



Advances in biology through agronomy, aquaculture, coastal and environmental sciences

— Volume II —

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**Advances in biology through
agronomy, aquaculture, coastal and
environmental sciences**
Volume II



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Advances in Biology through Agronomy, Aquaculture, Coastal and Environmental Sciences, Volume II, is an e-book that continues the work of the first version (<https://editorapantanal.com.br/ebooks/2023/advances-in-biology-through-agronomy-aquaculture-coastal-and-environmental-sciences/ebook.pdf>), published in 2023 by Leandris Argente-Martínez and Ofelda Peñuelas-Rubio.

Our e-book compiles 25 manuscripts that present scientific results and reviews based on biological aspects. All of them contribute to explaining the responses of living organisms to agricultural, aquaculture, and coastal ecosystems, as well as those facing fragility or threat of climate change. This e-book was edited by Leandris Argente-Martínez, Ofelda Peñuelas-Rubio, and Joe Luis Arias-Moscote, members of the Consolidated Academic Group ITVAYA-CA-3.

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Bacterial consortia as a sustainable strategy for disease management and productivity improvement in maize

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ABSTRACT

Maize is among the most important agricultural crops worldwide because of its nutritional value, versatility, and role in food security; however, its cultivation faces various challenges from biotic and abiotic stressors. In recent decades, the use of agrochemicals has increased crop yields; however, environmental consequences such as biodiversity loss, pollution, and soil degradation highlight the need to integrate more sustainable strategies. In this context, plant growth-promoting microorganisms, particularly rhizobacteria (PGPR), offer alternatives; however, the use of individual strains has certain limitations under field conditions. By integrating microorganisms that can synergistically combine functions, microbial consortia have emerged as a promising biotechnological strategy, thereby improving their stability and effectiveness in real agricultural systems. This chapter explores the role of microbial consortia as a sustainable strategy for disease management and productivity improvement in maize cultivation. Additionally, the limitations of the conventional agricultural model and the role of beneficial microorganisms in terms of crop health and yield are examined. Similarly, the use of consortia as an integrated strategy and their implications for the sustainability of agricultural systems are discussed. Finally, future perspectives are proposed to optimize their design and application using emerging tools.

Keywords: microbial consortia, PGPR, maize, sustainable agriculture, plant–microbe interactions.

INTRODUCTION

In recent decades, farmers have increased agricultural production to meet global food demand. Agrochemicals, genetic improvements in crop varieties, and mechanization support this increase (Lam et al., 2022; Chen, 2025). Nevertheless, this agricultural model creates sustainability challenges. It causes

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biodiversity loss and soil degradation and leads to the emergence of resistant pathogens (Miller et al., 2022; Jing et al., 2025). These limitations highlight the growing need for more sustainable strategies in current agricultural models.

Maize (*Zea mays* L.) is among the most important crop species because of its role in food security, versatility, and a wide range of uses (Shiferaw et al., 2011; Erenstein et al., 2022). However, its production is subject to various stress factors that can affect and limit yield (Nsibo et al., 2024; Hudson et al., 2024; Costantini et al., 2025). Conventional management strategies have traditionally relied heavily on agrochemicals to maximize productivity (Popp et al., 2013; Baum et al., 2025). Recently, interest in using beneficial microorganisms to improve crop health and increase yields has increased. Among these organisms, plant growth-promoting rhizobacteria (PGPR) have received attention because they are known to promote plant growth, improve nutrient uptake, and enhance plant defense against pathogens (de Andrade et al., 2023; Hasan et al., 2024). However, plants in agricultural systems interact with complex microbial communities rather than only individual strains. Therefore, addressing this complexity requires a new approach to plant–microorganism interactions. In this context, the use of microbial consortia has emerged as a promising alternative to single-strain inoculants. This approach enables the integration of diverse biological functions that can act together, increasing the likelihood of successful field application.

This chapter explores the role of microbial consortia as a sustainable strategy for disease management and productivity improvement in maize cultivation. From this perspective, the limitations of the conventional agricultural model and the role of beneficial microorganisms in crop health and yield are first examined. The chapter subsequently discusses the use of consortia as an integrated strategy and evaluates their implications for sustainability. Finally, future perspectives are proposed to optimize consortia design and application using emerging tools.

MODERN AGRICULTURE AND THE CHALLENGE OF SUSTAINABILITY

Currently, modern agriculture must increase production to meet global food demand and ensure environmental sustainability. For decades, intensification has relied on advanced technology and excessive use of agrochemicals, which have increased yields (Tilman et al., 2002; Foley et al., 2011). Despite these yield gains, intensive agriculture has also caused negative effects, including soil degradation, reduced microbial biodiversity, resistance of phytopathogens, the emergence of resistant weeds, and water pollution (VanGessel, 2001; Bijay-Singh & Craswell, 2021; Zhou et al., 2025).

The widespread use of agrochemicals such as pesticides has led to adverse health effects. These include immunosuppression, reproductive abnormalities, cancer, and, in extreme cases (exposure to high doses), death (Gupta, 2004). Given these significant risks, this evidence reinforces the need to rethink agricultural management practices.

In this context, it is essential to redirect cultivation strategies toward agricultural models that achieve optimal production without depleting resources in the long term (Beddington, 2010). Rather than fully replacing conventional practices, agriculture should instead move toward systems focused on resource conservation and ecological strategies. In line with this transition, incorporating beneficial microorganisms into crops is becoming a strategic alternative to improve plant health, increase productivity, and promote sustainability.

LIMITATIONS OF AGROCHEMICAL USE FOR CROP PRODUCTION AND DISEASE CONTROL

Historically, agrochemicals have been the primary alternative for achieving the required production levels and controlling disease. Fertilizers, pesticides, and fungicides have helped prevent and reduce losses from phytosanitary problems. They can also quickly correct nutrient deficiencies in crops (Popp et al., 2013; Virk et al., 2024; Sharafi et al., 2025). However, despite these advantages, this approach reveals important limitations to the system's sustainability.

In disease management, repeated fungicide application exerts selective pressure on microbial populations. Sensitive populations are eliminated, and resistant populations survive (Bradley et al., 2016). Over time, this leads to an increase in resistant populations. Consequently, a production system that is increasingly dependent on the application of external chemical inputs has emerged.

The intensive use of chemical fertilizers negatively alters the diversity of microbial communities in agricultural soils. This can significantly reduce plant–microorganism interactions and the benefits they provide, such as nutrition and pathogen suppression (Dasgupta et al., 2026; Zhang et al., 2022). Long-term studies have shown that chemical fertilization reduces fungal diversity and alters the structure of bacterial communities. It also significantly alters chemical properties, which can affect nutrient dynamics and ecological processes important for crop health (Bai et al., 2020).

The conventional system focuses on agrochemical use and tends to address problems in isolation. It does not account for the complexity of biological networks, which are essential for maintaining crop health. This approach limits the ability to generate comprehensive solutions for plant nutrition, growth, and phytosanitary aspects.

BENEFICIAL MICROORGANISMS AS A STRATEGIC ALTERNATIVE

As alternatives to the limitations of agronomic models based on agrochemicals, interest in the use of beneficial microorganisms as tools to improve productivity and plant health has increased. Building on previous arguments for ecological strategies, among these, plant growth-promoting rhizobacteria

(PGPR) stand out. These bacteria colonize the rhizosphere and, in some cases, the interior of plant vascular tissues.

PGPR can influence the development of its host through both direct and indirect mechanisms. Direct mechanisms induce plant growth through biological nitrogen fixation, phytohormone production, phosphate solubilization, and siderophore production. PGPRs can indirectly function as biocontrol agents by enhancing the defense response to phytopathogen attack (Vessey, 2003; Shahwar et al., 2023; Sun et al., 2024).

Experimental studies have shown that PGPR inoculation can optimize nutrient uptake, increase plant biomass and yield, and increase tolerance to both biotic and abiotic stresses in various crops, including maize. These effects are observed under both controlled and field conditions. However, the effects can vary depending on the edaphoclimatic context and interactions with the native microbiota (Pereira et al., 2020; Nabati et al., 2025; Al-Barakaha & Alghamdi, 2025).

Although the potential of PGPR applied individually to crops has been demonstrated, evidence shows that plant–microorganism interactions occur within complex, dynamic microbial communities. Specifically, in the field, the rhizosphere is an ecosystem in which diverse microorganisms interact with each other and host plants, forming ecological networks that can limit or amplify the effects observed under controlled conditions (Saleem et al., 2021; Molina-Romero et al., 2021). Therefore, the use of individual strains with specific functions may not replicate the stability and functional diversity found in natural microbial systems. Recognizing these limitations has led to the development of bioinoculants based on microbial consortia that integrate complementary functions to increase crop benefits. From this perspective, functional consortia serve as strategic biotechnological tools.

MAIZE HEALTH AND YIELD IN THE CURRENT AGRICULTURAL CONTEXT

Maize is among the most important crops worldwide because of its economic and cultural relevance, as well as its importance to global food security (Tanumihardjo et al., 2020). Furthermore, it is a highly versatile crop across agricultural systems in both developed and developing countries. Its uses are diverse and include food for human consumption, bioethanol production, animal feed, and industrial products, among others (Shiferaw et al., 2011; Ranum et al., 2014).

From a production standpoint, maize is among the three most widely produced cereals in the world, along with wheat and rice. Global production now exceeds 1.2 billion tons annually. For example, in 2024, global production reached approximately 1.218 billion tons (FAO, 2024). Maize grows in diverse soils and climates, but yields depend on intensive agronomic management. This reliance makes maize susceptible to both biotic and abiotic stressors.

Maize is closely related to the soil microbiota, especially in the rhizosphere. These microbial communities influence plant efficiency in acquiring essential nutrients such as phosphorus and nitrogen. In turn, this influences plant growth and defense against pathogens. As a result, healthy agricultural soils and stable microbiota are essential for sustaining long-term productivity (Luo et al., 2025; Boloch, 2025).

MAIZE GROWTH AND YIELD AND THE USE OF BACTERIAL CONSORTIA

Maize growth and yield depend on interactions among plant genotype, environment, and agronomic management (Fischer et al., 2014). Many biotic and abiotic stress factors can limit plant growth and decrease crop productivity (Mittler, 2006; Gull, et al., 2019). Abiotic factors include salinity, drought, and poor nutrient bioavailability (Hu et al., 2022; Deribe, H., 2024). Among the biotic stress factors, plant pathogens pose a major threat because of their ability to cause disease, compromising health and productivity (Savary et al. 2019; Matos et al., 2024).

Maize can be affected by a wide range of pathogens. The main disease-causing agents are fungal, bacterial, and viral microorganisms. These can infect maize, limit its growth and productivity, and cause major economic losses. In some cases, pathogens cause mycotoxins to accumulate, posing health risks to humans and animals (Albarracín et al., 2012; Redinbaugh & Zambrano, 2014; Guerra et al., 2022; Bryla et al., 2022).

On the other hand, agronomic practices directly impact soil health and structure, as well as microbial communities (Meena et al., 2020). Excessive agrochemical use results in negative effects, such as loss of microbial diversity, nutritional imbalances, and reduced long-term fertility (Steiner et al., 2024; Yasir et al., 2025). A shift to sustainable agriculture cannot rely only on replacing chemical inputs. This change requires the integration of different tools and knowledge from agronomy, ecology, and microbiology. Designing and implementing integrated strategies is essential for promoting more sustainable agricultural systems.

The combination of plant stress factors highlights the need for a comprehensive approach to crop production. This approach must account for interactions among the environment, cultivated plants, and soil microbiota—microorganisms that live in the soil and influence plant growth. Given this context, the use of beneficial microorganisms, such as plant growth-promoting rhizobacteria (PGPR), which increase plant growth, is a promising way to improve crop productivity and health (Vessey, 2003; Olanrewaju et al., 2017). However, the use of individual strains may be limiting in the field because of competition with the native microbiota (Yang et al., 2024). Microbial consortia provide an alternative to these limitations. The integration of diverse biological functions within a single community enables improved plant nutrition, growth promotion, and stronger defense against pathogens (Sarma et al., 2015; Santoyo et al., 2021; Negi et al., 2024).

In the rhizosphere, microorganisms exist in a complex system. They interact with each other and with their plant host (Iqbal, 2026). Soil microbiota play key roles in pathogen suppression, nutrient availability, and plant growth promotion (Trivedi et al., 2020). On this basis, bacterial consortia aim to mimic the functions of natural microbial communities.

Consortia offer benefits not seen with single-strain PGPR inoculation. They combine microorganisms with complementary functions, resulting in their coexistence and collaboration (Niu et al., 2017; Trivedi et al., 2020). Consortia also maintain functionality under variable conditions (Shade, 2012). Their strength lies in the interactions among their members, enabling processes such as functional cooperation, metabolic complementarity, and niche partitioning (Hu et al., 2016; Carreras, 2025). These microbial interactions increase individual functions and stability (De Roy et al., 2014; Niu et al., 2017). The main differences between solitary and consortium inoculation are shown in Figure 1.

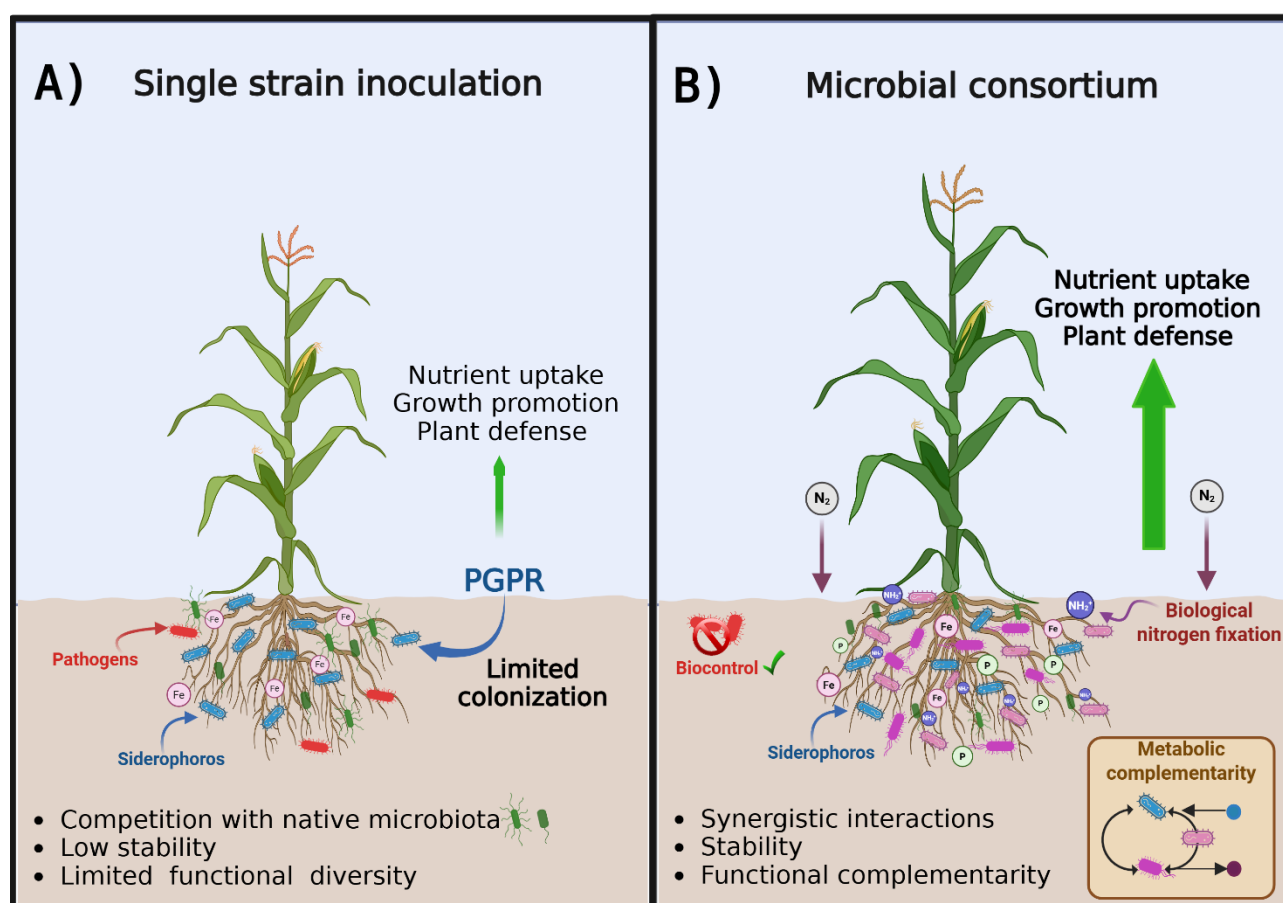


Figure 1. Schematic comparison between A) a single PGPR strain inoculation and B) inoculation with a bacterial consortium.

In the field, competition for resources and space can be a limitation (Hibbing et al., 2010). Integrating consortia creates complementarity between microorganisms, which favors adaptation and stability (Pascual et al., 2020; Zhang et al., 2026). Consortia are more likely to establish and perform better than single-strain inoculants are. Their use as biocontrol agents is notable because they combine multiple

mechanisms of action to control phytopathogens more effectively (Negi et al., 2024). For example, De la Vega-Camarillo et al. (2023) reported a biocontrol effect using a microbial consortium composed of *Achromobacter xylosoxidans*, *Burkholderia* sp., *Klebsiella variicola*, *Pantoea ananatis*, *Kosakonia pseudosacchari*, *Phytobacter diazotrophicus*, and *Pseudomonas protegens*, resulting in a reduction in maize rust incidence (8 to 12.5%) in a field experiment.

Various greenhouse and field studies have shown that the application of microbial consortia can significantly improve maize growth and yield (Table 1). For example, an experiment by Olanrewaju & Babalola (2019) evaluated native maize rhizosphere strains. The strains were inoculated individually or in pairs or triplets. The consortia of two or three strains significantly increased plant biomass and grain weight, with the three-strain consortia being the most efficient. Similarly, a study in semiarid environments revealed that bacterial consortia improved the number and weight of maize kernels. Organic matter and phosphorus availability also increased. However, these results varied by application rate and plant genotype, as four maize varieties showed different responses, highlighting the complexity of plant–microorganism interactions under real-world conditions (Kurt, 2025).

Compared with individual strains, a consortium composed of *Azospirillum brasilense*, *Pseudomonas putida*, *Acinetobacter* sp., and *Sphingomonas* sp. increases rhizosphere colonization in maize. Inoculation with the consortium, combined with 50% chemical fertilization, maintained yields similar to those with 100% fertilization, demonstrating its potential to reduce reliance on external inputs (Molina-Romero et al., 2021).

This evidence suggests that microbial consortia can promote pathogen defense, growth, and productivity. They also help agriculture adapt to environmental variability. Understanding the basis of these interactions and their implications for functionality requires an integrated approach.

Table 1. *In vitro*, greenhouse and field experiments in maize using diverse microbial consortia.

Reference	Microbial consortium	Effects	Experimental conditions
Olanrewaju & Babalola, 2019	Native PGPR	↑ plant height	Field trials
	including <i>Bacillus</i> ,	↑ root and stem length	
	<i>Pseudomonas</i> , and	↑ number of leaves	
	<i>Streptomyces</i>	↑ weight of 100 seeds	
		consortia better than individual inoculation	
Pacheco et al., 2021	<i>Rhizoglyphus irregularis</i>	↑ P absorption	Field trials
	<i>Pseudomonas putida</i>	↑ P use efficiency	

Reference	Microbial consortium	Effects	Experimental conditions
		↑ Productivity associated with P	
Saleem et al., 2021	<i>Bacillus</i> sp.	higher efficiency of photosynthesis	Greenhouse (pots)
	<i>Enterobacter</i> sp.	(14%) and an increase in antioxidant	under water stress,
	<i>Pseudomonas fluorescens</i>	systems (20%)	consortium vs. individual inoculants
Molina-Romero et al., 2021	<i>Azospirillum brasilense</i>	↑ height	Field trials with
	<i>Pseudomonas putida</i>	↑ root length and dry weight	different nitrogen
	<i>Acinetobacter</i> sp.	↑ grain yield from 3.91 to 5.35 t/ha	fertilization regimes
	<i>Sphingomonas</i> sp.	(consortium + 50% urea vs. control)	(0%, 50%, 100%)
Peng et al., 2021	<i>Pseudomonas</i> sp.	↑ plant biomass	Greenhouse: tests in
	<i>Peribacillus</i> sp.	↑ antioxidant enzymatic activity	saline soils (pots)
	<i>Streptomyces</i> sp.	↑ chlorophyll content	
		↑ abundance of beneficial rhizobacteria	
Ahmad et al., 2022		↑ salinity tolerance	
	<i>Bacillus subtilis</i>	↑ grain yield +17%	Greenhouse (pots)
	<i>Paenibacillus polymyxa</i>	↑ 1000-grain weight +12%	and field trials (two cycles)
De la Vega-Camarillo et al., 2023	<i>Bacillus aryabhatai</i>	↑ nutrients in grain	
	<i>Achromobacter xylosoxidans</i>	↑ Root length (4.2 folds)	Greenhouse (pots) and field trials
	<i>Burkholderia</i> sp.	↑ Air length (3.0 folds)	
		↑ Yield of 11 to 16 t/ha	
	<i>Klebsiella variicola</i>	↓ Rust incidence from 12.5% to 8%	
	<i>Pantoea ananatis</i>		
	<i>Kosakonia pseudosacchari</i>		
	<i>Phytobacter diazotrophicus</i>		
Manjunath et al., 2023	<i>Pseudomonas putida</i>	↑ yield from 3.02 to 3.86 t/ha (↑ 27.8% or ↑ 0.84 t/ha)	Field trial (three years,
	<i>Paenibacillus favisporus</i>	↑ biomass (stubble) from 6.93 to 9.11 t/ha (↑ 31.4%)	rainfed/subhumid conditions) with seed + soil application

Reference	Microbial consortium	Effects	Experimental conditions
Zelaya-Molina et al., 2025	<i>Aureobasidium</i> sp.	↑ Germination rate	Early-stage <i>in vitro</i> assay
	<i>Clavispora</i> sp.	↑ Root architecture development	
	<i>Pantoea</i> sp.	↑ Seedling biomass	
Kurt, 2025	<i>Azotobacter</i> spp.	↑ grain yield	Field trials in a semiarid region
	<i>Bacillus</i> sp.	↑ soil organic matter	
	<i>Paenibacillus</i> sp.	↑ P availability	
	<i>Pantoea</i> sp.	↑ cation exchange capacity	
	<i>Pseudomonas</i> sp.	↑ [Zn and Cu] in plant and soil	
Patil et al., 2026	<i>Bacillus haynesii</i>	↑ yield 8.53 t/ha	Field trials in semiarid conditions
	<i>Shonchella clausii</i>	↑ aerial dry biomass	
	<i>Aspergillus versicolor</i>	↑ root length	
	<i>Aspergillus proliferans</i>	↑ number of leaves	
		↑ grains per ear	

FUTURE PERSPECTIVES

The development and use of bacterial consortia are a promising strategy in agricultural biotechnology. They are especially useful for addressing issues caused by intensive agrochemical use. However, implementing consortia in cropping systems poses several challenges. Addressing these issues requires an interdisciplinary approach that combines knowledge from microbiology, agronomy, ecology, and biotechnology.

Additionally, the effectiveness of consortia is influenced by plant genotype, environmental conditions, and native microbiota. Evidence suggests that these variables can influence the effectiveness of consortia in agronomic systems (Wagner et al., 2016; Trivedi et al., 2020; Yang et al., 2024), underscoring the need to develop consortia with strategies tailored to each system rather than more general approaches.

Recent research emphasizes the importance of designing consortia that incorporate functional interactions and complementary strategies, tailored to specific objectives, to ensure their effectiveness and stability under real agricultural conditions (Singh et al., 2023).

Combining microorganisms with complementary functions can result in synergistic effects. These processes improve pathogen defense, increase plant growth, and yield (Olanrewaju & Babalola, 2019; Molina-Romero et al., 2021; Pacheco et al., 2021; Wang et al., 2025). However, designing stable,

functional consortia remains a challenge. Key knowledge gaps exist about their interactions and performance (persistence, stability, and functionality) in the field.

In this context, the integration of omics tools (such as genomics, proteomics, transcriptomics, and metabolomics—methods for comprehensively studying genes, proteins, RNA, and metabolites) has allowed for a deeper understanding of plant–microorganism interactions. These tools enable the investigation and elucidation of biological systems and their interactions. Taken together, these approaches enable an unprecedented understanding of the mechanisms underlying plant responses to microbial colonization, facilitating the identification of key functions, gene expression, metabolic pathways, and microbial communication mechanisms that promote plant growth and defense against pathogens (Mmotla et al., 2025). The integration of these tools, along with agroecological approaches, such as the reduction of chemical inputs and the optimization of soil–plant–microorganism system interactions, will allow progress toward more productive and environmentally responsible agricultural systems.

CONCLUSIONS

Microbial consortia are presented as a strategic alternative by integrating microorganisms with complementary functions, allowing greater stability and efficiency under variable agricultural conditions. Their potential to improve maize productivity positions them as a key tool for agricultural sustainability. The design of microbial consortia requires an interdisciplinary approach; in this sense, the integration of omics tools will allow for a more detailed understanding of plant–environment–microbiome interactions. The integration of these strategies will help optimize the performance of microbial consortia under real agricultural conditions, contributing to sustainable agricultural management.

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