Review Article

The Gut Microbiota — A Key Regulator of Human Health

[1]Kanan K. Patil*, [2]Divya J. Doble, [3]Prof. N. M. Wakchaware, [4]Dr. N. B. Kohale, [5]Dr. H. S. Sawarkar
[1,2]UG Scholar, Dr. Rajendra Gode College of Pharmacy, Amravati, Maharashtra, India.
[3]Assistant Professor, Dr. Rajendra Gode College of Pharmacy, Amravati, Maharashtra, India.
[4]Professor, Dr. Rajendra Gode College of Pharmacy, Amravati, Maharashtra, India.
[5]Principal, Dr. Rajendra Gode College of Pharmacy, Amravati, Maharashtra, India.
***Corresponding author's E-mail:** kananpatil17@gmail.com

Received: 14-04-2026; **Revised:** 26-06-2026; **Accepted:** 05-07-2026; **Published online:** 20-07-2026.

ABSTRACT

The human gut microbiota is a diverse and ever-changing group of bacteria, viruses, fungi, archaea, and eukaryotes that play a big role in how the body works. The gut microbiota's composition, its temporal variations, primary functions (such as nutrient degradation, immune system maturation, barrier maintenance, and inter-system signalling between the nervous and endocrine systems), the implications of dysbiosis for disease, diagnostic and analytical methodologies, therapeutic interventions (including dietary modifications, prebiotics, probiotics, postbiotics, faecal microbiota transplantation, and precision microbiome therapeutics), and the prevailing clinical, regulatory, and societal challenges. The last parts talk about questions that are still open, problems with methods, and possible new paths for translation and research.

Keywords: Gut microbiota, Dysbiosis, Faecal microbiota transplantation [FMT], Dietary Modification, Gut – brain axis, Endocrine system.

INTRODUCTION

The term "gut microbiota" refers to all the microorganisms that live in the gut. The gut microbiome, sometimes called the body's "second genome," is made up of the genes of the body.[1] In the last twenty years, advances in high-throughput sequencing, culture methods, and computational biology have changed how we think about these groups of microbes and how they affect human [2] Studies indicate that the gut microbiota influences not only digestion but also the host's metabolism, immune system, nervous system, [3] and pharmacokinetics. The aim of this article is to provide a comprehensive overview of the principal concepts, their mechanisms, implications for health, and the present condition of the gut microbiota as a regulator of human health.

Microbial Composition and biogeography of the gut

The gut contains trillions of microorganisms such as bacteria, fungi, viruses, and others. In healthy adults, the major bacteria present are Firmicutes and Bacteroidetes, [4] while Actinobacteria, Proteobacteria, and Verrucomicrobia are present in smaller amounts. These microbes [5] are not evenly distributed in the gut; different regions like the small intestine and large intestine have different microbial populations, [6] and even microbes in the gut lumen differ from those attached to the gut lining. Also, each person has a unique microbial composition, but many microbes perform similar functions, showing functional redundancy. [7] The distribution and growth of these microbes depend on local conditions like pH, oxygen levels, and mucus. Therefore, understanding how these microbes vary in different locations and over time is important to link their composition with their function.

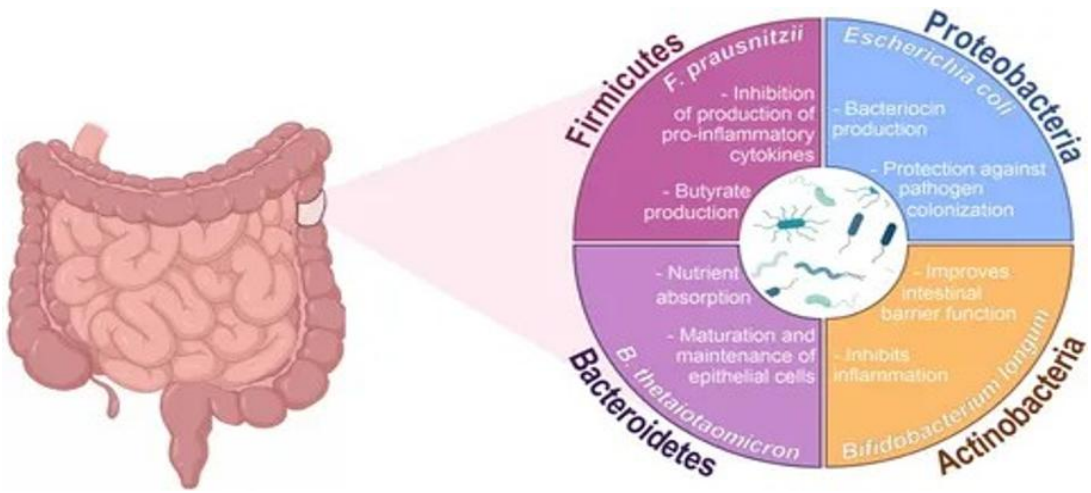

Figure 1: Composition of the gut microbiota[8]

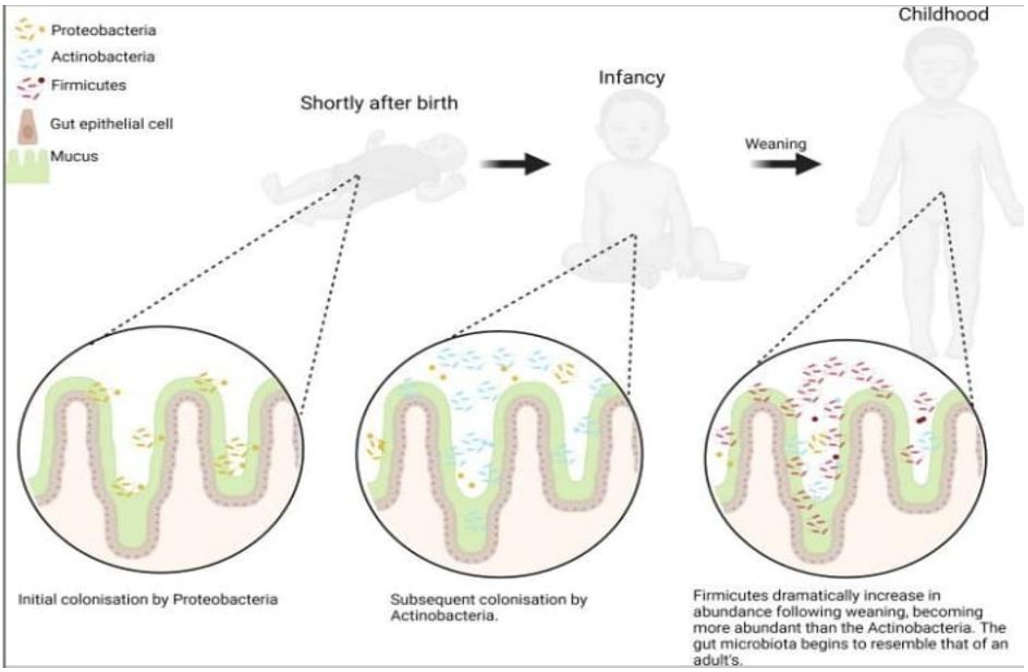

Figure 2: Development of Gut Microbiota [12]

Development and determinants of gut microbiota

The growth of gut microbiota starts from birth (and some studies suggest even before birth, though this is still debated) and continues through all stages of life like infancy, childhood, adulthood, and old age.[9]Many factors influence this process, such as the mode of delivery (normal or cesarean), type of infant feeding (breastfeeding or formula),[10] and use of antibiotics. Apart from this, diet throughout life, genetics, immune system, and lifestyle factors like environment, hygiene, and living conditions also play an important role. The Microbiota usually becomes stable by around 2–3 years of age, but it can still change due to factors like diet, illness, and medications [11]

Core Function of the Gut Microbiota

The gut microbiota plays an important role in our body, especially in metabolism. It helps in digestion and improves nutrient absorption from food. These microbes also produce essential vitamins like vitamin K and some B vitamins. [13] They break down fibers that our body cannot digest and convert them into short-chain fatty acids (SCFAs) such as acetate, propionate**,** and butyrate. These SCFAs provide energy to colon cells (colonocytes) and help maintain gut health. [14]

The gut microbiota plays many important roles in the body. It helps in digestion, produces vitamins, and forms short-chain fatty acids (SCFAs) that provide energy to gut cells. These SCFAs also help in controlling metabolism and act as signaling molecules that influence insulin sensitivity, appetite, and fat metabolism [15]. Gut microbes are also very important for the immune system, as they help the body learn to tolerate harmless substances like food while still protecting against harmful pathogens. They support the development of immune cells and maintain immune balance. In addition, they help keep the intestinal barrier strong by promoting mucus production, maintaining tight junctions, and producing antimicrobial substances. If this balance is disturbed, it can lead to increased inflammation and problems like a "leaky gut," which is linked to many diseases.

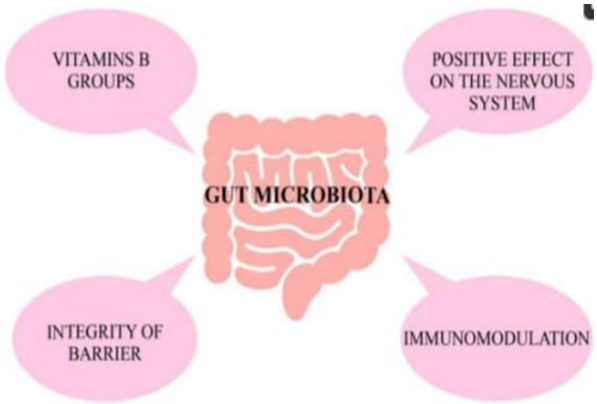

Figure 3: Function of Gut Microbiota [16]

The gut microbiota also communicates with the brain through the gut–brain axis.[17] It uses different pathways like microbial metabolites (such as SCFAs and tryptophan metabolites), immune signals, and even the nervous system, especially the vagus nerve.[18]These microbes can influence gut hormone-producing cells and send signals to the brain. Because of this connection, gut microbes can affect our mood, behavior, and overall brain function. Studies in animals and some human research also suggest that changes in gut microbiota may impact mental health and neurological conditions .[19]

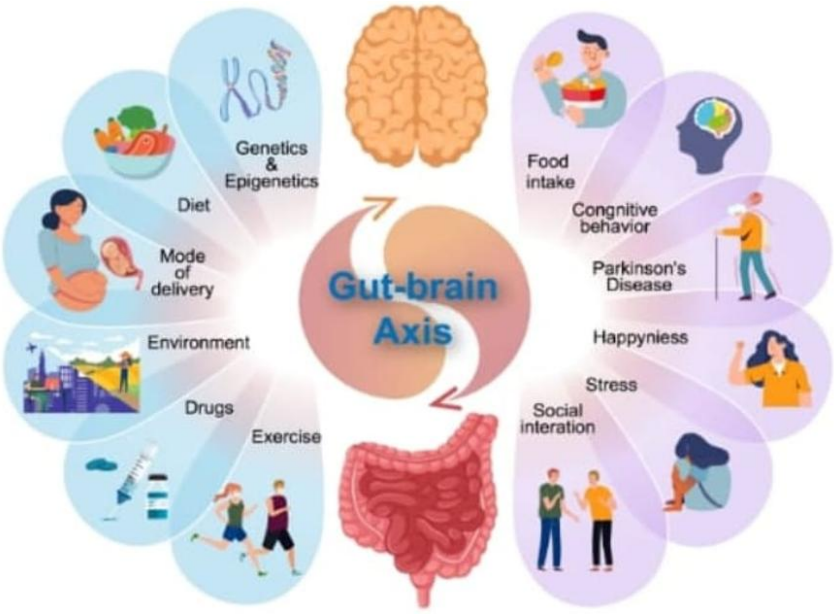

Figure 4: Gut brain axis [20]

Mechanisms of host – microbe communication

KEY MECHANISMS INCLUDED

The gut microbiota works through several important mechanisms. It produces different metabolites like SCFAs, bile acid metabolites, and neurotransmitter precursors, which help in signaling inside the body. It also interacts with the host immune system through pattern recognition receptors that detect microbial components (MAMPs). Gut microbes can modify bile acids and influence signaling pathways like FXR and TGR5, which are important for metabolism. In addition, microbes can exchange genes among themselves (horizontal gene transfer), which can change their metabolic abilities. However, research is still ongoing to clearly understand whether these mechanisms directly cause effects or are just associated with them. [21]

Dysbiosis: Definitions causes, and disease associations

Dysbiosis refers to a disruption or imbalance in the normal community of microorganisms living in the human body, particularly in the gut. A healthy microbiome supports digestion, The gut microbiota is very important for immunity, proper nutrient absorption, and overall health. When this balance is disturbed—meaning beneficial microbes decrease or harmful microbes increase—it leads to a condition called dysbiosis. This imbalance can negatively affect normal body functions and may contribute to various health problems.[22]

Causes of Dysbiosis

Several factors can disturb the natural microbial balance, including: [22]

- Taking antibiotics or medicines for a long time can disturb good bacteria
- Eating unhealthy food (less fiber, more fat/junk food) affects gut balance
- Infections or food poisoning can damage gut microbes
- Too much stress also impacts gut health
- Poor sleep and lack of physical activity worsen the condition
- Genetic factors also influence how our body interacts with microbes

1. Metabolic Disorders

- Changes in gut microbiota are linked with conditions like obesity, type 2 diabetes, and insulin resistance[23]
- Dysbiosis can increase energy extraction from food, leading to weight gain[24]
- It affects SCFA signaling, which is important for metabolism[25]
- Harmful substances like endotoxins (LPS) can cause low-grade inflammation[26]
- It can alter bile acid metabolism, affecting digestion and metabolic processes[27]
- All these changes together contribute to metabolic disorders

2. Gastrointestinal Diseases

- Conditions like IBD and IBS are linked with changes in gut microbiota[28]
- There is a decrease in microbial diversity (less variety of good bacteria)
- Beneficial bacteria like Faecalibacterium are reduced
- No single bacteria is responsible for these diseases[29]
- However, dysbiosis plays an important role in worsening symptoms and disease progression[30]

3. Neurological and Psychiatric Disorders

Research shows that gut microbiota can affect brain development, behavior, and mood

This connection is known as the gut–brain axis

Animal studies show that microbes can influence behavior[31]

In humans, dysbiosis is linked with conditions like:

Autism spectrum disorders [32]

Depression and anxiety

Parkinson's disease

However, more research is needed to prove direct cause-and-effect relationships.[28]

4. Liver, Cardiovascular Disease and Cancer

Gut microbiota also plays a role in several other diseases. Certain microbial metabolites like TMAO [29] are associated with an increased risk [33] of cardiovascular diseases. When gut microbial balance is disturbed, it can also contribute to conditions like non-alcoholic fatty liver disease (NAFLD) [34]. In the case of colorectal cancer, dysbiosis may lead to chronic inflammation and the production of harmful substances that can damage cells. Overall, imbalance in gut microbiota can have serious effects on different body systems and disease development. [35]

Methods and Technologies Used in Microbiome Research

Modern microbiome research uses advanced techniques to study the composition, diversity, and functions of microbes present in the human body. Scientists use different molecular and culture-based methods to identify not only which microorganisms are present but also to understand their roles and how they affect human health and disease.

Commonly Used Approaches

- **16S rRNA Gene Sequencing:**

This method is commonly used to identify and classify bacteria based on the 16S rRNA gene. It helps in understanding overall microbial diversity and gives an idea about the types and relative amount of bacteria present. [36]

- **Shotgun Metagenomic Sequencing**:

This technique studies all the genetic material in a sample, not just specific genes. It provides more detailed information at the strain level and helps to understand the functional abilities and metabolic potential of microbes. [37]

- **Multi-omics Approaches:**

These include methods like metatranscriptomics, metaproteomics, and metabolomics. They help in studying different aspects of microbial activity such as gene expression, protein production, and metabolite formation. Together, they give a clear idea about what microbes are actually doing and how they interact with the host. [38]

- **Culturomics:**

This technique uses advanced and high-throughput culture methods with different growth conditions to grow and identify microbes that were earlier difficult or impossible to culture. It helps in discovering new microorganisms and also supports detailed functional studies of these microbes .[39]

Limitations and Challenges

Sampling variability:

Stool samples may not fully represent the actual microbiota present in specific areas of the gut, especially the mucosal layer.[40]

Batch effects:

Differences in sample processing or sequencing methods can affect the results and create variation between studies.

Limited functional understanding:

Techniques like 16S sequencing mainly identify bacteria but do not clearly explain their exact functions. [41]

Lack of standardization:

Different bioinformatics methods and analysis pipelines can lead to inconsistent results and interpretations. Interventions to modulate the Gut Microbiota

The composition of the gut microbiome is not fixed; it can be shaped and improved through several lifestyle and therapeutic strategies. These interventions aim to restore microbial balance, enhance beneficial bacteria, and support overall gut health.

Diet and Lifestyle Approaches

Diet is one of the most important factors that affects gut microbiota. Eating a balanced diet rich in fiber and plant-based foods helps increase microbial diversity and promotes the production of short-chain fatty acids (SCFAs), which are essential for gut health and help reduce inflammation.[42] On the other hand, diets high in fat, processed foods, and low in fiber can disturb the gut microbiota and lead to dysbiosis. Along with diet, regular exercise, proper sleep, and stress management also help in maintaining a healthy and stable gut microbiota. In addition, approaches like prebiotics, probiotics, synbiotics, and postbiotics are used to support and improve gut health. [43]

- **Prebiotics:**

Prebiotics are non-digestible fibers that act as food for beneficial gut bacteria. They help in promoting the growth of good microbes and improve their activity in the gut. [44]

- **Probiotics:**

Probiotics are live microorganisms that provide health benefits when taken in proper amounts. Their effects depend on the specific strain used, and different strains may work for different health conditions. [45]

- **Postbiotics:**

Postbiotics are substances produced by microbes, such as metabolic products or cell components.[46] Even though they are not live, they can have beneficial effects like reducing inflammation, providing antioxidant action, and supporting the immune system.

- **Synbiotics**

Synbiotics combine prebiotics and probiotics to optimize their synergistic benefits and improve microbial survival and function. [47]

Antibiotic Use

Antibiotics can significantly disrupt the natural microbial balance. While essential for treating bacterial infections, they may cause short-term or long-lasting changes in the microbiome and increase susceptibility to infections such as Clostridioides difficile, especially after repeated or broad-spectrum antibiotic use. [48]

Fecal Microbiota Transplantation (FMT)

FMT involves transferring stool from a healthy donor into the digestive tract of a recipient to restore microbial diversity.[49] It has shown remarkable success in treating recurrent C. difficile infection and is currently being studied as a potential therapy for IBD, IBS, and metabolic disorders. Questions regarding safety, donor screening, and long-term outcomes are still being actively researched.[50]

Next-Generation Therapeutics

- Emerging microbiome-based therapies are moving toward greater precision. These include
- Engineered microbial strains
- Defined multi-strain microbial consortia (live biotherapeutics)[51]
- Bacteriophage therapy targeting specific pathogens
- Small-molecule drugs designed to modify microbial metabolism
- These advanced strategies represent the future direction of microbiome[52]

Clinical Translation and Current Developments in Microbiome Science

Regulatory Environment and Clinical Trials

Microbiome research is now moving from basic studies to clinical applications, but its translation into medical practice is still developing. Scientists are working on therapies like probiotics, prebiotics, and microbiome-based treatments, but their use requires proper regulation to ensure safety and effectiveness. The regulatory environment is complex because microbiome products can be classified as drugs, supplements, or biologics depending on their use. Clinical trials are ongoing to test these therapies for different diseases, but results can vary due to differences in individuals and microbial composition. Although there is promising progress, more well-designed clinical trials and standardized guidelines are needed before microbiome-based therapies can be widely used in healthcare.

Clinical translation in microbiome science is still developing, as researchers are working to convert scientific findings into real medical treatments. Many therapies like probiotics, prebiotics, and fecal microbiota transplantation (FMT) are being studied in clinical trials to evaluate their safety and effectiveness. However, the regulatory environment is still not fully clear, as microbiome-based products do not always fit into traditional categories of drugs or supplements. Different countries have different guidelines, which makes approval and standardization challenging. Ongoing clinical trials are helping to better understand how microbiome-based therapies can be used for treating various diseases, but more research is needed to establish clear evidence and guidelines for their use.

The field of microbiome-based therapeutics is rapidly developing, and several live biotherapeutic products and defined microbial consortia are currently being evaluated in clinical trials for conditions such as inflammatory bowel disease, metabolic disorders, and other chronic illnesses. Regulatory bodies, including the U.S. [53] FDA, are actively working on guidelines for evaluating the safety, quality, and efficacy of microbiome therapies. Since the science is still evolving, regulatory frameworks continue to adapt to new discoveries and clinical needs. [54] Gut microbiota also plays a role in several other diseases.

Commercial Microbiome Testing: Potential and Challenges

An increasing number of commercial companies now offer direct-to-consumer microbiome tests, claiming to provide personalized dietary or health recommendations based on stool samples. [57] While these services attract interest, recent analyses show significant variation between laboratories, with differences in sequencing techniques and data interpretation. Because of this lack of standardization, results may not be accurate or clinically meaningful.

Experts emphasize caution, noting that most consumer microbiome tests have not been validated for medical diagnosis or treatment decisions, and should not replace professional healthcare guidance. [58]

Role of the Microbiome in Personalized Medicine

The microbiome is expected to play a major role in precision healthcare. Research is exploring how microbial composition may influence: [59]

Response to medications (pharmacomicrobiomics)

Nutritional needs and personalized diet plans

Risk prediction for chronic diseases

For this vision to become reality, the field requires reliable causal evidence, standardized analytical approaches, and clear regulatory pathways that ensure safety and effectiveness.

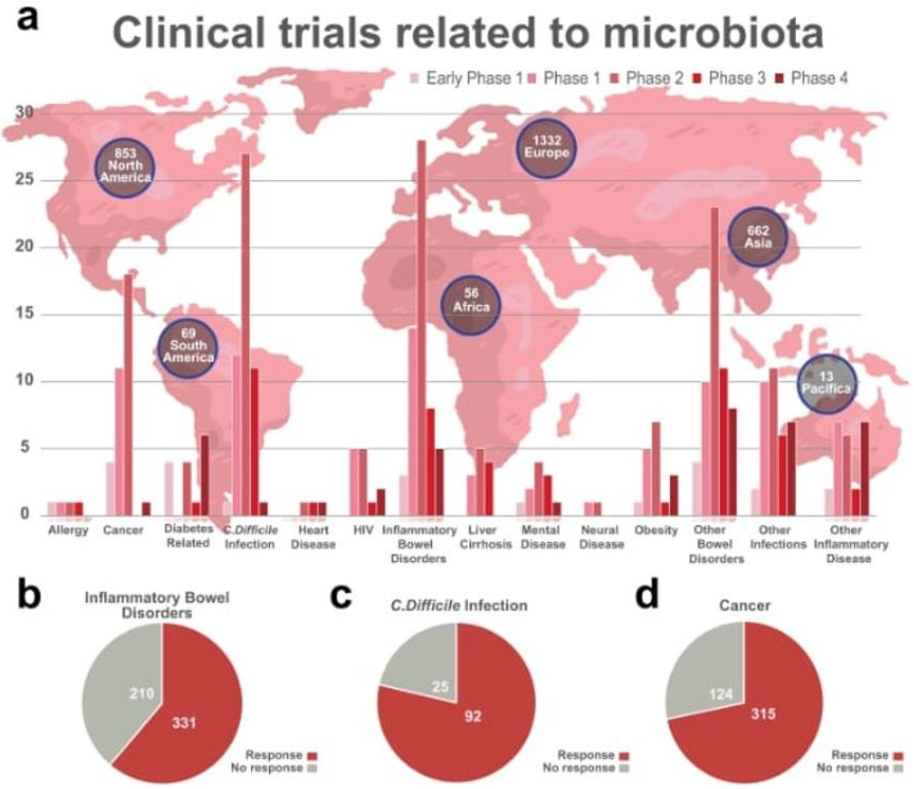

Figure 5: Clinical trials related to gut microbiota by regions[56]

Ethical, Societal, and Practical Considerations

As microbiome research moves closer to clinical and commercial application, several important ethical and practical challenges need careful attention. One major concern involves informed consent, particularly in procedures such as fecal microbiota transplantation (FMT), where donor material is transferred from one individual to another. Ensuring that donors and recipients understand potential risks, long-term uncertainties, and regulatory safeguards is essential.

Another significant issue relates to privacy and data protection. Microbiome and genomic information can reveal sensitive personal details, and improper handling or unauthorized use of such data may pose serious privacy risks. Establishing robust data security and transparent policies is therefore critical. [59]

Fair access to microbiome-based therapies is also an emerging concern. Advanced interventions, commercial diagnostics, and personalized treatments may become expensive, creating inequity between different socioeconomic groups. Ensuring accessibility and affordability will be important for ethical implementation.[60]

Additionally, the rapid growth of the microbiome industry has generated substantial public excitement, sometimes accompanied by exaggerated commercial claims. Experts caution that scientific evidence must guide clinical and consumer decisions, preventing misinformation and unrealistic expectations.[60]

Gaps in Knowledge and Future Directions (Expanded, Human-Written Version)

Although microbiome research has advanced rapidly over the last decade, there are still many unanswered questions that limit full clinical translation. One of the most significant challenges is the difficulty in distinguishing causation from correlation. Many studies show strong associations between microbial patterns and diseases [59] but it is still unclear whether the altered microbiome triggers the disease or whether the disease itself causes microbial disruption. Establishing causality will require controlled clinical trials, mechanistic studies, and advanced experimental models.

Another major area requiring improvement is standardization. Microbiome research relies heavily on sequencing-based approaches, yet methods for sample collection, storage conditions, DNA extraction, sequencing platforms, and bioinformatic pipelines vary widely between laboratories [60]. These inconsistencies make it difficult to compare results across studies and create reliable clinical benchmarks.

There are also unanswered questions surrounding the long-term safety, stability, and regulatory oversight of microbiome-based therapies, including fecal microbiota transplantation (FMT), live biotherapeutics, and engineered microbial strains. Issues such as durability of treatment effects, potential pathogen transfer, immune complications, and unintended ecological disruptions need careful evaluation through long-term follow-up studies.

Additionally, while most research focuses on bacteria, the gut ecosystem contains many other key members — including viruses (especially bacteriophages), fungi, archaea, and protozoa—whose roles remain poorly understood. These non-bacterial communities may significantly influence immune function, metabolism, and infection resistance, yet they remain understudied.

Moreover, the detailed molecular mechanisms of microbe–host communication at the strain level are not well characterized. Understanding how specific microbial molecules interact with intestinal cells, immune receptors, and neural signaling pathways will be essential for developing precision therapies.

Promising Future Research Directions

To overcome existing limitations, the field is moving towards more integrated and powerful research strategies, including:

Longitudinal cohort studies that monitor individuals over time to understand dynamic microbiome changes and disease progression [59]

Multi-omics integration, combining genomics, transcriptomics, proteomics, metabolomics, and immune profiling for a holistic understanding of function rather than just composition.

Synthetic ecology and rational design of microbial consortia, creating defined combinations of strains engineered for therapeutic purposes.

Pragmatic clinical trials assessing real-world efficacy of dietary strategies, lifestyle interventions, and microbiome-targeted therapies [60]

Advanced computational modeling and AI tools to predict microbial interactions and host responses

These approaches are expected to provide stronger mechanistic evidence, improve therapeutic precision, and accelerate translation into effective clinical application

CONCLUSION

The gut microbiota has emerged as one of the most influential regulators of human physiology, extending far beyond digestion to affect immunity, metabolism, brain function, and overall health. The microbial ecosystem living within us acts like a dynamic organ, constantly interacting with the host through biochemical, neurological, and immune pathways. Understanding these interactions has reshaped modern perspectives on chronic diseases and has opened new avenues for prevention and treatment.

In recent years, research has rapidly advanced from basic observational studies to mechanistic exploration and clinical translation. Novel technologies have made it possible to analyze microbial communities with increasing precision and to explore how they contribute to disease processes. However, despite remarkable progress, microbiome-based therapies are still in their early stages. For the field to achieve reliable clinical implementation, strong causal evidence, standardized research methodologies, and robust regulatory guidance are critically important. Without these elements, real-world medical application remains limited.

Diet and lifestyle continue to be the most grounded and accessible strategies for shaping the gut microbiome. A fiber-rich, diverse diet and healthy lifestyle habits provide consistent benefits and form the cornerstone of microbiome-based health interventions. Meanwhile, next-generation therapeutics such as engineered microbes, defined microbial consortia, bacteriophage treatments, and precision metabolite-based therapies represent a rapidly evolving frontier with tremendous potential.

As research expands to consider long-term outcomes, safety, and equitable access, the future of microbiome science appears highly promising. Integrating multi-omics, computational modeling, and real-world clinical trials will likely transform personalized medicine, enabling treatments tailored to individuals based on their microbial signatures. With thoughtful development and responsible translation, microbiome-based interventions may become transformative tools in healthcare, helping prevent disease, enhance treatment effectiveness, and improve lifelong well-being.

Source of Support: The author(s) received no financial support for the research, authorship, and/or publication of this article

Conflict of Interest: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

1. Thursby E, Juge N. Introduction to the human gut microbiota. Biochemical Journal. 2017;474(11):1823-36.
2. Valdes AM, Walter J, Segal E, Spector TD. Role of the normal gut microbiota in nutrition and health. BMJ. 2018;361:k2179.
3. Hou K, Kato K, et al. Microbiota in health and diseases. Signal Transduction and Targeted Therapy. 2022;7(1):135.
4. Afzaal M, et al. Human gut microbiota in health and disease: Unveiling the relationship. Frontiers in Microbiology. 2022;13:999001.
5. Thursby E, Juge N. Introduction to the human gut microbiota. Biochem J. 2017.
6. Fan Y, Pedersen O. Gut microbiota in human metabolic diseases. Nat Rev Microbiol. 2021.
7. Marchesi JR, et al. The gut microbiota and host health. Nat Rev Genet. 2016.
8. Clemente JC, et al. The impact of the gut microbiome on health. Science. 2012.
9. Shreiner AB, Kao JY, Young VB. Role of the gut microbiota in infectious and inflammatory diseases. Gastroenterology. 2015;148(6):1085–1098.
10. Valdes AM, Walter J, Segal E, Spector TD. Role of the gut microbiota and diet. BMJ. 2018;361:k2179.
11. Rinninella E, Raoul P, Cintoni M, Franceschi F, Miggiano GAD, Gasbarrini A, et al. Gut microbiota composition and diet. Eur Rev Med Pharmacol Sci. 2019;23(2):152–162.
12. Daliri EB, Ofosu FK, Chelliah R, Oh DH. Prebiotics, probiotics, and synbiotics. Foods. 2021;10(9):2096.

13. Selvakumar D, Evans D, Coyte KZ, McLaughlin J. Understanding the development and function of the gut microbiota in health and inflammation.
14. Pickard JM, Zeng MY, Caruso R, Núñez G. Gut microbiota and immune homeostasis. Nat Rev Immunol. 2017;17(12):708–720.
15. LeBlanc JG, Milani C, de Giori GS, Sesma F, van Sinderen D, Ventura M. Bacteria as vitamin suppliers to their host: a gut microbiota perspective. Curr Opin Biotechnol. 2017;49:1–8.
16. Koh A, De Vadder F, Kovatcheva-Datchary P, Bäckhed F. From dietary fiber to host physiology: short-chain fatty acids as key bacterial metabolites. Nat Rev Gastroenterol Hepatol. 2016;13(10):661–678.
17. Augustynowicz G, Lasocka M, Szyller HP, Dziedziak M, Mytych A, Braksator J, Pytrus T. The role of gut microbiota in the development and treatment of obesity and overweight: a literature review. 2025.
18. Chambers ES, Morrison DJ, Frost G. Control of appetite and energy intake by SCFAs: mechanisms and therapeutic potential. Nat Rev Endocrinol. 2023;19(7):415–432.
19. Cryan JF, O'Riordan KJ, Cowan CSM, Sandhu KV, Bastiaanssen TFS, Boehme M, et al. The microbiota–gut–brain axis. Nat Rev Neurosci. 2019;20(3):145–166.
20. Sarkar A, Lehto SM, Harty S, Dinan TG, Cryan JF, Burnet PWJ. Psychobiotics and the manipulation of bacteria–gut–brain signals. Trends Neurosci. 2021;44(11):747–759.
21. Hou K, Wu ZX, Chen XY, Wang JQ, Zhang D, Xiao C, Zhu D, Koya JB, Wei L, Li J, Chen ZS. Microbiota in health and diseases. Signal Transduct Target Ther. 2022;7:135.
22. Kelly JR, Borre Y, O'Brien C, et al. Transferring the blues: Depression-associated gut microbiota induces neurobehavioural changes in the rat. J Psychiatr Res. 2016.
23. Heintz-Buschart A, Pandey U, Wicke T, et al. The Human Parkinson's disease microbiome. Nat Commun. 2018.
24. Wu GD, Chen J, Hoffmann C, et al. Linking long-term dietary patterns with gut microbial enterotypes. Science. 2011.
25. Ley RE, Turnbaugh PJ, Klein S, Gordon JI. Microbial ecology: Human gut microbes associated with obesity. Nature. 2006.
26. Cani PD, Amar J, Iglesias MA, et al. Metabolic endotoxemia initiates obesity and insulin resistance. Diabetes. 2007.
27. Qin J, Li Y, Cai Z, et al. A metagenome-wide association study of gut microbiota in obesity. Nature. 2010.
28. Aron-Wisnewsky J, Prifti E, Belda E, et al. Major microbiota dysbiosis in severely obese patients undergoing bariatric surgery. Gut. 2019.
29. Zinöcker MK, Lindseth IA. The Western diet–microbiome interaction and chronic disease. Nutrients. 2018.
30. Sinha R, Ahn J, Sampson JN, et al. Fecal microbiota and colorectal cancer. Nat Rev Gastroenterol Hepatol. 2016.
31. Tilg H, Adolph TE, Dudek M, Knolle P. Non-alcoholic fatty liver disease and the gut–liver axis. Nat Rev Gastroenterol Hepatol. 2020.
32. Tang WH, Wang Z, Levison BS, et al. Intestinal microbial metabolite TMAO and cardiovascular risk. N Engl J Med. 2013.
33. Lloyd-Price J, Arze C, Ananthakrishnan AN, et al. Multi-omics of the gut microbiome in IBD. Nature. 2019.
34. Zhuang ZQ, Shen LL, Li WW, et al. Gut microbiota is altered in Alzheimer's disease. J Transl Med. 2018.
35. Rajilić-Stojanović M, Jonkers DM, Salonen A, et al. Intestinal microbiota and IBS. Gastroenterology. 2015.
36. Paramsothy S, Kamm MA, Kaakoush NO, et al. Multidonor intensive faecal microbiota transplantation for ulcerative colitis. Lancet. 2017.
37. Ooijevaar RE, et al. Update on fecal microbiota transplantation. Gastroenterology. 2019.
38. Allegretti JR, et al. FMT clinical pipeline. Gut Microbes. 2020.
39. Browne HP, et al. Culturomics. Nat Microbiol. 2016.
40. Almeida A, et al. Microbial genome catalogue. Nature. 2019
41. Gilbert JA, et al. Microbiome standards. Nat Microbiol. 2016.
42. Integrative Human Microbiome Project. 2021.
43. Suez J, et al. Probiotics: problems and promises. Cell. 2019.
44. Thursby E, Juge N. Gut barrier integrity. Biochem J. 2017.
45. Martinez KB, et al. Gut barrier dysfunction. Am J Physiol. 2021.
46. Vangay P, et al. Microbiome shifts with migration. Cell. 2018.
47. Faith JJ, et al. Strain-level microbiota dynamics. Science. 2013.
48. Marco ML, et al. Probiotic regulatory framework. Gut Microbes. 2021.
49. 45. FDA Guidance for Live Biotherapeutic Products. 2024.
50. Suez J, et al. Personalized responses to probiotics. Cell. 2018.
51. Flandroy L, et al. Western lifestyle and microbiome. Front Microbiol. 2018.
52. Sonnenburg ED, Sonnenburg JL. Diet–microbiota co-evolution. Nature. 2019.
53. Zmora N, et al. Microbiome variability. Cell Host Microbe. 2018.
54. Hill C, et al. Definition of probiotic. Nat Rev Gastroenterol Hepatol. 2018.
55. Moayyedi P, et al. Probiotics for IBS. BMJ. 2010.
56. Dehingia M, et al. Indian gut microbiome transitions. Microbiome. 2022.
57. Bajaj JS. Microbiome and liver disease. Nat Rev Gastroenterol Hepatol. 2019.
58. Xu X, et al. Microbiome and can cancer immunotherapy. Nat Rev Clin Oncol. 2020.
59. El Hage R, et al. Postbiotics. Nutrients. 2022.
60. Barr JJ. Phage therapy and microbiome. Cell Host Microbe. 2019.
61. Aguilar-Toalá JE. Post-COVID microbiome shifts. Gut Microbes. 2023.
62. World Health Organization. Review of antibiotics and microbiome. 2024.
63. Nature Editorial. Microbiome hype vs evidence. Nature. 2024.
64. Time Magazine. Gut health and mood. 2025.