



Advances in Soil Microbiome Engineering for Sustainable Crop Productivity: A Review

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Review Article

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Abstract

Soil microbiome engineering is increasingly recognised as a sustainable approach for improving crop productivity by managing beneficial microbial communities and their functions in agricultural soils. The soil microbiome comprises bacteria, fungi, archaea, viruses and other microorganisms that influence nutrient cycling, organic matter decomposition, soil structure, plant growth and ecosystem stability. This review summarises current understanding of soil microbial diversity, plant-microbe interactions and the major approaches used to manipulate soil microbiomes for agricultural benefit. It considers microbial inoculants, biofertilisers, synthetic microbial communities, host-mediated microbiome selection, soil amendments, habitat engineering and genetic or metabolic engineering of beneficial microorganisms. The review also discusses the contribution of metagenomics, other multi-omics methods, genome editing, synthetic biology, artificial intelligence, machine learning and precision agriculture tools to the characterisation, prediction and management of microbial functions. Evidence presented in the manuscript indicates that microbiome-based strategies can support nutrient acquisition, improve plant growth, suppress pathogens, enhance tolerance to abiotic stress and promote soil health. However, the practical use of these approaches is constrained by microbial community complexity, environmental variability, inconsistent field performance, limited persistence of introduced microorganisms, biosafety issues, regulatory requirements and adoption barriers. The synthesis is limited to the themes addressed in the manuscript and therefore emphasises practical engineering strategies, enabling technologies and implementation constraints rather than presenting a quantitative meta-analysis of crop responses. Future progress will require crop-specific and site-specific microbiome management, resilient microbial consortia, improved formulation and delivery systems, and integration with sustainable and climate-smart agricultural practices. Soil microbiome engineering offers a biologically based pathway to support productive, resilient and resource-efficient farming systems while reducing dependence on external chemical inputs.

Keywords: *Soil microbiome engineering; sustainable agriculture; plant-microbe interactions; biofertilisers; synthetic microbial communities; precision agriculture; crop productivity; rhizosphere management; microbial inoculants; soil health.*

1. Introduction

1.1 Soil Microbiome

The soil microbiome refers to a vast and diverse assemblage of microorganisms, including bacteria, fungi, archaea, viruses, protozoa, and microalgae, that inhabit the soil environment and establish complex interactions with plants, soil fauna, and one another (Chauhan et al., 2023). These microbial communities represent one of the most biologically diverse and functionally significant components of terrestrial ecosystems. They regulate numerous ecological processes, including nutrient transformation, organic matter decomposition, soil aggregation, carbon storage, and biological control of pathogens. Through their metabolic activities, soil microorganisms influence soil fertility, plant health, and ecosystem stability. Recent developments in molecular techniques, metagenomics and high-throughput sequencing have expanded our understanding of microbial diversity and functionality, demonstrating that the soil microbiome is a key driver of plant productivity and environmental resilience under both optimal and adverse growing conditions.

1.2 Role of Soil Microorganisms in Agricultural Ecosystems

Soil microorganisms perform essential functions that sustain agricultural productivity and ecosystem services (Wang et al., 2024). They enhance nutrient availability through processes such as biological nitrogen fixation, phosphate solubilisation, potassium mobilisation, and decomposition of organic residues. Many beneficial microbes also synthesise plant growth-promoting substances, including auxins, gibberellins, and cytokinins, which stimulate root growth and improve plant development. Furthermore, soil microorganisms contribute to plant protection by suppressing pathogens through competition, antibiosis, parasitism, and induction of systemic resistance. Their involvement in nutrient cycling, soil structure maintenance, and stress mitigation makes them indispensable for maintaining sustainable and productive agricultural systems.

1.3 Challenges in Sustainable Crop Production

Modern agriculture faces the dual challenge of increasing food production while ensuring environmental sustainability. Intensive farming practices involving excessive application of chemical fertilisers and pesticides, continuous monocropping, and poor soil management have resulted in soil degradation, nutrient depletion, biodiversity loss, and declining soil quality. The impacts of climate change, including rising temperatures, irregular rainfall patterns, prolonged droughts, flooding events, and other environmental stresses, further threaten agricultural productivity and food security. Moreover, concerns regarding environmental contamination, greenhouse gas emissions, and reduced efficiency of conventional agricultural inputs have intensified the search for alternative and sustainable production strategies. These challenges underscore the necessity of innovative approaches that enhance soil biological functioning, improve resource-use efficiency, and support resilient agricultural systems.

1.4 Emergence of Soil Microbiome Engineering as a Novel Approach

Advancements in microbial ecology, biotechnology, synthetic biology, and genomics have facilitated the emergence of soil microbiome engineering as a promising tool for sustainable agriculture (Thakur et al., 2023). Soil microbiome engineering involves the intentional modification and management of microbial communities or their functional attributes to improve plant growth, nutrient uptake, stress tolerance, and disease resistance. Unlike conventional agricultural practices that primarily depend on external chemical inputs, this approach seeks to exploit the natural capabilities of beneficial microorganisms to optimise plant–soil–microbe interactions. Various strategies, including microbial inoculation, development of synthetic microbial consortia, habitat engineering, host-mediated microbiome selection and microbial genome modification, are being investigated to enhance agricultural performance. The integration of advanced sequencing platforms, multi-omics technologies, and computational modelling has accelerated the identification and deployment of beneficial microbial communities, making microbiome engineering a transformative frontier in agricultural innovation.

Research Gap: Despite rapid progress in microbiome research, the translation of soil microbiome engineering from controlled studies to reliable field application remains uneven. Existing knowledge is still fragmented across microbial ecology, crop management, biotechnology and digital agriculture, while the interactions among introduced microorganisms, native soil communities, plant genotypes and environmental conditions remain difficult to predict. The manuscript therefore addresses the need to synthesise current engineering strategies, enabling technologies and implementation barriers so that microbiome-based interventions can be evaluated as practical tools for sustainable crop productivity.

1.5 Objectives and Scope of the Review

The increasing recognition of the soil microbiome as a critical factor influencing agricultural sustainability has generated substantial interest in microbiome-based technologies and management strategies (Sharma et al., 2025). This review aims to provide a comprehensive assessment of soil microbiome engineering and its applications in improving crop productivity. It examines the composition and functional roles of soil microbial communities, evaluates current engineering approaches used to manipulate beneficial microbiomes, and discusses their contributions to plant growth, nutrient acquisition, stress tolerance, and disease management. Particular attention is given to microbial inoculants, synthetic microbial consortia, genome-assisted technologies, and precision agriculture tools that enable targeted microbiome interventions. In addition, the review highlights emerging technological advancements, identifies existing challenges, and outlines future research priorities necessary for successful field-scale implementation. Through the synthesis of recent scientific developments, this review seeks to demonstrate the potential of soil microbiome engineering as a sustainable strategy for enhancing agricultural productivity, improving soil health, and strengthening global food security.

2. Soil Microbiome Structure, Functions and Plant Interactions

2.1 Diversity and Composition of Soil Microbial Communities

The soil microbiome represents one of the most complex and diverse biological systems in terrestrial ecosystems, consisting of bacteria, archaea, fungi, actinomycetes, protozoa, algae, and viruses that interact

within highly dynamic ecological networks (Satya et al., 2025). The diversity, abundance, and composition of these microbial communities are influenced by various biotic and abiotic factors, including soil characteristics, vegetation type, climatic conditions, land-use patterns, and agricultural management practices. Among these groups, bacteria constitute the dominant microbial population and participate in numerous biochemical and ecological processes, while fungi contribute significantly to decomposition, nutrient mobilisation, and soil aggregation through their extensive mycelial networks. Recent advances in metagenomics, metatranscriptomics, and high-throughput sequencing have uncovered an extraordinary level of microbial diversity within soils, revealing that many microorganisms remain uncultured and functionally unexplored. This rich microbial diversity provides functional redundancy and ecological resilience, enabling soil ecosystems to maintain stability and productivity under changing environmental conditions.

2.2 Rhizosphere, Endosphere, and Bulk Soil Microbiomes

On the basis of their proximity to, and interactions with, plant roots, soil microbial communities are commonly classified into bulk soil, rhizosphere, and endosphere microbiomes (Ling et al., 2022). Bulk soil refers to the portion of soil that is not directly influenced by root activity and serves as a reservoir of microbial diversity. The rhizosphere is the biologically active zone surrounding plant roots in which root exudates create favourable conditions for microbial growth and colonisation. These exudates, composed of sugars, amino acids, organic acids, and secondary metabolites, selectively recruit beneficial microorganisms and influence microbial community structure. The endosphere comprises microorganisms that inhabit internal plant tissues and often establish mutualistic associations that enhance plant growth and stress tolerance. Interactions among these microbiome compartments contribute significantly to nutrient acquisition, root development, disease suppression, and adaptation to environmental stresses, thereby influencing overall plant performance and ecosystem functioning.

2.3 Microbial Roles in Nutrient Cycling and Soil Fertility

Soil microorganisms are essential mediators of nutrient cycling processes that sustain soil fertility and agricultural productivity (Sahu et al., 2017). Through the decomposition of plant residues and organic matter, microbial communities release nutrients into the soil, making them available for plant uptake. Nitrogen-fixing bacteria convert atmospheric nitrogen into biologically usable forms, while phosphate-solubilising and potassium-mobilising microorganisms increase the availability of otherwise inaccessible nutrients. Mycorrhizal fungi establish symbiotic relationships with plant roots, enhancing the uptake of nutrients and water through expanded absorptive networks. In addition to nutrient transformations, microbial activities improve soil structure through aggregate formation, stabilise soil organic carbon, and contribute to long-term carbon sequestration. These processes collectively enhance soil quality, promote sustainable nutrient management, and support crop productivity across diverse agricultural systems.

2.4 Plant–Microbe Interactions and Signalling Mechanisms

The establishment and maintenance of plant–microbe interactions are regulated by intricate signalling mechanisms that facilitate communication between plants and soil microorganisms (Chagas et al., 2018). Plants release a variety of root exudates that function as biochemical signals, attracting specific microbial populations and shaping rhizosphere community composition. Beneficial microorganisms recognize these signals and respond by colonising root surfaces or internal tissues, where they produce growth-promoting substances, improve nutrient acquisition, and enhance plant defence responses. Symbiotic associations, such as those between legumes and rhizobia or plants and arbuscular mycorrhizal fungi, depend on highly coordinated molecular signalling pathways that enable mutual recognition and successful colonisation.

2.5 Influence of Environmental and Management Factors on Soil Microbiomes

Environmental conditions and agricultural management practices exert profound influences on the composition, diversity, and functionality of soil microbial communities (Chen et al., 2020). Soil pH is widely recognised as a major determinant of microbial distribution because it directly affects microbial metabolism, survival, and nutrient availability. Other factors such as temperature, moisture content, soil texture, organic matter concentration, and climatic variability also play critical roles in shaping microbial community dynamics. Agricultural practices including tillage, crop rotation, fertilization, irrigation, pesticide application, and residue

management can significantly alter microbial populations and ecological functions. Intensive farming systems often reduce microbial diversity and disrupt beneficial plant–microbe interactions, whereas conservation agriculture, organic production systems, cover cropping, and diversified crop rotations generally enhance microbial abundance and functional diversity. As global climate change continues to modify environmental conditions and agricultural landscapes, understanding the responses of soil microbiomes to these factors will be essential for developing resilient, sustainable, and climate-smart microbiome-based agricultural technologies.

3. Principles and Approaches of Soil Microbiome Engineering

3.1 Concept and Evolution of Microbiome Engineering

Soil microbiome engineering is an emerging scientific discipline that focuses on the intentional modification of soil microbial communities and their functional characteristics to improve plant performance, nutrient-use efficiency, stress tolerance, and agricultural sustainability (Joshi et al., 2025). The concept has progressed substantially from conventional practices involving the application of individual microbial strains to more advanced approaches that integrate microbial ecology, genomics, systems biology, bioinformatics, and biotechnology. Historically, microbial interventions in agriculture were largely limited to biological nitrogen-fixing organisms and plant growth-promoting rhizobacteria. Rapid developments in next-generation sequencing, metagenomics, metatranscriptomics, and other multi-omics technologies have provided unprecedented insights into microbial diversity, interactions, and ecosystem functions. These advances have facilitated the design of targeted strategies aimed at manipulating entire microbial networks rather than isolated organisms, enabling more effective enhancement of crop productivity, soil health, and ecosystem resilience.

3.2 Microbial Inoculants and Biofertilisers

Microbial inoculants and biofertilisers constitute one of the most established and widely utilised approaches in soil microbiome engineering due to their capacity to enhance plant growth and nutrient availability through biological processes (Alori et al., 2017). These formulations commonly contain beneficial microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Pseudomonas*, and arbuscular mycorrhizal fungi that contribute to nutrient mobilisation, phytohormone production, and disease suppression. Rhizobial inoculants play a particularly important role in biological nitrogen fixation in leguminous crops, thereby reducing dependence on synthetic nitrogen fertilisers. Likewise, phosphate-solubilising microorganisms convert insoluble forms of phosphorus into bioavailable forms, improving nutrient uptake and crop performance. In addition to nutrient enhancement, many biofertiliser microorganisms stimulate root growth and improve plant resilience against environmental stresses. Although these technologies have shown promising results across diverse agricultural systems, their effectiveness is often influenced by soil properties, climatic conditions, inoculant quality, and competition with native microbial populations, necessitating continued improvements in formulation technologies and delivery methods.

3.3 Synthetic Microbial Communities (SynComs)

Synthetic microbial communities (SynComs) represent a next-generation microbiome engineering strategy involving the deliberate assembly of selected microorganisms with complementary functions to create predictable and stable microbial consortia. Unlike conventional inoculants that rely on individual strains, SynComs are designed to mimic the complexity and functionality of natural microbial communities while maintaining greater control over community composition and performance. These engineered microbial assemblages may combine organisms capable of biological nitrogen fixation, phosphorus solubilisation, phytohormone production, disease suppression, and stress mitigation, thereby generating synergistic effects that enhance plant growth and productivity. Recent advances in microbial ecology, ecological network analysis, computational modelling, and genomics have enabled the identification of key microbial taxa and interactions essential for ecosystem functioning. Despite significant progress, challenges associated with community stability, ecological adaptability, persistence under field conditions, and large-scale commercialisation remain important areas of ongoing research. Nevertheless, SynComs are increasingly viewed as a promising avenue for developing robust microbiome-based agricultural technologies.

3.4 Host-Mediated Microbiome Manipulation

Host-mediated microbiome manipulation exploits the inherent capacity of plants to influence the composition and function of their associated microbial communities through root exudation patterns, immune responses, and genetic traits (Jones et al., 2019). Plants actively release a wide range of chemical compounds, including sugars, amino acids, organic acids, flavonoids, and secondary metabolites, which selectively attract and support beneficial microorganisms in the rhizosphere. Variations in plant genotype can significantly influence microbial recruitment and community assembly, creating opportunities to develop crop varieties capable of fostering advantageous microbial associations. Modern breeding programmes are increasingly incorporating microbiome-related traits to improve nutrient acquisition, disease resistance, and tolerance to abiotic stresses. By enhancing the natural ability of plants to shape their microbiomes, host-mediated approaches provide a sustainable and environmentally friendly strategy for improving agricultural productivity while minimising external inputs.

3.5 Soil Amendments and Habitat Engineering

Soil amendments and habitat engineering approaches focus on modifying soil conditions to create favourable environments for beneficial microorganisms and improve microbial community stability (Singh et al., 2024). Organic amendments such as compost, farmyard manure, crop residues, green manures, vermicompost, and biochar enrich soil organic matter and provide energy sources that support microbial growth and activity. Among these amendments, biochar has received considerable attention because its porous structure offers protective habitats for microorganisms, enhances nutrient retention, improves water-holding capacity, and contributes to carbon sequestration. Habitat engineering also encompasses agronomic practices such as cover cropping, conservation tillage, crop diversification, intercropping, and crop rotation, which promote microbial diversity and ecological resilience. These interventions not only facilitate the establishment and persistence of introduced beneficial microorganisms but also stimulate indigenous microbial populations, thereby improving nutrient cycling, soil fertility, and overall ecosystem functioning.

3.6 Genetic and Metabolic Engineering of Beneficial Microorganisms

Recent advances in genetic engineering, metabolic engineering, and synthetic biology have significantly expanded the potential of soil microbiome engineering by enabling the development of microbial strains with enhanced or novel functional traits (Ko et al., 2020). Genome-editing technologies such as CRISPR-Cas systems allow precise modification of microbial genomes to improve characteristics including nitrogen fixation efficiency, phosphorus solubilisation, stress tolerance, and pathogen suppression. Metabolic engineering strategies can optimise biosynthetic pathways involved in phytohormone production, antimicrobial compound synthesis, nutrient transformation, and stress-responsive metabolite generation. Furthermore, synthetic biology enables the design of programmable microorganisms capable of sensing environmental signals and performing specific functions within the rhizosphere. These innovations offer important opportunities for creating highly efficient microbial tools tailored to agricultural needs. However, the successful implementation of genetically engineered microorganisms requires careful evaluation of ecological risks, biosafety concerns, regulatory requirements, and public acceptance to ensure their responsible and sustainable use in agricultural ecosystems.

4. Applications of Soil Microbiome Engineering in Crop Productivity

4.1 Enhancement of Nutrient Acquisition and Use Efficiency

One of the most significant applications of soil microbiome engineering is the improvement of nutrient acquisition and utilisation efficiency in agricultural systems (Thakur et al., 2023). Beneficial microorganisms enhance nutrient availability through processes such as biological nitrogen fixation, phosphorus solubilisation, potassium mobilisation, and mineralisation of organic matter, thereby reducing dependence on synthetic fertilisers. Nitrogen-fixing bacteria including *Rhizobium*, *Azospirillum*, and *Azotobacter* contribute substantial amounts of biologically available nitrogen to crops, while phosphate-solubilising microorganisms convert insoluble phosphorus compounds into plant-accessible forms. Arbuscular mycorrhizal fungi extend root absorptive capacity through extensive hyphal networks, facilitating nutrient and water uptake from otherwise inaccessible soil zones. Microbiome engineering strategies that promote the abundance and activity of these beneficial microorganisms have demonstrated considerable potential for increasing nutrient use efficiency, lowering fertiliser requirements, and enhancing agricultural sustainability.

4.2 Improvement of Plant Growth and Yield

Engineered soil microbiomes can significantly improve plant growth and crop productivity through multiple direct and indirect mechanisms (Arif et al., 2020). Plant growth-promoting microorganisms produce phytohormones such as auxins, gibberellins, and cytokinins that stimulate root development, increase nutrient uptake, and enhance overall plant vigour. Certain microbial species also produce enzymes and metabolites that improve nutrient availability and regulate plant physiological processes under diverse environmental conditions. In addition, beneficial microbial communities can improve photosynthetic efficiency, biomass accumulation, and reproductive development, leading to higher crop yields. Advances in microbiome engineering have enabled the development of microbial consortia specifically designed to promote plant productivity through complementary functional traits, offering a sustainable alternative to conventional agricultural inputs. As a result, microbiome-based technologies are increasingly being integrated into crop management programmes to support sustainable yield enhancement.

4.3 Biological Control of Plant Pathogens

The suppression of plant diseases through beneficial microorganisms represents an important application of soil microbiome engineering and contributes to reducing reliance on chemical pesticides (Bano et al., 2021). Beneficial microbes can inhibit pathogens through competition for nutrients and ecological niches, production of antimicrobial compounds, induction of systemic resistance, and direct antagonistic interactions. Species belonging to genera such as *Bacillus*, *Pseudomonas*, *Trichoderma*, and *Streptomyces* have demonstrated strong biocontrol activity against a wide range of fungal, bacterial, and nematode pathogens. Engineering microbial communities to enhance disease-suppressive functions can improve crop protection while maintaining environmental sustainability and soil biodiversity.

4.4 Abiotic Stress Tolerance Enhancement

Microbiome engineering offers promising solutions for enhancing plant tolerance to abiotic stresses such as drought, salinity, temperature extremes, nutrient deficiencies, and heavy metal contamination, which are becoming increasingly important under changing climatic conditions. Beneficial microorganisms can improve plant stress tolerance through mechanisms including osmolyte production, antioxidant enhancement, phytohormone regulation, and improved nutrient and water acquisition. Certain rhizobacteria and mycorrhizal fungi help plants maintain physiological stability under water-deficit conditions by improving root architecture and water-use efficiency. Similarly, salt-tolerant microbial communities can mitigate the negative effects of salinity through modulation of ion homeostasis and stress-responsive signalling pathways. Engineering microbial communities with stress-mitigating traits therefore represents a valuable strategy for improving crop resilience and ensuring agricultural productivity under increasingly variable environmental conditions.

4.5 Promotion of Soil Health and Ecosystem Resilience

Beyond direct effects on crop performance, soil microbiome engineering contributes to the maintenance of soil health and the resilience of agricultural ecosystems (Liang et al., 2025). Diverse and functionally active microbial communities play essential roles in organic matter decomposition, nutrient cycling, soil aggregation, and carbon sequestration, thereby supporting long-term soil fertility and ecosystem stability. Beneficial microorganisms enhance soil structure by promoting aggregate formation and improving water infiltration and retention, which are critical for sustainable crop production. Microbiome engineering strategies that increase microbial diversity and functional redundancy can improve ecosystem resistance to environmental disturbances, pathogen invasion, and climatic stresses. By strengthening ecological processes and promoting balanced microbial interactions, engineered microbiomes contribute to the development of resilient agricultural systems capable of sustaining productivity while minimising environmental impacts.

4.6 Case Studies in Major Agricultural Crops

The successful application of soil microbiome engineering has been demonstrated across numerous economically important crops (Foo et al., 2017). In legumes such as soybean and chickpea, inoculation with *Rhizobium* and other nitrogen-fixing bacteria has significantly enhanced nitrogen fixation, plant growth, and grain yield while reducing fertiliser requirements. In cereal crops including wheat, maize, and rice, plant growth-promoting rhizobacteria and mycorrhizal fungi have improved nutrient uptake, drought tolerance, and

productivity under diverse environmental conditions. Microbial inoculants containing *Azospirillum*, *Bacillus*, and *Pseudomonas* species have shown positive effects on root development and yield enhancement in maize and wheat production systems. In horticultural crops such as tomato, cucumber, and pepper, engineered microbial consortia have been used to suppress soil-borne diseases and improve plant performance under both greenhouse and field conditions. These examples demonstrate the growing potential of microbiome engineering technologies to support sustainable crop production across a wide range of agricultural systems.

Table 1. Applications of Soil Microbiome Engineering in Crop Productivity (Source: Thakur et al., 2023, Bano et al., 2021)

Application Area	Microbiome Engineering Strategy	Key Microorganisms Involved	Mechanism of Action	Benefits for Crop Productivity
Nutrient Acquisition	Inoculation with beneficial microbial consortia	Rhizobium, Azotobacter, Azospirillum, Phosphate-Solubilising Bacteria (PSB)	Biological nitrogen fixation and nutrient solubilisation	Enhanced nutrient uptake, increased yield
Biofertiliser Development	Formulation of microbial biofertilisers	Bacillus spp., Pseudomonas spp., Mycorrhizal fungi	Improved nutrient availability and root growth	Reduced dependence on chemical fertilisers
Plant Growth Promotion	Introduction of Plant Growth-Promoting Rhizobacteria (PGPR)	Bacillus, Pseudomonas, Enterobacter	Production of phytohormones and growth stimulants	Increased biomass and crop vigour
Disease Suppression	Engineering disease-suppressive microbiomes	Trichoderma, Bacillus subtilis, Streptomyces	Antagonism against pathogens and induced systemic resistance	Reduced disease incidence and crop losses
Stress Tolerance Enhancement	Manipulation of stress-resilient microbial communities	Arbuscular Mycorrhizal Fungi (AMF), Bacillus spp.	Improved water and nutrient use efficiency	Enhanced tolerance to drought and salinity
Rhizosphere Engineering	Modification of root-associated microbial communities	Diverse rhizobacteria and fungi	Optimisation of plant-microbe interactions	Improved root development and nutrient absorption
Seed Microbiome Engineering	Seed coating with beneficial microbes	Rhizobium, Pseudomonas fluorescens, Bacillus spp.	Early root colonisation and growth promotion	Improved germination and seedling establishment
Biocontrol Applications	Deployment of microbial antagonists	Trichoderma spp., Pseudomonas spp.	Competition, antibiosis, and parasitism	Sustainable pest and pathogen management
Soil Health Restoration	Reintroduction of beneficial soil microbes	Actinomycetes, AMF, PGPR	Enhancement of soil biological activity	Improved soil fertility and long-term productivity
Carbon Sequestration	Promotion of carbon-stabilizing microbial communities	Mycorrhizal fungi, Actinobacteria	Increased carbon storage in soil aggregates	Enhanced soil quality and climate resilience
Microbiome-Assisted Breeding	Selection of crops with beneficial microbiome associations	Host-specific microbial assemblages	Improved recruitment of beneficial microbes	Higher nutrient-use efficiency and yield stability

Application Area	Microbiome Engineering Strategy	Key Microorganisms Involved	Mechanism of Action	Benefits for Crop Productivity
Synthetic Microbial Communities	Design of customised microbial consortia	Multi-species bacterial and fungal consortia	Synergistic interactions among microbes	Consistent crop performance across environments
Residue Decomposition	Engineering decomposer communities	Cellulolytic fungi, <i>Bacillus</i> spp.	Accelerated breakdown of crop residues	Improved nutrient recycling and soil fertility
Heavy Metal Remediation	Use of metal-tolerant microorganisms	<i>Pseudomonas</i> , <i>Bacillus</i> , Mycorrhizal fungi	Metal immobilisation and detoxification	Improved crop growth in contaminated soils
Precision Agriculture Integration	Microbiome monitoring and targeted interventions	Site-specific microbial communities	Data-driven microbiome management	Optimized resource use and productivity
Climate Change Adaptation	Development of resilient microbiome networks	Stress-adapted bacteria and fungi	Enhanced plant adaptation to environmental fluctuations	Sustained yields under changing climatic conditions
Root Microbiome Manipulation	Alteration of root exudates and microbial recruitment	PGPR, AMF, Endophytes	Enhanced beneficial microbial colonisation	Increased nutrient uptake and crop performance
Biostimulant Production	Microbial metabolite-based formulations	<i>Bacillus</i> , <i>Pseudomonas</i> , <i>Trichoderma</i>	Production of enzymes, hormones, and signalling molecules	Improved growth, yield, and quality
Sustainable Intensification	Integrated microbiome-based crop management	Diverse beneficial microbial communities	Enhanced ecosystem services	Increased productivity with lower environmental impact
Regenerative Agriculture	Restoration of native microbial diversity	Indigenous bacteria and fungi	Improved soil ecological functions	Long-term enhancement of crop productivity and soil health

5. Emerging Technologies and Tools for Microbiome Engineering

5.1 Metagenomics and Multi-Omics Approaches

Metagenomics and multi-omics technologies have revolutionised the study of soil microbiomes by enabling comprehensive characterisation of microbial diversity, community structure, and functional potential without the need for cultivation. Metagenomic sequencing provides detailed information on the taxonomic composition and genetic capabilities of microbial communities, allowing researchers to identify key microorganisms involved in nutrient cycling, disease suppression, and plant growth promotion. Complementary approaches such as metatranscriptomics, metaproteomics, and metabolomics offer insights into microbial gene expression, protein production, and metabolic activities under specific environmental conditions. The integration of these datasets through multi-omics analyses facilitates a systems-level understanding of plant–microbe–soil interactions and enables the identification of functional traits that can be targeted for microbiome engineering.

5.2 Genome Editing and Synthetic Biology

Genome editing and synthetic biology have opened new opportunities for the targeted improvement of beneficial microorganisms and the development of advanced microbiome engineering strategies (Yadav et al., 2018). Technologies such as CRISPR-Cas systems enable precise modification of microbial genomes, allowing enhancement of traits related to nutrient acquisition, stress tolerance, phytohormone production, and pathogen suppression. Synthetic biology further extends these capabilities by facilitating the design of engineered microbial circuits, synthetic pathways, and customised microbial consortia capable of performing specific ecological functions within agricultural systems. These approaches can improve the efficiency and stability of beneficial microbial interactions while enabling the development of microorganisms that respond dynamically to environmental signals and crop requirements. Although regulatory and biosafety considerations remain important challenges, genome editing and synthetic biology are increasingly recognized as transformative tools for sustainable agriculture and microbiome management.

5.3 Artificial Intelligence and Machine Learning Applications

Artificial intelligence (AI) and machine learning technologies are emerging as powerful tools for analysing the vast and complex datasets generated by microbiome research (Dakal et al., 2025). Soil microbial communities consist of thousands of interacting species whose relationships are often difficult to interpret using conventional analytical methods. Machine learning algorithms can identify hidden patterns, predict microbial interactions, and determine the factors influencing microbiome assembly and function. AI-driven models are increasingly being used to predict plant responses to microbial inoculation, identify beneficial microbial taxa, optimise synthetic microbial communities, and forecast ecosystem responses under different environmental scenarios. These computational approaches enhance decision-making by integrating microbiome data with environmental, agronomic, and genomic information, thereby accelerating the development of effective microbiome engineering strategies and improving agricultural productivity.

5.4 Precision Agriculture and Digital Farming Tools

The integration of microbiome engineering with precision agriculture technologies offers new opportunities for site-specific and data-driven management of agricultural ecosystems. Precision agriculture utilises sensors, geographic information systems (GIS), remote sensing technologies, drones, satellite imagery, and Internet of Things (IoT) devices to collect real-time information on soil properties, crop performance, environmental conditions, and management practices. These technologies enable the monitoring of factors that influence soil microbial communities and facilitate targeted interventions aimed at optimising microbial functions and crop productivity. Digital farming platforms can integrate microbiome data with agronomic information to support evidence-based decision-making and improve resource-use efficiency. As a result, precision agriculture provides an important framework for translating microbiome engineering research into practical applications that enhance sustainability and agricultural resilience.

5.5 High-Throughput Microbial Screening and Phenotyping

High-throughput screening and phenotyping technologies have significantly accelerated the discovery and evaluation of beneficial microorganisms for agricultural applications (Jangra et al., 2021). Conventional methods for microbial isolation and characterisation are often time-consuming and limited in their ability to capture the extensive diversity present within soil ecosystems. Modern high-throughput platforms enable rapid assessment of thousands of microbial strains and communities based on functional traits such as nutrient solubilisation, nitrogen fixation, stress tolerance, antimicrobial activity, and plant growth promotion. Automated cultivation systems, microfluidic technologies, robotics, and advanced imaging techniques further enhance the efficiency and accuracy of microbial phenotyping. These innovations facilitate the identification of elite microbial candidates and support the rational design of microbial consortia for specific agricultural purposes.

6. Challenges and Limitations of Soil Microbiome Engineering

6.1 Complexity and Variability of Microbial Communities

One of the greatest challenges in soil microbiome engineering is the immense complexity and variability of soil microbial communities, which comprise thousands of interacting microorganisms whose functions and

relationships are influenced by numerous biotic and abiotic factors. Soil microbiomes exhibit substantial spatial and temporal variability, with community composition differing across soil types, climatic regions, cropping systems, and management practices. The intricate ecological interactions among bacteria, fungi, archaea, viruses, and plants make it difficult to predict the outcomes of microbiome manipulation strategies. This complexity often results in inconsistent responses to microbiome engineering interventions and presents a major obstacle to the development of universally effective microbial solutions for agricultural systems.

6.2 Environmental and Ecological Constraints

Environmental and ecological factors significantly influence the success of microbiome engineering strategies by affecting microbial survival, activity, and interactions within soil ecosystems (Islam et al., 2020). Variables such as soil pH, temperature, moisture, organic matter content, nutrient availability, and climatic conditions can alter microbial community structure and function, thereby influencing the performance of introduced microorganisms. Agricultural practices including tillage, irrigation, fertiliser application, and pesticide use may further disrupt microbial populations and ecological balance, reducing the effectiveness of microbiome-based interventions. Climate change introduces additional uncertainty through altered precipitation patterns, temperature fluctuations, and increased frequency of extreme weather events that may affect microbial ecosystem stability. These environmental and ecological constraints highlight the need for context-specific microbiome engineering approaches that account for local conditions and ecosystem dynamics.

6.3 Establishment and Persistence of Introduced Microbes

A major limitation of microbial inoculation strategies is the difficulty of ensuring successful establishment, colonisation, and long-term persistence of introduced microorganisms within native soil communities (Duell et al., 2023). Indigenous microbial populations are often highly competitive and can outcompete introduced strains for nutrients, ecological niches, and root colonisation sites. Even when inoculated microorganisms initially establish successfully, their populations may decline over time due to environmental stress, predation, antagonistic interactions, or lack of adaptation to local conditions. The effectiveness of microbial inoculants can therefore vary considerably among locations, crop species, and growing seasons, limiting the reproducibility of field results. Improving inoculant formulation, delivery methods, and understanding of microbial community assembly processes remains essential for enhancing the persistence and functionality of engineered microbiomes in agricultural systems.

6.4 Biosafety, Regulatory, and Ethical Considerations

The application of microbiome engineering technologies, particularly those involving genetically modified microorganisms and synthetic biology approaches, raises important biosafety, regulatory, and ethical concerns (Ebadi et al., 2025). Potential risks include unintended ecological impacts, horizontal gene transfer, disruption of native microbial communities, and unforeseen effects on non-target organisms and ecosystem functions. Regulatory frameworks governing the development, testing, and release of engineered microorganisms vary considerably among countries and are often not fully adapted to emerging microbiome technologies. In addition, public concerns regarding the safety and environmental consequences of genetically modified organisms may influence acceptance and adoption of microbiome-based innovations. Addressing these issues requires comprehensive risk assessment, transparent regulatory processes, long-term ecological monitoring, and effective communication between scientists, policymakers, industry stakeholders, and the public.

6.5 Economic and Adoption Barriers

Despite significant scientific advances, the widespread adoption of soil microbiome engineering technologies is constrained by several economic and practical challenges (Afridi et al., 2022). The development, production, quality control, and commercialisation of microbial products often involve substantial financial investment and technical expertise, which can increase costs for producers and end users. Variability in field performance and uncertainty regarding economic returns may discourage farmers from adopting microbiome-based products, particularly in regions where conventional agricultural inputs remain readily available and cost-effective. Limited awareness, insufficient technical knowledge, and lack of extension services can further hinder technology adoption among farming communities. Additionally, challenges related to product shelf life, storage conditions, application methods, and compatibility with existing farming practices may affect farmer confidence

and market acceptance. Overcoming these barriers will require improved product reliability, supportive policies, farmer education programmes, and economic incentives that demonstrate the long-term benefits of microbiome engineering for sustainable agriculture.

7. Future Directions and Research Priorities

7.1 Next-Generation Microbial Consortia Development

The development of next-generation microbial consortia represents a promising direction in soil microbiome engineering because naturally occurring microbial communities often function through complex cooperative interactions rather than the activity of individual species (Zhu et al., 2026). Future research is increasingly focused on designing synthetic microbial consortia composed of complementary microorganisms that perform multiple functions simultaneously, including nutrient mobilisation, disease suppression, stress mitigation, and growth promotion. Advances in microbial ecology, systems biology, and network analysis are facilitating the identification of keystone taxa and functional interactions that contribute to ecosystem stability and productivity. The integration of multi-omics technologies with computational modelling is expected to improve the rational design of microbial communities that are more stable, resilient, and effective under field conditions. Such next-generation consortia may overcome many limitations associated with single-strain inoculants and provide more reliable solutions for sustainable agriculture.

7.2 Personalised and Crop-Specific Microbiome Management

Future microbiome engineering strategies are likely to move towards personalised and crop-specific approaches that account for differences in plant genotype, soil characteristics, climatic conditions, and management systems. Research has demonstrated that different crop species and cultivars selectively recruit distinct microbial communities through root exudates and host-specific signalling mechanisms. As understanding of these interactions improves, it may become possible to develop tailored microbiome management programmes that optimise beneficial microbial functions for specific crops and production environments. Precision microbiome management could involve customised microbial inoculants, crop-specific microbial consortia, and targeted interventions designed to address particular agronomic challenges such as nutrient deficiencies, disease pressure, or environmental stress. This personalised approach has the potential to maximise the effectiveness of microbiome engineering while improving resource-use efficiency and crop productivity.

7.3 Integration with Climate-Smart Agriculture

The integration of soil microbiome engineering with climate-smart agriculture offers significant opportunities for enhancing agricultural resilience and sustainability under changing climatic conditions (Rawal et al., 2026). Beneficial microbial communities can improve plant adaptation to drought, salinity, heat stress, and nutrient limitations, thereby helping crops maintain productivity in increasingly challenging environments. Microbiome-based strategies can also contribute to climate change mitigation through enhanced carbon sequestration, improved nutrient-use efficiency, and reduced dependence on synthetic fertilisers that contribute to greenhouse gas emissions. Future research should focus on identifying microbial traits associated with climate resilience and developing microbiome engineering approaches that complement climate-smart farming practices such as conservation agriculture, diversified cropping systems, and sustainable land management. Such integration will be critical for ensuring food security while minimising the environmental impacts of agricultural production.

7.4 Advances in Microbiome-Based Biostimulants and Biofertilisers

Rapid advances in microbiome research are driving the development of next-generation biostimulants and biofertilisers that exploit beneficial microbial functions to enhance crop growth and soil health (Garg et al., 2024). Unlike conventional products based on single microbial strains, future formulations are expected to incorporate multifunctional microbial consortia with improved adaptability, persistence, and efficacy across diverse environmental conditions. Advances in formulation technologies, encapsulation methods, carrier materials, and delivery systems are likely to improve microbial survival and field performance. These innovations are expected to expand the commercial viability of microbiome-based products and accelerate their adoption as sustainable alternatives to chemical fertilisers and pesticides.

7.5 Opportunities for Sustainable Agricultural Intensification

Soil microbiome engineering offers substantial opportunities for achieving sustainable agricultural intensification by increasing crop productivity while reducing environmental impacts and conserving natural resources (Rao et al., 2015). Engineered microbial communities can improve nutrient-use efficiency, enhance plant resilience, suppress diseases, and maintain soil fertility, thereby supporting higher yields with lower external inputs. As global demand for food continues to rise, microbiome-based technologies may play an increasingly important role in closing yield gaps and improving productivity on existing agricultural land without further expansion into natural ecosystems. The integration of microbiome engineering with precision agriculture, digital farming technologies, and sustainable land management practices has the potential to create highly efficient and environmentally responsible production systems. Continued investment in research, technology development, policy support, and farmer education will be essential for realising the full potential of soil microbiome engineering as a cornerstone of future sustainable agriculture.

8. Limitations

This review is limited by its narrative scope and by its reliance on the themes and evidence discussed in the manuscript. It does not provide a quantitative meta-analysis of crop yield responses, microbial persistence or economic performance across different soils, crops and climates. The effectiveness of soil microbiome engineering may vary according to soil properties, native microbial communities, crop genotype, management practices and environmental conditions, and these context-specific responses cannot be fully resolved within a broad review. In addition, several approaches discussed, including synthetic microbial communities, genome editing, artificial intelligence and precision microbiome management, remain developing areas with limited long-term field validation. The review also does not evaluate regulatory frameworks in detail, although biosafety, public acceptance and commercial scalability are recognised as important constraints. These limitations indicate the need for controlled field trials, long-term ecological monitoring and standardised evaluation methods before wider agricultural adoption across diverse production systems and regions.

9. Conclusions

Soil microbiome engineering provides a biological approach to supporting sustainable crop productivity by managing microbial functions that contribute to nutrient cycling, plant growth, disease suppression, stress tolerance and soil health. The review shows that microbial inoculants, biofertilisers, synthetic microbial communities, host-mediated microbiome manipulation, soil amendments and engineered microorganisms each offer useful but context-dependent routes for improving plant-soil-microbe interactions. Advances in metagenomics, multi-omics analysis, genome editing, synthetic biology, artificial intelligence, machine learning and precision agriculture have strengthened the capacity to characterise microbial communities and design more targeted interventions. However, field application remains constrained by microbial complexity, environmental variability, competition with native communities, inconsistent persistence, biosafety considerations and economic barriers. Therefore, future work should prioritise crop-specific and site-specific microbial consortia, improved formulation and delivery systems, long-term field validation and practical integration with climate-smart and sustainable farming practices. Interdisciplinary collaboration among microbiologists, agronomists, breeders, data scientists, policymakers and farmers will be essential to translate microbiome research into reliable agricultural tools. This contribution should be viewed as complementary to, rather than a replacement for, agronomic management. When applied responsibly and evaluated under realistic production conditions, soil microbiome engineering can contribute to resilient farming systems, improved resource-use efficiency and reduced dependence on synthetic agricultural inputs.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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