Microbial Biotechnology for Soil Health and Plant Nutrition: Mechanisms and Future Prospects

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Abstract

Microbial biotechnology is emerging as a transformative solution for restoring soil health and promoting sustainable agriculture amid escalating climatical challenges. This review explores the integral roles of beneficial microbes, such as nitrogen-fixing bacteria, phosphate- and potassium-solubilizing microorganisms, mycorrhizal fungi, and plant growth-promoting rhizobacteria, in enhancing nutrient cycling, soil fertility, and crop productivity. The microbial interactions in the rhizosphere that promote nutrient uptake, inhibit soil-borne diseases, and increase plant resistance to abiotic stress are disscussed. The review details how microbial consortia, microbial enzymes, and bioinoculants influence soil structure, water retention, and humus formation are contributing to improved soil functionality. It also highlights microbial biofertilizers' application methods, including seed coating and foliar sprays, which reduce dependency on chemical inputs and mitigate environmental degradation. Advanced techniques such as bioremediation, metagenomics, and synthetic biology offer promising avenues for rehabilitating polluted soils and designing crop-specific microbial formulations. Despite proven benefits, field-level challenges including strain viability, environmental adaptability, and regulatory hurdles hinder wide-scale adoption. The review addresses these constraints and suggests solutions through formulation technologies, policy reforms, and farmer education. Future perspectives integrate microbial biotechnology with AI-driven precision agriculture, genome editing tools like CRISPR, and smart delivery systems for enhancing field performance. Collectively, microbial biotechnology stands as a pillar for next-generation agriculture by improving soil health, fostering ecological balance, and enabling food security in a climate-resilient manner.

Keywords: Soil, Plant growth, Microbial biotechnology, Plant nutrition, Sustainable agriculture

Significance | Microbial biotechnology strengthens soil health and plant nutrition by utilizing beneficial microbes, promoting sustainability, reducing chemical inputs, and enhancing crop resilience.

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1. Introduction

Ecosystem stability together with farm productivity relies directly on the condition of soil in the environment. Traditional farming practices caused soil degradation together with nutrient disorders because they rely extensively on chemical pesticides and fertilizers. The use of helpful microbes through microbial biotechnology leads to sustainable soil improvements through better structure development while facilitating nutrient cycling and supporting plant growth and development. This section investigates the

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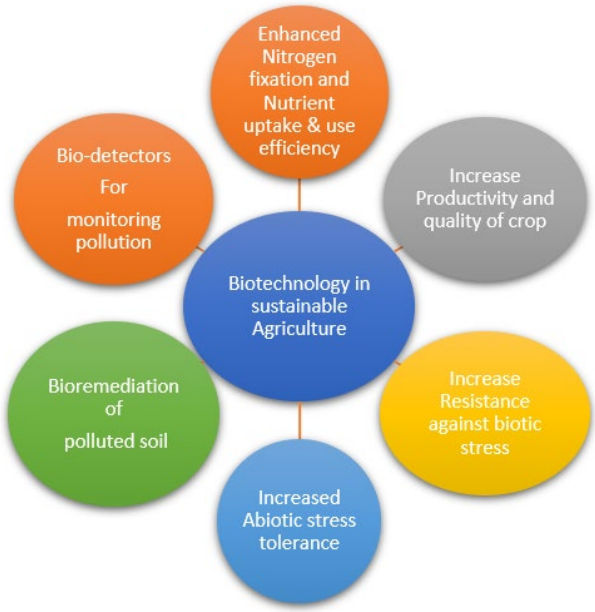

Figure 1. Microbial Biotechnology: A key to sustainable Agriculture

function of microbial biotechnology solutions as they affect plant nutrition together with soil health maintenance. Microbial biotechnology is employed to enhance plant nutrient uptake and improve soil ecosystem health. The growing need for increased food production due to population growth and environmental changes makes microbial biotechnology a practical alternative to produce more soil productivity than chemical pesticide or fertilizer use (Vassilev et al., 2017). Through raising nutrient bioavailability microbial biotechnology improves plant nourishment while reducing synthetic chemical consumption and enabling soil health management through biofertilizers and biocontrol agents as well as other microbial products (Zhao et al., 2020). Lal (2015) defines soil health as the soil's ability to enable plant system growth and fulfill its role within natural environmental systems and ecosystems as an essential living system. Reaction to plant growth occurs in healthy soils through their combined physical, chemical and biological characteristics and their balanced microbial population and biodiversity. Soil processes benefit remarkably from microbial communities, as they develop soil structure through their activities of nutrient cycling, organic matter degradation, and aggregate construction. The purpose of microbial biotechnology is to improve soil bioprocesses through particular strain applications, which activate natural microbial functions (Liu et al., 2016).

Plant development together with soil fertility improvements received recent attention through microbial biotechnology as a promising approach to decrease chemical input impact (Singh et al., 2020). Jacoby et al. (2017) show that the soil functions supported by beneficial microorganisms encompass nutrient cycling through nitrogen-fixing bacteria while mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR) do organic matter breakdown and disease prevention.

The environmental community supports microbial inoculants and biofertilizers as bio-based replacements for synthetic fertilizers because they enhance nutrient supply and reduce environmental contamination (Basu et al., 2021). Microorganisms significantly contribute to soil structural stability by promoting aggregation and enhancing water retention (Glick, 2018). Research advances in microbial genomics and biotechnology allow scientists to identify suitable microbial strains with enhanced solubilization abilities for nutrients and stress tolerance capabilities along with disease protection features as reported by Compant et al. (2019).

Poor microbial presence, inadequate field performance, and legal limitations are the factors to hindering microbial technology. Improved microbial formulations and reliable agricultural system performance require additional research with technological advancements (Vessey2022).

The applications of microbial biotechnology provide critical benefits to plant nutritional requirements significantly (Figure 1). Plant growth requires all essential nutrient categories including minerals, zinc, iron, copper, and essential plant elements nitrogen (N), phosphorus (P), and potassium (K). Soil shows limited availability of these nutrients on many occasions. The cycling of vital components depends heavily on microorganisms through their nitrogen fixation while they also carry out phosphate solubilization and organic matter breakdown and these processes influence nutrient bioavailability (Haas & Défago, 2005). The plant nutrition process includes symbiotic bacteria Rhizobium species which fix nitrogen in legumes together with non-symbiotic

nitrogen-fixing bacteria found in plant roots. The utilization of synthetic fertilizers costs money and requires significant energy consumption and results in environmental harm, thus minimizing their usage (Fendrik et al., 2014).

Rhizosphere microorganisms together with the nearby plant roots, develop complex relationships while also participating in nutrient cycling. The positive plant-health effects occur when bacteria enhance stress resistance and help plant development and protect against diseases through beneficial relationships. Sustainable agriculture has found favor in microbial biocontrol agents particularly Bacillus and Trichoderma strains to defend plants against pesticides while either maintaining plant yields or improving them (Haas & Défago, 2005).

The application of biofertilizers with living microorganisms serves as active nutrient providers in plants showing increased crop growth and yield for different agricultural products (Vassilev et al., 2017). Substantial use of chemical fertilizers with pesticides during traditional farming causes damage to soil structure and reduces biodiversity while generating pollutants that pollute water ecosystems. Soil conditions and sustainable crop production benefit from microbial biotechnology through the utilization of naturally occurring organisms as it forms an environmentally friendly agricultural approach (Bashan et al., 2014).

The dual strength of microbial biotechnology consists of maximizing agricultural output while promoting sustainable farming through complete nutritional support for plants and soil health preservation or recovery. Introducing microbial inoculants as biofertilizers and biocontrol agents offers a way to decrease agricultural environmental effects while reducing dependence on external resources (Schroeder et al., 2016).

The review paper explores microbial biotechnology applications for plant nutrition and soil health with clear details about important microbial functions and usage possibilities and potential growth areas.

2. Soil Microbiome and Its Functions

The stability and health of soil depends on the soil microbiome which encompasses numerous bacterial species together with fungal entities and archaea and other microbial populations. The study conducted by Fierer (2019) demonstrates that soil microbes play an essential role by assisting in disease protection and organic decomposition and nutrient recycling and the formation of soil arrangements. The soil microbiome is a dynamic component of the ecosystem that responds to land-use practices, environmental fluctuations, and soil management strategies (Compant et al., 2019).

The primary role of the soil microbiome includes nutrient cycling because microorganisms transform and prepare essential nutrients such as sulfur, phosphorus and nitrogen. Plants gain access to absorbed nitrogen because Rhizobium among other bacterial genera naturally transform atmospheric nitrogen into assimilable forms (Singh et al., 2021). The soil phosphorus availability increases when Bacillus and Pseudomonas bacteria break down insoluble phosphate compounds present in the soil according to Basu et al., 2021. Sustainable soil fertility management as well as decreasing chemical fertilizer use requires the essential microbial interactions.

New metagenomic and high-throughput sequencing technologies demonstrate that the bulk of the soil microbiome is not only taxonomically diverse but also dynamically varied, with specific functions in plant-initiated immune response regulation and mediation of plant-soil feedback (Kalachova et al., 2023; Wani et al., 2024). The functional genes known for nitrogen metabolism, phosphate solubilization, and secondary metabolism are commonly found in soil microbial communities, which enable the plants to adapt to abiotic stress like drought, salinity, and toxicity of heavy metals (Koza et al., 2022). In addition, keystone taxa such as Burkholderia, Streptomyces, as well as Arthrobacter have been reported as microbial hubs that determine the overall soil microbial stability and resilience of soil through synergistic relationships (D. Liu et al., 2021). These interactions govern the assembly and reassembly of microbial networks under varying environmental conditions, thus making the soil microbiome a powerful, adaptive system that maintains soil multifunctionality and crop productivity under climate-induced pressures (Yang et al., 2023).

2.2 Role of Microbes in Soil Fertility

The ability of soil to uphold plant development alongside productivity depends on its fertility status because sustainable agricultural management depends on it. Various soil elements including nutrient supplies with their association to biological activity and soil structural elements contribute to fertility status. Soil microbes play a vital role in maintaining fertility by improving nutrient availability and enhancing soil quality. Soil fertility receives significant effects from three major microbial groups known as bacteria, fungi, and actinomycetes says Schroeder et al. (2016).

Soil microbes play an important role in soil fertility; this is achieved when soil microbes regulate the availability of essential nutrients through soil enzymatic activities ("Soil Enzyme Activities and Soil Fertility Dynamics," 2012). Certain microbial enzymes which are critical in transforming organic matter into more accessible forms by plants include the phosphatases, dehydrogenases, and ureases. For example, the phosphate-solubilizing bacteria produce organic acids which liberate the insoluble phosphates to be available to the crop. Likewise, bacteria that fix nitrogen including Rhizobium and free-living Azotobacter contribute to the thickness of the nitrogen pool in the soil, which does not require artificial fertilizer to accomplish. These processes do not only maintain the productivity of the soil in the long term, but also limit dependence on external inputs of agrochemicals (Nosrati et al., 2014; Yadav & Smritikana Sarkar, 2019).

Besides the transformation of nutrients, microbes enhance the soil fertility by organic matter and forming humus. Saprophytic fungi decompose complex organic polymers, like lignin or cellulose, converting them to nutrients at a low rate, which improves soil structure (Kögel-Knabner, 2002; Nivethadevi et al., 2021). The decomposition products of microbial nature also play a role in enhancing the development of humic substances, that enhance cation exchange capacity and water holding in soils (Vrábl et al., 2025). Moreover, (Vrábl et al., 2025) shows the contact of microbes to the root surfaces of the plants, e.g., formation of mycorrhizal types of association, increases the rate of root surface area and intensity of nutrient assimilation, mostly, decreased phosphorus soils. Therefore, a diverse and active microbial community is essential for sustaining and improving soil fertility.

2.3 Improving Soil Structure

The fertility of soil directly relies on soil structure because it regulates air circulation and water entry and root advancement together with nutrient storage. By creating aggregates microbes boost soil stability along with enhancing soil porosity to improve the structure of the soil. Soil particles join together into aggregates because of the combination of microorganisms and organic materials as well as their secretions. The passing of both air and water occurrences through soil results from these soil aggregates.

Microorganisms also help in soil structure improvement, biologically stimulated and root-microbe interactions help develop and bond micro- and macro-aggregates. As microbes colonize the rhizosphere they enhance the growth of fine root hairs and root exudation which subsequently results in microenvironments due to which aggregates can be formed (Chen & Liu, 2024; Ma et al., 2022). There are some micro Microbial groups that have indirect effects on soil architecture, including actinomycetes and arbuscular mycorrhiza fungi (altering the chemical environment and encouraging the deposition of mineral particles surrounding roots) (H. Liu et al., 2021). Also, the interactions of the microbes encourage the formation of soil microhabitats that encourage biodiversity and improves structural heterogeneity. The change enhances the physical quality of soil which facilitates in the sense that improved anchorage of plants, water holding capacity and degradation resistance (Pot et al., 2022).

Soil bacteria generate externally produced polysaccharides that link particles together to form soil aggregates. Soil structure becomes better through microbial exudates which lets plants grow deeper roots while keeping water in and raising overall soil fertility (Bashan et al., 2014). These microbes enable plant development while enhancing nutrient uptake by improving both the physical characteristics and the development of plants.

2.4 Suppressing Plant Pathogens and Enhancing Soil Health

The microbial community of soil enhances both disease suppression in soil and overall soil health. The harmful bacteria limit the absorption of nutrients in addition to harming plants thus leading to decreased soil fertility. Helpful microorganisms protect plants from illnesses by doing active work to challenge pathogenic intruders and block their effect on plant development.

Symbiotic soil microbes in turn extend a form of natural soil-based defense mechanisms to soil-borne plant pathogens since they occupy space, nutrients and ecological niches in the rhizosphere (Minchev et al., 2021). Dangerous pathogens are directly repressed by using methods like those of antibiosis, whereby microorganisms synthesize antimicrobial compounds (e.g., antibiotics, hydrogen cyanide, and lytic enzymes) (Chinemerem Nwobodo et al., 2022). Mycoparasites Such as Trichoderma spp. and Pseudomonas are well-known for their ability to inhibit fungal pathogens through mycoparasitism and secretion of antifungal metabolites. Such interactions not only decrease the pressure of the disease but also decrease the requirements of chemical pesticides, approaching the plant protection sustainability (Ferreira & Musumeci, 2021; Poveda, 2021).

In addition to pathogen control, a diverse and alive microbial community is directly related to general soil health. Plant immune system. During the preceding microbe-induced growth promotion phase, beneficial microbes modify plant immune system responses through induced systemic resistance (ISR); this makes the plants better prepared to resist biotic and abiotic stresses (Yu et al., 2022). In addition, the biological buffering capacity of the soil increases with an increase in microbial diversity thus restoring the soil faster after it has been disturbed in forms like heavy metal contamination or salinization. Bidirectional interactions between plants and microbes shore up root networks, result in balanced soil nutrients, and help create biologically active soil conditions that facilitate sustainable crop productivity and ecological stability (Mao et al., 2022).

2.4.1 Biological Control Agents

Plant diseases are inhibited through the use of biological agents including Bacillus spp. bacteria and Trichoderma spp. fungi (Haas & Défago, 2005). These microbial entities terminate dangerous plant diseases through their combinations of antimicrobial chemical production and nutrient and space competition. Crops receive increased soil fertility through two microbial functions including disease pathogen reduction which promotes a balanced soil environment that enables plant growth.

Biological control agents (BCAs) are chosen microorganisms being deposited in the soil ecosystem to handle plant diseases by acting precisely on certain pathogens instead of detrimental microbial communities. Unlike broad-spectrum chemical treatments, BCAs include Bacillus subtilis, Streptomyces spp., and some non-pathogenic common Fusarium, which are specific and have their own mechanisms of action, inhibiting quorum sensing, competing on root exudates coupled with disruption of pathogen signaling.

(Pacios-Michelena et al., 2021) These agents can be applied as seed coatings, soil drenches, or compost inoculants, offering targeted disease suppression with minimal environmental impact (Zhang et al., 2022). Furthermore, Rao et al. (2025) demonstrated that developments in microbial formulation activities, including microcapsulation and biofilm-based suppliers, have enhanced the shelf-life and field efficacy of BCAs and this development makes BCAs a potential part of the wider disease management techniques.

2.4.2 Soil Health

A well-graded microbial population in the soil requires balanced distribution with diverse types for optimal health to be maintained. Multiple types of microbes working together preserve soil quality by allowing the use of organic material additives and crop sequencing along with reduced chemical pesticide usage (Hassan et al., 2017).

Furthermore, microbial diversity, functional redundancy of microbial communities is critically important to ensure the functional robustness in response to changing environmental dynamics. Despite the stress that may cause the decline of a specific group of microbes (e.g., drought or exposure to a chemical), very similar functional microbes can be substituted, and essential processes such as nutrient cycling or organic matter breakdown can carry on (Philippot et al., 2021). This resilience is also enhanced by conservation practices which include minimum tillage, organic amendments and cover cropping which enhances microbial habitats and stabilizes microbial networks. The result of such practices is not just biological balancing, but an increase in the adaptive capacity of soil which spells to the prolonged productivity and ecological harmony (Crystal-Ornelas et al., 2021).

2.5 Microbial Fertilizers and Bioinoculants

Research today seems to focus on microbial fertilizers along with bioinoculants when society seeks alternative sustainable alternatives to chemical fertilizers. Soil development along with increased fertility and better nutrient access occurs through the addition of live microbes to the soil by these products. The major microbial fertilizers consist of mycorrhizal fungi together with phosphorus-solubilizing bacteria and nitrogen-fixing bacteria according to Vassilev et al., (2017). Bioinoculants enable significant reductions in usage of harmful chemical fertilizers thus protecting environmental and soil health. Scientific evidence proves that including microbial fertilizers enhances both land health and supports lasting agricultural practices.

Recent experiments in microbial biotechnology over the last few years has resulted in the developments of crop- and soil-specific bioinoculant which are responsible to enhance uptake of nutrients and plant rigidity (Massa et al., 2022; "Microbial Diversity and Multifunctional Microbial Biostimulants for Agricultural Sustainability," 2021). Such compositions usually consist of partnerships of synergistic microorganisms that not only increase the availability of macro-nutrients, but they also produce substances that promote the growth of plants like indole-3-acetic acid (IAA), siderophores which involve in stimulation of root-development enzymes (Devi et al., 2024). Experiments conducted in the field have revealed that these bioinoculants are able to enhance crop yield, especially in soils that lack nutrients and are subjected to stress, as a result of restoration of microbial balance and increase biological activities (Benmrid et al., 2023). Consequently, they are becoming incorporated in the precision agriculture platforms to enhance the low-input, high-efficiency models of agriculture that are geared towards achieving the sustainability targets worldwide.

3. Bioremediation and Soil Restoration Practices

3.1 Bioremediation

The use of living organisms to reduce or eliminate contaminants from the environment, especially from contaminated soils, is known as bioremediation. Compared to more conventional approaches to pollution control, including chemical treatments or excavation, this procedure is more economical and ecologically benign (Ramos et al., 2004). Conversely, soil restoration describes methods intended to improve the fertility, structure, and overall health of damaged soils. Since bioremediation is frequently used to detoxify contaminated soils and speed up the restoration process, the two ideas overlap.

Several methods that use organisms like bacteria, fungi, and plants to remove contaminants are referred to as bioremediation. Microbial bioremediation, in which organic pollutants like hydrocarbons, insecticides, and solvents are broken down by microorganisms like bacteria or fungi, is one of the most widely utilized techniques (Gadd, 2001). While mycoremediation uses fungi to break down organic contaminants, phytoremediation uses plants to absorb, accumulate, or detoxify toxins from the soil (Baldwin et al., 1996). Every technique targets distinct contaminants, and the organisms used depend on the kind of contaminant and the site's environmental circumstances.

Cost-effectiveness, sustainability, and environmental compatibility are among bioremediation's main advantages. Bioremediation is typically less expensive than previous techniques and use natural processes to restore the environment over the long term (Gadd, 2001). Oil spills, industrial regions, and agricultural sites are frequently cleaned with this technique (Vance et al., 2003).

3.2 Soil restoration practices

The goal of soil restoration techniques is to restore deteriorated soils caused by pollution, erosion, or inadequate land management. Enhancing soil fertility, structure, and microbiological health is the goal of these techniques. Replanting plants to stop erosion, using cover crops to replenish soil nutrients, and adding organic matter

through compost or manure are other techniques (Lal, 2004). The restoration of soil requires the improvement of soil environment and texture. The methods of Tillage and deep plowing help decrease soil compaction and strengthen plant growth according to Steinberger et al. (2005). When inoculating soil with mycorrhizal fungi one can enhance plant nutrient uptake through beneficial root interactions thus improving total soil health (Smith & Read, 2008).

3.3 Integration of Bioremediation in Soil Restoration

Soil restoration receives substantial benefits from bioremediation because this process removes restrictions that impede plant growth. Soil conditions suitable for plant recolonization become possible through microbial or phytoremediation processes that resolve heavy metal and organic pollutant contaminations (Ramos et al., 2004). After bioremediation techniques soil quality can be advanced through methods of erosion management combined with the application of organic materials in order to build enduring soil health while recovering natural ecosystems

The concept of bioremediation incorporated into the process of soil restoration also facilitates re-establishment of microbial diversity and functional activity that are vital in long-term recovery of the ecosystem ("Bioremediation Approaches for Soil and Aquatic Environmental Restoration to Revive Ecosystems," 2025). The microorganisms that participate in bioremediation (indigenous ones and those that are introduced) do not only degrade pollutants, but they also restart the formation of the soil microbial colonies, a significant concern making the nutrient cycling and organic matter stabilization. With microbial communities re-establishing, they aided populating of vegetation, root-soil interaction increased and rebuilding of soil structure and fertility (P. Liu et al., 2025; Yousuf et al., 2022). This integrated model does not only clean polluted soils but also provides a biologically active background of long-term land use, and rehabilitation of the degraded landscapes.

4. Microbial Contributions to Plant Nutrition

The nutritional needs of plants greatly depend on microorganisms because they enhance access to nutrients and their absorption and recycling processes thus promoting plant growth cycles. The soil's bacteria together with fungus along with actinomycetes create plant partnerships that secure iron and zinc micronutrients plus vital elements of potassium and phosphorus and nitrogen (Bais et al., 2004). Plants receive necessary help from their symbiotic relationships and particularly need these among nutrient-deficient soils.

Microbial biotechnology plays a crucial role in enhancing the nutrient content of the soil, and hence sustainability of plants growth and soil fertility. Nitrogen-fixing organisms, one of the helpful microorganisms, convert atmospheric nitrogen into a usable form that facilitates soil nitrogen. The presence of mycorrhizal fungi increases surface areas over which absorption of nutrients and water, in particular phosphorus and other essential micronutrients can occur (Basu et al., 2021). Moreover, phosphate and potassium solubilizing bacteria help in converting the insoluble mineral forms into a readily absorbable form of nutrients thereby improving plant nutrition. All these microbial activities lead to decomposition of organic matter, the formation of soil aggregates, and improve the physical and chemical characteristics of soil, which is crucial to the maintenance of soil health and production (R. Sharma et al., 2024; Wang et al., 2022).

In addition to providing nutrients, microbial biofertilizers are significant in managing and regulating diseases. The beneficial microbes such as plant growth-promoting rhizobacteria (PGPR) and some beneficial microbes produce phytohormones, siderophores, and antimicrobial compounds that trigger the systemic resistance towards soil borne diseases (Nerling et al., 2022; Shahwar et al., 2023). This is a biological control which reduces the dependency on man-made pesticides and thus reduces environmental contamination as well as protects the soil biodiversity (Sulaiman & Bello, 2024). The microbial inoculants enhance plant vigor and promote resistance to biotic stresses by triggering the plant own immune system which establishes a stronger crop environment that supports sustainable agricultural production (U. C. Sharma et al., 2022).

The resilience of microbial community is a crucial response that ensures resilience of soil ecosystems under pressure and in agricultural interventions. Communities of soil microbes promote biotic resistance to environmental change by maintaining biodiversity and redundancy of functions (Kumari et al., 2023). Stable microbial communities are able to recover stable processes caused by intensive farm practices, chemicals, and climate changes; therefore, continuous nutrient cycling and soil energy is maintained. Innovations in microbial biotechnology aim to make biofertilizers more viable and have a longer shelf-life and field performance; however, barriers still lie in formulation, shelf-life, and field efficacy. Research into encapsulation technologies, nano-carriers, and slow-release delivery systems is very important in order to enhance microbial robustness as well as tapping in more into their long-term benefits in agriculture (Mehmood et al., 2025; Velloso et al., 2024).

4.1 Nitrogen Fixation

Nitrogen fixation functions as the key microbial plant nourishment mechanism since certain bacteria turn atmospheric nitrogen (N_2) into ammonia (NH_3) plants can consume. The most famous nitrogen-fixing bacteria exist between Rhizobia species and leguminous plants (Beck et al., 1997). Plant growth and productivity benefit from bacterial microbial populations that reside inside legume plant root nodules where they convert atmospheric nitrogen into forms plants are able to accept.

The soil receives additional nitrogen from free-living bacteria including Clostridium and Azotobacter despite the lack of plant root systems according to Dilworth (1993). The practice functions to generate fertile regions by mitigating the requirement for commercial nitrogenous fertilizers.

4.2 Phosphate Solubilization

Plants require phosphorus as a vital nutrient but they cannot use the abundant form of phosphorus present in many soil environments. The availability of phosphorus depends mostly on various soil microbial communities yet mycorrhizal fungi and phosphate solubilizing bacteria (PSB) play the most significant role. Insoluble substances release phosphate ions when PSB create organic acids that lower rhizosphere acidity (Khan et al., 2007). Through their expansive hyphal expansion into soil and exploring unavailable phosphorus forms plant roots cannot acquire arbuscular mycorrhizal fungi (AMF) provide better phosphorus uptake to their host plants (Smith & Read, 2008).

4.3 Potassium Mobilization

Osmotic regulation together with enzymatic activation relies on potassium as a macronutrient for plant operation. Plant roots show poor capability to absorb potassium even though measured amounts exist in soil environments. Through the release of organic acids and additional substances the microorganisms convert solid potassium forms into soluble compounds which enhances potassium accessibility to plants. Plants require potassium transformation through KSB bacteria like Bacillus and Pseudomonas because soils containing low potassium levels prevent them from using insoluble potassium effectively (Liu et al., 2006).

4.4 Nutrient Cycling and Plant Growth Promotion

The cycle of all soil nutrients heavily depends on microbial processes in addition to making key nutrients accessible. Plants can obtain essential nutrients through the breakdown process of organic matter which produces multiple elements for absorption. Plants grow better because microbes produce the plant growth-promoting hormones known as PGPH which improve the root development process and enhance nutrient absorption. Hormones like auxins gibberellins among others fall under this category (Glick, 2012). The Bacillus and Pseudomonas species help protect plants first through antimicrobial chemical production or second by hormonally stimulating growth in two distinct ways.

In addition to hormonal stimulation and antimicrobial activity, microbes make significant contribution to the nutrient cycle by mobilizing other unavailable nutrients in a process via solubilization and mineralization (Timofeeva et al., 2023). In a given example, phosphate-solubilizing microorganisms will produce organic acids that will liberate insoluble phosphates into forms that can be easily absorbed by plants and the sulfur-oxidizing bacteria which will help in the conversion of elemental sulfur to sulfates (Li et al., 2023). In addition, Pallucchini, 2023) analyzed the data in his latest publication that some diazotrophic bacteria other than just the nitrogen fixation to the atmosphere also replenish the rhizosphere with some amino acids and vitamins that aid the vigor of the plants. The presence of these microbial actions not only guarantees a constant supply of nutrients but will also enhance soil quality and soil structure gradually, which will lead to the development of sustainable plant growth in various environmental circumstances (Hartmann & Six, 2023).

4.5 Micronutrient Acquisition

A group of microbes possesses fundamental functions by facilitating the absorption of essential plant micronutrients including iron manganese zinc and copper. Plants get access to iron through siderophores created by Pseudomonas species as well as various iron-chelating bacteria (Schwyn & Neilands, 1987). The essential function of mycorrhizal fungi lies in their role of micronutrient acquisition particularly in mineral-poor soils that lack available nutrients or have elements bound in insoluble structures.

4.6 Decomposition of Organic Matter

The decomposition process of all organic materials ranging from deceased plant remains through animal excrement and additional organic substances becomes possible because of microorganisms. The breakdown of organic matter by soil bacteria, fungi and actinomycetes generates humus as a nutrient-rich compound that improves soil structure. The breakdown of organic matter creates different types of plant-available nutrients which include potassium and phosphorus and nitrogen (Schroeder et al., 2016). Soil fertility together with nutrient cycles depends on microbial decomposition for long-term existence.

5. Microbial Biofertilizers and Their Applications

The use of living microorganisms called microbial biofertilizers enhances soil resources and supports plant growth and enhances the ecological conditions of soil (Table 1). The biological fertilizers function as an eco-friendly and sustainable replacement for chemical fertilizers in modern agricultural systems. Microbial biofertilizers perform through many biological mechanisms, including nitrogen fixation, solubilization of phosphate and potassium, mineralization of organic matter, and enhancement of plant development through phytohormone synthesis. These advantageous microorganisms—comprising nitrogen-fixing bacteria (e.g., Rhizobium, Azotobacter), cyanobacteria (such as Anabaena, Nostoc), phosphate and zinc-solubilizing bacteria, mycorrhizal fungi, and diverse plant growth-promoting rhizobacteria—either directly provide essential nutrients or improve plants' nutrient absorption by transforming unavailable forms into bioavailable ones and enhancing soil structure. Moreover, several microbial biofertilizers promote systemic

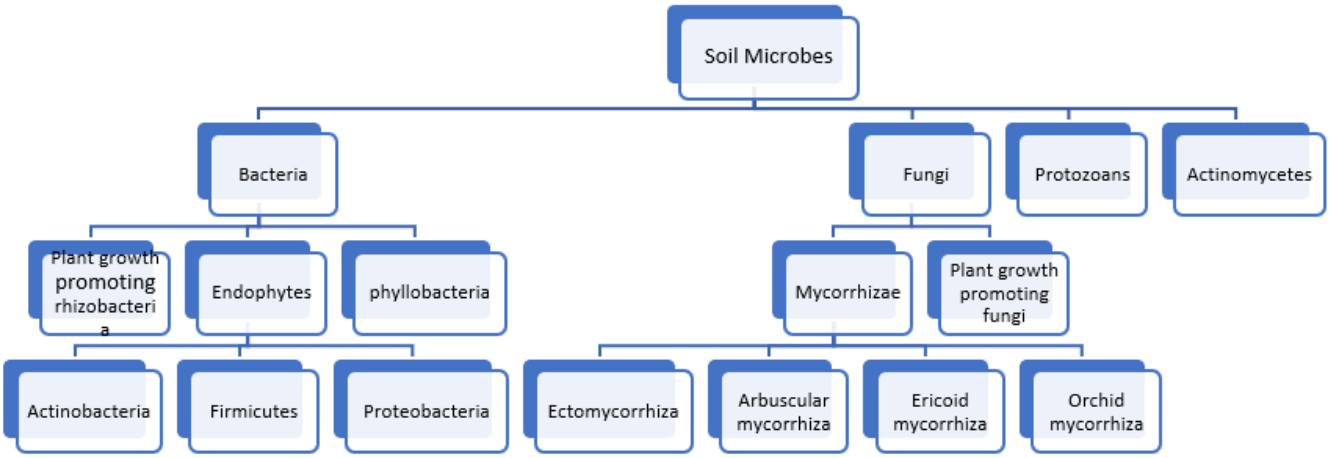

Figure 2. Classification of Soil Microbes Involved in Microbial Biotechnology.

resistance to soil-borne diseases and enhance overall soil health by sustaining balanced microbial communities. Their use can enhance crop output, promote sustainable farming practices, and significantly lessen reliance on chemical fertilizers, as shown by the variety of categories and their mechanism in Table 1.

5.1 Types of Microbial Biofertilizers

Nitrogen-Fixing Bacteria

Azotobacter along with Azospirillum and Rhizobium microbes transform atmospheric nitrogen (N_2) into ammonia (NH_3) while plants absorb this substance. The nitrogen fixation process fulfills plant nutrient requirements since it reduces the need for manufactured artificial nitrogen fertilizers (Glick, 2012).

Phosphorus-Solubilizing Microorganisms (PSM)

The soil contains insoluble phosphorus molecules which alongside Bacillus Pseudomonas and mycorrhizal fungi and several other microorganisms help transform into soluble forms that are usable by plants. The requirement of phosphorus for root development and energy transfer exists yet many soils contain insufficient phosphorus (Khan et al., 2007).

Mycorrhizal Fungi

Plant roots form symbiotic relationships with Glomus species which belong to the arbuscular mycorrhizal fungus (AMF) groups to expand their root systems while increasing nutrient absorption including micronutrients, phosphorus, and nitrogen. The connection between plants and stress resistance to drought and salinity conditions improves because of these mutual relationships (Smith & Read, 2008).

Plant Growth-Promoting Rhizobacteria (PGPR)

The beneficial bacteria designated as PGPR use their capacity to produce auxins and cytokinins together with their capacity to enhance nutrient supplies and suppress microbial plant pathogens to support crop development. The beneficial microbial species Azospirillum and Bacillus together with Pseudomonas form part of this group (Bais et al., 2004).

5.2 Applications of Microbial Biofertilizers

Agricultural Soil Enrichment

Unique soil benefits derive from microbial biofertilizers because they enhance the release of essential elements which strengthen soil fertility (Figure 2). Biofertilizers have the potential to decrease chemical fertilizer usage because they protect environmentally damaging water pollution and soil acidification (Rai, 2008). Legume soil inoculated with Rhizobium increases nitrogen availability while Bacillus species transform soil phosphorus into a more accessible form for plants.

Sustainable Agriculture

These biological fertilizers align with lasting agricultural practices because they enhance yield production while minimizing chemical usage and preserving soil condition using natural resources (Vessey, 2003). The soil structure and drought-related plant stress can be reduced by PGPR strains when farmers increase organic matter content in soil.

Seed Coating and Foliar Application

Microbial biofertilizers are normally used by spraying foliage or coating seeds. Seedlings receive early beneficial bacterial symbiosis through the application of Azospirillum nitrogen-fixing bacteria that enhances their early development. The topical application of Pseudomonas species and other useful bacteria helps plants absorb nutrients when they need them most (Kloepper et al., 1980).

Improved Crop Yield and Quality

Multiple studies establish microbial biofertilizers as leading factors to enhance crop quality and harvest quantities. Agroforestry crops along with horticultural plants show better yield through AMF

Table 1. Significant types of microbial biofertilizers, their modes of action, representative genera, and plant nutrients or advantages.

Type/Key Microbe	Mechanism(s) of Action	Key Examples	Target Nutrient(s)/Benefit
Nitrogen-fixing Bacteria	Convert atmospheric nitrogen (N_2) into ammonia usable by plants (biological N-fixation)	*Rhizobium, Azotobacter, Azospirillum, Frankia*	Nitrogen enrichment
Cyanobacterial Biofertilizers	Photosynthetic N-fixation; symbiotic or free-living in aquatic/wet soils	*Anabaena, Nostoc Blue-green algae, Azolla*	Nitrogen enrichment (mostly for rice)
Phosphate-solubilizing Microbes	Solubilize/convert insoluble phosphorus into bioavailable forms via acid/enzyme production	*Bacillus, Pseudomonas, Aspergillus, Penicillium*	Phosphorus bioavailability
Phosphate-mobilizing Microbes	Mobilize soluble and organic phosphorus, release phosphatases, organic acids, and interact with AMF	*Bacillus, Pseudomonas, Rhizobium, AMF fungi*	Phosphorus transport & uptake
Potassium-solubilizing Microbes	Solubilize potassium from soil minerals via acids/enzymes, make K+ available to plants	*Bacillus mucilaginosus, Frateuria aurantia*	Potassium availability
Mycorrhizal Fungi (AMF/VAM)	Symbiotic association with roots, increase surface area for nutrient & water uptake, stress tolerance	*Glomus spp., Acaulospora spp., Paraglomus spp.*	Phosphorus, micronutrients, stress reduction
Plant Growth Promoting Rhizobacteria (PGPR)	Produce phytohormones (IAA, gibberellins), siderophores, vitamins; induce systemic resistance (ISR)	*Pseudomonas, Bacillus, Serratia, Streptomyces*	Multi-nutrient, disease resistance
Sulfur-solubilizing Microbes	Oxidize/sulfurize minerals to supply plant-available sulfur	*Thiobacillus spp.*	Sulfur supply and soil structure
Zinc-solubilizing Bacteria	Solubilize unavailable zinc compounds to plant accessible zinc	*Bacillus spp., Pseudomonas spp.*	Zinc bioavailability

applications because AMF enhances nutrient absorption which results in superior crop growth (Gianinazzi et al., 2010).

6. The progress of Microbial Biotechnology meets several difficulties and technological constraints in its path of development

Extensive usage of microbial biofertilizers remains limited due to manufacturing and strain selections as well as inconsistent environmental results. Further research needs to be conducted to uncover superior microbial strains along with cheaper methods of application and better formulation development (Rai, 2008). Farmers need to receive detailed education regarding biofertilizers advantages for sustainable farming and learn appropriate techniques to handle inoculants. Through microbial biotechnology multiple industries improved their operations by using beneficial microorganisms in agricultural and environmental sectors as well as healthcare management. Limitations within microbial biotechnology applications constrain its potential to reach its maximum achievement level. Biological and technical performance limits and regulatory framework requirements together with environmental factors affect microbial biotechnology operations.

The survivability and adaptability of the introduced microbial strains to various fields in different conditions are one of the major biological challenges. When native soil microbial communities prevailed over introduced inoculants, they minimized their effectiveness and survival in rhizosphere (Mawarda et al., 2022; Zhao et al., 2024). Also, the variables including soil pH, temperature, moisture, and diversity of microbes present can play significant roles in determining the success of applications of microbial biotechnology. The inoculant tailing factor to specific agroecological regions and, above all, developing stress-tolerant and strong strains that will be consistent field performers are still major areas of research to be addressed in the future (X. Liu et al., 2022; Yahya et al., 2023).

From a technological standpoint, the lack of advanced delivery systems and scalable production techniques further hampers the widespread adoption of microbial biotechnology (Elazzazy et al., 2025). A large number of bioformulations possess limited shelf-life, need a particular storage environment, or are very susceptible to deterioration as soon as used in the field (Khan et al., 2023). Advancements to formulation technologies, e.g., encapsulation, nano-carriers, and slow-release delivery mechanisms, are required to boost the microbial viability and efficiency (Kant et al., 2025). Besides, there is no uniformity in terms of quality control, and there is no uniformity in terms of the regulatory approval processes in most countries, which is an added challenge to commercial development and accessibility on the part of the farmers. Microbial biotechnology will also need interdisciplinary research as well as supportive policy frameworks to unlock its potential by addressing the challenges.

6.1 Biological and Environmental Constraints/Challenges

Microbial Adaptability and Stability

Using microbes in biotechnology presents researchers with the main difficulty they encounter due to microorganisms' cellular adaptations. Industrial microbes become ineffective since they show high sensitivity to temperature alongside changes in salinity levels, as well as pH and moisture conditions (Nakamura et al., 2009). Culture stability issues present themselves during some microbial system operations. The useful characteristics of strains tend to decline with each passing year and as manufacturing conditions deteriorate (Reddy et al., 2012).

Competition with Native Microbial Communities

The process of microbial genetic modification, together with non-native microbial strains leads to competition after operators conduct releases into native microbial communities of environmental areas or agricultural sites. Native bacteria reduce the efficiency and durability of imported strains because they outcompete foreign bacteria successfully (Pimentel 2005). Special attention must be given to choosing biofertilizers and bioremediation agents because foreign microbes sometimes fail to produce desired outcomes in particular uses.

6.2 Technological and Economic Challenges

High Production Costs

Complex and expensive technological systems represent a requirement for industrial microorganism product manufacturing. The manufacturing process of large microbial production levels remains expensive because it involves the challenges of maintaining sterile conditions and overall optimization (Sharma et al., 2011). The expenses for microbial biotechnology product manufacturing surpass those of chemical products for enzymes along with biofuels and medications.

Scale-Up Challenges

It becomes difficult to sustain microbial performance and consistent product output when producing at industrial-scale facilities through both economic and technological means. The commercial manufacture of microbial biotechnology products experiences significant hurdles when adopting production models developed in laboratory settings. Laboratory-scale systems that perform well typically deal with scale-up obstacles from issues regarding bioreactor mass transfer together with problems of oxygen supply and nutrient delivery (Karvinen et al., 2009).

6.3 Regulatory and Ethical Concerns

Regulatory Approval

Biotechnology applications that utilize genetically modified microorganisms (GMMs) encounter significant regulatory challenges during approval processes. The approval process for environmental deployment together with agricultural use or medical utilization of genetically modified microorganisms (GMMs), becomes very complex. The process of acquiring commercial authorization demands complete safety data and long-term results together with environmental impact information about these organisms from both governments and regulatory agencies (WHO, 2004). The present situation might result in extended delays throughout the development and commercialization stages of microbial biotechnology products.

Public Perception and Ethical Issues

Public acceptance of these technologies remains limited since people continue to question genetic modification ethics together with microorganisms' safety characteristics for biotechnological applications. Regulatory approvals together with market approval processes risk prolonged delays because the public demonstrates worries about uncharacterized adverse effects like environmental harm and genetic material transfer (Rivette & Wilke, 2005).

6.4 Limited Application Scope

Narrow Range of Target Organisms

Microbial biotechnology practices demonstrate success through pharmaceutical production and bioremediation methods but they operate exclusively with specific microbial species and environmental environments. Bioremediation by microorganisms fails to work on various environmental pollutants and on those hard-to-treat substances that stay persistent (Gadd, 2001). The development of microbial biofertilizers faces obstacles during specific agricultural stages because beneficial plant microbe partnerships do not deliver efficient results across complete agricultural regions (Kloepper et al., 2004).

Resistance Development

A wide-scale application of biopesticides and biofertilizers leads to resistance development in the same manner that antibiotics demonstrate resistance. Repelling microorganism defense mechanisms facilitate the creation of processes which lead to a diminution of biotechnological treatment effectiveness over time

(Reddy et al., 2012). The continuous use of biopesticides leads to pesticide-resistant pest strains becoming a major challenge for pest management operations.

6.5 Unintended Environmental Impact

Ecological Disruption

The irregular release of modified microbes aimed for bioremediation and biofertilization can generate environmental perturbations. Some microbes can produce adverse effects on unidentified organisms and create functional changes to regular microbial ecological systems. Pimentel (2005) states that the water ecosystems and soil environments cannot determine the impacts of bioremediation on modified microbes. Scientists should prioritize the evaluation and monitoring of these creatures' extended ecosystem effects even though conducting this research is hard to accomplish.

Gene Flow and Horizontal Gene Transfer

Enzymes yet to undergo modification in nature can pick up altered characteristics from engineered microbes since engineered microbes maintain the ability to share their genetic material with native strains. Genes will freely spread throughout native organisms because of this leading to antibiotic resistance alongside adoption of additional genetically modified traits (Glick, 2012).

7. Future Directions in Microbial Biotechnology

The potential of microbial biotechnology in the future in terms of global challenges appears to be enormous in terms of food security, environmental sustainability, and climate resilience. Due to the high development rate in the field of genomics, metagenomics, and synthetic biology, scientists gained a possibility to investigate unprecedentedly rich soil microbiomes. These tools can be used to identify new microbial species and functional genes that cycle nutrients, tolerate stress and promote plant growth, allowing for the development of next-generation biofertilizers and biopesticides tailored to specific crops and environments.

It has been shown in recent studies that microbial consortia, i.e. combination of complementary microbes, contribute effectively to soil health, to increased crop yields and to resistance to various stresses, drought, salinity, and pathogens. The technology of precision agriculture is also incorporating microbial biotechnology through sensors, AI- datasets and modeling to provide a real-time understanding of inoculant application according to soil and plants conditions. The purpose of such technologies is to lower the cost of input, lessening environmental effects, and maximizing production.

Moreover, the future research is focusing on plant-microbe signaling pathways and the possibility of modifying the rhizosphere interactions towards better symbiosis. Genome editing applications in common higher organisms, such as the CRISPR-Cas system currently also being utilized to edit microbial genomes to improve functional traits and biocontrol abilities. An interest also exists in using endophytic microbes, those found inside the plants, to help them long-term with protection and growth promotion, particularly long-term in perennial crops and in forest ecosystems.

In order to achieve maximum benefits of these innovations, there will be a need to cooperate among academia, the industry and government agencies. Research funding policies, biosafety regulations, and educating the farmers are some of the policies that will be of great significance in bringing laboratory discoveries into field-ready solutions. As global society is transitioning toward carbon-smart farming and regenerative food production, microbial biotechnology will serve as a foundational pillar in reshaping sustainable food systems and restoring ecological balance in degraded landscapes.

8. Conclusion

Microbial biotechnology has become a radical solution to increase soil fertility, spur up plant growth and restoring the degraded ecosystems in a way that is environmentally friend and acceptable. The soil microbiome supports the nutrient cycling and diseases suppression processes coupled with maintaining soil structures; it consists of diverse and metabolically active microbial assemblages. The discovery of these microbial functions presents new opportunities of getting rid of dependency on chemical inputs and enhancing the sustainability of agri-systems.

Microbial fertilizers and bioinoculants have had positive results in different agro-ecological environments by boosting the supply of nutrients, stimulating root growth with the aid of plant development-promoting hormone, and enhance the health of soil. Moreover, the beneficial microbe in bioremediation has been shown to have the potential to be used in detoxifying polluted soils as well as aid in ecological restoration. uch trends correlate with international attempts to support sustainable agricultural intensification and reduce the use of traditional farming mechanisms that impose environmental burdens.

Although with the evident positive aspects, microbial biotechnology has come under several issues that need to be addressed to boost its wider application and potential. The major barriers might be biological variability, poor field performance, and poor formulation and delivery of technologies. Moreover, it cannot be implemented on large scale due to regulatory uncertainties and farmer ignorance. The solution to these problems includes additional research, comprehensive policies, and farmer training programs (FTPs) that will be instrumental in realization of the true potential of microbial-based solutions.

The use of microorganisms in agriculture in the future is likely to be changed by advances in molecular biology, metagenomics and synthetic biology. These technologies, brought together via AI and combined with precision agricultural tools, that can be customized

microbial interventions which will wrap around the needs of crops and soils. With continued innovation and interdisciplinary collaboration, microbial biotechnology should become an indispensable component of future food systems, offering sustainable solutions to feed a growing population while preserving soil and environmental health.

Author contributions

Hina Fatima, Muhammad Anas, and Mujeeb collected and analyzed the literature and prepared the initial draft of the manuscript. Momina and Muhammad Ali contributed to the design and illustration of the table, diagrams, and figures. Muhammad Sajad supervised the overall work and provided expert guidance throughout the project. Muhammad Aizaz and Fayyaz Hussain assisted in reference management and manuscript formatting.

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