Microbiome Modulation: The Nexus of Nutrition, Environment, and Holistic Wellbeing

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Abstract

Modulating the human microbiome has emerged as a transformative frontier in precision medicine, offering substantial promise for chronic disease prevention and long-term health optimization. This chapter explores how strategic microbiome interventions influence systemic physiology. Incorporating fiber-rich and fermented foods was shown to enhance microbial diversity, support gut barrier integrity, and modulate immune and metabolic pathways. These dietary shifts contribute to reductions in systemic inflammation and improved nutrient metabolism. Reduced reliance on antibiotics, alongside greater exposure to natural environments, also played a key role in maintaining microbial balance and preventing dysbiosis. The chapter further highlights the application of advanced microbiome profiling techniques to tailor individualized interventions. Personalized approaches have proven effective in addressing metabolic disorders, autoimmune conditions, and mental health issues through targeted modulation of the gut microbiota. Such evidence reinforces the concept that microbiome composition is not only a reflection of health but also a powerful tool for intervention, with implications spanning dietary therapy, immunomodulation, and neurobehavioral regulation.

Keywords: Microbiome, Gut health, Nutrition, Immune health, Mental health

Cite this Article as: Naseer A, Noor M, Latif S, Zafar R, Shafiq L, Alam S, Rao QT and Hussain R, 2025. Microbiome modulation: The nexus of nutrition, environment, and holistic wellbeing. In: Şahin T, Ameer K, Abid M and Tahir S (eds), Nutritional Foundations of Holistic Health: From Supplements to Feed Strategies. Unique Scientific Publishers, Faisalabad, Pakistan, pp: 265-271. https://doi.org/10.47278/book.HH/2025.339

A Publication of Unique Scientific Publishers

Chapter No: 25-038

Received: 13-Feb-2025
Revised: 04-Apr-2025
Accepted: 05-May-2025

Introduction

The human microbiome (also known as the 'hidden organ') is a complex community of microorganisms that live in or on the human body including bacteria, viruses, fungi and archaea (Ogunrinola et al., 2020). The umbrella of this diverse global ecosystem is most populated in the gut, where trillions of microbes live and interdepend upon the host to uphold and sustain homeostasis. Essential roles are occupied by the microbiome in digestion, immune modulation, nutrient absorption and the (ddot) production of vital compounds such as short chain fatty acids and neurotransmitters (Zhang, 2022). Beyond the gut, its effect is profound, influencing the ways a person metabolizes, regulates mood, and remains health. A great understanding of the microbiome is a prerequisite to fully appreciate its role on health and disease (Aggarwal et al., 2022).

Nutrition, environment, and well-being are just a few of the many things the microbiome is tied. Dietary choices influence microbial diversity and functionality in a way that nutrition is a paramount modulator of the microbiome. Foods high in fiber, like fruits, vegetables, and legumes, support growth of the beneficial microbes; while processed foods and high sugary diets cause dysbiosis, the state of a microbial imbalance which is linked to a range of diseases (de Vries et al., 2022; Warbrick et al., 2023). Toxin, pollutant among others exposure, and even urbanization, can also radically change the state of microbial ecosystem. In contrast, the natural environment and physical activity promote microbial diversity in keeping with the interconnectedness between lifestyle, environment, and microbiome health (Bhardwaj et al., 2024). The importance of the microbiome in exhibiting relationships that link holistic well-being from nutrition and the environment to physical, mental and emotional health (Wilson et al., 2024).

2. The Microbiome and Its Functions

The most complex human body ecosystem is the microbiome, more specifically the gut microbiota, made up of trillions of microorganisms that differ in number and types. At the level of physiological processes, this diversity plays a critically important role in maintaining health and homeostasis, while at multiple other levels of biologic organization, it enables intricate communication pathways between the gut and the other body systems (Gomaa, 2020; Tretter et al., 2021).

2.1 Gut Microbiota Diversity

In fact, on any average normal day, the human gut microbiota is a complex community consisting of over 1,000 different species of microorganisms, primarily bacteria, but also archaea, fungi and viruses. Together, these microorganisms represent genes encoding many more genes that are found in the human genome itself, enabling a broad collection of metabolic capabilities which the human host cannot accomplish without (Adak & Khan, 2021). Gut bacteria include *Firmicutes, Bacteroidetes, Actinobacteria* and *Proteobacteria*, but their proportions between individuals differ greatly, being influenced by diet, genetic, age, or environment. In other words, this diversity is not due to randomness but instead because of microbes specialized roles in maintaining gut health. One example is that Bacteroides species are so efficient at breaking down complex carbohydrates to short chain fatty acids (SCFAs) like butyrate, acetate, and propionate that they supply colonocytes with the energy and regulate inflammatory response (Rinninella et al., 2019; Wang et al., 2019; Syromyatnikov et al., 2022). One instance of such disorders with associated reduced microbial diversity, often referred to as dysbiosis, is obesity, diabetes, inflammatory bowel disease (IBD) and neurodegenerative disorders, including Alzheimer's (Doroszkiewicz et al., 2024). Gut microbiota diversity also reflects resilience. A more diverse microbiome is better equipped to adapt to dietary changes, environmental stressors, and pathogenic invasions. This adaptability underscores the importance of nurturing microbial diversity through balanced nutrition, exposure to natural environments, and reduced reliance on antibiotics. The gut microbiome performs several essential functions that are vital to overall health, encompassing digestion, immunity, and neurotransmitter production (Bodawatta et al., 2021).

2.2 Nutrition and Digestion & Absorption of Nutrients

It is the microbiome that can digest dietary components that the host's digestive enzymes cannot. Gut bacteria ferment complex carbohydrates (dietary fiber) into SCFAs to provide energy as well as to regulate pH levels in the colon away from acidic to slightly alkaline, to inhibit the growth of pathogenic organisms. But importantly, too, microbes also help to manufacture needed vitamins, such as vitamin K, and B vitamins, which are vital for metabolism and neurological functions (Peled & Livney, 2021).

2.3 Immune System Modulation

Immune system development and function depends on the gut microbiome. It had a conversation with the immune system in the gut-associated lymphoid tissue (GALT) and teaches the immune system what is harmful and what is harmless (antigens) (Scarpellini et al., 2020). The *Faecalibacterium prausnitzii* is a commensal bacterium that produces anti-inflammatory metabolites, and others regulate the production of cytokines to prevent excessive immune responses (He et al., 2021).

2.4 Neurotransmitter Production

The fact that the microbiome influences brain function through the production of neurotransmitters and neuromodulators is well known. Gut bacteria also can make gamma-aminobutyric acid (GABA), which calms the central nervous system, or serotonin, an important mood, emotion, and sleep regulator (Liwinski et al., 2023). In fact, as much as 90 % of the body's serotonin is produced in the gut, and that's got to make a dent in mental health (Akram et al., 2024). Changes in microbial populations can lead to imbalances of neurotransmitter production associated with anxiety, depression and other neuropsychiatric disorders (Anand et al., 2022).

2.5 Microbiome Body Communication

To influence systemic physiology, the microbiome is tightly wired into elaborate pathways that connect gut health to broader physiological systems. The gut brain axis is the first and immune modulation pathway is the second primary channel of communication (Aburto & Cryan, 2024). The gut brain axis is a bidirectional system of communication through the gut and CNS using neural, hormonal, and immune pathways. The longest cranial nerve, the vagus nerve, acts as a direct route of gut to brain microbial input, dictating mood, behavior and cognition (Makris et al., 2021). There are interventions aimed at the microbiome (probiotics and prebiotics) that have shown promise in returning the communication between the gut and brain to normal and solving mental health disorders (Sasso et al., 2023).

Interactions of gut microbiome with epithelial barrier and immune cells in the gut lining can directly affect immune responses. Commensal bacteria, trigger the production of the immunoglobulin A (IgA), which coats the lining of the gut and prevents the pathogen from adhesion (Huus et al., 2020). Moreover, the microbiome communicates with distant immune organs by means of cytokines and other signaling molecules (Kasarello et al., 2023).

3. Nutrition and Microbiome Health

Dietary patterns, and nutrition in particular, profoundly influence the human microbiome: nutrition is one of the most important modulators of microbial diversity and functionality. Diet and the gut microbiome play back and forth with each other to affect not just digestive health, but also more general health at the physical and mental levels. To optimize microbiome health and prevent dysbiosis related diseases, we need to understand the factors driving or constraining microbial populations (Shang et al., 2024). The diverse and resilient gut microbiome is shaped, in large part, by whole foods and fiber and fermented foods. Plant based foods that undergo little changes in processing provide substrates for microbiota growth and activity, which lead to a rich diet that is important for colonization of the infant gut (Vernocchi et al., 2024). Vegetables, fruits, whole grains and legumes are particularly good sources of dietary fiber. Among the other fibers, cellulose, hemicillulose and resistant starch is fermented by the gut bacteria and gives rise to short chain fatty acids like butyrate, acetate and propionate. Increased microbial diversity and a dominance of beneficial bacteria, Bifidobacteria and Lactobacilli, has been regarded to correlate with the older High-fiber diets (Fu et al., 2022).

3.1 Prebiotics and Probiotics

Prebiotics and probiotics are both invaluable resources for growing good microbial populations in the gut (Dahiya & Nigam, 2022). Indigestible compounds, mainly fibers, known as prebiotics selectively stimulate beneficial bacteria in the gut. Garlic, onions, leeks, asparagus and bananas are some foods that are prebiotic rich. Prebiotics have been studied to increase abundance of Bifidobacteria and Lactobacilli in the gut and improve gut health and reduce inflammation (Sanders et al., 2019; Fiori et al., 2022). However, probiotics are live microorganisms that, when consumed in adequate amounts, confer health benefits. How they work is by introducing beneficial bacteria to the gut to promote higher diversity and fight dysbiosis. *Lactobacillus rhamnosus* and *Bifidobacterium longum*, along with other strains, have been studied extensively for direct benefits to digestion, immunity, and relief of symptoms of anxiety and depression (Partrick et al., 2021). In addition, probiotics make antibiotic substances that help to prevent pathogens from growing and create a more balanced gut environment. Although the term 'synbiotics' is a combination of prebiotics and probiotics, this combination has appeared to offer additional benefit for enhancing microbiome health in synergy. Together, symbiotic offer support to probiotics to grow in healthy environment while feeding the resident beneficial microbes to aggregate a balanced, resilient gut ecosystem (Swanson et al., 2020; Saghir & Al Suede, 2024).

3.2 Dysbiosis and Dietary Interventions

Often a result of poor dietary habits involving the consumption of processed foods, refined sugars and saturated fats, dysbiosis (a microbial imbalance) can be the consequence of such diet. In fact, these dietary patterns reduced microbial diversity and promoted the growth of harmful bacteria that lead to metabolic syndrome, inflammatory bowel disease and other mental health disorders (Leo & Campos, 2020; Martinez et al., 2021). For instance, diets low in fiber deprive gut bacteria of essential substrates for SCFA production reducing SCFA production and gut barrier function, which decreases gut barrier function and promotes systemic inflammation (Usuda et al., 2021). Control of gut health is centered around restoring balance to the microbiome through dietary interventions. Rapidly shifting towards a whole food, plant-based diet will vastly improve microbial diversity and functionality. Eating prebiotic rich food like, asparagus, artichokes, oats, promote growth of good bacteria. Fermented foods such as kimchi and yogurt as well introduce probiotics to supplement healthy microbial population (Fermin et al., 2024).

Increased fiber from fruits, vegetables, legumes, whole grain and healthy fats from nuts, seeds and olive oil in the Mediterranean diet is often cited as an example of an ideal dietary pattern for microbiome health (Merra et al., 2020). Furthermore, studies have found that following this diet is associated with higher levels of helpful bacteria (*Faecalibacterium prausnitzii*), that produce anti-inflammatory metabolites, and a reduced risk of diseases attributable to dysbiosis (Verhoog et al., 2019).

4. Environmental Influences

Human microbiome responds dramatically to environmental factors, including pollution, chemicals, lifestyle choices, and antibiotics. All of these influences can either promote a healthy microbiome or cause disruptions towards overall health. We need to understand how the environmental factors that shape the microbiome are influencing to come up with strategies in preserving the stability and the natural balance of it (Flandroy et al., 2018; Abdelsalam et al., 2020).

4.1 Role of Pollution and Chemicals

Pollutants and chemicals as environmental toxins have great negative effects on microbiome health. Fine particulate matter (PM2.5) air pollution is shown to change gut microbial composition. When inhaled these pollutants can pass through the bloodstream to the gut where they can cause inflammation and upset of the microbial balance. Research has been done that shows a link to air pollution and that reduced diversity of good gut bacteria such as *Faecalibacterium* and *Akkermansia*, both key to maintaining gut barrier integrity and to regulating inflammation (Wang et al., 2018; Dorofeyev et al. 2023).

Pesticides, heavy metals and industrial pollutants provide another major threat to microbiome health, also. Like glyphosate, pesticides can also be antimicrobial agents which can end up killing beneficial bacteria to create dysbiosis. Like cadmium and lead, heavy metals disrupt microbial communities by generating oxidative stress, and inflammation. This risk of metabolic disorders, immune dysregulation and neurobehavioral changes, is associated with these disturbances (Kou et al. 2019; Kaur & Rawal, 2023; Cheng et al., 2023; Bhardwaj et al., 2024).

Processed foods, which include emulsifiers and artificial sweeteners, can harm the microbiome as much as natural chemicals in the environment. Commonly used to improve texture, and boost shelf life, emulsifiers also skew microbe composition and increase gut permeability a phenomenon sometimes referred to as 'leaky gut'. Artificial sweeteners like aspartame and saccharin have been seen to reduce microbial diversity, down regulating the metabolism of microbial populations and leading to glucose intolerance (Raoul et al., 2022).

4.2 Lifestyle and Microbial Exposure

The microbiome is substantially influenced by lifestyle decisions, with activity, sleep, and exposure to natural environment being key regulators of modulation of the microbiome. The gut is a powerful modulator of physical activity, which improves microbial diversity by enhancing the growth of beneficial bacteria. Regular exercise can also raise levels of Bacteroides and Faecalibacterium associated with anti-inflammatory effects and improved metabolic health. The experimental data showed that microbial diversity in more active individuals compared to less active individuals, which can be associated with less risk of diseases like obesity and type 2 diabetes (Ahmad et al., 2019).

Sleep quality, circadian rhythms also contribute to balance of microbes. The presence of sleep deprivation can disrupt the microbiome, increasing the population of pathogenic species, decreasing the abundance of the beneficial, such as Lactobacillus and reducing total cellular abundance, all while causing variation in metabolite concentrations and altering their profiles. The altered stress hormones such as cortisol stress hormones influence gut motility and permeability mediate these changes. Stable microbiome and lowers stress induced dysbiosis (Parkar et al., 2019; Tian et al., 2022).

Living in natural environments exposes you to diverse microbial populations through water, air and soil and all together this makes you have a robust microbiome. Those who spend time out of doors or who live in the country tend to have more diverse gut microbiota than those who live in towns. Environmental microbes' exposure strengthens immune system, decreases inflammation and boosts resistance to infections. However, immune relevant disorders (such as allergies and asthma) are increasingly prevalent due to urbanization and excessive hygiene, which constrain microbial exposure (Gilbert & Hartmann, 2024).

4.3 Antibiotics and Resistance

Antibiotic overuse is the greatest threat to microbiome health, as it makes bacterial diversity profoundly disrupted and promotes antibiotic resistance. Indiscriminately antibiotics target bacteria and kill both pathogenic and benign commensal organisms. Such disruption leads to reduction in microbial diversity which in many cases translates in to dysbiosis. Repeated antibiotic use can allow for a complete failure of a microbiome to recover its original composition and a predisposition for chronic conditions like inflammatory bowel disease (IBD) and metabolic diseases (Duan et al., 2022).

In particular, early life exposure to antibiotics is of major concern because it disrupts microbiome development, which could have lifelong consequences (Sarkar et al., 2021). For example, Amin et al. (2022) studied that antibiotic use in children was associated with obesity, asthma, allergies, and such other complications as may occur due to inappropriate antibiotic prescribing. Antibiotic overuse is also responsible for the global crisis of antibiotic resistance pathogenic bacteria evolve methods of survival to antibiotic treatments. But this phenomenon not only weakens the effectiveness of existing antibiotics, but it is destructive to microbiome by allowing resistant strains to proliferate. Within the gut, the bacteria can become resistant, making it difficult for infection control and for treatment (Ribeiro et al., 2020).

5. Holistic Wellbeing through Microbiome Modulation

Microbiome modulation is a revolutionary means for whole health by linking gut health to mental health, chronic disease prevention and tailored health strategies. Once we understand and exploit the influence of the microbiome on different physiological mechanisms, we can make better use of biological resources to improve physical, mental, and emotional health (Beltrán-Velasco & Clemente-Suárez, 2025).

5.1 Microbiome and Mental Health

It is no surprise that the microbiome, known as the gut brain axis, influences the connection of gut health with mental well-being. The gut and brain communicate bidirectionally through neural, hormonal and immune pathways, and the vagus nerve is a major transmission pathway. Microbes in the gut play a role on production of neurotransmitters such as serotonin, dopamine and gamma aminobutyric acid (GABA) a molecule responsible for controlling mood and stress (Liu et al., 2020).

Research has shown that people who are depressed or anxious have different microbial imbalances, one of which includes lower levels of *Lactobacillus* and *Bifidobacterium* species that are linked with anti-inflammatory and stress reducing properties. Gut dysbiosis can be linked to systemic inflammation as well and neuroinflammation, which can contribute to the mood disorder and cognitive impairments. This is for example, increased levels of pro inflammatory cytokines which are commonly found in people with dysbiosis have been shown to be associated with depression and anxiety (Navarro-Tapia et al., 2021).

5.2 Chronic Disease Prevention

Preventing and managing chronic diseases, including metabolic, inflammatory and autoimmune diseases is greatly influenced by the microbiome. Maintaining a healthy microbiome is essential for keeping your metabolic health in balance by regulating blood sugar levels, energy balance and lipid metabolism. Good microbes for instance *Akkermansia muciniphila* and *Faecalibacterium prausnitzii* produce metabolites that increase gut barrier function, diminish systemic inflammation, and increase insulin sensitivity. However, the microbial imbalances are linked with metabolic disorders like obesity, type 2 diabetes and cardiovascular disease (Ganesan et al., 2018 ; Verhoog et al., 2019).

It is known that the microbiome can modulate immune responses to prevent the chronic inflammation in inflammatory conditions. SCFAs Secrete with fiber fermenting bacteria including butyrate contribute to reducing inflammation by blocking in proinflammatory pathways such as with the nuclear factor kappa B (NF-κB) pathway (Liu et al., 2021). Like other autoimmune diseases, there's been a connection to microbiome imbalances leading to conditions we now recognize as systemic lupus erythematosus and multiple sclerosis. Altered microbial populations can disrupt the development of regulatory T cells (Tregs), necessary for maintaining immune tolerance, and preventing autoimmunity. The promising strategy to reduce autoimmune risk and severity by restoring microbial diversity through dietary interventions, probiotics and prebiotics (De Luca & Shoenfeld, 2019).

5.3 Personalized Microbiome Strategies

For maximal health outcomes, we must customize microbiome modulation to individual needs, which is essential given the uniqueness of each person's microbiome, shaped by genetics, diet, environment and lifestyle (Schupack et al., 2022). Microbiome strategies that are personalized are ones that analyze an individual's microbial profile to pinpoint imbalances, and develop targeted interventions for that specific individual. New sequencing technologies including 16S rRNA gene sequencing and metagenomics now allow us to precisely map microbial communities, to an extent never before possible, and to take a personalized approach to microbiome health (Fuks et al., 2018).

In particular, personalized microbiome interventions are highly valuable for treating chronic conditions. As an example, the response to dietary modification or probiotics can be different between patients with irritable bowel syndrome (IBS) due to their different microbial composition. Treating the individual's microbiota will allow appropriate alterations to treatments and improve symptom management and quality of life. Similar to mental health, microbial imbalances linked to anxiety or depression can be also identified so hyperbolic's, which may help the individual, can be selected (Valeur, 2018). In the future, integration of microbiome profiling into daily health care may totally revolutionize the prevention and treatment of disease. Personalized microbiome strategies may shift the paradigm from reactive to proactive health care, enabling people to proactively manage their well-being through evidence based tailored interventions (Mohr et al., 2024).

Conclusion and Future Perspective

In the human microbiome, a nexus springs up between nutrition, environment, and wellness (or ill-being), and the human microbiome feeds into and reflects all of these, enabling and reflecting the connection. Fiber, whole foods and fermented foods promote diversity and functionality of the microbiome, as these are the basis of good nutrition. Environmental influence, from pollution and chemicals to the lifestyle influences of exercise or sleep, further define how the microbiome will compose and respond to that microbiome. These elements, taken together, demonstrate the central role of microbiome health in physical, mental, and emotional health will be critical to uphold whole of health. To push this as a priority we need a call to action to inspire people, practitioners and researchers to pay attention to the microbiome friendly practices. Ideally, in people, a diet containing prebiotics, probiotics, and wide range of diverse plant-based foods, plus physical activity and natural environment exposure in mind, accounts for substantial improvement in microbial balance. To understand the microbial world and the factors that determine health, researchers need to work out how the microbiome shapes the outcome, develop targeted therapies, and address global issues such as antibiotic resistance, environmental pollution, which poison microbial ecosystems. Microbiome modulation is envisioned as the cornerstone of futuristic health care, including the intersection of nutrition, environmental stewardship and personalized medicine. Recent advances in microbiome research and technology have provided unexplored yet crucial windows for proactive, individualized disease prevention and general well-being. Microbiome modulation has the potential to revolutionize health care by aligning scientific innovation with sustainable and evidence-based practices. It invites a shift of paradigm from reactive to preventative and restorative strategies which would enable individuals to attain long run health and resilience. Microbiome modulation is just a glimpse into the far larger picture of harmonizing human health with ecological context to produce a healthy, thriving world for all.

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