TBS Trends in
Biological Sciences

OPEN ACCESS

Beneficial Microorganisms in Plant Health: Mechanisms, Challenges and Future Directions

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ABSTRACT

Modern agriculture has faced growing sustainability challenges as a result of declining soil quality, increasing climate variability, and the widespread reliance on chemical fertilizers and pesticides. These pressures have intensified interest in biologically based alternatives that support productivity while reducing environmental harm. Beneficial microorganisms have therefore emerged as important components of plant health, as they contribute to improved growth, nutrient acquisition, and tolerance to both biotic and abiotic stresses. A detailed understanding of how these microorganisms function and interact with plants is essential for their successful application in agricultural systems. This review drew upon recent peer-reviewed publications focusing on plant-associated beneficial microorganisms, with particular attention given to bacterial and fungal groups involved in plant growth promotion and disease control. Studies examining molecular, physiological, and ecological processes were assessed in order to clarify dominant functional mechanisms. In addition, reported limitations related to field application and emerging directions in microbial-based technologies were carefully analyzed. The reviewed literature indicated that beneficial microorganisms supported plant performance through multiple, interconnected pathways. These processes included biological nitrogen fixation, mobilization of phosphorus and potassium, regulation of plant hormone signaling, stimulation of induced systemic resistance, and direct suppression of plant pathogens. Although such effects were repeatedly confirmed under controlled experimental conditions, outcomes in field settings varied considerably. This variability was largely attributed to environmental heterogeneity, specificity of host–microbe interactions, competition with indigenous microbial populations, and challenges associated with formulation stability and delivery methods. Beneficial microorganisms constitute an important foundation for sustainable plant health management. Recent progress in omics-based research, the development of microbial consortia, and advances in synthetic biology has expanded opportunities to enhance consistency and effectiveness. Moving forward, research and application efforts should emphasize systems-level integration, aligning microbial functions with crop genetics and agronomic practices to achieve reliable field performance and support long-term agricultural resilience.

KEYWORDS

Plant microbiome, biocontrol agents, nutrient solubilization, induced systemic resistance, sustainable agriculture

ISSN: 3105-0573 (Print)
ISSN: 3105-0581 (Online)
https://doi.org/10.21124/tbs.2026.201.209

Received: 16 Jan. 2026
Accepted: 13 Apr. 2026
Published: 30 Jun. 2026

INTRODUCTION

Plant health remains a fundamental driver of agricultural productivity and the long-term stability of ecosystems[1]. For many years, explanations of crop performance relied mainly on plant genetics, soil nutrient status, and climatic conditions[2]. These factors clearly matter, yet they do not fully account for the wide variation in plant performance observed under field conditions. In practice, plants rarely behave as isolated biological entities. Their growth and survival are shaped by continuous interactions with surrounding organisms, particularly microorganisms[3]. Plants host diverse microbial populations across the rhizosphere, phyllosphere, and internal tissues[4]. These communities do not remain constant. Their composition shifts with plant age, soil conditions, and environmental fluctuations, and they interact continuously with plant metabolic processes. Through such interactions, microorganisms affect nutrient availability, root system development, stress responses, and disease dynamics. In certain agroecosystems, microbial activity has been observed to partially offset poor soil quality or environmental stress, enabling plants to sustain growth under conditions that would otherwise be restrictive. The rise of intensive agriculture altered many of these long-standing biological relationships[5]. Synthetic fertilizers and pesticides were adopted widely to increase yields and suppress pests, often producing immediate and measurable benefits. With repeated application, however, their influence on soil ecosystems became increasingly apparent. Reduced microbial diversity, disrupted nutrient cycling, degradation of soil structure, and accumulation of toxic residues have all been documented[6]. At the same time, pathogen populations adapted to these inputs, leading to reduced control efficacy and growing resistance. Together, these developments have raised serious concerns regarding the long-term sustainability of chemically dependent cropping systems. In response to these challenges, beneficial microorganisms have attracted attention as biological tools for restoring soil function and improving plant health[7]. Their modes of action differ fundamentally from those of chemical inputs. Rather than targeting a single physiological process, microorganisms influence plant systems through multiple, interconnected pathways[8]. They are involved in nutrient transformations, modify hormonal signaling, and interact with plant immune responses. Many also suppress pathogens through competition, antibiosis, or direct parasitism. These processes often occur simultaneously and are shaped by local environmental conditions. Even so, the performance of microbial products in agriculture has remained inconsistent[9]. Plant-microbe interactions are strongly influenced by soil properties, climatic factors, plant genotype, and the structure of native microbial communities. Consequently, microorganisms that show consistent benefits in laboratory or greenhouse experiments frequently exhibit variable or diminished effects under field conditions[10]. Such variability suggests that current application strategies oversimplify the ecological complexity of soil-plant systems.

This review considers beneficial microorganisms as integral components of plant systems rather than as external inputs. Attention is given to the mechanisms that govern plant-microbe interactions, the ecological constraints that limit their effectiveness, and emerging strategies aimed at improving field-level performance. By integrating perspectives from microbiology, ecology, and agronomy, this article seeks to clarify how microbial-based approaches can be applied more reliably and sustainably in agricultural production.

DIVERSITY OF BENEFICIAL MICROORGANISMS ASSOCIATED WITH PLANTS

Bacterial communities and functional specialization: Bacteria are the most abundant and functionally diverse members of the plant microbiome. In many cropping systems, beneficial bacterial populations tend to accumulate around roots, where carbon-rich exudates sustain microbial activity[11]. These communities do not behave as a single functional unit. Some bacteria occupy narrow ecological niches, while others perform broader roles that support plant health. Where nitrogen is limited, nitrogen-fixing bacteria have long been recognized as important contributors, converting atmospheric nitrogen into ammonium that plants can assimilate[12]. Other bacterial groups were shown to increase the availability of phosphorus, potassium, and several micronutrients. This usually occurs through the release of organic

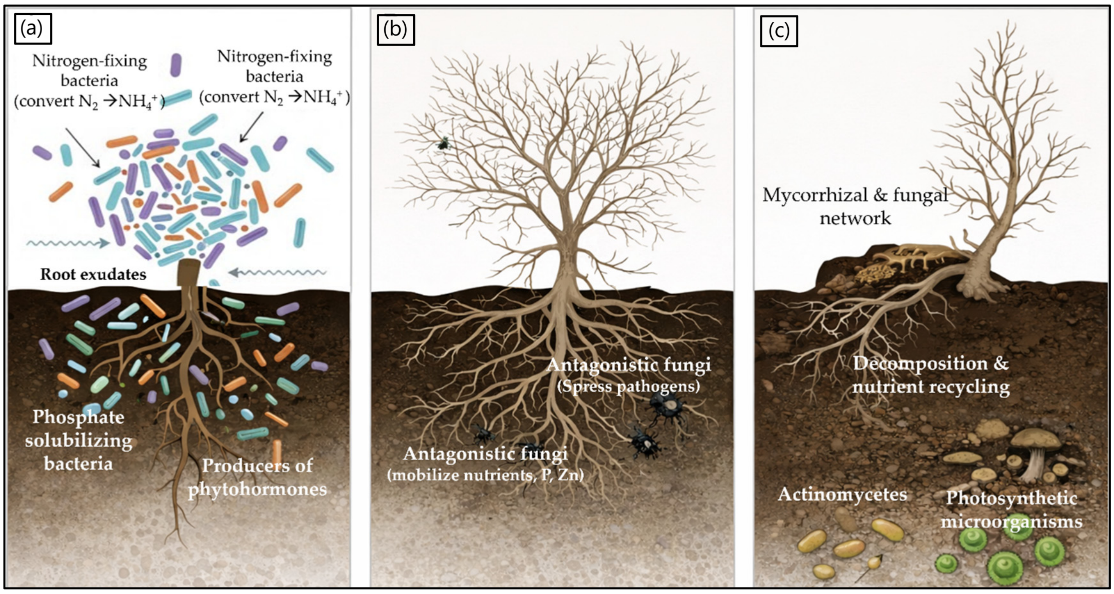

Fig. 1(a-c): Microbial interactions in the rhizosphere contribute to plant nutrition, growth, and health, (a) Nutrient mobilization and growth promotion by rhizosphere bacteria, (b) Antagonistic fungi and nutrient mobilization and (c) Mycorrhizal networks and nutrient recycling

acids, chelating compounds, or hydrolytic enzymes that gradually modify soil mineral chemistry[13]. As these processes continue, nutrient availability in the rhizosphere increases and uptake by roots becomes more efficient. The influence of beneficial bacteria is not restricted to nutrient dynamics. Many strains produce bioactive metabolites, including phytohormones, vitamins, and signaling molecules, that affect plant growth. These compounds can alter root system architecture, promote lateral root formation, or support shoot development, depending on environmental conditions[14]. Over time, the combined effects of nutrient mobilization and growth regulation lead to improved plant vigor and productivity (Fig. 1a).

Fungal contributions to plant health: Fungi are another important group of beneficial microorganisms associated with plants, and their contributions extend well beyond simple nutrient exchange[15]. Mycorrhizal fungi, which associate symbiotically with the majority of terrestrial plant species, effectively enlarge the functional root system. Through the development of extensive hyphal networks, these fungi expanded the soil volume accessible to plants and improved the acquisition of nutrients with limited mobility, particularly phosphorus and zinc[16]. In many cases, enhanced nutrient uptake was accompanied by noticeable improvements in plant growth and overall performance. Beyond nutrition, mycorrhizal associations have been reported to strengthen plant tolerance to abiotic stresses such as drought and salinity[17]. These effects were not driven by a single process but emerged from improved water absorption, modifications in root physiology, and changes in the regulation of stress-related genes. Mycorrhizal fungi also influenced soil properties by promoting aggregate formation, which improved soil aeration and increased water-holding capacity[18]. At the same time, antagonistic fungi played a complementary role in plant protection. They suppressed pathogenic microorganisms through competition for resources, production of antimicrobial substances, and direct parasitism[19]. Importantly, several antagonistic fungi were found to activate plant defense mechanisms, resulting in prolonged resistance against disease development (Fig. 1b).

Actinomycetes and supporting microbial groups: Actinomycetes represent a distinctive group of microorganisms that share features of both bacteria and fungi, giving them a unique ecological role in soil environments[20]. They are especially abundant in soils rich in organic residues, where they actively participate in the decomposition of complex materials and the recycling of essential nutrients[21].

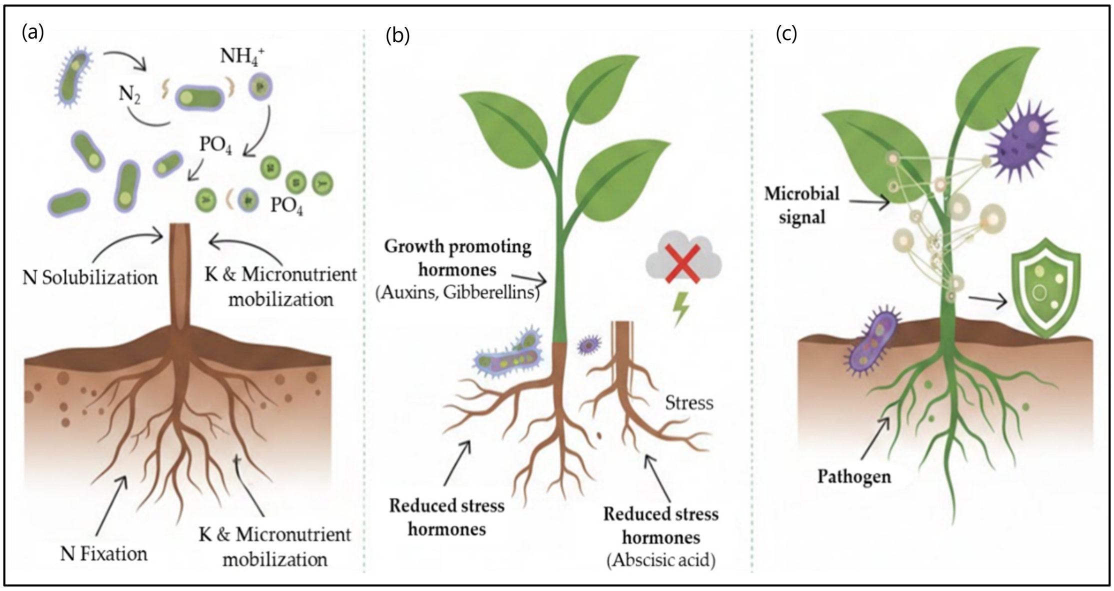

Fig. 2(a-c): Mechanisms of microbial enhancement of plant health, (a) Transformation of nitrogen, phosphorus, potassium, and micronutrients from unavailable to plant-available forms through microbial activity, (b) Regulation of plant growth through enhanced root and shoot development and improved stress resilience mediated by microbial hormonal interactions and (c) Priming of plant defense responses for faster and stronger protection against pathogen attack

Their well-known capacity to produce a broad spectrum of secondary metabolites, including many antibiotics, has made actinomycetes important agents in the natural suppression of plant pathogens[22]. In several systems, their presence was associated with improved soil quality and enhanced biological control. Alongside actinomycetes, other microbial groups such as yeasts and photosynthetic microorganisms also contributed to ecosystem functioning[23]. These organisms supported soil fertility, promoted the turnover of organic matter, and assisted plant establishment in stressed or degraded habitats. Although they have been studied less intensively than other soil microorganisms, their ecological roles remain significant[24]. Collectively, these groups highlight the importance of maintaining microbial diversity for sustaining plant health and stable soil ecosystems (Fig. 1c).

MECHANISMS OF MICROBIAL ENHANCEMENT OF PLANT HEALTH

Microbial-mediated nutrient cycling: Limited nutrient availability has often restricted plant growth across many agricultural systems. Beneficial microorganisms help to alleviate this limitation by transforming nutrients that are otherwise unavailable into forms that plants can absorb[25]. In practice, these microbial processes reduce the need for external fertilizer inputs and improved the efficiency with which plants used available nutrients. Nitrogen-fixing microorganisms supplied plants with biologically usable nitrogen, while phosphorus-solubilizing microbes released phosphate from stable mineral complexes in the soil[26]. Other nutrients were also influenced by microbial activity. The mobilization of potassium and trace elements supported key physiological processes, including enzyme function and photosynthesis, and contributed to improved stress tolerance[27]. These transformations were not uniform but varied with soil conditions, microbial activity, and plant nutrient demand. As a result, nutrient dynamics within the soil-plant system were shaped by continuous interactions among these factors (Fig. 2a).

Regulation of plant growth through hormonal interactions: Plant hormones govern nearly every stage of plant growth and development, from early root formation to shoot expansion. Beneficial microorganisms interact with these regulatory systems by producing phytohormones themselves or by influencing hormone signaling within the plant[28]. In several studies, microbial activity was associated with enhanced root elongation, greater lateral root proliferation, and improved shoot growth, effects that ultimately contributed to stronger plant establishment[29]. At the same time, microorganisms shown to regulate hormones linked to stress responses. By lowering the accumulation of stress-related hormones, they helped plants to maintain growth under adverse conditions such as drought, salinity, or nutrient limitation. This adjustment of hormonal balance allowed plants to respond more effectively to environmental challenges. Overall, microbial modulation of plant hormone dynamics emerged as a key process underlying enhanced plant resilience and adaptability (Fig. 2b).

Activation of plant defense systems: Plants have evolved intricate immune systems that allow them to detect and respond to diverse microbial cues present in their environment. Beneficial microorganisms engage with these systems in a finely regulated manner, stimulating defensive pathways while avoiding any harmful effects on the host. As a consequence, plants maintained in a primed condition, enabling them to mount quicker and more effective responses when exposed to pathogenic challenge[30]. This preparatory state is widely known as induced systemic resistance. The establishment of induced resistance depended on coordinated signaling networks that linked hormonal signaling with metabolic reprogramming[31]. These interactions resulted in defense responses that were activated earlier and expressed more strongly, thereby restricting pathogen spread and limiting damage to plant tissues. Importantly, because defenses were not continuously expressed, plants avoided the substantial metabolic costs associated with constant immune activation[41]. For these reasons, induced systemic resistance is considered a highly efficient and sustainable strategy for long-term plant protection (Fig. 2c).

CHALLENGES LIMITING FIELD APPLICATION OF BENEFICIAL MICROORGANISMS

Environmental and ecological constraints: Environmental variability continues to pose a major challenge to the practical use of beneficial microorganisms. Soil pH, temperature, moisture availability, and nutrient status strongly affect microbial survival and functional activity. After application, introduced microorganisms were also required to compete with well-established native microbial populations, which often limited successful colonization and long-term persistence[32]. Given the inherent complexity and heterogeneity of soil ecosystems, predicting microbial performance under field conditions remains difficult. As a consequence, products that performed reliably in laboratory or greenhouse experiments frequently showed inconsistent or reduced effectiveness when applied under real agricultural conditions[33].

Formulation, storage, and delivery issues: The commercial viability of microbial products is closely tied to their formulation and ease of use. Many beneficial microorganisms are highly sensitive to environmental stresses such as desiccation, temperature fluctuations, and ultraviolet radiation[34]. Ensuring microbial viability during storage, transport, and field application therefore remains a key technological limitation. In addition, the mode of delivery influences product performance[35]. Application strategies including seed coating, soil drenching, and foliar spraying exposed microorganisms to distinct environmental pressures, which affected their ability to establish, survive, and express beneficial traits after application[36].

Host specificity and genetic compatibility: Plant-microbe interactions are rarely universal and are often shaped by a high degree of host specificity. A microorganism that promoted growth or stress tolerance in one plant species, or even in a particular cultivar, did not necessarily produce similar outcomes in another[37]. Such specificity reflects variation in root exudate composition, plant immune signaling, and microbial recognition processes. Understanding the genetic and physiological determinants of host compatibility is therefore essential. Integrating microbial screening with plant breeding programs may help improve consistency and enhance the overall effectiveness of microbial-based interventions[38].

Regulatory and socioeconomic barriers: In addition to biological and technical constraints, regulatory and socioeconomic factors further limit widespread adoption of microbial products. Regulatory frameworks differ markedly among countries and are often fragmented or poorly harmonized[39]. Lengthy approval procedures and inconsistent quality control standards have slowed product development and commercialization. Moreover, limited awareness among farmers, coupled with skepticism regarding the reliability of microbial inputs, has reduced adoption rates, particularly within smallholder farming systems. Overcoming these barriers will be critical for the successful integration of beneficial microorganisms into sustainable agricultural practices[40].

FUTURE DIRECTIONS AND EMERGING OPPORTUNITIES

Omics-driven discovery and precision microbiology: The expanding use of genomics, transcriptomics, proteomics, and metabolomics has markedly changed the way plant-microbe interactions are investigated. These techniques make it possible to examine microbial functions and plant responses in a highly resolved and integrated manner. In several cases, they revealed mechanisms underlying beneficial effects that were previously observed only at the phenotypic level. Such information has increasingly guided strain selection and functional refinement. When omics-derived insights are interpreted together with ecological conditions and agronomic practices, they enable the development of precision microbial applications that are better suited to specific crops and production environments[41].

Microbial consortia and community engineering: In soil ecosystems, plants coexist with diverse microbial assemblages rather than individual microorganisms acting alone. Recognizing this complexity has encouraged the development of microbial consortia that combine organisms with complementary biological roles. Compared with single-strain inoculants, these consortia often display improved stability under fluctuating field conditions. Functional redundancy within the community further ensured that essential processes were maintained even when certain strains declined or failed to establish[42].

Synthetic biology and metabolic engineering: Advances in synthetic biology have opened new avenues for enhancing microbial performance in agriculture. Through targeted genetic modification and metabolic engineering, microorganisms can be designed to improve nutrient mobilization, tolerate abiotic stresses, or exert stronger antagonistic effects against plant pathogens. Despite these possibilities, the application of engineered microorganisms must carefully address issues of biosafety, regulatory approval, and public perception to ensure responsible use[43].

Integration into climate-resilient agriculture: Climate variability and increasing environmental stress continue to challenge agricultural productivity. Beneficial microorganisms have shown the capacity to support plant growth under drought, salinity, and temperature extremes, highlighting their potential role in climate-resilient farming systems. Their effective integration with sustainable agronomic practices, such as soil conservation and reduced chemical inputs, will be essential for maintaining productivity under changing climatic conditions[44].

CONCLUSION

Beneficial microorganisms constitute a fundamental component of sustainable plant production systems. Through multiple and interconnected mechanisms, they enhance nutrient availability, regulate plant growth, strengthen immune responses, and suppress pathogens. Although achieving consistent performance under field conditions remains difficult, ongoing progress in molecular biology, microbial ecology, and systems-based agriculture provides a strong foundation for future applications. The strategic integration of beneficial microorganisms will be crucial for the development of resilient, sustainable, and environmentally responsible agricultural systems.

SIGNIFICANCE STATEMENT

Agricultural systems today must meet rising food demands while minimizing risks to environmental and human health. The widespread use of chemical fertilizers and pesticides has increased crop productivity, but it has also led to soil deterioration and contamination of water resources. In recent years, beneficial microorganisms naturally associated with soils and plant roots have emerged as promising tools for sustainable crop management. These organisms contribute to improved nutrient uptake, enhanced plant growth, and suppression of plant diseases. Nevertheless, their performance in open-field conditions has frequently been less reliable than in controlled experiments, due to variations in climate, soil characteristics, and microbial interactions. Strengthening scientific understanding and optimizing application practices are therefore essential for reducing chemical dependence and promoting resilient, sustainable agricultural production systems.

ACKNOWLEDGMENT

The authors thank colleagues and institutions for general academic support and constructive discussions during the preparation of this review. The authors also sincerely acknowledge the editor and anonymous reviewers for their valuable comments and insightful suggestions, which substantially improved the quality and clarity of the manuscript.

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