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Review Article



Biotechnological Applications of Microbiome Research: A Review of Current Advances and Future Prospects

Ogbaji Henderson Onah¹ , Ochuele Dominic Agida^{2,3} , Moses Adondua Abah^{2,3} , Micheal Abimbola Oladosu^{2,4} , Ibejo Blessing Ugojoo⁵ , Tryphosa Tibile Sojay⁶ , Adaora Chiamaka Ekekwe⁷  and Olorunda Monday⁸ 

¹Department of Genetics and Biotechnology, Faculty of Biological Sciences, University of Calabar, Calabar, Cross River State, Nigeria

²Department of Biochemistry, Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria

³ResearchHub Nexus Institute, Nigeria

⁴Department of Biochemistry, Faculty of Basic Medical Sciences, University of Lagos, Lagos State, Nigeria

⁵Department of Biotechnology, I.M. Sechenov First Moscow State Medical University (Sechenov University)

⁶Department of Food, Nutrition and Home Sciences, Faculty of Agriculture, Prince Abubakar Audu University, Anyigba, Kogi State, Nigeria

⁷Department of Community Health and Primary Care, Faculty of Clinical Sciences, University of Lagos, Lagos State, Nigeria.

⁸Department of Plant Biology, Faculty of Life Sciences, University of Ilorin, Ilorin, Kwara State, Nigeria

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✉ Corresponding Author: : Moses Adondua Abah; m.abah@fuwukari.edu.ng

Abstract

Microbiome research has rapidly transitioned from descriptive ecology to a powerful driver of biotechnological innovation, reshaping approaches to human health, agriculture, industry, and environmental sustainability. Advances in high-throughput sequencing, multi-omics integration, and computational modeling have unraveled the functional complexity of microbial communities, enabling precise characterization of their roles in metabolism, immunity, disease, and ecosystem stability. These insights have catalyzed the emergence of microbiome-based technologies, including next-generation probiotics, engineered microbial consortia, postbiotic therapeutics, and microbiome-guided diagnostics that offer unprecedented opportunities for personalized medicine. Targeted manipulation of plant, animal, and soil microbiomes is increasing crop yield, boosting nutrient efficiency, strengthening disease resistance, and assisting bioremediation techniques that tackle pollution and climate-related issues in agriculture and environmental biotechnology. Enzymes, metabolites, and artificial microbial communities created from microbiomes are also being used by industrial sectors to produce sustainable biomanufacturing, bioenergy, and circular bioeconomy solutions. Despite these promising developments, there are still significant challenges, including as differences in the microbiome's composition, a lack of mechanistic understanding, issues with data harmonization, and evolving regulatory and biosafety concerns. Emerging technologies like organoid co-culture systems, CRISPR-based microbiome editing, and AI-driven ecosystem modeling could eliminate many of these barriers and expedite the transition from discovery to application. This review outlines current advancements in the main fields of microbiome biotechnology, points out persistent gaps, and recommends important directions for future research. By combining scientific discoveries with pragmatic perspectives, it provides a forward-looking approach to harnessing microbiome discoveries to solve global health, environmental, and industrial concerns.

Keywords: Microbiome biotechnology, Multi-omics integration, Microbial engineering, Bioremediation, Precision medicine and Synthetic microbial consortia

Introduction

The microbiome has emerged as one of the most transformative concepts in modern biological science, reshaping how researchers understand health, disease, and ecosystem function. Microbial communities that inhabit humans, animals, plants, and environmental niches influence processes ranging from nutrient cycling to immune development and metabolic regulation. These communities perform essential biochemical transformations that far exceed the capabilities of their hosts, establishing the microbiome as a critical determinant of biological performance and environmental resilience (Lloyd-Price et al., 2016; Anih et al., 2025). As research expands beyond descriptive cataloging to functional characterization, the microbiome has become a cornerstone for innovative biotechnological applications.

Advances in sequencing technologies and multi-omics platforms have significantly accelerated microbiome science. Integration of metagenomics, metatranscriptomics, metabolomics, and metaproteomics now allows researchers to map microbial composition, functional pathways, and metabolic outputs with unprecedented detail (Knight et al., 2018). Coupled with machine learning and advanced computational modelling, these approaches reveal the dynamic, context-dependent interactions that define microbial ecosystems. Such insights have laid the foundation for precise manipulation and engineering of microbiomes to enhance health, agricultural productivity, and environmental sustainability (Gilbert et al, 2018). As the field continues to mature, the transition from association studies to mechanistic and translational research has accelerated.

Human health has benefited significantly from microbiome-driven innovations. Microbiome-based diagnostics, probiotic and postbiotic therapies, engineered microbial consortia, and fecal microbiota transplantation (FMT) illustrate how manipulating microbial ecosystems can prevent or treat disease (Zmora and Elinav, 2019). Beyond medicine, microbiome biotechnology is revolutionizing agriculture through plant growth-promoting microbes, soil microbiome restoration, biological pest management, and animal microbiome modulation to improve productivity. Environmental and industrial sectors are using microbial communities for pollutant degradation, bioenergy production, and biomanufacturing of high-value compounds (Khan and Kelly, 2021). These cross-sectoral applications demonstrate the vast potential of microbiome research as a driver of sustainable innovation.

Despite remarkable progress, major challenges hinder the full deployment of microbiome-based technologies. Microbial communities vary widely across individuals, environments, and temporal scales, complicating reproducibility and generalization (Eisenstein, 2020). Mechanistic understanding remains incomplete, and translating laboratory findings to real-world applications requires greater clarity on host-microbe interactions, ecological stability, safety, and potential

unintended consequences. Ethical and regulatory issues including data privacy, biocontainment, and oversight of engineered microbes also demand attention as microbiome products enter clinical and commercial markets. Addressing these barriers is essential for safe and effective implementation of microbiome-driven innovations.

This review aims to provide a comprehensive and forward-looking synthesis of the biotechnological applications emerging from microbiome research, while identifying gaps and opportunities that will shape future directions. Specifically, the review examines current scientific advances, including microbiome-based therapeutics, agricultural microbiome engineering, industrial bioprocesses, and environmental remediation strategies. It explores the technological foundations such as multi-omics integration, synthetic biology, and computational modelling that enable these applications. The review also discusses emerging innovations such as engineered microbial consortia, CRISPR-mediated microbiome editing, microbial metabolite therapeutics, and AI-guided ecosystem design. Furthermore, it evaluates key challenges involving variability, standardization, regulatory complexity, and biosafety, drawing attention to areas where further research is urgently needed. By synthesizing recent developments across multiple disciplines, this review positions microbiome biotechnology as a central contributor to global health, food security, environmental sustainability, and industrial innovation. Ultimately, the goal is to provide scholars, policymakers, and practitioners with a detailed, integrative perspective on how microbiome science is transitioning from discovery to scalable, real-world solutions while outlining strategic priorities necessary to realize its full potential.

The Microbiome: Composition, Function, and Analytical Advances

Microbiomes, the complex communities of microorganisms including bacteria, archaea, fungi, viruses, and protists, which inhabit diverse ecological niches such as the human gut, skin, soil, and aquatic environments, and the composition of these communities underlies their functional capacities (Foster et al, 2017.). They play essential roles in health, development, and ecosystem functioning. Their diversity, composition, and functional capacities underpin processes such as nutrient cycling, immune modulation, pathogen resistance, and metabolic regulation (Gilbert et al, 2018 , Foster et al, 2017). Microbiome research has moved from basic taxonomic surveys to extensive functional and mechanistic studies due to recent technology advancements. Detailed characterization of microbial communities is now possible because to high-throughput sequencing, multi-omics investigations, and computational modeling, which connect structure to function and show dynamic interactions between microorganisms and their hosts or environments (Knight et al, 2018, Franzosa et al , 2014). The composition and ecological functions of microbiomes, state-of-the-art analytical methods for their

profiling, and bioinformatic and computational advancements that facilitate functional predictions, ecosystem modeling, and translational applications in biotechnology are all covered in this section.

Microbiome Structure and Ecological Roles

The microbiome comprises complex communities of microorganisms, including bacteria, archaea, fungi, viruses, and protists, which inhabit diverse ecological niches such as the human gut, skin, soil, and aquatic environments as shown in **figure 1**. Microbial diversity within these ecosystems is a key determinant of stability, resilience, and functional

potential. Functional guilds groups of microbes performing similar biochemical functions mediate critical processes such as nutrient cycling, host metabolism, immune modulation, and pathogen resistance (Foster et al, 2017). Host microbe interactions are dynamic and context-dependent, influencing development, disease susceptibility, and environmental adaptability. For instance, symbiotic gut microbes produce short-chain fatty acids that regulate host metabolism, while plant-associated microbiota enhance nutrient uptake and stress tolerance (Vandenkoornhuysse et al, 2015). Understanding these ecological roles provides the foundation for microbiome targeted biotechnological interventions.

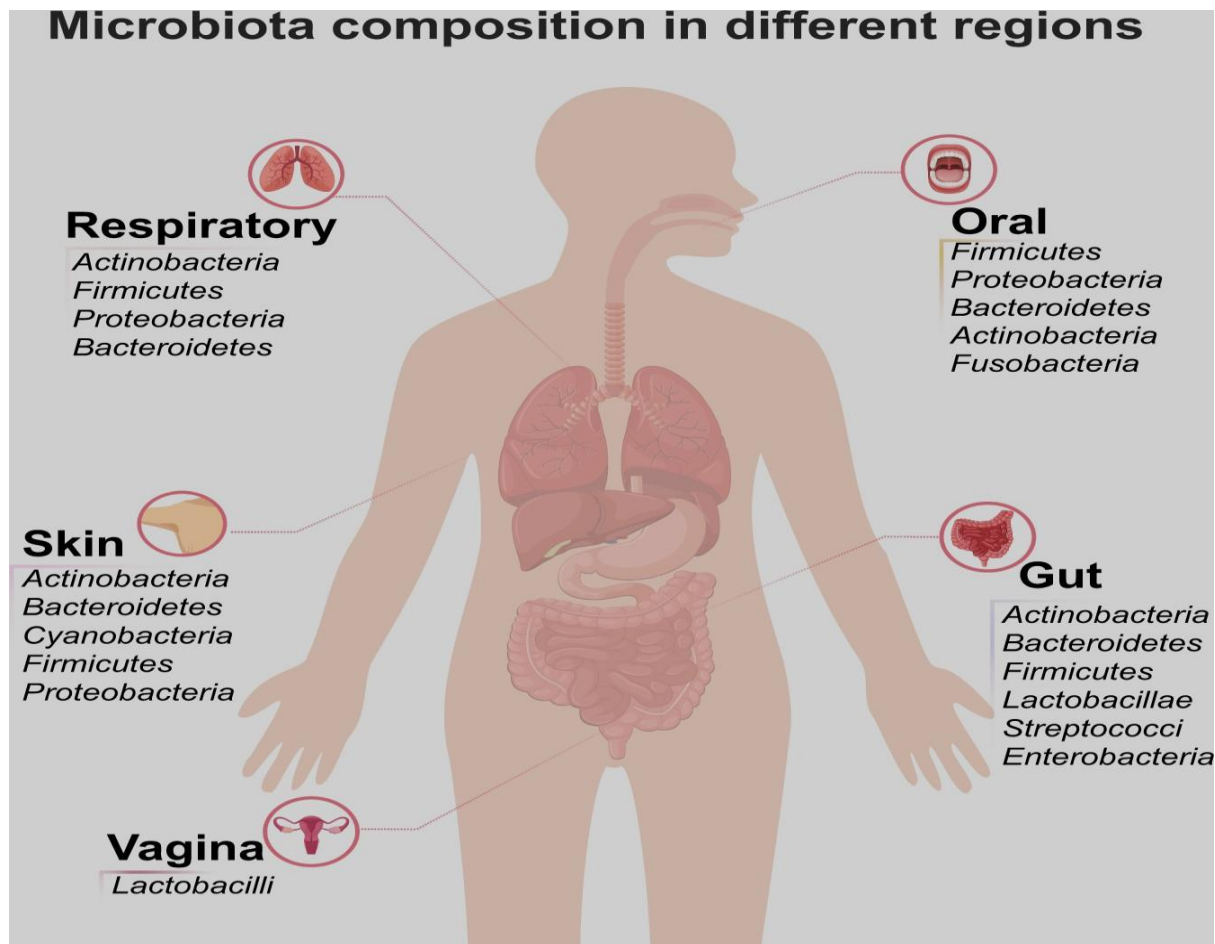


Figure 1. Human microbiota composition in different locations. Predominant bacterial genera in the oral cavity, respiratory tract, skin, gut, and vagina are highlighted **Source:** Hou et al. (2022)

Advances in Microbiome Profiling

High-resolution characterization of microbiomes has been revolutionized by multi-omics technologies. Metagenomics enables the identification of microbial taxa and their genetic potential, while metatranscriptomics and metaproteomics capture functional gene expression and protein production, respectively (Franzosa et al, 2014). Metabolomics provides insights into microbial metabolic outputs and host microbe

chemical interactions (Anih et al, 2015 ,Marx, 2021). Complementary approaches such as single-cell sequencing and culturomics allow researchers to study rare or uncultivable microbes and their functional roles (Lagier et al, 2015). Emerging spatial omics techniques map microbial distribution within host tissues or environmental matrices, linking community composition with localized functional effects (Marx, 2021). Together, these profiling strategies deliver a

comprehensive understanding of microbial ecosystems, facilitating predictive and functional microbiome research.

Computational and Bioinformatic Innovations

The vast datasets generated by multi-omics studies necessitate advanced computational approaches. Artificial intelligence (AI) and machine learning (ML) are increasingly applied to detect patterns, predict functional potential, and identify

microbial signatures associated with host phenotypes or environmental states. Network modeling captures complex interspecies interactions and microbial co-occurrence patterns, providing insights into ecological stability and functional redundancy (Faust, 2012). Integrative bioinformatics platforms enable functional prediction and simulation of microbiome responses to perturbations, supporting rational design of microbiome-based interventions in medicine, agriculture, and industry.

Table 1. Key Microbiome Profiling Techniques and Their Applications

Techniques	Target/output	Applications	Advantages	Limitations
Metagenomics	DNA sequences; taxonomic composition (Knight et al, 2025)	Microbial diversity, gene potential	High-throughput; culture-independent (Franzosa et al, 2014)	Cannot capture active gene expression.
Metatranscriptomics	RNA; gene expression	Functional activity; host-microbe interactions	Dynamic functional insight (Franzosa et al, 2014)	Sensitive to RNA degradation
Metaproteomics	Proteins; functional products	Microbial activity; enzyme profiling	Direct functional readout (Franzosa et al, 2014)	Complex sample prep; low throughput
Metabolomics	Metabolites; small molecules (Wishart, 2018)	Metabolic output; signaling molecules	Links microbes to phenotype	Interpretation can be complex (Franzosa et al, 2014)
Single-cell sequencing	Individual microbial cells (Greene et al, 2016)	Rare taxa identification; heterogeneity	Resolves population variability	Technically challenging; costly (Greene et al, 2016)
Culturomics	Cultured microbes	Novel species discovery; functional testing	Enables experimental validation(Lagier et al, 2015)	Limited to culturable organisms
Spatial omics	Spatial distribution of microbes & molecules	Tissue-specific interactions; ecological mapping	High-resolution mapping	Requires specialized equipment (Marx,2021)
AI/ML & Network Modeling	Large datasets; functional predictions (Faust, 2012)	Predict community behavior; identify key interactions(Faust, 2012)	Integrates multi-omics data (Greene et al, 2016)	Requires computational expertise (Greene et al, 2016)

Human Health and Medical Biotechnology

The human microbiome plays a central role in maintaining physiological homeostasis, influencing metabolism, immune function, and neurodevelopment. Dysbiosis, or disruption of microbial balance, has been implicated in a wide range of diseases, including metabolic disorders, autoimmune conditions, infections, and neurodegenerative diseases (Cho and blaser, 2012, Lynch and pedersen, 2016). Advances in microbiome research have enabled the development of innovative medical biotechnologies, from diagnostics to therapeutics, that leverage the microbiome to improve human health. This section explores the current state of microbiome-based diagnostics, therapeutics, and personalized medicine.

Microbiome-Based Diagnostics

Microbiome profiling has emerged as a powerful tool for disease diagnosis and stratification. By identifying microbial biomarkers and functional signatures, researchers can detect early disease states and classify patients based on microbial composition (Anih et al, 2025). For instance, distinct gut microbiome patterns have been associated with metabolic disorders such as obesity and type 2 diabetes, autoimmune diseases like inflammatory bowel disease (IBD), and neurodegenerative conditions including Parkinson’s and Alzheimer’s disease (Greene et al, 2016). These microbial signatures provide not only diagnostic potential but also insights into disease mechanisms, enabling stratified patient care and facilitating the development of targeted interventions.

Table 2. Diagnostic methods involving microbiota in cancer

Diagnostic methods	Sample type	Cancer type	Sensitivity and specificity	Advantages	Limitations
Stool Microbiome analysis	Stool	Colorectal, pancreatic and prostate	High for CRC($\geq 90\%$)	Non-invasive, easy collection	Affected by diet and lifestyle
Saliva Microbiome profiling	Saliva	pancreatic, oral, lung	Moderate	Easy to collect, low cost	Microbiome varies over time
Blood microbial DNA(cmDNA)	Plasma	Breast, lung, Colorectal	Emerging	Minimally invasive	Low microbial DNA concentration
Bronchoalveolar lavage (BAL) Microbiome	BAL fluid	Lung	Moderate	Direct tumor site sampling	Invasive procedures required
Urinary Microbiome analysis	Urine	Prostate	Emerging	Non-invasive	Requires further validation

Adapted from [Eslami et al. \(2025\)](#)

Microbiome-Driven Therapeutics

Therapeutic strategies targeting the microbiome include probiotics, next-generation probiotics, synbiotics, and microbial consortia therapies. Probiotics and synbiotics can modulate host immunity, enhance gut barrier function, and restore microbial balance, showing benefits in gastrointestinal disorders and metabolic diseases. Fecal microbiota transplantation (FMT) has demonstrated remarkable efficacy in treating recurrent *Clostridioides difficile* infections and is being explored for other dysbiosis-related conditions ([Zmora and Elinav, 2019](#)). Postbiotics microbial-derived metabolites such as short-chain fatty acids offer therapeutic benefits by modulating inflammation and host metabolism, representing a novel class of microbiome-derived interventions ([Anih et al, 2025](#)). Collectively, these approaches underscore the translational potential of microbiome science in therapeutic development. This is illustrated in **Figure 2**, which shows how microbiome-based therapies including probiotics, prebiotics, synbiotics, and fecal microbiota transplants are used to restore healthy microbial balance and improve host health

Precision and Personalized Medicine

The integration of microbiome data into precision medicine enables individualized treatments by considering host-microbe interactions and microbial functional profiles. Personalized microbiome-guided interventions can optimize drug efficacy, predict adverse responses, and tailor dietary or probiotic regimens to an individual’s microbial composition ([Zmora and Elinav, 2019](#)). For example, microbiome-based biomarkers can predict patient response to immunotherapy in cancer or modulate drug metabolism in metabolic disorders ([Greene et al, 2016](#)). By leveraging these insights, microbiome-guided precision medicine represents a paradigm shift from generalized therapeutic strategies to personalized, ecosystem-informed healthcare. This concept is illustrated in **Figure 3**, which shows how individual patient microbiomes are analyzed using meta-omics to classify responders and non-responders, how ex vivo microbiome assays can predict drug responses and how precise interventions such as commensal or engineered bacteria, microbiome-targeted drugs, or bacteriophages can be applied for health and disease management.

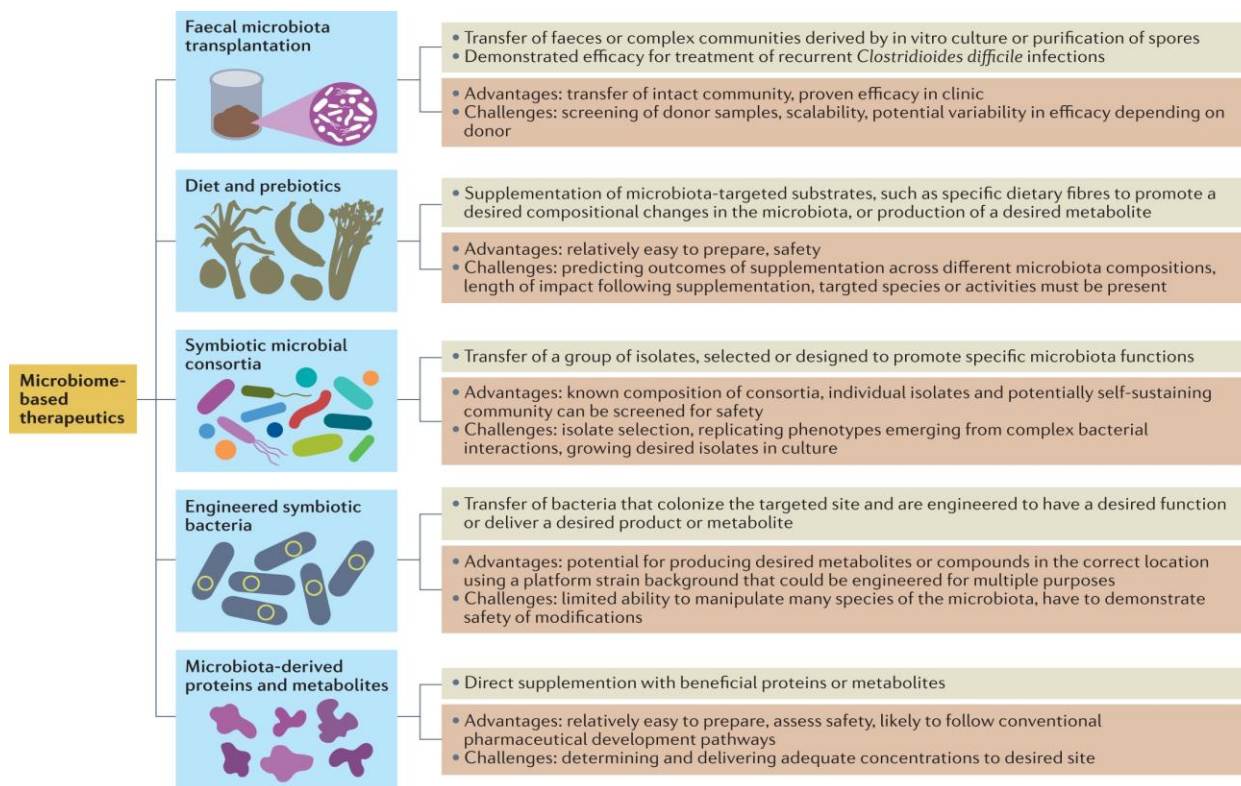


Figure 2. Microbiome based therapeutics. This figure shows how microbiome-based therapies, including probiotics, prebiotics, synbiotics, and faecal microbiota transplants, are used to restore healthy microbial balance and improve host health. **Source:** Sorbara *et al.* (2022)

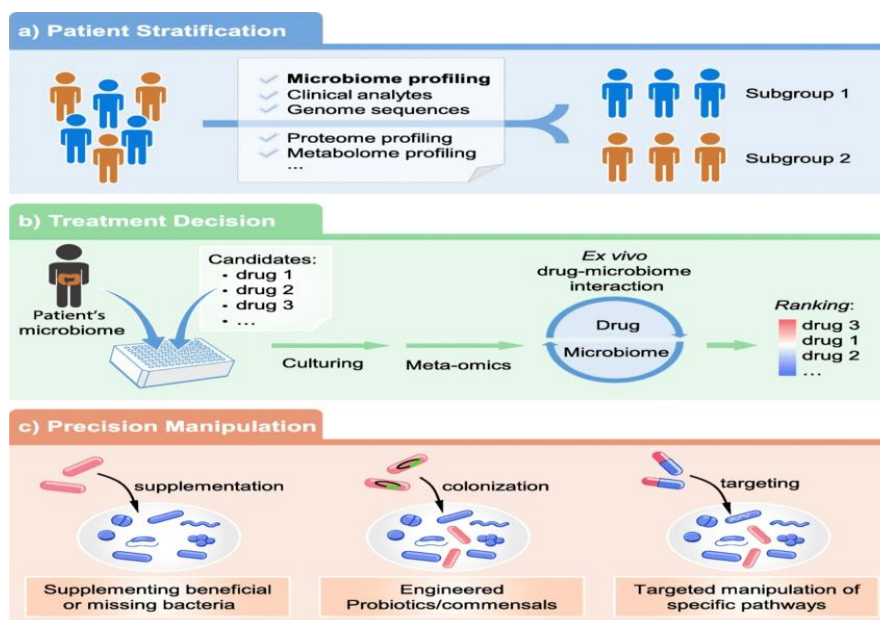


Figure 3. Introducing microbiomes into clinical practice for precision medicine. The profiles of individual patient microbiomes are analyzed with meta-omics, which allow for patients to be classified into sub-groups, i.e., responders vs. non-responders to treatments (a). The in vivo response of an individual’s microbiome to drugs can also be predicted with ex vivo microbiome assays, allowing the selection of the best drugs or adjuvant treatments for different patients (b). Finally, health and disease management could be carried out by precisely manipulating of the microbiome through supplementing commensal bacteria, engineered bacteria, microbiome-targeted drugs or bacteriophages (c) **Source:** Zhang *et al.* (2019)

Agricultural and Environmental Biotechnology

The application of microbiome research in agriculture and environmental systems is reshaping global strategies for food security, ecosystem restoration, and climate resilience. Microbial communities associated with plants, animals, and natural ecosystems play essential roles in nutrient cycling,

disease suppression, and environmental detoxification (Anih et al, 2025). This section examines current progress in plant microbiome engineering, livestock and aquaculture modulation, and environmental microbiome applications, highlighting their biotechnological potential and translational impact.

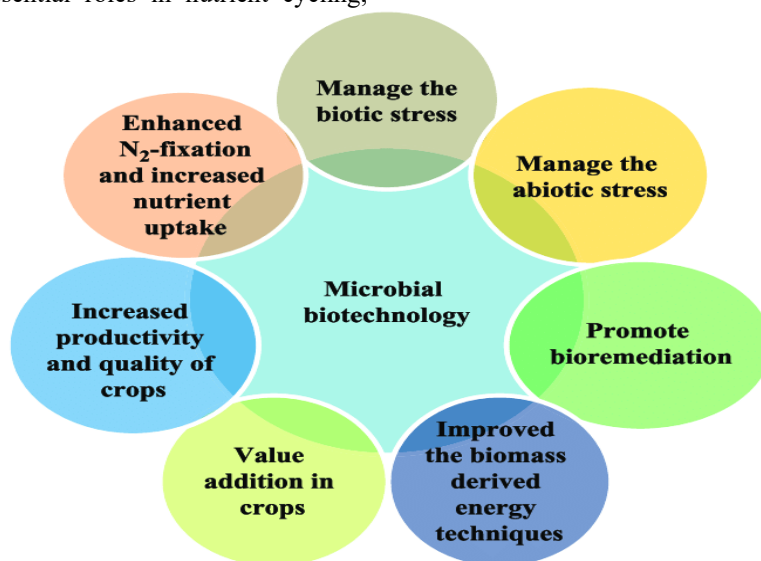


Figure 4. Application of microbial biotechnology in sustainable agriculture. This figure illustrates how microbial biotechnology is applied in sustainable agriculture, including enhancing soil fertility, promoting plant growth, controlling pests and diseases, and improving nutrient cycling through the use of beneficial microbes such as biofertilizers, biopesticides, and plant growth-promoting rhizobacteria (PGPR).

Source: Singh et al. (2019)

Plant Microbiome Engineering

Microbiome-based approaches in plant systems have emerged as powerful tools for sustainable agriculture. Biofertilizers, biopesticides, and plant growth-promoting microbes (PGPMs) including *Rhizobium*, *Bacillus*, and *Pseudomonas* species enhance nutrient availability, stimulate phytohormone production, and improve plant immunity (Anih et al, 2025). These microbial inputs reduce chemical fertilizer dependence, improve crop quality, and support long-term soil fertility. An essential function of the plant microbiome is its contribution to

stress tolerance and soil health restoration. PGPMs can induce systemic resistance, enhance drought and salinity tolerance, and improve nutrient acquisition under challenging environmental conditions (Greene et al, 2016). Additionally, microbial communities contribute to soil structure, organic matter decomposition, and nutrient cycling, making them critical to sustainable land management practices. Through microbiome engineering via inoculants, synthetic microbial consortia, and targeted microbial recruitment plant resilience and agricultural productivity can be enhanced in the face of climate change.

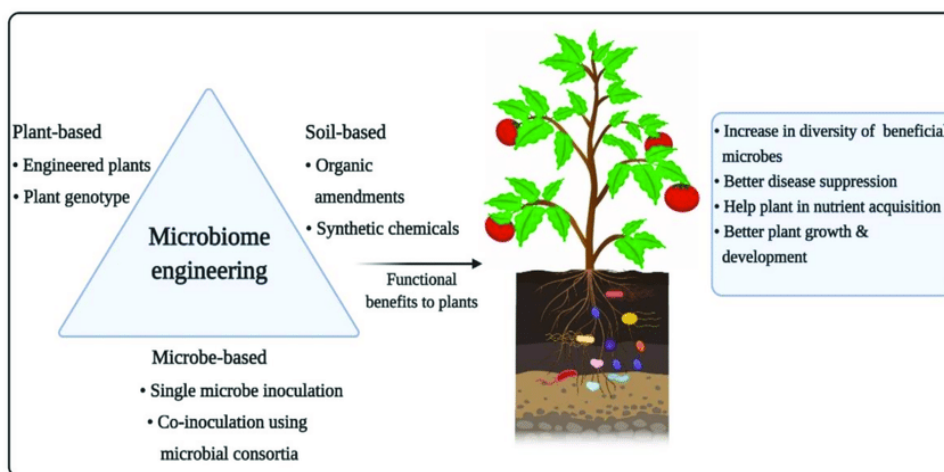


Figure 5. Microbiome Engineering. Cultivating microbe-recruiting plant cultivars, inoculating synthetic microbial communities, and conditioning soil with appropriate amendments are some of the various microbiome engineering techniques that enhance the diversity of diverse and functionally active microbial communities, improving plant health in challenging environmental circumstances. **Source:** [Noman et al. \(2021\)](#)

Livestock and Aquaculture Microbiomes

Microbiome research is increasingly integral to livestock and aquaculture biotechnology, where the gut microbiome influences growth, feed conversion, immunity, and pathogen resistance. Modulating the microbial community through probiotics, prebiotics, or designer microbial consortia supports improved productivity and reduces disease incidence in poultry, cattle, swine, and fish ([Zmora and Elinav, 2019](#)). In aquaculture, microbial dysbiosis often leads to infectious outbreaks and reduced yields. Microbial additives such as

lactic acid bacteria and yeasts enhance nutrient absorption and strengthen immune responses in fish and shrimp ([Anih et al, 2025](#)). Additionally, phage-based strategies are emerging as alternatives to antibiotics for the control of bacterial pathogens. Bacteriophages offer species-specific pathogen targeting with minimal ecological disruption, making them promising tools against antimicrobial resistance challenges ([Khan and Kelly, 2021](#)). Collectively, these microbiome-centered interventions support sustainable animal production systems and reduce reliance on chemical antimicrobials.

Table 3. Microbiome Modulation Strategies in Livestock and Aquaculture

Target system	Microbial intervention	Mode of action	Benefits
Livestock Gut Microbiome	Probiotics (LAB, Bifidobacterium)	Competitive exclusion; immune stimulation	Improved feed efficiency; reduced enteric infections
Livestock Disease Control	Phage therapy	Pathogen-specific bacterial lysis	Reduced antibiotic use; targeted pathogen control
Aquaculture Microbiome	Probiotic yeasts, Bacillus strains	Gut barrier enhancement; enzyme modulation	Increased growth rate; stress tolerance
Aquaculture Pathogen Control	Bacteriophages; beneficial bioflocs	Disruption of harmful bacteria	Lower mortality; improved water quality

Environmental Microbiome Applications

Environmental microbiomes are central to bioremediation and pollutant degradation, serving as natural agents capable of transforming hydrocarbons, pesticides, heavy metals, and plastics. Engineered or naturally enriched microbial communities, including *Dehalococcoides*, *Pseudomonas*, and fungal consortia, have been used to remediate contaminated soils, groundwater, and industrial waste sites ([Anih et al,](#)

[2025](#)). Beyond pollutant degradation, microbiomes contribute to carbon sequestration and climate resilience. Soil and marine microbial communities regulate carbon fluxes by decomposing organic matter and stabilizing carbon in long-term pools ([Zmora and Elinav, 2019](#)). In wastewater treatment systems, microbial consortia remove nitrogen, phosphorus, and organic pollutants, enhancing water quality and supporting circular bioeconomy models ([Greene et al, 2016](#)). As environmental pressures intensify globally, leveraging microbiomes offers scalable and sustainable solutions for ecosystem restoration and climate mitigation. **Figure 6,**

illustrate this, which shows how environmental microbiomes influence ecosystem processes including nutrient cycling, pollutant degradation, soil health, and carbon sequestration

highlighting their key role in maintaining ecological balance and environmental sustainability

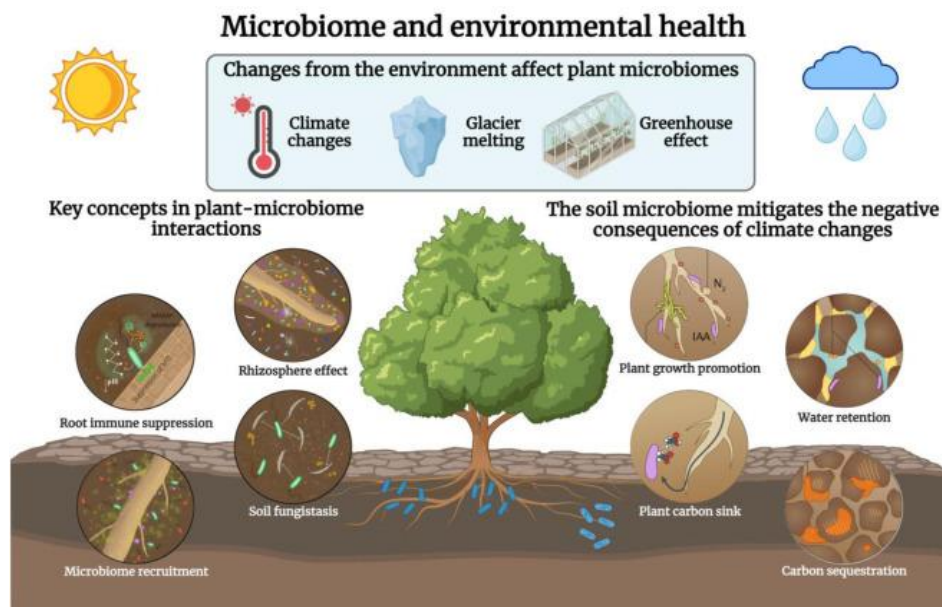


Figure 6. Effect of the Microbiome on the Environment. This figure illustrates how environmental microbiomes influence ecosystem processes, including nutrient cycling, pollutant degradation, soil health, and carbon sequestration, highlighting their crucial role in maintaining ecological balance and environmental sustainability.

Source: [Kasendra et al. \(2018\)](#)

Industrial and Synthetic Biology Applications

Recent advances in microbiome science and synthetic biology have transformed how microbial systems are applied in industrial biotechnology. Microbiome-derived insights now guide the engineering of microbial consortia, enabling more efficient, sustainable, and resilient bioprocesses across sectors such as energy, materials, and pharmaceuticals. Synthetic biology tools including CRISPR-based genome editing, systems modelling, and metabolic engineering further enhance

our ability to design, regulate, and optimize both natural and synthetic microbial communities ([Greene et al, 2016](#)). Together, these innovations support the emergence of microbiome-enabled biomanufacturing platforms capable of producing high-value biomolecules, improving bioconversion efficiencies, and offering environmentally friendly alternatives to conventional chemical synthesis. This is illustrated in **Figure 7**, which presents a schematic of wastewater and plastic bioremediation using microbial consortia, highlighting the integration of molecular tools to enhance degradation and biotransformation processes.

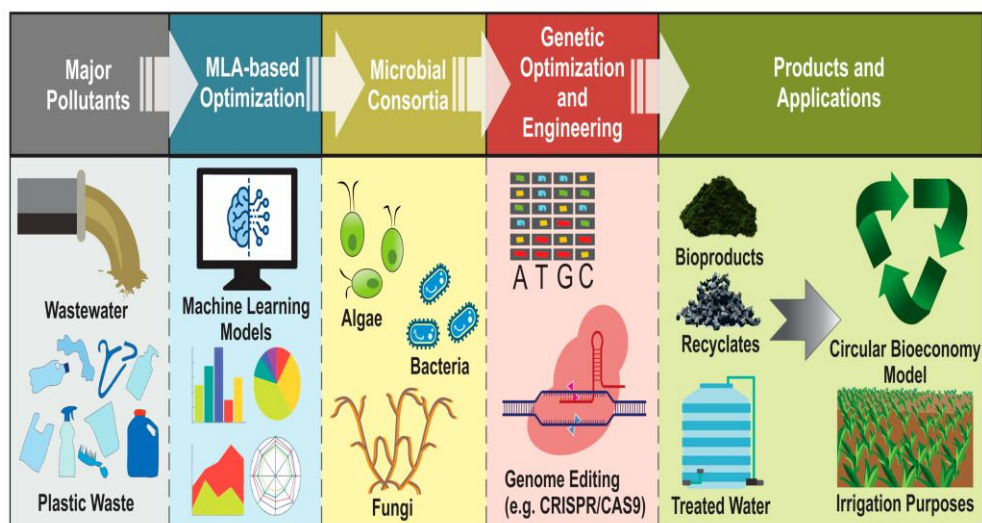


Figure 7. Schematic illustration of bioremediation of wastewater and plastic using microbial consortia, highlighting the integration of molecular tools. **Source:** Zhou and UI Haq (2025)

Table 4. Overview of different microbial consortia and their wastewater bioremediation efficiencies

Microbial Consortia	Pollutants targeted	Wastewater	Pollutant Removal Efficiency
Chlorella vulgaris, Bacillus licheniformis	COD, total dissolved phosphorus, total dissolved nitrogen	Municipal wastewater	86.6% COD, 80.3% phosphorus, and 88.9% nitrogen removal
A. flavus, Fusarium oxysporium	COD	Textile wastewater	77.6% COD removal
Chlorella vulgaris, Rhizobium sp.	TOC, total nitrogen, total phosphate	Synthetic wastewater	49.5 TOC, 55.7% TN, and 95.6 TP
Bacillus pumilus, Bacillus subtilis, Bacillus coagulans, Nitrosomonas sp., and Pseudomonas putida	BOD, COD, TSS, Ammonia	wastewater origin wastewater treatment plant (WWTP)	BOD 71.93%, 64.30% COD, TSS 94.85%, and 88.58% ammonia removal
Chlorella sp., Heterotrophic bacteria	COD, Total Nitrogen	Municipal wastewater	86.0% COD and 97.0% Total Nitrogen removal
A. fumigatus, A. terreus, Paenibacillus dendritiformis	Cadmium	Industrial wastewater	95% removal of Cd
Genus pseudomonas and Acinetobacter	pharmaceuticals paroxetine (Prx) and bezafibrate (Bzf)	Activated sludge from WWTP	>97% Prx and Bzf removal
Bacillus clausii and Bacillus amyloliquefaciens	Tetracycline antibiotics (TCs)	Laboratory	76.6% removal of TCs by B. clausii and 88.9% removal of TCs by B. amyloliquefaciens

Adapted from Zhou and UI Haq (2025)

Microbiome-Inspired Bioprocessing

Microbiome research has enabled the development of advanced bioprocessing systems that harness natural microbial interactions to improve industrial productivity. Engineered microbial consortia are increasingly used in fermentation, where cooperative metabolic pathways enhance substrate conversion efficiency and product yields (Anih et al, 2025). In biofuel production, microbiome-derived lignocellulose-degrading microbes accelerate biomass breakdown, supporting more sustainable bioethanol and biogas generation. These microbial systems are also applied in the synthesis of biopolymers, where community-level metabolic networks enable the production of polyhydroxyalkanoates (PHAs) and other biodegradable materials with reduced environmental burden (Greene et al, 2016).

Synthetic Microbial Communities

Advances in systems biology have made it possible to rationally design synthetic microbial consortia that perform specific, targeted metabolic functions. By manipulating interspecies interactions and metabolic cross-feeding, synthetic communities can be optimized for pollutant

degradation, nutrient recycling, or precision biosynthesis (Khan and Kelly, 2021). The integration of CRISPR-based genome engineering further enhances microbiome manipulation by enabling precise control of gene expression, metabolic flux, and species composition within a consortium (Zmora and Elinav, 2019). CRISPR tools also facilitate the construction of programmable strains capable of self-regulation, biosensing, and targeted metabolic output (Anih et al, 2025). Collectively, these advances support the development of robust, resilient, and highly functional microbial ecosystems.

Microbiome-Enabled Biomanufacturing

The industrial microbiome has become a key platform for the biomanufacturing of high-value compounds, including specialty enzymes, bioactive metabolites, nutraceuticals, and pharmaceutical precursors. Microbial chassis such as *E. coli*, *Bacillus*, and *Streptomyces* are increasingly engineered to incorporate microbiome-derived genes, enabling the production of rare or previously inaccessible natural products

(Zmora and Elinav, 2019). Microbiome-inspired design principles also support the development of modular biomanufacturing pipelines that improve yield, reduce toxic by-products, and enhance sustainability. These innovations position microbiome-based technologies as central to the future of industrial biotechnology.

Emerging Technologies Shaping Microbiome Biotechnology

Advances in microbiome science are increasingly driven by cutting-edge technologies that allow deeper, more precise manipulation and interpretation of microbial ecosystems. These innovations extend far beyond classical sequencing approaches, enabling spatiotemporal control of microbial communities, improved modeling of host-microbe interactions, and the integration of computational intelligence for predictive microbiome engineering (Greene et al, 2016). Collectively, these tools represent the next frontier in microbiome biotechnology, helping to bridge gaps between fundamental research, translational applications, and industrial deployment.

Spatial and Temporal Microbiome Engineering

Recent developments in spatial and temporal microbiome engineering allow researchers to control microbial behavior with unprecedented precision. In situ genome editing technologies, including CRISPR-based delivery systems tailored for gut and environmental settings, enable targeted manipulation of microbial genes without culturing organisms *ex vivo* (Zmora and Elinav, 2019). Engineered bacteriophages have emerged as highly specific tools for reshaping microbial communities through precision lysis, gene delivery, and modulation of pathogenic or metabolically important strains. Another key innovation involves quorum-sensing modulation, where synthetic circuits are engineered to disrupt or enhance microbial communication pathways to regulate community behavior, virulence, biofilm formation, and metabolite production (Greene et al, 2016). Together, these approaches facilitate fine-scale control over microbiome composition, activity, and evolution, establishing a foundation for next-generation therapeutic, agricultural, and environmental interventions.

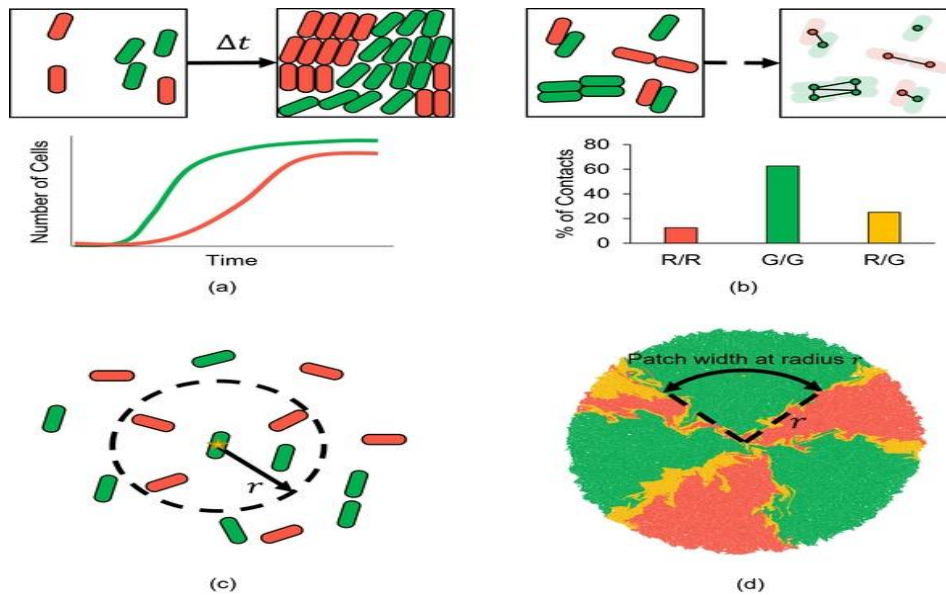


Figure 8. Calculating spatiotemporal summary statistics for microbial communities. (a) Population counts over time capture the overall dynamics in amultispecies community. (b) The frequency of adjacent species in physical contact, determined by a contact network, provides a measure of intermixing between different species. (c) Summary statistics can be calculated from data averaged within a particular cell’s neighbourhood. (d) Single-species patchmetrics, such as patch width and number of sectors, are useful for quantifying spatial patterns on a larger colony scale
Source: Yip *et al.* (2022)

Organoid- and Lab-on-Chip Systems

Organoid and microfluidic “lab-on-chip” systems have revolutionized the ability to model host–microbiome interactions under physiologically relevant conditions. Intestinal and multi-organ organoids provide 3D structures that recapitulate native tissue architecture, enabling controlled co-culture with microbial communities for mechanistic

studies, pathogen research, and drug toxicity evaluations. Lab-on-chip platforms integrate microfluidics, biosensors, and dynamic flow conditions to mimic real-time physiological environments, allowing continuous monitoring of microbial metabolism, immune interactions, and barrier function (Greene *et al.*, 2016). These systems significantly reduce reliance on animal models, provide better translational accuracy, and support personalized medicine through patient-derived organoid–microbiome co-cultures (Anih *et al.*, 2025).

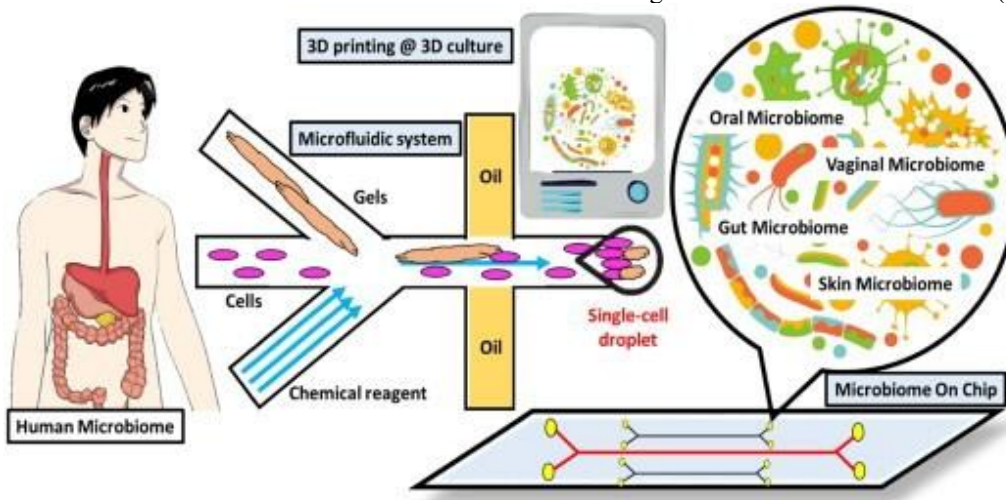


Figure 9. The organoid and lab on chip system. This figure illustrates organoid and lab-on-chip systems, which mimic human organ functions in vitro. These platforms enable precise modeling of physiology and disease, high-throughput drug testing, and the study of host microbiome interactions in a controlled microenvironment.
Source: Ramezani *et al.* (2025)

AI-Integrated Microbiome Platforms

Artificial intelligence (AI) and machine learning (ML) now play central roles in microbiome biotechnology by enabling large-scale data integration, pattern recognition, and predictive ecosystem modeling. Deep learning frameworks are

increasingly used to predict microbial interactions, metabolic fluxes, and community responses to perturbations (Zmora and Elinav, 2019). AI-enhanced tools also improve precision microbiome engineering by identifying optimal strain

combinations, forecasting therapeutic outcomes, and enabling the rational design of microbial consortia for clinical, agricultural, and industrial applications (Greene et al, 2016). Emerging AI-microbiome platforms integrate multi-omics datasets, environmental metadata, and host factors, supporting real-time decision making and accelerating translational pathways from dataset to functional intervention. This is illustrated in **Figure 10**, which shows an AI-driven pipeline for personalized atherosclerosis interventions using individual patient data and gut microbiome signatures to guide tailored treatment strategies.

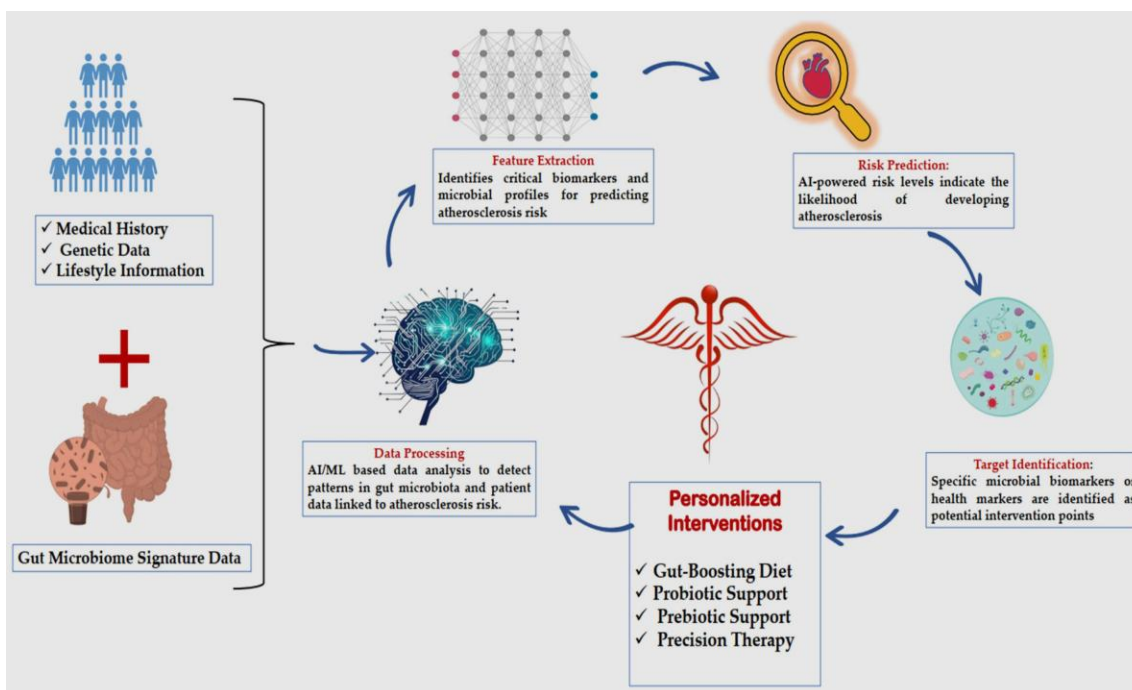


Figure 10. AI/ML technology in Microbiome biotechnology. This diagram illustrates an AI-driven pipeline for personalized atherosclerosis interventions by utilizing individual patient data and gut microbiome signatures for tailored treatment strategies. **Source:** Majumder et al. (2025)

Challenges and Limitations

Despite significant advances in microbiome biotechnology, multiple challenges constrain the translation of research into consistent industrial, clinical, and environmental applications. These limitations span technical, ethical, regulatory, and computational domains, and addressing them is crucial to ensure reproducibility, safety, and societal acceptance.

Variability, Reproducibility, and Standardization Issues

Microbiome studies frequently face high variability due to differences in host genetics, environmental conditions, sampling methods, and sequencing protocols. Such heterogeneity complicates reproducibility and cross-study comparisons (Zmora and Elinav, 2019). In industrial or

clinical applications, this variability can lead to inconsistent product yields, therapeutic outcomes, or diagnostic accuracy. Additionally, lack of standardized protocols for sample collection, microbial profiling, and data reporting hampers the establishment of universally accepted microbiome benchmarks (Greene et al, 2016). Standardization initiatives, such as MIxS (Minimum Information about any Sequence), are gradually improving consistency but widespread adoption remains incomplete.

Ethical, Biosafety, and Regulatory Barriers

Microbiome manipulation, particularly in humans, livestock, or environmental ecosystems, raises ethical and biosafety concerns. Interventions such as engineered microbial consortia or CRISPR-based in situ editing may inadvertently alter ecosystems or cause unintended health effects (Anih et al, 2025). Regulatory frameworks are still evolving, and the lack

of clear guidelines for synthetic or modified microbiomes complicates risk assessment and approval pathways. Ethical debates also surround data privacy and ownership of human microbiome information, particularly in personalized medicine contexts.

Data Integration Challenges and Gaps in Mechanistic Understanding

The vast amounts of multi-omics, environmental, and clinical data generated in microbiome studies present significant

computational challenges. Integrating metagenomics, metatranscriptomics, metabolomics, and proteomics data into coherent, mechanistic models remains a bottleneck (Zmora and Elinav, 2019). Moreover, while correlations between microbial communities and host or environmental phenotypes are increasingly documented, the causal mechanisms underlying these interactions are often poorly understood. This gap limits the ability to design predictive models or rational interventions (Anih et al, 2025). Bridging these gaps requires interdisciplinary collaboration between microbiologists, bioinformaticians, engineers, and clinicians.

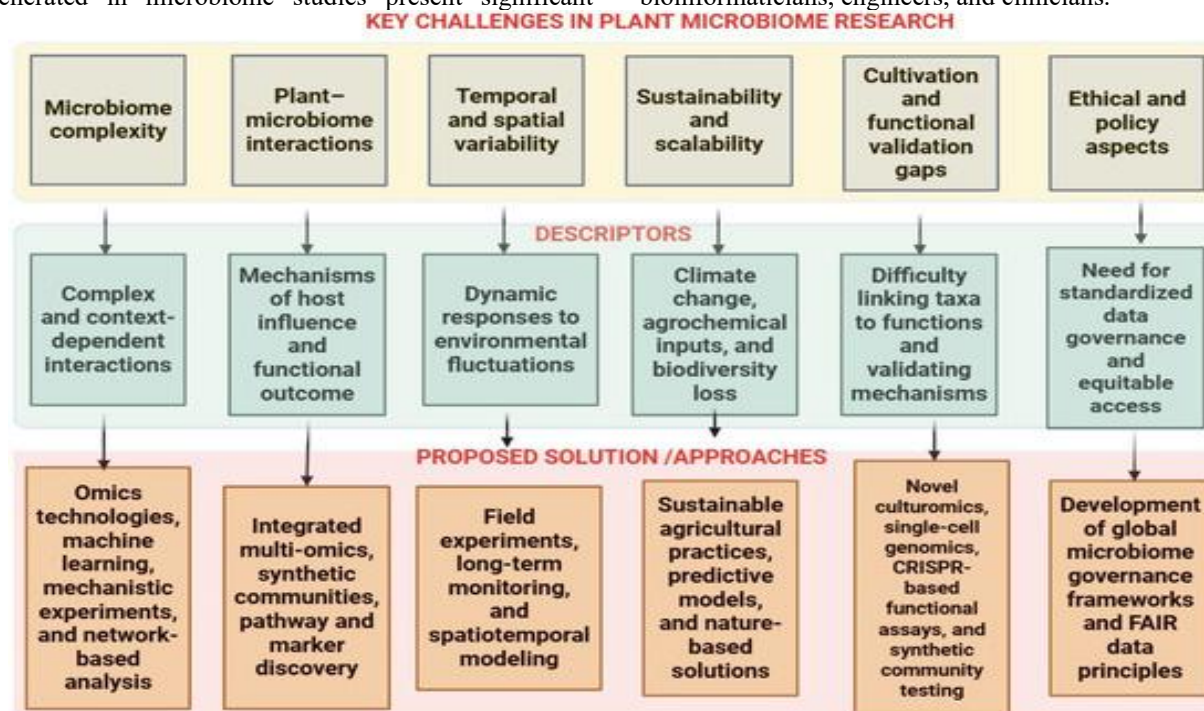


Figure 11. Structured overview of challenges, mechanistic descriptors, and proposed interventions in microbiome research.

Source: Fadiji et al. (2025)

Future Prospects

The future of microbiome biotechnology lies in the development of precision microbiome engineering strategies and personalized ecosystem interventions. Advances in synthetic biology, genome editing, and computational modeling now allow the design of microbial communities tailored to specific hosts, environmental contexts, or industrial applications (Anih et al, 2025). Such precision approaches promise to optimize microbial functions for therapeutic, agricultural, and environmental outcomes, enabling interventions that are both effective and context-specific. Personalized microbiome modulation, whether through targeted probiotics, engineered consortia, or microbiome-guided therapeutics, offers the potential to improve human health, enhance crop productivity, and restore ecosystem balance in a controlled, predictable manner (Khan and Kelly, 2021).

A critical enabler of this precision paradigm is the integration of multi-omics data, which allows high-resolution functional mapping of microbial communities. By combining metagenomics, metatranscriptomics, metaproteomics, and metabolomics, researchers can capture both the taxonomic composition and dynamic functional activity of microbiomes (Greene et al, 2016). This holistic understanding facilitates predictive modeling of microbial interactions, metabolic fluxes, and community responses to environmental or therapeutic perturbations. The convergence of multi-omics with artificial intelligence and machine learning further accelerates the identification of functional biomarkers, key regulatory nodes, and novel targets for engineering microbial systems. Beyond clinical and agricultural applications, microbiome biotechnology holds promise for advancing a circular bioeconomy and sustainable industrial processes. Microbial consortia can be harnessed to valorize waste streams, produce biofuels, generate high-value biochemicals, and restore degraded ecosystems, thereby reducing reliance on non-renewable resources and minimizing environmental impact (Khan and Kelly, 2021). Integrating microbiome-

driven strategies into circular economy frameworks can transform biotechnology into a sustainable, closed-loop system that balances economic development with ecological stewardship. Finally, future prospects depend on expanding translational research and global collaborations. Multidisciplinary partnerships among microbiologists, synthetic biologists, engineers, clinicians, and policymakers are essential to bridge fundamental discoveries with real-world applications. International collaboration will facilitate standardization of methods, harmonization of regulatory frameworks, and equitable access to microbiome technologies across regions and populations (Zmora and Elinav, 2019). By combining technological innovation, ecological insight, and collaborative frameworks, microbiome biotechnology is poised to revolutionize human health, agriculture, industry, and environmental management in the coming decades.

Conclusion

Microbiome biotechnology has emerged as a transformative field with significant applications in health, agriculture, industry, and environmental sustainability. Advances in multi-omics, synthetic microbial communities, and computational modeling are enabling precision interventions and predictive manipulation of microbial ecosystems. Integrating these technologies with genome editing, organoid systems, and artificial intelligence opens new opportunities for targeted therapeutics, sustainable bioprocessing, and ecosystem restoration. Future progress depends on deepening mechanistic understanding, standardizing methodologies, and fostering interdisciplinary collaboration to translate discoveries into practical solutions. By harnessing microbial diversity with precision and innovation, microbiome biotechnology is poised to drive sustainable and impactful advancements across multiple sectors.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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