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Prebiotics and Probiotics as Emerging Nutraceuticals in Gut Health

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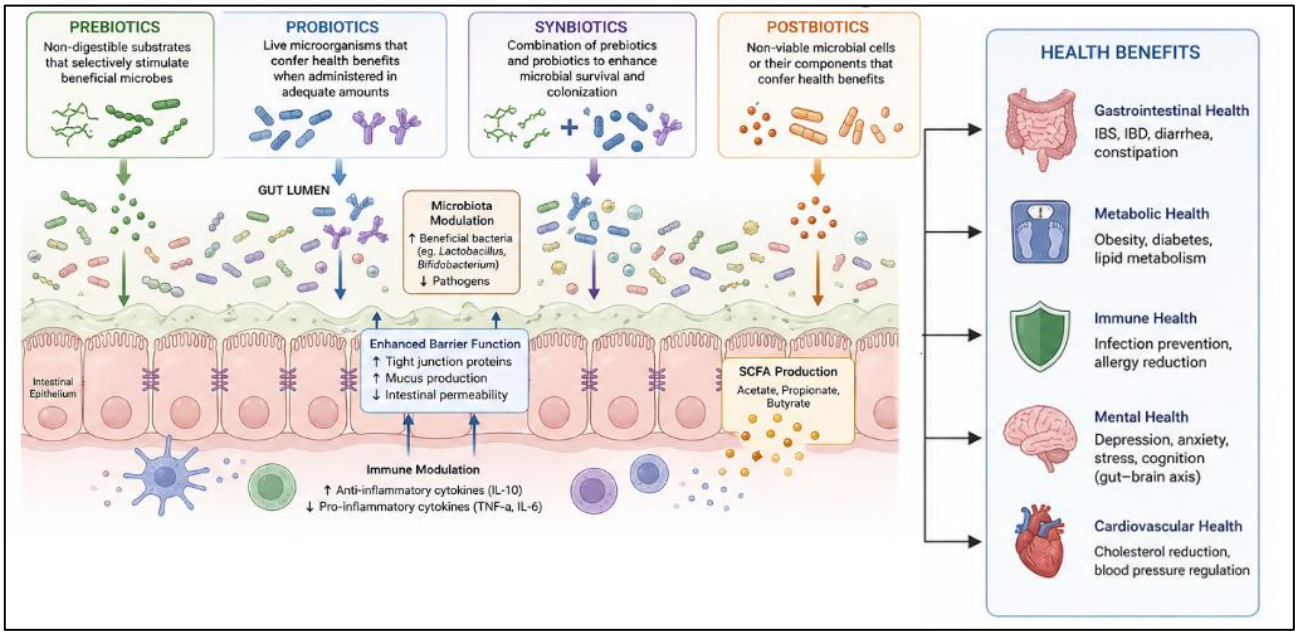
ABSTRACT

The gut microbiota is a complex and dynamic ecosystem that is critical for maintaining health and in the development of disease. Over the past few decades, prebiotics and probiotics have emerged as key nutraceuticals with the ability to influence the gut microbiota. These active components have diverse effects, including strengthening of the mucosal barrier, immune modulation and metabolic regulation. This review offers a holistic overview of the existing scientific literature on prebiotics and probiotics, including their modes of action, therapeutic benefits and formulation into nutraceuticals. It also reviews technological innovations in delivery systems, regulatory and safety aspects and limitations. It also explores recent developments in next-generation probiotics, postbiotics, and microbiome-tailored nutrition, and future perspectives in this rapidly growing area.

Keywords: Gut microbiota; Prebiotics; Probiotics; Synbiotics; Postbiotics; Nutraceuticals

Graphical Abstract



1. INTRODUCTION

Over the past 20 years, the notion of gut health has undergone a seismic shift, thanks to developments in microbiology, genomics, and systems biology. The gut is no longer just seen as an organ of digestion, but as a dynamic and interactive ecosystem home to trillions of microbes. The rich microbial population, collectively known as the gut microbiota, is composed of bacteria, archaea, viruses and fungi, the genetic repertoire of which collectively termed the microbiome - far surpasses the human genome in size and complexity [1,2]. This genetic diversity allows the microbiota to carry out a myriad of biochemical and physiological processes essential for its host. In terms of its function, the gut microbiota is intimately involved in host metabolism, through fermentation of

dietary constituents that are otherwise indigestible, production of essential vitamins (e.g. vitamin K, B vitamins), and bile acid metabolism. The microbiota also profoundly impacts the host immune system through regulation of immune cell development and maturation and regulation of inflammation. Furthermore, recent studies also show its role in neural signaling via the gut-brain axis, which impacts on cognitive, mood and behaviour [2,3]. These complex relationships place the gut microbiota at the centre of systemic homeostasis. However, the integrity of this microbial ecosystem is very vulnerable to lifestyle and environmental influences, such as diet, antibiotic usage, stress and urbanization. Disruptions in the microbial community structure and function, known as dysbiosis, have been implicated in the development of a range of chronic and non-communicable diseases, including obesity, type 2 diabetes, cardiovascular diseases, inflammatory bowel diseases and even mental disorders [3].

The increasing prevalence of these lifestyle-related diseases has sparked renewed interest in clinical and research efforts to restore and maintain the balance of microbes to prevent and manage diseases. In this regard, nutraceuticals are a group of bioactive compounds that intersect the conceptual and practical spaces between food and drugs. Generally described as food ingredients that have health-promoting properties, nutraceuticals provide a proactive and integrated approach to health maintenance. In this regard, prebiotics and probiotics have attracted considerable interest for their specific effects on the microbiota population and function. Prebiotics are selectively fermented ingredients that stimulate the growth and/or activity of beneficial microorganisms, thereby increasing microbial diversity and activity. Probiotics, on the other hand, are live microorganisms that, when present in sufficient quantities, confer health benefits by directly increasing the number of micro-organisms in the gut and by their functional contribution in the host [4,5]. Critically, the simultaneous administration of prebiotics and probiotics (commonly known as synbiotics) is a powerful approach that improves the survival, colonisation and functional activity of microorganisms. This multifaceted strategy has provided new opportunities for primary care, functional food formulation and therapeutic strategies to address gut microbiota-related diseases. As the field progresses, prebiotics and probiotics are emerging as leading players in the development of nutraceuticals, providing scientifically supported and clinically relevant strategies to improve gut health and well-being.

Thus, the purpose of the present review is to conduct a systematic study of the role of emerging nutraceuticals in gut-health, prebiotics and probiotics. It aims to critically examine their mechanisms of action, therapeutic potential and uses in disease management and also discusses the recent developments in synbiotics, postbiotics and new delivery systems. More so, the given study will be used to emphasize the existing challenges, safety concerns, and future outlook of the development of microbiome-targeted nutraceutical approaches.

2. Gut Microbiota and Gut Health

The gut microbiota is a rich and dynamic microbiome of microorganisms, predominantly bacteria from the phyla Firmicutes, Bacteroidetes, Actinobacteria and Proteobacteria, along with archaea, viruses (mostly bacteriophages) and eukaryotic microorganisms [6]. The microbiota is dynamic, and changes throughout life and is influenced by various factors such as delivery mode, nutrition, antibiotics, geographic location and lifestyle. Infancy is a critical period for the establishment of long-lasting microbial composition and immune responses. The gut microbiota is a metabolic organ that enhances host metabolic potential. A key function is the fermentation of otherwise indigestible dietary polysaccharides to produce bioactive byproducts such as short-chain fatty acids (SCFAs), gases, and secondary metabolites. Moreover, gut microbes produce micronutrients such as vitamin K and various B vitamins, making an important contribution to host nutrition [7]. Furthermore, gut microbes are involved in the metabolism of bile acids, xenobiotics and regulation of glucose and lipid homeostasis, highlighting the microbiota's systemic effects [9].

A fundamental concept relevant to microbiome studies is eubiosis and dysbiosis. Eubiosis describes a balanced, diverse microbiome that maintains normal physiological function while dysbiosis describes an altered microbial community with reduced diversity, depletion of beneficial microbes and expansion of potentially pathogenic microbes [8]. Dysbiosis may be induced by dietary factors, antibiotic overuse, environmental contaminants, or disease, and is increasingly being recognised as both a cause and an effect of disease. Dysbiosis has wide-ranging clinical implications. It has been strongly linked to gastrointestinal diseases such as inflammatory bowel disease (IBD) and irritable bowel syndrome (IBS) and colorectal cancer [9]. Dysbiosis also plays a major role in the development of metabolic syndrome, obesity, insulin resistance and type 2 diabetes through mechanisms such as altered energy extraction and low-grade inflammation [10]. In addition, emerging evidence establishes a connection between gut dysbiosis and neurodegenerative and neuropsychiatric diseases such as Parkinson's disease, Alzheimer's disease, anxiety and depression [11].

Dysbiosis alters the integrity of the intestinal epithelium, resulting in "leaky gut." This permits microbial byproducts, including lipopolysaccharides (LPS), to enter the bloodstream, leading to endotoxemia and chronic inflammation [12]. Continuous inflammation, by itself, is a common pathomechanism in various metabolic and degenerative conditions. What's more, changes in microbial products such as SCFAs and neurotransmitter precursors further contribute to systemic dysfunction. The gut microbiota is also closely linked to the central nervous system through the gut-brain axis, a bidirectional communication system involving neural, hormonal and immune pathways. Metabolites from microbial fermentation impact neurotransmitter production, vagal nerve

activity, and responses to stress, among other things, and play a role in cognitive, behavioral, and emotional processes [13]. Such emerging knowledge of microbiota-host relations underscores the importance of microbial eubiosis for human health and the therapeutic potential of interventions to promote eubiosis.

3. Prebiotics: Types, Sources, and Mechanisms

Prebiotics are described as selectively fermented ingredients that are metabolised by beneficial microbiota, resulting in specific changes in the microbiota and their activity that result in host health benefits [4]. Prebiotics have specific functions in contrast to general dietary fibers as they selectively promote the proliferation of beneficial bacteria. Well-studied prebiotics include inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS) and resistant starch, which vary in structure, fermentability and their point of action in the colon [14]. These substances are mainly found in plant foods including chicory root, Jerusalem artichoke, onions, garlic, leeks, asparagus, bananas and whole grains. Their presence in the traditional diet is in contrast to the modern diet that is low in fermentable fiber and therefore leads to a reduction in microdiversity and microbial functions [15]. Thus, supplementation with dietary prebiotics is thought to be an effective way of re-establishing microbial equilibrium. The main mode of action of prebiotics is that they undergo fermentation by the colonic microbiota, leading to the formation of SCFAs acetate, propionate and butyrate [16]. These metabolites play a variety of physiological functions. SCFAs provide fuel for colonocytes, help to maintain the pH of the gut, and suppress pathogenic bacterial growth. They also act as signaling molecules, binding to G-protein-coupled receptors and modulating metabolism and immune responses [17]. Of these, butyrate is the most important because it has been shown to increase the integrity of the epithelial barrier, promote mucin expression and induce apoptosis in cancer cells, thus providing protection against colorectal cancer [18]. Prebiotics also selectively enrich the microbiota by promoting the growth of beneficial microbes, such as *Bifidobacterium* and *Lactobacillus* (often termed the "bifidogenic effect") [19]. This enrichment of beneficial bacteria enhances microbial diversity and resilience, promoting gut health. Moreover, prebiotics have a profound effect on immune responses by regulating cytokine synthesis and response, increasing regulatory T cell activity, and suppressing pro-inflammatory pathways [20]. Recent studies also indicate prebiotics may have broader health effects beyond the gut, such as regulating lipid metabolism, enhancing insulin sensitivity and satiety via gut hormones. These complex effects make prebiotics an essential element in nutraceutical approaches to achieving optimal health.

4. Probiotics: Strains, Sources, and Mechanisms

Probiotics are defined as live microorganisms that, when administered in adequate amounts, confer health benefits to the host [5]. Probiotics have strain-specific effects, and their health-promoting properties are contingent on their survival in the gastrointestinal tract, adhesion to the intestinal epithelium, and interaction with the host microbiome. Well-studied probiotic genera include *Lactobacillus, Bifidobacterium, Saccharomyces* and *Streptococcus*, which have different physiological and therapeutic characteristics [21]. Probiotics are typically administered in fermented dairy products (yogurt, kefir, fermented milk), traditional foods and encapsulated supplements. Recent technological advances have led to the production of functional foods containing probiotics with enhanced stability and delivery [22]. The mode of action of probiotics is complex and includes both microbial and host-dependent mechanisms. A key mechanism is competitive exclusion, where probiotics prevent the growth of pathogenic bacteria through competition for attachment sites and nutrients in the gut. They also secrete antimicrobial compounds such as bacteriocins, hydrogen peroxide and organic acids that inhibit pathogenic microbe growth [23]. Probiotics improve the intestinal barrier by increasing the expression of tight junction proteins and promoting mucus production, thus reinforcing the barrier to prevent microbial invasion [24]. This enhances intestinal integrity and prevents leakiness of harmful substances. Probiotics also engage with gut-associated lymphoid tissue (GALT), where they regulate immune functions by stimulating the production of anti-inflammatory cytokines and promoting immune tolerance [25]. Apart from these effects, probiotics exert systemic effects via metabolic and neuroendocrine mechanisms. They play a role in the synthesis of active molecules, such as neurotransmitters and regulators, thus influencing the gut-brain axis. They also play a role in regulating oxidative stress, inflammation, and metabolism, highlighting their potential therapeutic applications. Overall, the multifaceted effects of probiotics reflect their ability to restore the microbial ecosystem, bolster host immunity, and promote overall health, confirming their role as important components of nutraceuticals and functional foods.

5. Synbiotics and Postbiotics

Synbiotics are a next-generation and targeted combination of prebiotics and probiotics aimed at having a synergistic effect on the gut microbiome. Synbiotics differ from the separate administration of prebiotics and probiotics in that the prebiotic component selectively enhances the survival, colonization and metabolism of the probiotic strains in the gut environment [26]. This combined effect results in improved survival of the microorganisms in the gut, improved functionality and increased tolerance against environmental factors, such as low pH and bile salts [27]. Synbiotics can be classified as complementary or synergistic. Complementary synbiotics employ separate function of prebiotics and probiotics, while synergistic synbiotics are engineered so that the prebiotic substrate is used exclusively by the co-supplied probiotic strain. This targeted approach is increasingly being considered

in the field of personalised nutrition and microbiome interventions, where strain-specific interactions play a key role. Recent studies indicate that synbiotics may be more effective in inflammatory bowel disease, metabolic syndrome and immune dysfunction by improving microbial viability and performance. Similarly, the term postbiotics is emerging as a next-generation probiotic. Postbiotics are defined as preparations of inactivated microorganisms and/or their inactive components that have a beneficial effect on the host [28]. Postbiotics comprise a broad spectrum of bioactive compounds including short-chain fatty acids, microbial peptides, enzymes, polysaccharides, cell wall components (e.g., peptidoglycans, lipoteichoic acids) and extracellular vesicles [29]. Postbiotics retain biological activity without the need for viability, overcoming issues of stability, storage and safety. Postbiotics hold therapeutic promise as they can directly modulate host cell pathways without the safety concerns of microbial translocation and infection. This makes them a good option for patients with compromised immune systems, newborns and the elderly [30]. Additionally, postbiotics have benefits in terms of consistent dosing, stability and reproducibility, which are essential for clinical and industrial use. With ongoing research, postbiotics are being increasingly incorporated into functional foods and medicinal formulations, highlighting their potential as a new avenue for microbiome-based therapies.

6. Mechanisms of Gut Health Modulation

Prebiotics and probiotics influence gut health via a multidimensional web of interrelated mechanisms, both within and beyond the gut. Microbial-level mechanisms include alterations to the microbiota's composition, diversity and function, favouring the establishment of beneficial microbiota and the suppression of pathogenic strains [7]. This microbial ecology drives resistance and promotes eubiosis. A key process is the generation of short-chain fatty acids (SCFAs) from the microbial fermentation of prebiotics. SCFAs serve as important signals that modulate host gene expression, epigenetic, and metabolic processes [16].

These bind to G-protein-coupled receptors such as GPR41 and GPR43, impacting on inflammation, energy metabolism, and immune response. Butyrate, in particular, is crucial for maintaining gut barrier function by providing an energy source for colonocytes and facilitating tight junction formation. Prebiotics and probiotics also strengthen the epithelial barrier by upregulating tight junction proteins, promoting mucus secretion, and decreasing epithelial permeability. This strengthens the barrier, preventing the leakage of microbial products into the bloodstream, and thereby lowering endotoxemia and systemic inflammation. At the same time, they regulate immune functions by affecting both innate and adaptive immunity. They upregulate anti-inflammatory cytokines (e.g., IL-10) and downregulate pro-inflammatory cytokines (e.g., TNF-α and IL-6) [25]. Another key aspect of gut health modulation is the interaction with the gut-brain axis. Prebiotics and probiotics modulate the production and metabolism of neurotransmitters like serotonin, dopamine and gamma-aminobutyric acid (GABA), which in turn impacts neural signaling and behavior [13]. The bidirectional communication occurs through neural (vagus nerve), endocrine (hormonal) and immune mechanisms that connect gut microbiota with the brain and emotions. Besides neural impacts, these nutraceuticals modulate systemic metabolism. They regulate lipid metabolism via bile acid profile and cholesterol absorption, enhance glucose homeostasis by improving insulin sensitivity, and affect energy homeostasis by regulating hormones related to energy balance (ghrelin and peptide YY) [31]. These effects highlight the systemic and holistic impact of prebiotics and probiotics in regulating homeostasis. Figure 1 illustrates various mechanisms of action of prebiotics and probiotics.

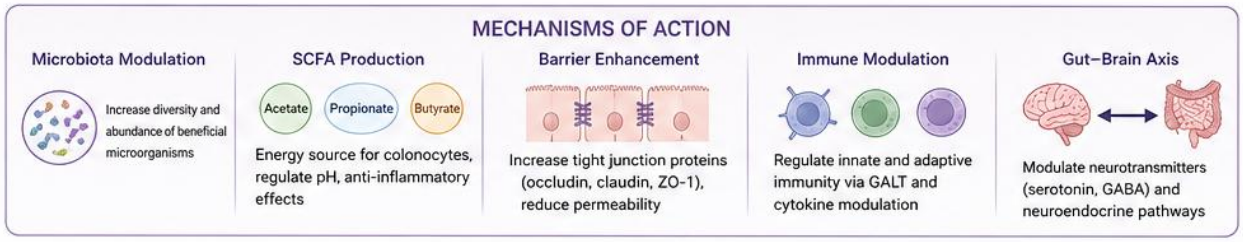


Figure 1. Mechanisms of Action of Prebiotics and Probiotics in Host Health Modulation

7. Health Benefits and Therapeutic Applications

Prebiotics and probiotics have a wide range of therapeutic applications, which have been well studied. Within the gut, they have been shown to be effective in irritable bowel syndrome (IBS), inflammatory bowel disease (IBD) and antibiotic-associated diarrhoea. They improve the microbial community structure, decrease inflammation and strengthen the mucosal barrier, leading to symptom relief and reduction in disease activity [32,33]. Metabolic health is another area where prebiotics and probiotics have demonstrated potential benefits, such as enhanced insulin sensitivity, decreased body fat, and favourable lipid profiles. This is achieved via changes in bacterial diversity, enhanced SCFA production and modulation of inflammatory pathways [34]. These treatments are being explored as supplementary treatments for obesity and type 2 diabetes. The immune-modulatory effects of these nutraceuticals are important. They improve mucosal immunity and induce immune tolerance, thereby preventing infections and

allergic diseases. They have been shown to prevent atopic dermatitis, respiratory and gastrointestinal infections, particularly in children [35]. Prebiotics and probiotics have also been shown to have a role in psychiatric disorders. By affecting the gut-brain axis, they have been shown to ameliorate depression, anxiety and stress-related disorders. These mechanisms are thought to be related to altered neurotransmitter synthesis, inflammation and hypothalamic-pituitary-adrenal (HPA) axis responses [36]. In addition, they have shown benefits to the cardiovascular system, including lowering of serum cholesterol, regulation of lipid metabolism, and blood pressure [38]. Some probiotics have been found to deconjugate bile acids and absorb cholesterol, impacting cardiovascular health [37]. Overall, these varied therapeutic uses highlight the potential for prebiotics and probiotics as nutraceuticals.

8. Nutraceutical Applications and Delivery Systems

The use of prebiotics and probiotics in nutraceutical products has grown significantly due to rising consumer interest and scientific evidence supporting their health effects. Probiotics and prebiotics fortified functional foods, such as dairy-based products, drinks, cereals, and snacks, are a significant part of the food market. They not only offer nutritional benefits but targeted health benefits, in line with the notion of preventative medicine [40]. One major hurdle in probiotic use is the preservation of their viability throughout processing, storage and the transit through the gastrointestinal tract. To overcome these challenges, sophisticated delivery technologies such as microencapsulation, nanoencapsulation and biopolymer delivery systems have been developed [38]. These technologies shield probiotic cells from environmental challenges such as heat, oxygen and gastric acid, facilitating their viability and efficacy in the intestine. Microencapsulation involves entrapping probiotic cells in protective matrices made of polymers like alginate, chitosan or gelatin. Nanoencapsulation enhances delivery of probiotic cells by providing controlled release and site-specific delivery in the gastrointestinal tract. These technologies not only enhance stability and shelf-life, but also bioavailability and efficacy [39]. Figure 2 shows the nutraceutical applications and delivery systems of prebiotics and probiotics. Besides encapsulation, other strategies include synbiotics, triggered delivery (pH or enzymes) and delivery in new food formats. The creation of dairy-free probiotic products is also becoming more significant, addressing lactose intolerances and veganism.

Figure 2: Nutraceutical Applications and Delivery Systems of Prebiotics and Probiotics

In summary, the development of delivery systems is key to the advancement of prebiotic and probiotic research into nutraceutical products. These technologies are likely to lead to future expansion of the field, allowing for the creation of more potent, stable and individualized products for improving gut health. Table 1 offers a brief overview of the definitions, mechanisms and therapeutic impacts of prebiotics, probiotics, synbiotics and postbiotics on gut health and systemic physiological processes.

Table 1. Integrated Functional Overview of Prebiotics, Probiotics, Synbiotics, and Postbiotics in Gut Health

Category	Definition	Components / Examples	Mechanisms of Action	Applications	References
Prebiotics	Non-digestible substrates selectively utilized by beneficial gut microbiota	Inulin, FOS, GOS, resistant starch	Fermentation → SCFA production; modulation of microbiota; immune regulation	Improved gut barrier, anti-inflammatory effects, metabolic regulation	[4], [14–20]
Probiotics	Live microorganisms that confer health benefits when administered in adequate amounts	*Lactobacillus*, *Bifidobacterium*, *Saccharomyces*, *Streptococcus*	Competitive exclusion of pathogens; antimicrobial production; immune modulation; barrier enhancement	Management of IBS, IBD, diarrhea; immune enhancement; mental health support	[5], [21–25], [32–36]

Synbiotics	Combination of prebiotics and probiotics designed for synergistic effects	Inulin + *Bifidobacterium*; FOS + *Lactobacillus*	Enhanced colonization and survival of probiotics; improved microbial balance	Improved efficacy in metabolic and inflammatory disorders	[26], [27]
Postbiotics	Non-viable microbial cells or their bioactive components	SCFAs, peptides, enzymes, cell wall fragments	Direct interaction with host pathways; anti-inflammatory and metabolic effects	Safe alternative for immunocompromised individuals; therapeutic potential	[28–30]
Gut Microbiota Modulation	Alteration of microbial composition and function	SCFAs, microbial metabolites	Regulation of gene expression; immune modulation; barrier integrity	Prevention of dysbiosis-related diseases	[7], [16], [25]
Gut–Brain Axis	Bidirectional communication between gut microbiota and CNS	Neurotransmitters (serotonin, GABA)	Neural, endocrine, immune signaling pathways	Mental health (depression, anxiety), cognition	[13], [36]
Metabolic Effects	Influence on host metabolism	SCFAs, bile acids	Regulation of lipid metabolism, glucose homeostasis, energy balance	Obesity, diabetes management	[31], [34]
Delivery Systems	Technologies to enhance stability and efficacy	Microencapsulation, nanoencapsulation	Protection from GI conditions; targeted release	Improved viability and bioavailability	[38], [39]

9. Safety and Regulatory Aspects

Prebiotics are considered safe (GRAS) due to their presence in routine foods and their history of consumption. They are non-digestible components of food, not absorbed in the upper gut and selectively fermented in the colon, and thus have limited systemic toxicity. But they may cause gastrointestinal symptoms such as bloating, flatulence or osmotic diarrhea at high intake levels in some people. Thus, dose and tolerance are crucial aspects of their clinical and nutritional use. On the other hand, probiotic safety is more intricate and influenced by factors such as strain-specificity, viability, dose, route of administration and health status of the host [5]. Although most commercially available probiotic strains, especially those from Lactobacillus and Bifidobacterium, have a well-documented safety record, there is still concern about the potential adverse effects, including bacteremia, sepsis, and horizontal gene transfer, particularly in immunocompromised patients, critically ill patients and newborn infants. Therefore, strain-specific identification, genomic profiling and clinical testing are key requirements to guarantee probiotic safety. The regulatory landscape of prebiotics and probiotics differs between countries, with implications for harmonization of regulations, labeling and quality control. Probiotics are often regulated as dietary supplements in many countries, leading to lower regulatory standards. For example, although regulatory agencies like the Food and Agriculture Organization/World Health Organization (FAO/WHO), the European Food Safety Authority (EFSA), and the U.S. Food and Drug Administration (FDA) have developed guidelines for safety assessment, there are differences in definition, claims and approval procedures [41]. These inconsistencies pose challenges for global marketing and consumer confidence.

Another important consideration in the development of probiotic products is quality control. Issues like strain identification, contamination, variation in viable cell numbers, and decrease in viable cell count during storage or transportation can affect product safety and efficacy. It's crucial that products contain the specified microbial strains at therapeutic levels throughout their shelf life to ensure therapeutic efficacy [42]. As such, new methods for microbial identification, manufacturing standards and stability studies will help to enhance quality. In summary, prebiotics and probiotics are generally safe, but with growing clinical and commercial interest, we need to ensure their safety, efficacy and quality through rigorous regulatory systems, standardised evaluation criteria and quality control.

10. Challenges and Future Perspectives

While significant progress has been made in microbiome research and development of nutraceuticals, there are several challenges in translating prebiotics and probiotics into clinical practice. A key challenge is the significant variability among individuals in gut microbial diversity and function. Genetic background, dietary habits, age, lifestyle factors and environmental factors affect the microbial response to interventions, resulting in variable clinical responses. This highlights the importance of individualised approaches to the microbiota. A further challenge is the absence of standardized dosing and treatment approaches. The specific type, combination and dose of prebiotics and probiotics needed to achieve particular health outcomes are still not well understood. Furthermore, variability in study designs, probiotic strain(s) used, and outcome measures used in clinical trials makes it difficult to interpret and extrapolate findings. Therefore, there is a need to define guidelines for dose, duration and formulation. Stability and viability is also a significant challenge, especially with probiotics. Preserving viability through processing, storage, and transit through the digestive system is critical for efficacy. While new encapsulation techniques have enhanced stability, there remains a need for further developments to increase efficiency and throughput [38]. Likewise, the stability of prebiotics under different processing conditions needs to be considered for product development. The advent of omics approaches, such as metagenomics, metabolomics, transcriptomics and proteomics, is transforming knowledge of host-microbiome interactions. These high-throughput technologies allow detailed profiling of microbial structures, functions, and metabolites, leading to a better understanding of the mechanisms involved in microbiome-related health and disease [43]. Leveraging multi-omics data with computational modeling and artificial intelligence is likely to aid the discovery of new therapeutic targets and diagnostic biomarkers.

The future of this field is increasingly moving towards next-generation probiotics, including new commensal organisms with specific functional effects, such as Akkermansia muciniphila and Faecalibacterium prausnitzii. These strains have specific therapeutic effects against metabolic, inflammatory and immunological diseases. Similarly, microbiome-based products such as engineered probiotics and microbial consortia are being developed for targeted approaches. Personalised nutrition is another exciting area, where dietary and nutraceutical strategies are developed based on an individual's microbiome, genetic and metabolic characteristics [44]. These targeted interventions help to enhance efficacy while reducing variability and side effects. Also, the emerging focus on postbiotics and paraprobiotics provides an approach that avoids issues with live organisms.

11. Discussion

The current review reveals some important findings on the role of prebiotics and probiotics in the modulation of gut health. One significant observation is that both prebiotics and probiotics have their effects mediated by multifactorial processes, including modulation of microbial composition, improvement of epithelial barrier integrity and regulation of immune and metabolic processes. A key process that connects microbial activity to physiological benefits in the host is the production of short-chain fatty acids (SCFAs), especially butyrate. The next significant finding is the strain specific and substrate specific nature of probiotic and prebiotic effects indicating that their therapeutic effects are very dependent on composition, dosage, and host factors. The review also shows that synbiotics have a better efficacy than an individual component through enhancement of microbial survival and colonization. Moreover, there is also the emerging evidence in support of the increasing importance of postbiotics as a safer and a more stable alternative, especially in vulnerable populations. Developments in delivery systems, including microencapsulation and nanoencapsulation have been outlined as some of the technological advances that enhance the viability and bioavailability of these nutraceuticals. Notably, the results highlight that the modulation of gut microbiota has systemic implications, as it can modulate not only the gastrointestinal health but other metabolic, immune, and neuropsychological functions via the gut-brain axis. Nevertheless, individual microbiota composition variability and standardization of dosing are the key issues. In general, the data indicate that both prebiotics and probiotics are promising, but complex, nutraceutical approaches that have to be further standardized, personalized, and clinically validated.

12. Conclusion

Prebiotics and probiotics are revolutionizing the field of nutraceuticals, with the potential to enhance gut health and well-being. Further research and technological advances are needed to address limitations and maximise their potential.

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