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Microbiome engineering and beneficial bio-inputs for sustainable nutrient management and soil-borne disease suppression

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Abstract
Modern agriculture faces the dual challenge of maintaining high crop productivity while reducing dependence on chemical fertilizers and pesticides. Microbiome engineering has emerged as a promising approach for enhancing nutrient availability, improving soil health, and suppressing plant diseases through the strategic use of beneficial microorganisms. This review examines the roles of key bacterial genera, including Bacillus, Pseudomonas, and Azotobacter, in nitrogen fixation, phosphorus solubilization, plant growth promotion, and suppression of soil-borne pathogens. The mechanisms underlying microbial nutrient mobilization, production of phytohormones, siderophores, antibiotics, and lytic enzymes are discussed. Advances in microbial consortia design, carrier formulations, seed treatments, and rhizosphere-targeted delivery systems are highlighted as important tools for optimizing bioinput performance under field conditions. The review also addresses challenges related to microbial survival, environmental variability, and interactions with native soil microbiota. Integration of microbiome engineering with precision agriculture and omics-based technologies ofers significant opportunities for developing next-generation biofertilizers and biocontrol agents capable of supporting sustainable and climate-resilient crop production.

Keywords: Microbiome engineering, bio-inputs, bacillus, pseudomonas, azotobacter, nitrogen fixation, phosphorus solubilization, plant growth-promoting rhizobacteria, soil-borne pathogens, sustainable agriculture

Introduction

Soil microorganisms constitute one of the most diverse and functionally important components of terrestrial ecosystems. They regulate nutrient cycling, organic matter decomposition, soil aggregation, and plant health through a wide range of biochemical processes [1]. In agricultural systems, the rhizosphere the narrow zone of soil influenced by plant roots hosts complex microbial communities that directly afect crop productivity and resilience [2]. Beneficial microorganisms, particularly plant growth-promoting rhizobacteria (PGPR), have attracted increasing attention as sustainable alternatives to synthetic fertilizers and chemical pesticides because they can enhance nutrient availability, stimulate plant growth, and suppress plant pathogens [3].

The intensive use of nitrogen and phosphorus fertilizers has significantly increased crop yields over the past decades; however, it has also contributed to environmental problems such as eutrophication, groundwater contamination, soil degradation, and greenhouse gas emissions [4]. Phosphorus fertilizers are often ineficient because a large proportion of applied phosphate becomes immobilized in soil through fixation with calcium, iron, or aluminum compounds, rendering it unavailable to plants [5]. Similarly, excessive nitrogen fertilization can lead to nitrate leaching and emissions of nitrous oxide, a potent greenhouse gas [6]. These challenges have accelerated the search for biologically based nutrient management strategies that improve fertilizer use eficiency while minimizing environmental impacts.

Among beneficial soil bacteria, Azotobacter species are recognized for their ability to fix atmospheric nitrogen independently of a plant host, thereby contributing biologically available nitrogen to the soil [7]. *Bacillus* species are widely studied for their capacity to solubilize insoluble phosphates, produce phytohormones, and form stress-resistant endospores that facilitate long-term survival under field conditions [8]. *Pseudomonas* species exhibit exceptional rhizosphere competence and produce a variety of siderophores, antibiotics, and volatile organic compounds that inhibit pathogenic microorganisms and promote plant growth [9]. Collectively, these bacterial groups represent key candidates for the development of nextgeneration bio-inputs aimed at enhancing nutrient acquisition and plant protection.

Recent advances in microbiome research have shifted the focus from single-strain inoculants to the broader concept of microbiome engineering, which involves the deliberate manipulation of microbial communities to improve ecosystem functions beneficial to plants [10]. Unlike conventional biofertilizers that rely on individual microbial strains, microbiome engineering seeks to design synergistic microbial consortia capable of performing multiple functions simultaneously, such as nitrogen fixation, phosphorus solubilization, stress mitigation, and pathogen suppression [11]. This approach recognizes that microbial interactions within the rhizosphere are often cooperative and that community-level functions may provide greater stability and efectiveness under variable environmental conditions [12].

In addition to nutrient mobilization, beneficial microorganisms play a critical role in the suppression of soil-borne diseases. Pathogens such as *Fusarium oxysporum*, *Rhizoctonia solani*, and Pythium spp. are responsible for substantial yield losses in many cropping systems worldwide [13]. PGPR can suppress these pathogens through competition for nutrients and ecological niches, production of antimicrobial metabolites, secretion of lytic enzymes, and induction of systemic resistance in plants [14]. The integration of nutrient-mobilizing and disease-suppressive functions within a single microbial consortium ofers considerable potential for reducing dependence on both fertilizers and fungicides.

Technological developments in metagenomics, transcriptomics, metabolomics, and high-throughput sequencing have greatly improved our understanding of plant-associated microbial communities [15]. These tools enable the identification of beneficial microbial taxa, functional genes involved in nutrient cycling, and interactions among microbial populations in the rhizosphere [16]. Coupled with precision agriculture and advanced formulation technologies, such as encapsulation and nano-enabled carriers, microbiome engineering is emerging as a powerful strategy for developing climate-resilient and environmentally sustainable agricultural systems [17].

Given the growing need for sustainable crop production, the optimization of beneficial bacterial bio-inputs has become a major research priority. This review examines the roles of Azotobacter, *Bacillus*, and *Pseudomonas* in nitrogen fixation, phosphorus solubilization, plant growth promotion, and suppression of soil-borne pathogens. Furthermore, it discusses recent advances in microbial consortia design, formulation technologies, and microbiome engineering approaches that can enhance the efectiveness of bio-inputs for sustainable nutrient management and disease control [18].

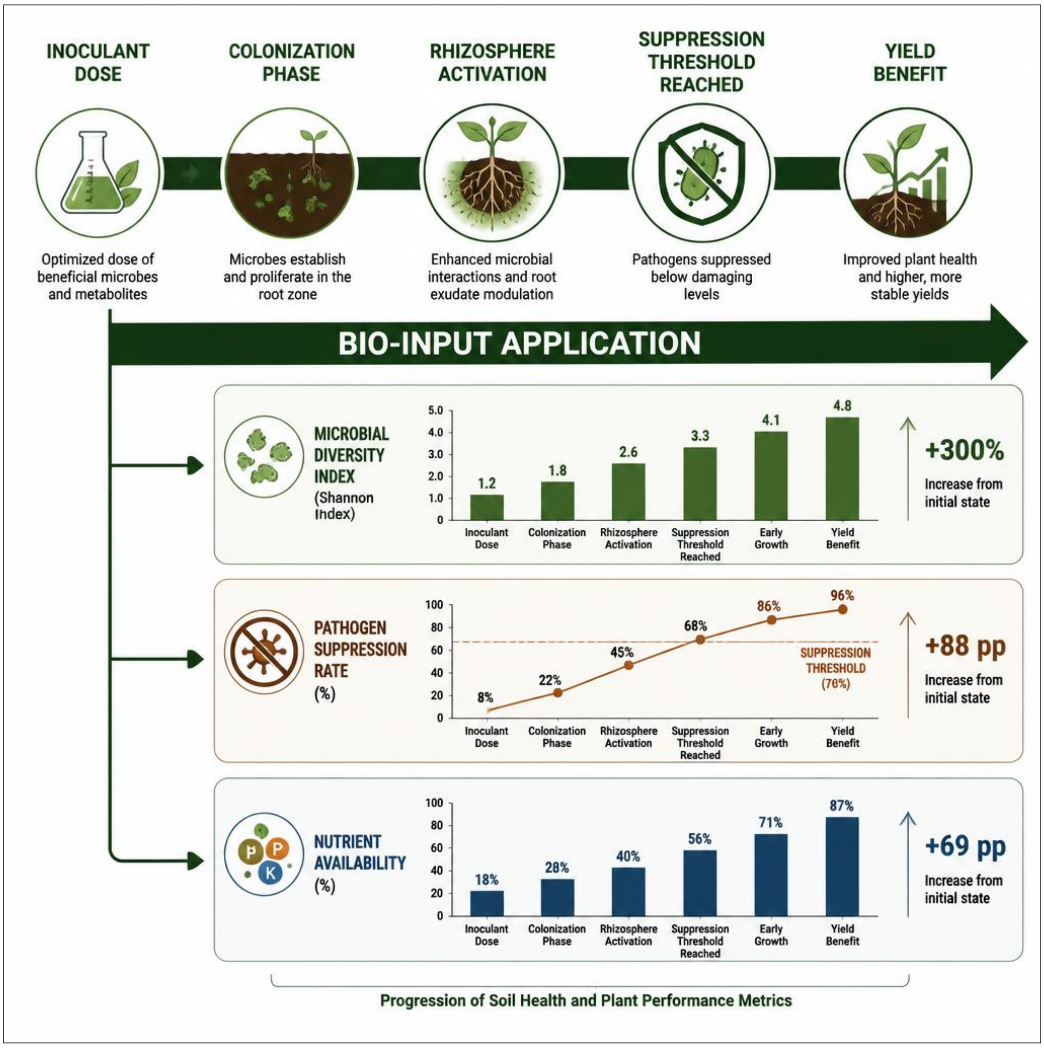

Fig 1: Bio-input application and plant response.

Beneficial Bacteria and Their Functional Roles

Azotobacter and Biological Nitrogen Fixation

Azotobacter species are free-living diazotrophic bacteria capable of converting atmospheric nitrogen into forms accessible to plants through the activity of the nitrogenase enzyme complex [19]. This process provides an important biological source of nitrogen in nonleguminous cropping systems, thereby reducing dependence on synthetic nitrogen fertilizers. The eficiency of nitrogen fixation is influenced by soil organic matter, pH, temperature, moisture, and the availability of micronutrients such as molybdenum and iron, which are essential cofactors for nitrogenase activity [20].

Beyond nitrogen fixation, Azotobacter synthesizes a wide range of bioactive compounds, including vitamins (B-group vitamins), amino acids, and phytohormones such as *indole-3-acetic acid* (IAA), gibberellins, and cytokinins [21]. These metabolites stimulate root elongation, lateral root formation, and overall plant vigor, leading to enhanced nutrient and water uptake. Some strains also produce exopolysaccharides that improve soil aggregation and water retention, contributing to better soil structure and resilience under drought conditions [22]. Field studies have demonstrated that inoculation with Azotobacter can partially replace synthetic nitrogen fertilizers while improving soil microbial activity and crop productivity. In cereals, vegetables, and horticultural crops, combined application of Azotobacter with reduced nitrogen fertilizer doses has frequently resulted in comparable yields to full fertilizer treatments, along with improvements in soil enzymatic activity and microbial biomass [23]. Such findings highlight the potential of Azotobacter as a key component of integrated nutrient management systems.

Table 1: Functional Characteristics of Major Beneficial Bacteria Used as Bio-Inputs

Bacterial genus	Primary function	Key mechanisms	Agricultural benefits
Azotobacter	Biological nitrogen fixation	Nitrogenase activity, phytohormone production	Improved nitrogen availability and root growth
Bacillus	Phosphorus solubilization and biocontrol	Organic acid secretion, phosphatases, lipopeptides	Enhanced phosphorus uptake and disease suppression
Pseudomonas	Rhizosphere colonization and pathogen suppression	Siderophores, antibiotics, ACC deaminase	Improved plant health and stress tolerance

Table 2: Mechanisms of Nutrient Mobilization by Beneficial Bacteria

Mechanism	Microbial activity	Nutrient affected	Outcome for plants
Nitrogen fixation	Conversion of N_2 to NH_4^+	Nitrogen	Enhanced nitrogen nutrition
Phosphorus solubilization	Release of organic acids and phosphatases	Phosphorus	Greater phosphate availability
Potassium	Weathering of mineral	Potassium	Improved potassium
mobilization	sources		uptake
Siderophore production	Iron chelation and transport	Iron	Better micronutrient acquisition
Phytohormone synthesis	Production of auxins and gibberellins	Indirect nutrient enhancement	Increased root surface area

Table 3: Major Mechanisms of Soil-Borne Pathogen Suppression

Mechanism	Representative bacteria	Target pathogens	Mode of action
Competition for nutrients	*Pseudomonas fluorescens*	*Fusarium oxysporum*	Exclusion from the rhizosphere niche
Antibiotic production	*Pseudomonas fluorescens*	*Rhizoctonia solani*	Inhibition of pathogen growth
Lipopeptide secretion	*Bacillus subtilis*	*Fusarium oxysporum*	Membrane disruption
Lytic enzyme production	*Bacillus*	*Pythium spp.*	Degradation of pathogen cell walls
Induced systemic resistance	*Pseudomonas fluorescens*	*Multiple pathogens*	Activation of plant defense pathways

Table 4: Advantages and Limitations of Microbial Consortia

Aspect	Advantages	Limitations
Nutrient management	Multiple nutrients mobilized simultaneously	Complex optimization of strains
Disease control	Broader pathogen suppression spectrum	Possible antagonistic interactions
Environmental adaptation	Greater resilience under field conditions	Variable performance across soils
Plant growth promotion	Synergistic enhancement of growth	Higher formulation complexity
Commercial application	Reduced dependence on agrochemicals	Regulatory and quality-control challenges

Bacillus and Phosphorus Solubilization

Many *Bacillus* species are eficient phosphate-solubilizing bacteria that mobilize insoluble phosphate compounds through the secretion of organic acids, including gluconic, citric, oxalic, and lactic acids [24]. These acids lower the pH of the rhizosphere and chelate cations such as calcium, iron, and aluminum that bind phosphate, thereby releasing phosphate ions that can be absorbed by plant roots. Several *Bacillus* strains also produce phosphatase enzymes that mineralize organic phosphorus compounds present in soil organic matter [25]. In addition to nutrient mobilization, *Bacillus* species contribute to plant growth promotion through the production of phytohormones, siderophores, and volatile organic compounds [26]. Their ability to form highly resistant endospores enables survival under extreme temperatures, desiccation, and nutrient-limited conditions, making them particularly valuable for commercial biofertilizer formulations with extended shelf life [27].

Bacillus subtilis and related species are also well known for their biocontrol properties. They produce lipopeptides such as surfactin, iturin, and fengycin, which disrupt the cell membranes of fungal pathogens and inhibit spore germination [28]. Consequently, Bacillusbased products are increasingly used in sustainable agriculture for both nutrient management and disease suppression.

Pseudomonas and Rhizosphere Competence

Pseudomonas species are among the most efective colonizers of the rhizosphere due to their rapid growth, metabolic versatility, and strong chemotactic response to root exudates [29]. Successful colonization enables these bacteria to establish stable associations with plant roots and compete efectively with indigenous microorganisms.

A major mechanism underlying their plant-protective activity is the production of siderophores, which chelate iron and limit its availability to pathogenic microorganisms [30]. Iron deprivation suppresses the growth of many fungal and bacterial pathogens in the rhizosphere. In addition, several *Pseudomonas* strains synthesize antibiotics such as phenazines, pyoluteorin, pyrrolnitrin, and 2,4-diacetylphloroglucinol, all of which exhibit broad-spectrum antimicrobial activity [31].

Pseudomonas fluorescens is particularly important because it can induce systemic resistance in plants by activating defense-related signaling pathways involving jasmonic acid and ethylene [32]. This induced systemic resistance enhances the plant's ability to withstand subsequent pathogen attacks. Furthermore, *Pseudomonas* species often produce ACC deaminase, an enzyme that lowers stress-induced ethylene levels in plants, thereby improving tolerance to drought, salinity, and other abiotic stresses [33].

The ability of *Pseudomonas* to establish persistent root associations and simultaneously promote growth and suppress pathogens makes it highly suitable for long-term disease management strategies in diverse cropping systems.

Mechanisms of Nutrient Mobilization

Beneficial bacteria enhance nutrient availability in the rhizosphere through several interconnected biochemical pathways that improve the eficiency of nutrient acquisition by plants. One of the most important mechanisms is biological nitrogen fixation, in which diazotrophic bacteria convert atmospheric nitrogen (N_2) into ammonium through the activity of the nitrogenase enzyme complex. This process provides a natural source of plant-available nitrogen and reduces the dependence on synthetic nitrogen fertilizers. Free-living and associative nitrogen-fixing bacteria contribute significantly to nitrogen inputs in many agricultural soils, particularly in systems with limited fertilizer application.

Another major mechanism is phosphorus solubilization. Although soils may contain substantial quantities of phosphorus, much of it occurs in insoluble forms that cannot be absorbed by plants. Phosphate-solubilizing bacteria release organic acids and phosphatase enzymes that dissolve mineral phosphates and mineralize organic phosphorus compounds. The resulting increase in soluble phosphate concentration enhances phosphorus uptake by roots and improves plant growth, especially in phosphorus-deficient soils.

Beneficial microorganisms also participate in potassium mobilization by weathering potassium-bearing minerals such as feldspar and mica. Through the secretion of organic acids and chelating compounds, these bacteria release potassium ions into the soil solution, making them accessible to plants. In addition, many rhizobacteria facilitate micronutrient acquisition by producing siderophores, which are high-afinity iron-chelating molecules. Siderophores bind ferric iron and transport it to microbial and plant cells, thereby improving iron availability under conditions where iron is poorly soluble.

A further contribution of beneficial bacteria is root stimulation through phytohormone production. Many plant growth-promoting rhizobacteria synthesize auxins, gibberellins, and cytokinins that stimulate root elongation, lateral root formation, and root hair development. Enhanced root architecture increases the surface area available for nutrient and water absorption. Collectively, these processes improve nutrient uptake eficiency, strengthen plant vigor, and contribute to higher productivity and stress tolerance in crops.

Suppression of Soil-Borne Pathogens

Soil-borne pathogens such as *Fusarium oxysporum*, *Rhizoctonia solani*, and Pythium spp. are responsible for substantial yield losses in many cropping systems worldwide. Beneficial bacteria suppress these pathogens through multiple direct and indirect mechanisms that collectively create a disease-suppressive rhizosphere environment. One important strategy is competition for nutrients and ecological niches. Rapid colonization of root surfaces by beneficial bacteria limits the resources available for pathogen establishment and proliferation. Many rhizobacteria also produce antibiotics and volatile organic compounds that inhibit the growth of fungal and bacterial pathogens. These antimicrobial metabolites interfere with cell membrane integrity, energy metabolism, and spore germination. In addition, beneficial bacteria secrete lytic enzymes, including chitinases, β-1,3-glucanases, and proteases, which degrade structural components of pathogen cell walls and reduce pathogen viability in the rhizosphere. Another critical mechanism is the induction of systemic resistance in host plants. Certain beneficial bacteria activate plant defense signaling pathways, leading to enhanced production of defense-related proteins, phenolic compounds, and reactive oxygen species. This primed defensive state enables plants to respond more rapidly and efectively to subsequent pathogen attacks.

For example, *Bacillus subtilis* produces lipopeptides such as surfactin and fengycin that disrupt fungal cell membranes and inhibit mycelial growth. Similarly, *Pseudomonas fluorescens* induces defense-related pathways in plants and produces antimicrobial metabolites that suppress a wide range of soil-borne pathogens. Through the combined actions of competition, antimicrobial production, enzymatic degradation, and activation of plant immunity, beneficial bacteria provide an efective and environmentally sustainable approach for managing soilborne diseases while simultaneously supporting plant growth and nutrient acquisition.

Microbial Consortia and Synergistic Interactions

Single-strain microbial inoculants often exhibit inconsistent performance under field conditions because environmental factors, soil characteristics, and interactions with indigenous microbial communities can limit their establishment and activity. To overcome these limitations, researchers are increasingly focusing on the development of microbial consortia that combine complementary functional traits. A consortium containing Azotobacter, *Bacillus*, and *Pseudomonas* can simultaneously provide biological nitrogen fixation, phosphorus solubilization, production of plant growth regulators, and suppression of soil-borne pathogens.

Such multifunctional systems more closely resemble natural rhizosphere communities and often perform better than individual strains.

Synergistic interactions among consortium members can improve microbial establishment on plant roots, broaden adaptation to diverse environmental conditions, and enhance overall plant growth promotion. For example, Azotobacter may increase nitrogen availability, while *Bacillus* releases soluble phosphate and *Pseudomonas* suppresses pathogens through antimicrobial metabolite production. These complementary activities can lead to improved nutrient uptake, stronger root development, and greater resilience against biotic and abiotic stresses. Nevertheless, compatibility among strains must be carefully evaluated because antagonistic interactions, such as competition for nutrients or production of inhibitory compounds, can reduce consortium efectiveness. Proper selection of compatible strains and optimization of inoculum ratios are therefore critical for successful consortium design.

Formulation and Delivery Technologies

The efectiveness of microbial bio-inputs depends not only on the selected strains but also on the formulation and delivery technology used to introduce them into the plant environment. One widely adopted approach is seed coating, in which microbial formulations are directly applied to seeds to ensure early root colonization immediately after germination. Granular formulations provide controlled release of microorganisms into the rhizosphere and are particularly useful for field crops where prolonged microbial activity is desired.

Liquid inoculants ofer ease of application through irrigation systems, fertigation networks, or foliar sprays and allow uniform distribution of microbial cells. Encapsulation technologies, including alginate or polymer-based matrices, protect microbial cells from desiccation, ultraviolet radiation, and other environmental stresses during storage and application. More recently, nano-enabled carriers have emerged as promising delivery systems because they can enhance microbial stability, improve adhesion to roots, and facilitate targeted release in the rhizosphere. Advances in carrier materials and formulation chemistry are significantly improving shelf life, stress tolerance, and field performance of microbial products, thereby increasing their commercial viability.

Challenges in Field Implementation

Despite encouraging results obtained under laboratory and greenhouse conditions, several challenges continue to limit the large-scale adoption of microbial bio-inputs. Environmental variability, including fluctuations in soil pH, temperature, moisture, and nutrient availability, can strongly influence microbial survival and activity. Introduced microorganisms must also compete with established native microbial communities that may restrict their colonization and persistence.

Another major challenge is the reduced survival of microbial cells during storage, transportation, and field application. Inconsistent colonization of plant roots can lead to variable performance across locations and growing seasons. Furthermore, regulatory requirements, quality-control standards, and the need for consistent product eficacy present additional obstacles for commercialization. Addressing these constraints requires improved strain selection, development of robust formulations, optimization of carrier materials, and adoption of site-specific application strategies tailored to local soil and climatic conditions.

Future Perspectives

The future of microbiome engineering is likely to be driven by the integration of metagenomics, transcriptomics, metabolomics, and artificial intelligence to identify highperformance microbial combinations and predict their behavior in diferent agricultural environments. Precision agriculture technologies, including soil sensors, remote sensing, and geospatial mapping, can enable targeted application of bio-inputs based on soil nutrient status, microbial composition, and crop requirements.

Emerging tools such as genome editing and synthetic biology may further enhance beneficial microbial traits, including nitrogen fixation eficiency, phosphorus solubilization capacity, stress tolerance, and antimicrobial production. The development of climate-resilient microbial consortia adapted to drought, salinity, heat, and other environmental extremes will become increasingly important under changing climatic conditions. Future research should also focus on understanding microbial network interactions and designing stable, multifunctional consortia capable of maintaining performance across diverse agroecosystems.

Conclusion

Microbiome engineering represents a transformative strategy for sustainable agriculture by harnessing beneficial bacteria such as *Bacillus*, *Pseudomonas*, and Azotobacter. These microorganisms contribute to nitrogen fixation, phosphorus solubilization, plant growth promotion, and suppression of soil-borne pathogens through diverse biochemical and ecological mechanisms. The development of optimized microbial consortia, advanced formulations, and precision delivery systems has substantially improved the efectiveness of bio-inputs for crop production. Although challenges related to environmental variability, microbial establishment, and product standardization remain, the integration of omics technologies, artificial intelligence, and precision agriculture ofers significant opportunities for the development of next-generation microbial products. Such innovations have the potential to enhance crop productivity, improve soil health, and reduce dependence on synthetic fertilizers and pesticides, thereby contributing to more resilient and environmentally sustainable agricultural systems.

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