Representative application**
PGPR	Rhizosphere	Nutrient mobilization	Improved plant growth	Biofertilizers
Endophytes	Internal tissues	Stress modulation	Greater crop resilience	Stress-management inoculants
Mycorrhizal fungi	Root–soil interface	P and water acquisition	Better nutrient efficiency	Mycorrhizal products
Actinomycetes	Soil/rhizosphere	Decomposition and antibiosis	Soil health and disease suppression	Multifunctional inoculants
Microbial consortia	Multiple niches	Complementary functions	Improved functional stability	Multi-strain formulations

4. Microbial Innovations for Soil Fertility and Plant Nutrition

Microbial nutrition management is an alternative to fertilizer intensive approach to plant nutrition that is biologically efficient. Biological nitrogen fixation plays a key role in this strategy, as diazotrophic microorganisms are a key process in the conversion of atmospheric N into forms available to biological systems, and are a pathway for the addition of N into agricultural systems that does not involve industrial N production (De Bruijn & Hungria, 2022). The ability to effectively integrate legumes into cropping systems makes legume–rhizobia symbioses particularly valuable to boost soil fertility and N inputs and enhance productivity of subsequent crops (Kebede, 2021). Another important limitation in crop nutrition is the microbial mobilization of nutrients, such as phosphorus and potassium. Much of these nutrients are present in poorly available mineral or fixed form, and are not readily taken up by roots. Actinobacteria can be used to simultaneously release phosphate and potassium, and stimulate wheat growth, making their use as multifunctional nutrient-mobilizing inoculants (Boubekri et al., 2021). The response of rice showed that phosphate and potassium solubilizing bacteria have the potential of increasing the efficiency of the acquired and applied nutrient with a biological approach, which can lead to better nutrient uptake and plant growth (Bakhshandeh et al., 2017).

Additionally, the efficient uptake, storage and transport of macro and micro nutrients are essential for plant nutrition. Nutrient scarcity is especially relevant during drought, where drought-induced reduction in uptake forces plants to mobilize minerals held in their tissues to maintain metabolic functions and/or growth of new tissues (Etienne et al., 2018). These physiological processes can be enhanced by microbial interventions such as increased nutrient availability in the rhizosphere and increased biological activity of the soil. It should be noted that nutrient management does not only depend on the application rate of nutrient fertilizers, but also on soil organic matter, soil microbial processes, nutrient balance and physicochemical properties (Pandao et al., 2024). Biofertilizers make these functions by microbes into useful agricultural inputs. Beneficial microorganism preparations can increase nitrogen fixation, solubilization of available nutrients, soil mineralization, root development, and biological activity in soil, in addition to decreasing the reliance on synthetic fertilizers (Nosheen et al., 2021). Another innovation is going from single strains to microbial consortia. Complementary functions, ecological adaptability and synergistic plant growth responses, which may not be as readily obtained with any single microbe, can be obtained through carefully selected communities (Woo & Pepe, 2018).

Microbial innovations have the potential to enhance soil fertility by optimizing inputs, mobilization, cycling and acquisition of nutrients by plants and not by replacing one fertilizer source with another. The use of nitrogen fixers, nutrient-solubilizing microorganisms, biofertilizers and the use of functionally complementary consortia is promising to achieve more resource-efficient and biologically controlled plant nutrition. All major microbial mechanisms involved in plant nutrition have a common theme, which is increased efficiency of functioning in the rhizosphere and of plant nutrient use, leading to increased plant growth and soil fertility (Figure 1).

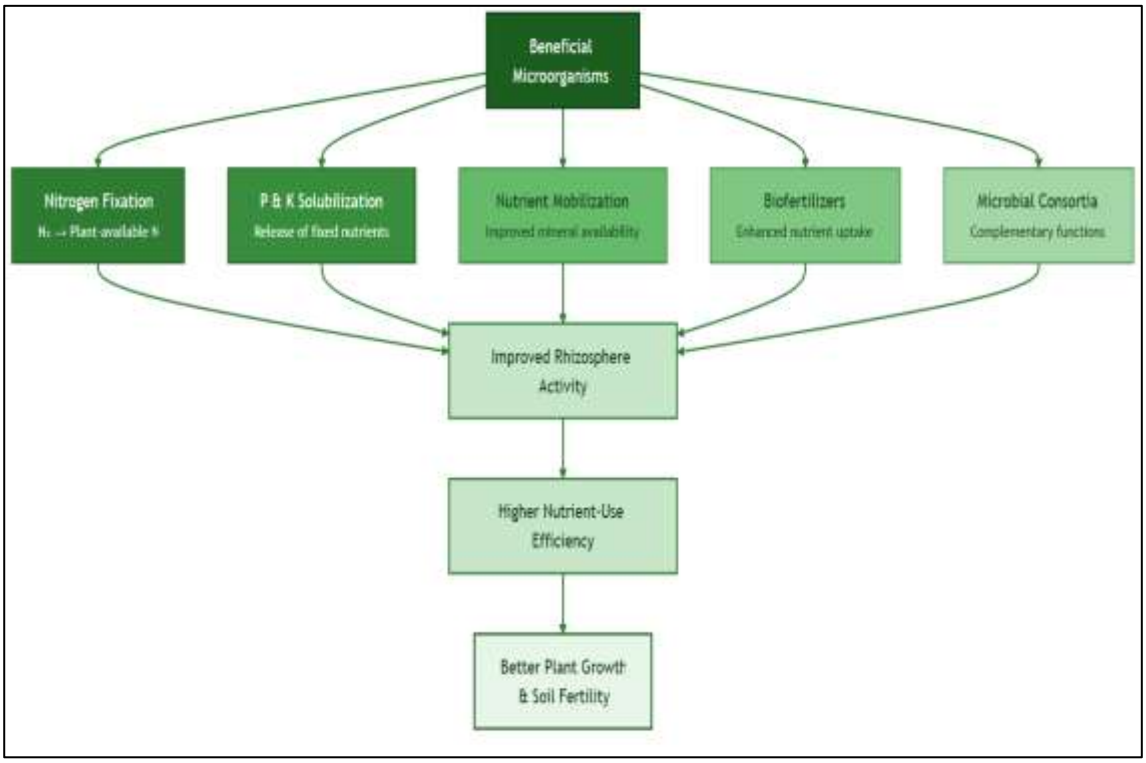

Figure 1. Microbial pathways enhancing soil fertility and plant nutrition

5. Microbial Solutions for Crop Protection and Stress Tolerance

Microbial biocontrol is an alternative to conventional crop-protection inputs, based on the use of microorganisms found in nature and their functional properties. Biocontrol strains can be used to suppress pathogens by competitive exclusion, nutrient depletion, production of antimicrobial compounds and triggering plant defense mechanisms, but their potential to be used in agriculture will depend on the ability to be reliably screened and characterized, as well as be adapted to field conditions (Pirttilä et al., 2021). The ecological strength and production of bioactive metabolites by *Bacillus* species against different phytopathogens make them good candidates for the integrated disease-management system (Khan et al., 2022). Microbe-mediated crop protection is important and comprises antimicrobial metabolites. *Bacillus velezensis* produces lipopeptides and polyketides with high efficacy against various pathogens of plants, and some of the produced compounds also have the ability to colonize the roots and help protect the host (Fazle Rabbee & Baek, 2020). Beneficial microorganisms can also trigger plant immune mechanisms and enhance biotic stress resistance by modulating defense mechanisms, antimicrobial responses, and mechanisms that limit infection (Enebe & Babalola, 2019).

Another possible livelihood generator, which is equally relevant under abiotic stress, is microbial applications. Plant growth-promoting rhizobacteria (PGPR) have been shown to enhance drought tolerance, which involves changes in root architecture, osmotic adjustment, phytohormone levels, water-use efficiency, and stress responses in plants (Zhang et al., 2022). The endophytic microorganisms also protect the plants from attack by other organisms because they live in the plant body, in close contact with other physiological activities. Endophytes can improve plant performance under stress, including drought, salinity, temperature extremes, pathogens and other stresses, by providing nutrients, regulating hormones, and regulating antioxidants and plant defense mechanisms (Anand et al., 2023). Besides providing protection against disease, beneficial microorganisms also help to enhance crop performance under a wide range of environmental stresses in terms of nutrient uptake, cellular homeostasis, production of stress-related metabolites and stress-adaptive response under salinity, drought and temperature stress (Rana et al., 2021). Oxidative stress is a widespread effect of all the bad conditions that can lead to an overproduction of ROS and subsequent damage to membranes, proteins and nucleic acids. Microbial treatments have the potential to affect the antioxidant defense systems and to help keep a balance between oxidation and reduction processes in plants when exposed to stress (Milentyeva et al., 2022). Microbial activities are not only protective to the plants, but also remediative to degraded agricultural soils. Immobilized, transformed, adsorbed, and mobilized metals in crops can be a concern for food systems due to heavy metal contamination, and selected microorganisms may have a variety of biochemical processes for immobilizing, transforming, adsorbing, and mobilizing metals. These microbial processes can help with bioremediation and can enhance the viability of contaminated soils for agricultural regeneration (Atuchin et al., 2023).

Microbial crop protection combines pathogen suppression, immune stimulation, stress mitigation and environmental remediation in a single biological package. The best future applications will probably be based on the use of good, strong strains or consortia together with management practices suited to the crop that will ensure activity in the field under varying conditions. The mechanisms of action of microbial crop-protection products are different, and their efficacy in the field depends on the stress as well as the field conditions (Table 2).

Table 2. Microbial strategies for crop protection, stress tolerance, and field translation

Strategy	Primary target	Main mechanism	Expected benefit	Key limitation
Biocontrol agents	Plant pathogens	Antibiosis and competition	Disease suppression	Variable field efficacy
PGPR	Drought stress	Hormonal and osmotic regulation	Improved drought tolerance	Environment dependence
Endophytes	Multiple stresses	Internal host modulation	Enhanced resilience	Host specificity
Stress-protective microbes	Oxidative stress	Antioxidant regulation	Cellular protection	Inconsistent colonization
Bioremediation microbes	Heavy metals	Transformation/immobilization	Soil recovery	Site-specific performance

6. Emerging Microbial Technologies

Microbial agriculture is developing from the use of naturally occurring beneficial strains to the intentional implementation of microbiomes to predictably serve agricultural purposes. Microbiome engineering aims to alter the composition, interactions, and/or metabolism of microbial communities to create microbiome systems with the desired functions. These strategies allow for optimizing nutrient cycling, plant growth, disease resistance, and ecosystem health while our understanding of communities as functional units, rather than simply strains (Foo et al., 2017). Synthetic microbial communities represent a more controlled extension of this concept. SynComs are blends of custom-tailored microorganisms with complementary or cooperative attributes to enable community composition and interactions to be targeted towards a specific agricultural goal. The simplicity of their structure in comparison to the natural microbiomes also allows mechanistic studies of plant–microbe and microbe–microbe interactions, and opportunities for applications in nutrient uptake, stress resistance, and disease control (Shayanthan et al., 2022). Finally, synthetic biology can be leveraged to further enhance microbiome engineering by either engineering the plant-associated microbes or their interactions to increase colonization, metabolic functions, and desired product generation (Ke et al., 2021).

Advancements in multi-omics technologies are increasing the capacity to characterize biological processes involved with the plant–microbe response. Genomics, transcriptomics, proteomics, metabolomics and related datasets can be integrated to link molecular variation to functional responses, and to identify regulatory networks linked to plant adaptation to environmental stress (Roychowdhury et al., 2023). Integrated profiling may help inform the identification of microbial functions and host responses that are hard to decipher with individual analytical techniques. AI and machine learning offer complementary solutions to uncover trends from ever-growing agricultural data. While robustness of the models and data quality are crucial factors to consider, machine-learning approaches can incorporate heterogeneous information, discover predictive relationships, label biological responses, and aid in data-informed agricultural management (Botero-Valencia et al., 2025). Explainable AI provides value in making model predictions understandable, assisting researchers in determining the variables that had a significant impact and biologically relevant relationships, rather than just model predictions that are hard to explain (Ryo, 2022).

Combining these fields of microbiome engineering, SynComs, synthetic biology, multi-omics, and interpretable computational tools is transforming the landscape of microbial innovation, making it more precise and function-based. The ability to tie microbial design with strong biological data and/or explainable prediction would enhance the selection of microbial solutions that would best meet a production constraint, a particular crop, and an environment. The use of microbiome engineering, synthetic communities, synthetic biology, multi-omics and Artificial Intelligence offers a technology-enabled approach for creating a microbial solution that is tailored for sustainable agriculture (Figure 2).

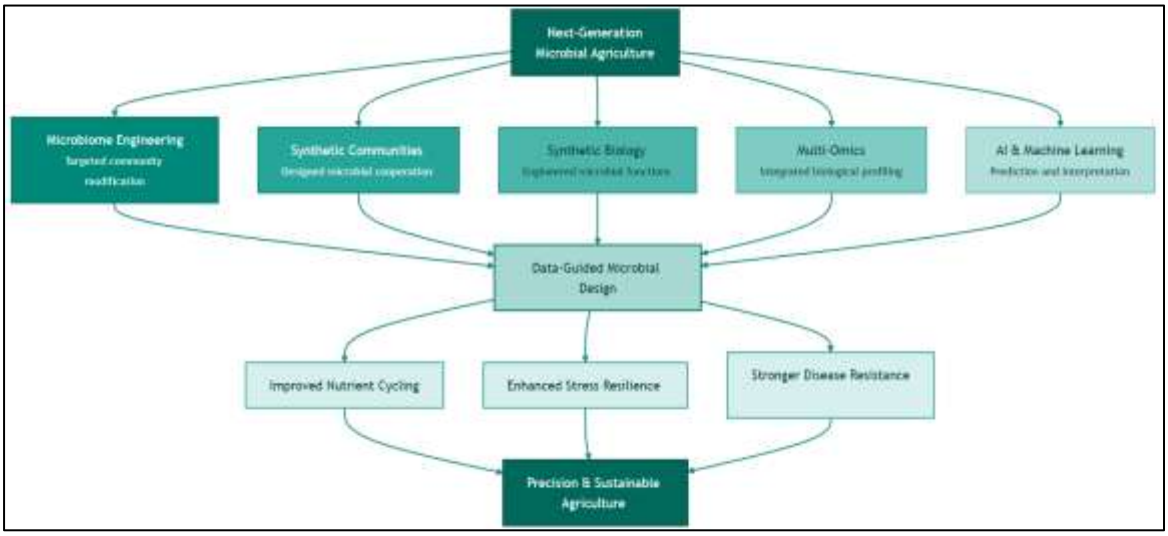

Figure 2. Integration of emerging microbial technologies for precision and sustainable agriculture

7. Challenges and Future Perspectives

Microbial technologies show great promise for the sustainable production of agricultural products, but performance in the field has been inconsistent. Selected strains can behave differently following their introduction into complex soils due to factors such as temperature, moisture and pH; as well as the presence of indigenous microorganisms and competition among them and the selected strain (Timmusk et al., 2017). Thus, increased focus on the microbiological ecology and interactions between communities is needed to better predict inoculant persistence and functional compatibility in native agricultural microbiomes (Gómez-Godínez et al., 2021). Another part of commercial translation is to translate promising microorganisms into stable and scalable products. The microbial inoculants should be able to withstand production, storage, transport, and crop application without losing viability, functional activity, colonization potential and crop compatibility. Recent advances focus more and more on locally adapted strains, microbial consortia, novel improved carriers, and application strategies that are adapted to the crop-soil environment (Díaz-Rodríguez et al., 2025). Formulation is especially significant as it can influence storage time and shelf life, as well as survival after application, due to the composition of carriers, protection from moisture, etc., and the way the product is to be administered to the host organism (Monica et al., 2025). Biological effectiveness is not enough to make it successful to use in agriculture. Microbial products should be presented with reproducible agronomic benefits at an affordable price, be practical, and be compatible with the farm management system. Better strategies for the evaluation of identity, quality, efficacy, biosafety and environmental impacts are also needed in order to better characterize the regulatory frameworks, especially given the increasing complexity of microbial products in the market (Batista & Singh, 2021). Improved quality-control and field validation in different agroecological zones would help minimise the experimental promise-commercial performance gap.

Innovations to come will be moving from general to targeted inoculations and from ecosystem reductionist to ecosystem-informed interventions in microbial agriculture. Microbial biotechnology can also be used to aid in the selection of better microbial strains, development of new generations of microbial bio-stimulants, mutation of microbial functions and the development of microbial consortia with desirable plant-beneficial properties (Singh & Vaishnav, 2022). This would also allow microbial interventions to be targeted to the specific crop, soil, stresses, and production goals if the integration with multi-omics, microbiome engineering, precision agriculture, and data-driven crop management is realized. Designing products based on ecological fitness will be as important as designing them for laboratory performance in order to have reliable microbial agriculture. To bring microbial innovation to the field, there are key priorities to address, such as field validation, formulation stability, biosafety, regulatory harmonization, and precision microbiome management. The major barriers to translating microbial technologies from laboratory research to field agriculture and the corresponding priority strategies are summarized in Table 3.

Table 3. Key challenges and future priorities for agricultural microbial technologies

Challenge	Major cause	Practical consequence	Future priority
Variable field performance	Soil and climate variability	Inconsistent efficacy	Multi-location validation
Poor establishment	Native microbial competition	Reduced persistence	Ecologically adapted strains
Limited shelf life	Formulation instability	Loss of viability	Improved carriers and encapsulation
Scale-up constraints	Production complexity	Higher commercial cost	Standardized manufacturing
Biosafety concerns	Ecological uncertainty	Restricted deployment	Long-term risk assessment
Regulatory barriers	Variable standards	Delayed commercialization	Harmonized regulations
Farmer adoption	Cost and uncertain benefits	Limited uptake	Field evidence and affordability
Precision application	Crop–soil specificity	Variable responses	Data-guided microbiome matching

8. Integrated Framework for Translating Microbial Innovations into Sustainable Crop Production

The future development of microbial agriculture requires a transition from the selection of individual high-performing microbial strains towards integrated, function-oriented and agroecosystem-specific microbial management. Although individual microorganisms can provide important benefits through nutrient mobilization, biological control and stress mitigation, their performance in agricultural soils is strongly influenced by crop genotype, soil properties, climatic conditions, indigenous microbial communities and farm management practices. Therefore, microbial technologies should be designed and evaluated within the context of specific crop–soil–environment combinations rather than being considered universally applicable inputs. Such an ecosystem-oriented approach may improve microbial establishment, persistence and functional expression under heterogeneous field conditions.

An integrated microbial management strategy can combine microorganisms with complementary functional traits to address multiple constraints simultaneously. Nitrogen-fixing and nutrient-solubilizing microorganisms can improve nutrient availability, while mycorrhizal fungi can enhance phosphorus and water acquisition. Similarly, biocontrol microorganisms and endophytes can contribute to pathogen suppression, plant defense and tolerance to abiotic stresses. Microbial consortia may provide greater functional complementarity and stability than individual strains when their members are compatible and occupy complementary ecological niches. However, consortium development should be based on experimentally demonstrated compatibility, functional complementarity, ecological fitness and stability rather than simply increasing the number of microbial components. The interaction between introduced microorganisms and the resident microbiome should also be considered during selection and formulation.

Translation of microbial innovations from laboratory research to field application requires a systematic validation pathway. This pathway should include isolation and characterization of candidate microorganisms, assessment of functional traits, compatibility testing, formulation development, controlled-environment evaluation, multi-location field validation and monitoring of microbial establishment and agronomic performance. Field evaluation should consider not only yield responses but also nutrient-use efficiency, disease suppression, stress tolerance, soil biological properties and the persistence of introduced microorganisms. Such multidimensional evaluation would provide a more realistic assessment of the contribution of microbial technologies to sustainable crop production.

Emerging molecular and computational technologies can further strengthen this translational framework. Genomics, transcriptomics, proteomics and metabolomics can help identify microbial traits and plant responses associated with successful colonization, nutrient acquisition and stress adaptation. Integration of these datasets with information on soil properties, crop genotype, climate and management practices may facilitate the identification of microbial functions that are most effective under particular agroecological conditions. Artificial intelligence and machine-learning approaches can complement these efforts by identifying complex relationships within heterogeneous datasets and supporting the prediction of suitable microbial interventions for specific crop-soil-environment combinations. Thus, integration of microbiome engineering, synthetic microbial communities, multi-omics and data-driven approaches can contribute to the development of more precise and predictable microbial technologies.

Successful agricultural application also depends on factors beyond biological efficacy. Microbial products must demonstrate adequate viability and stability during production, storage, transport and application, while maintaining functional activity under field conditions. Standardized quality-control procedures, appropriate carrier materials, effective delivery systems, biosafety assessment and harmonized regulatory frameworks are therefore essential for commercialization and farmer adoption. Economic feasibility and compatibility with existing nutrient, disease and pest-management practices should also be considered during technology evaluation. Microbial technologies are more appropriately viewed as components of integrated crop management rather than universal replacements for synthetic fertilizers or pesticides.

A systems-based framework integrating microbial diversity, functional traits, crop requirements, soil characteristics, environmental conditions, formulation technology and farm management can therefore help bridge the gap between microbial discovery and practical agricultural application. Future research should prioritize the identification of ecologically adapted microbial strains and consortia, development of stable and efficient delivery systems, multi-location validation and data-driven matching of microbial interventions with specific production environments. Such an integrated approach can enhance the reliability, scalability and sustainability of microbial technologies and strengthen their contribution to resource-efficient, climate-resilient and environmentally responsible agricultural production.

8. CONCLUSION

Microbial innovations represent an important biological foundation for developing more resource-efficient, resilient and environmentally sustainable agricultural systems. The evidence reviewed in this paper demonstrates that plant growth-promoting rhizobacteria, endophytes, mycorrhizal fungi, actinomycetes and microbial consortia can contribute to nutrient acquisition, soil fertility, pathogen suppression and tolerance to abiotic stresses through diverse and complementary mechanisms. Their value extends beyond individual microbial functions, as interactions among plants, introduced microorganisms and resident soil microbiomes can influence the overall stability and performance of agricultural systems. Recent advances in microbiome engineering, synthetic microbial communities, synthetic biology, multi-omics and artificial intelligence are providing new opportunities to move microbial agriculture from conventional strain-based applications towards more precise, function-oriented interventions. However, technological advancement alone will not ensure successful agricultural adoption. The major challenge remains the translation of laboratory and controlled-environment performance into consistent and economically viable field outcomes. Environmental variability, microbial establishment and persistence, formulation stability, scale-up, biosafety, quality control and regulatory requirements continue to constrain this transition.

Future microbial technologies should therefore be developed within an integrated crop–soil–microbiome framework in which microbial traits are matched with crop requirements, soil characteristics, environmental conditions and management practices. Greater emphasis should be placed on ecologically adapted strains and compatible microbial consortia, robust formulations, effective delivery systems, multi-location field validation and standardized assessment of agronomic, economic and environmental performance. Data generated through multi-omics, microbiome profiling and field-based experimentation can further support the development of predictive and site-specific microbial management strategies.

Ultimately, microbial technologies are unlikely to function as universal substitutes for conventional agricultural inputs; rather, their greatest potential lies in their strategic integration with existing nutrient, disease and crop-management practices. A transition towards such integrated and data-informed microbial management can improve resource-use efficiency, strengthen crop resilience and reduce the environmental burden associated with intensive agriculture. Continued interdisciplinary research linking microbial ecology, plant science, soil science, biotechnology, formulation technology and agricultural management will be essential for converting microbial innovations into reliable, scalable and sustainable solutions for future food production.

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