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Review Article

The Role of Dietary Nutraceuticals in Modulating Gut Microbiota and Gene Expression

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ABSTRACT

Nutraceuticals, originating from phytochemicals and bioactive food components, present an emerging field with promise for health promotion and disease prevention. They serve as a bridge between nutrition and pharmaceuticals for therapeutic benefits, which can include enhancement of metabolic function, immune modulation, and chronic disease prevention. The components of nutraceuticals, including, but not limited to, dietary fibres, probiotics, prebiotics, polyphenols, and polyunsaturated fatty acids, not only positively impact health throughout the body, but they also have active, or passive effects on gut microbiota (a unique microbial ecosystem where key aspects of human physiology operate). The gut microbiome is critical for digestion, immunity, neuro regulation, and modulation of disease processes, and can be altered through dietary means. Nutraceuticals have potential therapeutic value in obesity, cardiovascular disease, cancer, inflammatory bowel disease, and neuro degeneration, in part by influencing gut microbiota composition and/or function. An evolving array of omics technologies and machine learning is advancing knowledge on personal nutrition and diet- microbiome interactions. Barriers still exist, for example, the selection of a regulatory body and the standardization of products recognized as nutraceuticals, inter-individual differences and variability in response, and the need to develop systems and metrics to ensure clinical validity. In summary, the fields of nutrigenomics, artificial intelligence, and personalized medicine are advancing the future of functional foods and health-driven dietary shifts.

KEYWORDS: Nutraceuticals, Gut microbiota, Functional Foods, Gene Expression.**ARTICLE INFO:** Received 10 Sept. 2025 ; Review Complete 18 Oct ; Accepted 20 Nov. 2025; Available online 15 Dec. 2025**Cite this article as:**Drisya Mk , E. Aswathi, John MA, The Role of Dietary Nutraceuticals in Modulating Gut Microbiota and Gene Expression, Asian Journal of Pharmaceutical Research and Development. 2025; 13(6):177-182, DOI: <http://dx.doi.org/10.22270/ajprd.v13i6.1671>

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INTRODUCTION

Nutraceuticals are pharmaceutical products that use phytochemicals deduced from food as their active constituents.^[1] These are food or food ingredients that have health or medical benefits like for estallment or treatment of complaint. It produces good nutritive value, remedial exertion, and favorable safety profile. Nutraceuticals are decreasingly taking off around the world in numerous different orders, but especially in health creation and complaint for estallment^[2]

Foods that can be classified as nutraceuticals have included salutary fibres, prebiotics, probiotics, polyunsaturated dipose acids, antioxidants, and any number of medicinal or natural foods. These interventions can help with forestallment and alleviate some of the leading medical problems of the ultramodern period similar as rotundity, cardiovascular

complaint, cancer, osteoporosis, arthritis, diabetes, and hypercholesterolemia. Overall, nutraceuticals are creating a new period in the realm of drug and health by transubstantiating the food assiduity into an exploration driven assiduity^[3]

Microbiota describes the entire community of microorganisms abiding in specific terrain, including not only bacteria, but also fungi, archaea, contagions and protozoa. ^[4] The term "gut microbiota" refers to the vast community of bacteria, archaea, and eukaryotes that populate the gastrointestinal tract. It has been shown that the GI tract contains > 10¹⁴ microorganisms, and while it was traditionally believed that themortal body contained 10 times as numerous microorganisms as mortal cells, with > 100 times further inheritable material inclusively nominated the microbiome than themortal genome, more

recent substantiation suggests it's near to a 1:1 ratio with respect to microbial and mortal cells^[5,6]

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Traditionally Believed That The Mortal Body Contained 10 Times As Numerous Microorganisms As Mortal Cells, With > 100 Times Further Inheritable Material Inclusively Nominated The Microbiome Than The Mortal Genome, More Recent Substantiation Suggests It's Near To A 1:1 Ratio With Respect To Microbial And Mortal Cells.[7].



Figure: 01

Nutraceuticals are extensively available in concentrated forms similar as capsules, capsules, maquilages, and tinctures, either as a single component or in combination formulas. Nutraceuticals can include naturally nutrient-thick foods (spirulina, garlickor soy) or insulated food factors (omega-3 fish canvases). Nutraceuticals are also appertained to as medical foods, nutritive supplements, or indeed salutary supplements. They're gaining fashion ability encyclopedically, and there's a rising demand among consumers for both herbal and non-herbal excerpts. There are several exemplifications including green tea (weight operation and cancer forestallment) and Ginkgo biloba (cognitive function enhancement)^[8]

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The nutraceutical request has witnessed considerable growth over the once many times, primarily due to lesser experimenter interest and enhanced technology to assay the qualitative and quantitative features of nutraceutical products^[10] Food is a source of nutrients and energy, but food also has benefits that are medically salutary. All nutraceutical food sources can be put into the following orders:

1. Salutary fibres
2. Probiotics

3. Prebiotics
4. Polyunsaturated adipose acids
5. Antioxidant vitamins
6. Polyphenols
7. Spices^[11]

Concept of Nutraceuticals

Clinical testing, including animal studies and the therapeutic efficacy testing, is a required part of pharmaceutical development. In comparison to pharmaceuticals, traditional nutrition has not had an established methodology to demonstrate the disease preventing qualities of foods. However, the last decade has brought increased scientific evidence linking food composition to the development of lifestyle-related diseases, thus elevating it to a legitimate public health discussion. As result, nutraceuticals are receiving considerable recognition as a valuable health product. Nutraceuticals are commonly used for the possible reduction of risk factors for certain diseases (e.g., cancer, heart disease), as well as for the prevention and control of disease states such as hypertension, high cholesterol, obesity, osteoporosis, Type II diabetes, arthritis, macular degeneration, cataracts, menopausal symptoms, insomnia, memory loss, decreased concentration, gastrointestinal issues (e.g., constipation), and headaches. In addition, some nutraceuticals are also advertised to alleviate hair loss or thinning, poor self-image, skin issues, varicose veins, alcoholism, depression, and fatigue.^[12,13]

Gut Microbiota

The microbiota has many benefits to the host, providing key functions such as support of gut integrity, structure of intestinal epithelium, energy extraction, protection from harmful pathogens, and immune system modulation. These health-promoting processes can become disrupted

by a change in microbial composition, a situation referred to as dysbiosis. As our methods for investigation of and characterization of complex ecosystems become more sophisticated, the recognition of the contribution of the microbiota to both intestinal and extra-intestinal disease states is increasing.^[14]

Gut Microbiota and Human health

There is increasing recognition in medical records of the relationship between gut microbiota and human health. In fact, there is excellent evidence that a healthy gut flora is a major determinant of the health of the host. The normal gut microbiota comprises two predominant phyla representatives Bacteroidetes and Firmicutes. While the gut microbiota of infants are apparently chaotic, by age three the gut flora of infants starts to resemble what we would see in adults. However, it is important to acknowledge that from the esophagus to the rectum there are temporal and spatial variations in microbial distribution throughout an individual's life. Thanks to advanced genome sequencing technologies and bioinformatics, scientists are now able to study these microorganisms, their function and microbe-host interactions in great detail, both in health and in disease. The normal gut microbiota has a complex range of normal functions to impart on host nutrient metabolism, xenobiotic and drug metabolism, structural integrity of the gut mucosal barrier, immunomodulation and protection from pathogens. There are several variables that shape the normal gut microbiota:

- The mode of delivery (vaginal or caesarean),
- Diet during infancy (breast milk or formula feeds) and in adulthood (vegan based or meat based)
- Exposure to antibiotics and antibiotics like compounds, from the environment or the gut. ^[15]

Functions of Gut Microbiota

- Regulation of gut microbiota composition and functionality
- Acting as nutrition and affecting nutrient absorption
- Modulation of host metabolism
- Affecting the intestinal barrier and gut motility
- Influencing the systemic immune response
- Influencing the nervous system
- Modulating circadian rhythm
- Affecting drug efficacy and toxicity^[16]

Influence of Nutraceuticals on Gut Microbiota

A high consumption of fruits, vegetables, and whole grains is related to a decreased risk of chronic disease such as cancer and cardiovascular diseases (CVD), which are the two leading causes of death on the European and United States mortality lists and in many other developed countries. About one-third of all cancer related deaths in

these countries can be prevented with proper dietary decisions. This strongly advocates for the idea that dietary change, through an increase in fruits, vegetables, and whole grain, along with associated lifestyle changes, can have a major impact on the incidence of cancer. A large body of literature, though not unanimous, mostly reports a decreased risk of cancer with diets high in fruits and vegetables,

with epithelial cancers of the alimentary canal and respiratory systems specifically mentioned. Twenty-six human epidemiological studies and 206 animal studies showed that the protective effects of plant-based diets against cancers of the stomach, esophagus, lungs, oral cavity, pharynx, endometrium, pancreas, and colon. Fruits and vegetables that are most commonly recognized as high in cancer-preventive properties include raw vegetables, members of the Allium family (such as garlic, onions, every type of onion), carrots, green vegetables, cruciferous vegetables (like broccoli, cabbage, etc.), and tomatoes. ^[17]

• Probiotics

In the simplest terms, probiotics are live microorganisms that provide benefits beyond those offered in normal food and constitute the living microorganisms in the gut microbiota. Alternatively, probiotics may be described as live microorganisms that are part of the microbiota and have minimal or negligible pathogenicity. These microorganisms serve important roles in the health and well-being of the host.

Probiotics, historically, were consumed for the purpose of modifying which microorganisms inhabited the intestine to improve human health and nutrition. However, their benefit to nutrition and health, led to consumption of probiotics in foods and cereals (e.g., yogurt and notated on the finder's label) and clinical use in only single or mixed microbial culture preparations. ^[18]

• Prebiotics

A prebiotic, in essence, may be defined as fibres or selectively fermented ingredient that, once ingested, induces a specified change in the composition and/or activity of the gut microbiota and thereby confers a health benefit on the host. The indirect health benefits of prebiotics include the prevention of diarrhea or constipation, modulation of metabolism of enteric flora, chemoprevention of cancer, effects on lipid metabolism, stimulation for minerals in food, and immune modulation. Prebiotics also include a wide variety of carbohydrate ingredients; however, the source, efficiencies of fermentation, and dose necessary for health benefits remain largely unknown.

Prebiotics provide both nutraceutical and nutritionally functional foods. Currently, only bifidogenic, non digestible oligosaccharides

like insulin, a hydrolysate oligo fructose, and (trans) galacto oligo saccharides fulfill the criteria necessary to be classified as prebiotics. Recently, infant formula manufacturers have been able to successfully add fructose and galacto oligo saccharides to mimic breast milk. ^[19]

Probiotics and prebiotics have different roles, but they have similar results in human nutrition, primarily by affecting the populations and activities of the thousands of microbes that inhabit the gastrointestinal tract. Regular consumption of probiotics or prebiotics may produce one or more of the health benefits of enhanced immune function, improved colonic integrity, and reduced incidence and duration of intestinal infections, down regulation of allergic responses, and improved digestion and elimination.^[20]

• Polyphenols

The effect of polyphenols on human health depends on a number of variables, including the percentage of polyphenols in food, their bioavailability, their bioaccessibility, and the biological properties of their metabolites in the body. Certain polyphenolic compounds are poorly absorbed from the digestive tract, while some are very much metabolized, usually with derivatives that had lower activity or were rapidly eliminated. The composition of an individual's gut microbiota is also important; for one individual, a polyphenol might be metabolized by gut bacteria into something beneficial or something harmful, while in another individual, that same polyphenol could be metabolized in a different way so as to not have an effect.^[21]

Therapeutic and Clinical Implications

Nutraceuticals in the management of:

Metabolic disorders

Clinical studies have shown that nutraceuticals like L-carnitine, berberine, omega-3 polyunsaturated fatty acids, krill oil, and red yeast rice may aid in managing hypercholesterolemia and insulin resistance. When combined with standard pharmaceutical therapies, they can help enhance lipid profiles effectively, potentially reducing the need to raise statin dosages.²² Metabolic syndrome (MetS) is characterized by a cluster of

conditions including abdominal obesity, high triglyceride levels, low HDL (good) cholesterol, increased blood pressure, and elevated fasting blood sugar. These interconnected health issues significantly contribute to the development of cardiovascular disease and type 2 diabetes.²³

Inflammatory diseases

A variety of elements—such as dietary habits, immune function, environmental influences, genetic predisposition, and gut microbiota—play a role in the onset of inflammatory bowel disease (IBD). The condition often arises from a multifaceted interplay among these factors, leading to stimulation of the mucosal immune system and triggering the release of various cytokines.²⁴ Probiotics help preserve a healthy gut microbiome by suppressing harmful microbes. They achieve this by preventing pathogens from attaching to intestinal surfaces, out competing them for nutrients, and directly neutralizing or destroying disease-causing organisms.²⁵

Neurodegenerative disorders

Polyunsaturated fatty acids (PUFAs) are regarded as key nutraceuticals due to their notable biochemical properties, particularly their antioxidant and anti-inflammatory effects. They may help mitigate or prevent neurodegenerative conditions through several mechanisms, such as reducing neuro inflammation and neurotoxicity, promoting neural repair, and maintaining the structural integrity of the blood-brain barrier.²⁶

Cancer prevention and treatment

Modifying one's diet to include health-promoting phytochemicals can affect the equilibrium and accessibility of natural compounds that help prevent cancer. In preventive strategies, incorporating foods rich in anticancer agents can reduce the likelihood of developing precancerous conditions.²⁷

Table: 01

Target cancer	Compounds	Source	Biological activity
Breast	Fucoxanthin	Marine carotenoid	Anti-Proliferative ²⁸
	Punicalagin	Pomegranate juice	Apoptosis ²⁹
Lung	Apigenin	Flavonoids	Anti-proliferative ³⁰
	Taxol	Taxus brevifolia	Apoptosis ³¹
Pancreatic	Genistein	Soy	Anti-proliferative ³²
	Limonoids	Citradessabaccifera	Anti-proliferative ³³

Personalized Nutrition Approaches Based on Microbiota and Genetics

Host-derived factors are largely fixed and challenging to alter, the microbiome is more adaptable and can be significantly influenced by environmental elements like diet. It is now widely acknowledged that the microbiome plays a crucial role in human physiology—contributing

to digestion, nutrient absorption, the development of the mucosal immune system, and the production or regulation of numerous bioactive substances. Consequently, dietary changes that modify the microbiota may be a strategic means to influence host physiology, potentially affecting the onset and progression of various diseases.³⁴ The gut microbiome (GM) plays a vital role in determining the host's nutritional status. By enhancing the microbiome's ability to extract nutrients, targeted modulation could

boost overall health and help combat malnutrition and disease. However, due to the highly individualized nature of GM composition and function, universal strategies are of ten ineffective—highlighting the need for personalized interventions. Tailored modulation of the GM for nutritional benefits can be achieved by integrating traditional methods like probiotics, prebiotics, and symbiotic with advanced techniques such as microbiome profiling and individualized treatment plans. While some of these strategies are already practical, others require further research and validation to ensure their effectiveness and safety.³⁵

Challenges and Future Directions

Significant challenges remain in legislation and product approval, which must be addressed through harmonized global regulations. Aligning regulatory frameworks will help minimize conflicts and foster stronger international collaboration. Achieving this requires a comprehensive understanding of ingredient properties, robust safety regulations, Well-designed clinical trials, cutting-edge food processing technologies, and thorough analytical research. The ongoing nutraceutical revolution is poised to usher in a new era of health and medicine—transforming the food industry into a research-driven sector, much like the pharmaceutical industry.³⁶ The inter-individual relationship of certain plant-derived bioactive compounds may have strong effects in some individuals but little to no impact in others, highlighting the need

Advances in Multi-omics (Metagenomics, Transcriptomics, Metabolomics)

In nutrigenomics research, biotechnological omics tools serve a broad range of purposes—including the discovery, isolation, and development of novel functional compounds, as well as the exploration of their mechanisms of action, potential modifications, and safety profiles. These tools enable the design of targeted combinations of health-promoting metabolites and phytochemicals, offering promising strategies for complementary medicine. Omics-based methodologies are expected to remain central to advancing the fields of food and nutrition science. In-depth exploration of individual omics approaches will deepen our understanding of how key dietary components interact with the human body.³⁷ The swift advancement of omics research has led to the emergence of high-throughput technologies capable of analyzing the composition of crops, environmental samples, food products, and human bio fluids. Disciplines such as genomics, transcriptomics, proteomics, and metabolomics each provide insights into the functioning of various biological systems. Multi-omics integrates these diverse datasets to offer a comprehensive understanding of biological processes on a larger, systemic scale.³⁸

Potential of AI in predicting Diet-Microbiome Interaction

Technologies such as machine learning have become valuable tools for integrating and analyzing multi-omics

data related to diet, gut microbiota, and health across various biological scales. Despite their potential, these tools currently face challenges, including limited data availability and inconsistencies like batch effects. Looking ahead, as data quality and sampling techniques continue to improve, machine learning is expected to play an increasingly significant role—helping to overcome current gaps in spatial, temporal, and causal understanding within this field of research.³⁹ The emerging vision of personalized nutrition has sparked significant interest in developing advanced diagnostic tools and decision support systems (DSS). These innovations aim to enable continuous monitoring of an individual's dietary habits, alongside gut microbiome profiles and other relevant data—such as electronic health records (EHR), lifestyle and environmental factors, and physical activity tracked through biosensors and wearable health devices.⁴⁰

CONCLUSION

In summary, the relationship between diet, the gut microbiota, and gene regulation plays a central role in maintaining health and preventing disease. Nutraceuticals, including polyphenols, prebiotics, probiotics, and other bioactive compounds, offer promising avenues for modulating the gut microbiota and influencing key physiological processes at the molecular level. The diverse microbiota composition within the human gut, shaped by diet, lifestyle, and environmental factors, interacts with these bioactive compounds to regulate gene expression, modulate immune responses, and affect metabolic pathways, all of which have significant therapeutic potential.

The future of nutraceutical research lies in personalized nutrition strategies, where individual microbiome profiles and genetic factors are considered to optimize health outcomes. Advances in multi-omic technologies, coupled with the potential of artificial intelligence to predict diet-microbiome interactions, will be pivotal in advancing this field.

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