Explore the Potential of Probiotics and Prebiotics in Modulating Gut Health: A Comprehensive Review

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Abstract

The gut microbiota is found entirely in the alimentary tract of the human body, and the composition of microbiota is varied in all individuals, which is particularly altered by different components including inheritance, age, dietary pattern and lifestyle. Functional foods specifically, probiotics and prebiotics have gained consideration because of their potential to modulate gut flora and reduce the risk of chronic diseases. Probiotics are live micro-organism present in food components while prebiotics are non-digestible fiber that play a vital part in restoring the balance of microbiota in the body. The gut health has a strong connection with the central nervous system and any modification in bidirectional communication result in neurological issues or gastric ailments. Therefore, dysbiosis is associated with different diseases and causes intestinal permeability, which contributes to systemic inflammation and increases the level of pathogens in the body. This chapter highlights the concepts of gut microbiota, prebiotics, probiotics, symbiotics and how diet affect the gut balance. In addition, it also discussed the intestinal brain axis and the mechanism of prebiotics and probiotics to maintain the gut homeostasis.

Keywords: Gut microbiota, Functional foods, Dietary fiber, Gut health, Intestinal brain axis

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Introduction

The gut microbiome, also known as the microbiota or flora, is defined as the large collection of microorganisms mostly found in the large intestine that carry out a number of physiological and metabolic functions in the body (Patel, 2021). Each person's gut microbial composition is unique and stable; they will preserve over 60% of their gut microbial phylotypes (Anto & Blesso, 2022). The World Health Organization (WHO) defined as probiotics are live microorganisms, when given in sufficient amount microbes boost host organisms' health. Nowadays, probiotics, whether they're in the form of dietary supplements or whole meals, have raised prominence as functional foods. Probiotics have been an essential ingredient and marketing goal due to their possible health advantages. The best way to consume probiotics is either as a supplement or by including them in your favorite foods and drinks. Many fermented foods contain live microorganisms that are genetically related to probiotics strains. It has been noted that by converting substrates and generating bioactive and bioavailable end products, fermented foods improve their functional and nutritional qualities (Latif et al., 2023).

Any substrate that is specifically used by host microbes and provides health benefits are known as a prebiotic. Even though all substances regarded as prebiotics are fermentable dietary fiber or carbohydrates that are available to the microbiota (Valdes et al., 2018).

Types of Prebiotics

Prebiotics include different substances from oligosaccharides to polysaccharides which have distinct characteristics and functions. There are different types of prebiotics that perform various physiological roles in the body (Rezende et al., 2021). Prebiotics include inulin, galacto-oligosaacharides, fructo-oligosaccharides, beta glucan, pectin and resistant starches (Roy, 2023).

Inulin

The inulin is a common prebiotic which belongs to fructans class and is widely present in many natural foods such as chicory root. The common food sources are asparagus, garlic, onion, and bananas also contain an abundant amount of inulin (Mudannayake et al., 2022). The structure of fructose molecules is joint together by glycosidic bond through beta (2-1) linkage. The inulin has different lengths depending upon structure; short chain length of fructose is called oligofructans whereas longer chains are known as polysaccharides (Wan et al., 2020). The gut microbes ferment the inulin, which is considered prebiotic. The process of fermentation stimulates the activity of good bacteria, particularly *lactobacillus* and *bifidobacteria* (Tawfick et al., 2022). The fermentation of inulin increases the multiplication of bacteria, which provides healthier gut microbiota. Several benefits are associated with inulin consumption, which include reduce the risk of chronic ailments, enhance the health of digestive system and improve the immune health (Nazzaro et al., 2020). The fermentation of inulin synthesized the short-chain fatty acids (SCFA's) like acetate, butyrate and propionate in the colon region. A recent study reported by Mitchell et al. (2021), inulin improved the insulin sensitivity and reduced the postprandial glucose levels to maintain sugar levels due to SCFA's.

Galacto-oligosaacharides

Galacto-oligosaacharides (GOS) are a type of dietary fiber which consist of short chain galactose molecules. It improved the proliferation of gut bacteria due to the production of bifidobacteria. According to research study, the supplementation of GOS promote the microbial composition and result in more diverse bacterial balance. Also, aid in lowering the number of gastrointestinal diseases and created a positive influence on digestive health (Wang et al., 2021).

Fructo-oligosaccharides

Fructo-oligosaccharides are a kind of prebiotic fiber, made up of fructose molecules bond with one end containing glucose molecule (Rahim et al., 2021). They consist of oligosaccharides and are present in natural plants like fruits, vegetables and grains. The fructose molecules connected through glycosidic linkage by beta (2-1) with glucose molecule at one end of its structure (Nobre et al., 2022). The intake of FOS has been associated with various health benefits, include enhance immunity, improve gastrointestinal health and protect from the long-term conditions. The bifidogenic property of FOS to proliferate the bifidobacteria in gut to regulate bowel movements and prevent constipation (McRae, 2020).

Beta Glucan

The beta glucans are polysaccharides and contain glucose molecules joined together with beta bond through glycosidic linkage. They have the capacity to modify the immune system, may be because of their prebiotic effect. They are present in the cell walls of micro-organism like bacteria, viruses and fungi (Xin et al., 2022). The most common sources of beta glucan are mushroom, yeast, barley, and oats (Singla et al., 2024). The rich sources of dietary fiber are bran and germ portion of oats and barley, which contain a substantial amount of beta glucan. Numerous food products contain beta glucan like cereals, bread, rice and supplements (Lante et al., 2023)

Pectin

A type of fiber that is naturally found in peels of apples, berries and citrus which is collectively known as pectin. It is a complex structure made up of galactrounic acid and side chains of sugar such as rhamnose, arabinose and galactose (Kaczmarska et al., 2022). The distinctive characteristic of pectin is their use in food industry as a thickener and stabilizing agent in different food items like jams and jellies (Alam et al., 2023).

Resistant Starches

It consists of amylose and amylopectin that are made up of starch, digestion does not occur in upper part of gastrointestinal tract and utilized as a substrate by gut microbes for fermentation (BeMiller, 2020). Depending upon physical properties, RS is divided into four different types. RS1 is mostly present in whole or partial foods items, such as grains and seeds. While, RS2 is rich in amylose content found in potatoes, banana and corn. RS3 are produced after cooking starchy foods known as retrograded starch. Whereas the starch that goes through chemical alteration is termed as RS4 (Tian & Sun, 2020). Kim et al. (2020) investigated that use of resistant starches as a snack regulates the insulin signaling pathway by maintaining the blood glucose level significantly.

Human Gut Microbiota

The complex community of bacteria that reside in gastrointestinal system. Trillions of bacteria, viruses, fungi, and other microorganism make up the complex ecosystem that is the human gut microbiota. Human physiology, diet and lifestyle choices have molded and been influenced by this diverse microbiome throughout human evolution (Ji et al., 2023).

Commensal bacteria support the healthy anatomical growth and normal functioning of human organs, including the liver, brain, and intestine. The gut microbiota is primarily composed of bacteria; with over 1000 species identified, the three phyla that make up the majority of bacteria found in the human gut are Firmicutes, Actinobacteria, and Bacteroidetes with over 90% of all bacteria categorized into these groups (Anto & Blesso, 2022).

The fermentation of dietary fiber produces short-chain fatty acids (SCFA's). Acetate is one of the most common short- chain fatty acids which is a necessary for maturation of bacteria and plays an important role in lipogenesis and cholesterol metabolism. It may also have an impact on central appetite regulation (Valdes et al., 2018).

Gut Microbiota and Human Diseases

An altered gut microbiota has been linked to a number of serious human diseases, including diabetes, obesity, inflammatory bowel disease and cardiovascular diseases, (Afzaal et al., 2022).

Obesity

A number of gut microbiota species, including Firmicutes, Bacteroidetes, Rhizobium, Lactococcus, and Clostridium, are known as the obesogenic gut microbiota and can play a major role in obesity. Specifically, obesogenic gut bacteria may contribute to obesity by generating SCFAs like butyrate, giving the host more energy, and triggering low-grade inflammation brought on by metabolites of the intestinal microbiota. By inhibiting adenosine monophosphate kinase (AMPk), the gut microbiota can lower fatty acid oxidation. This enzyme function as a cellular energy indicator and is found in the liver and muscle fibers. Because AMPk inhibition decreases fatty acid oxidation, fat storage increases (Afzaal et al., 2022).

Inflammatory Bowel Disease

The incidence of inflammatory bowel disease has increased significantly in developed countries. It is a serious illness that is most common in western nations. The majority of research has shown that people with IBD have a reduced variety of gut flora. Most of the studies have claimed that change in gut microbiota composition in IBD patients are notable reductions in Firmicutes and proteobacteria. Therefore, altering the gut microbiota to restore immunological homeostasis is presently seen to be a viable therapeutic approach to treat IBD patients (Durack & Lynch, 2019).

Cardiovascular Diseases

The intestine has also been implicated in the pathogenesis and progression of CVDs, mostly as a result of intestinal barrier failure brought on by decreasing intestinal perfusion. The role of gut microbiota in heart disease and stroke has been investigated. Recent data have demonstrated that intestinal microbiota synthesis of metabolites and impairment of the gut endothelium barrier function is both associated with gut dysbiosis. Furthermore, coronary artery disease is associated with a higher abundance of *Streptococcus* and *Enterobacteriaceae* (Jie et al., 2017). In coronary artery disease patients, the most prevalent bacterial species that make up the gut microbiota have undergone changes; Firmicutes are more common and Bacteroidetes are less common. One metabolite that contributes significantly to atherosclerosis and can be used to predict cardiovascular risk is trimethylamine-N-oxide (Hou et al., 2022).

Role of diet in shaping Gut Microbiota

Human gut microbiota influenced by various factors such as genotype, sex, age, immune status, and various environmental elements. Among these factors, dietary habits play a pivotal role in shaping the composition of gut microbiota. Nutrient intake is not only important for survival and well-being, but also essential in regulating the symbiotic microbial communities within the gut. The source, quality and type of food play a significant role in growth of gut microbiota, influencing its composition, function, and interactions with the host. Thus, understanding a how diet influences its colony and identifying the nutritional components that best support a healthy microbial community is crucial (Ramos & Martín, 2021).

The Western Diet

Western diet is often implicated in intestinal dysbiosis, which promotes local inflammation and increases intestinal permeability through the growth of pro-inflammatory species. Key feature of the western diet include a high intake of red meat, saturated fats, sugar and processed foods alongside a low intake of dietary fiber (Campaniello et al., 2022). This dietary pattern leads to a decline in bacterial species linked to anti-inflammatory effects such as *Akkermansia, Muciniphila*, *Roseburia* and *Eubacterium* spp. Consequently, the guts ability to produce beneficial metabolites is significantly diminished (Ramos & Martín, 2021).

A high-fat, diet can stimulate the production of endotoxin (lipopolysaccharides) by the intestinal microbiota, creating favorable conditions for the proliferation of gram-negative bacteria, such as *Enterobacteriaceae*. Elevated endotoxin levels can lead to inflammation and disrupt gut microbiota composition by increasing intestinal permeability, thereby contributing to obesity. Studies on high fat dietary pattern have shown that regular consumption of red meat increases the incidence of colonic inflammation (Ross et al., 2024).

Plant-based Diet

The vegan diet consists of exclusively of food plant origin, emphasizing a high consumption of fruits and vegetables while minimizing saturated fat intake. It is well established that a higher fiber intake can increase the *prevotella*-to-*bacteroides* ratio. Conversely, a western-style diet may negatively influence gut microbiota alongside environmental, cultural, and genetic factors. Dietary fiber significantly influences both the quantitative and qualitative aspects of gut microbiota. For instance, high consumption of indigestible carbohydrates, such as wheat bran and whole grains, often increase the abundance of *Lactobacillus and Bifidiobacterium spp*. These increases are particularly beneficial for gut health, as their saccharolytic metabolism inhibits the colonization and growth of pathogenic bacteria, enhancing resistance to pathobionts (Beam et al., 2021).

Fermentable dietary fiber is well known substrates for the metabolism of intestinal bacteria, leading to production of short- chain fatty acids (SCFA's), such as acetate, propionate, and butyrate (Zhang, 2022) and shown in Figure 1. These SCFA's serve as energy sources for gut epithelial cells and are associated with numerous benefits, including colon acidification, reduced plasma cholesterol levels, improved glucose tolerance and inhibition of pathogens. Enterobacteria enhanced water and sodium absorption, and anti-inflammatory properties. Additionally, SCFA's support colonic epithelial cells, contribute to cancer prevention by inhibiting cell proliferation, promote fat oxidation, and help prevent obesity (Beam et al., 2021).

Gluten- free Diet

A gluten- free diet (GFD) can have a notable impact on gut microbiota. Research has shown that following a GFD for one month in healthy individuals led to a decrease in the population of Lactobacillus and Bifidobacterium alongside an increase in E-coli which are commonly associated with episodes of bacteremia (Coker et al., 2021). These findings highlight that, while GFD is an effective treatment for celiac disease, it is often linked to health challenges and insufficient intake of certain nutrients. Although this is essential for individuals with celiac disease, wheat allergy (Zhang, 2022).

The Mediterranean Diet (MD)

The (MD) primarily emphasize on whole grains, legumes, fresh vegetables, fruit and nuts, while reducing the intake of milk and high fat dairy products. For instance, a study involving 20 obese men found that adhering to the MD for one year decreased *revotella* populations while increasing *roseburia*. *Roseburia* produces butyrate, which supports microbial hemostasis and reduce inflammation (González et al., 2021).

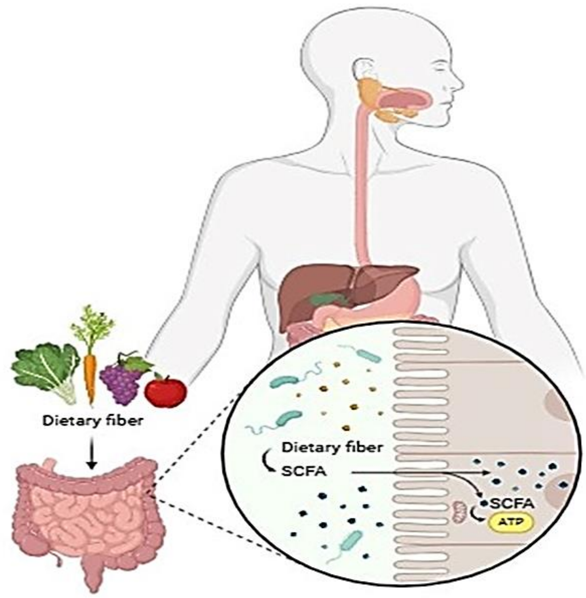

Fig. 1: Effect of Plant-based diet on gut microbiota.

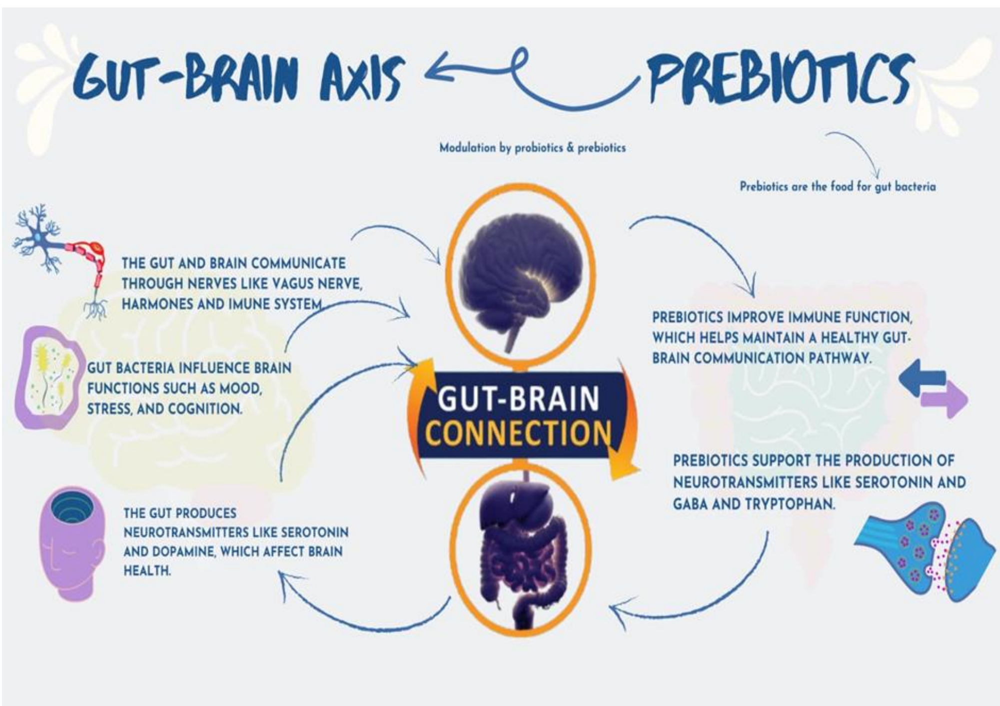

Fig. 2: Effect of probiotics and prebiotics in altering gut brain axis

Microbiome Gut Brain Axis

The two-way biochemical communication between the central nervous system (CNS) and the gastrointestinal tract is known as the gut-brain axis is shown in Figure 2. (Mayer et al., 2014). Neuronal messages are sent by vagal affections, intestinal hormones carry endocrine signals, and cytokines carry immunological signals, all of which contribute to the gut-brain axis communication. Owing to the large neuronal network in the gastrointestinal tract, ingested substances can cause the central nervous system to receive information about macronutrients and caloric value through customized and targeted detection systems located throughout the gastrointestinal tract (Olmo et al., 2021). Changes in the gut-brain-microbiota axis are associated with psychiatric conditions, such as schizophrenia, anxiety, mood disorders, and neurodevelopmental problems, in addition to metabolic and immunological illnesses (Tengeler et al., 2018). Changes in the control of the blood-intestinal barrier's permeability can trigger innate immunity, which in turn can lead to a systemic and cerebral inflammatory state, increased vulnerability to stress, and mental health disorders. The down-regulation of epithelial inflammatory responses, the expression of antimicrobial proteins, the defense of the epithelial surface through mucus formation, and the healing of intestinal tissue injury are really coordinated by the commensal flora (Ismail & Hooper, 2005).

Mechanism of Action (Probiotics)

In general, probiotics are those species of *Lactobacillus*, *Bifidobacterium*, and *Saccharomyces boulardii,* having individual benefits (Plaza-Diaz et al., 2019). The basic mechanism through which they exert their action includes the following:

1. Competitive Exclusion of Pathogens

Probiotics compete with pathogens for the epithelial cells lining the gut mucosa, thus occupying adhesion sites that pathogens might bind to otherwise. They make a physical barrier on the gut surface and limit the opportunity of harmful bacteria attaching to the intestinal mucosa. (Mazziotta et al., 2023). It competes with pathogens for the scarce nutrients that are available in the gut environment.

2. Intestinal Barrier Function Enhancement

In addition, probiotics may enhance tight junctions between the cells of the intestine by increasing proteins, such as occluding and claudins are critical for the structures. Harmful substances, including toxins and pathogens, are unable to penetrate the blood because of the tight junctions (Rose et al., 2021).

Some of the probiotics induce the secretion of mucus by the mucous membranes. Mucus offers a layer of defense that ensures that pathogens and toxins are not in direct contact with the epithelial cells. It also strengthens the gut wall so that it remains intact without leakage, which occurs in the condition known as "leaky gut syndrome." In such cases, there is the leaking of several substances and particles through the intestinal walls that cause systemic inflammation and even autoimmune reactions in some instances (Latif et al., 2023).

3. Release of Antimicrobial Agents

Most of the probiotics produce small proteinaceous compounds, known as bacteriocins, that show selectivity to some pathogenic bacteria. These harm the offending microbes by upsetting their cell wall. The metabolic by-products of probiotics include lactic acid and acetic acid, which lower the pH of the gut environment. Generally, most pathogenic bacteria do not thrive in conditions with acidic pH, therefore this would limit their growth (Rocchetti et al., 2021). Some probiotics produce hydrogen peroxide as a defense mechanism, which exerts a broad-spectrum antibacterial effect against pathogens (Monika et al., 2021).

4. Modulation of the Immune System

Probiotics interact with dendritic cells and macrophages with gut-associated lymphoid tissue (GALT) which are involved in modulation of immune system. It also influences the expression of cytokines and the signaling molecules of immune system. They can stimulate the release of anti-inflammatory cytokines, like IL-10, and reduce the levels of pro-inflammatory cytokines, such as IL-6 and TNF-α, which ensures balance within the immune system (Begum et al., 2021).

5. Enhanced Nutrient Intake and Formation of Positive Metabolites

Formation of Digestive Enzymes: Some probiotics, for example, are enzyme producers and produce lactase, which helps in lactose breakdown in milk products, thereby aiding the lactose intolerant person (Peredo-Lovillo et al., 2020).

Mechanisms of Action (Prebiotics)

Often, they are inulin, FOS and GOS that selectively stimulate beneficial gut bacteria, especially Bifidobacteria and Lactobacilli. Their mechanisms include the following:

Selective Fermentation and Promotion of Beneficial Microbes

Prebiotics are selectively utilized by beneficial bacteria. That is, they selectively feed microbes like Bifidobacterium and Lactobacillus over harmful bacteria. This specificity encourages a more balanced and health-promoting microbiota composition. This further helps in maintaining a balanced microbiome and reduces the risk of dysbiosis, an imbalance of gut bacteria (Guarino et al., 2020)

Producing Short-Chain Fatty Acids

Beneficial bacteria ferment prebiotics in the colon, producing SCFA's (acetate, propionate, and butyrate) as byproducts (Markowiak & Śliżewska, 2020).

Butyrate is an important energy source for colonocytes and, in general, for the maintenance of health in the mucosa lining the gut. It also acts as a non-inflammatory mediator and maintains the integrity of the gut barrier and decreases the incidence of colon cancer. SCFA's do enter the systemic circulation and can promote beneficial effects on metabolic health, glucose homeostasis, and body-level inflammation (Xiao et al., 2021).

Regulation of Immune Status and Anti-inflammatory Activity

The stimulation of beneficial bacteria growth indirectly acts to boost the production of anti-inflammatory compounds, which tend to promote a balanced response of the immune system.

They tend to favor a particular cytokine profile, mostly by either increasing the levels of anti-inflammatory cytokines or diminishing the levels of pro-inflammatory cytokines. The immune system of the gut, GALT, is stimulated by the end products of microbial fermentation of prebiotics that could facilitate improving immune tolerance and reduce the susceptibility of allergy and autoimmunity diseases (Pujari & Banerjee, 2021).

Enhanced Mineral Absorption

SCFAs formed during prebiotic fermentation reduce pH in the colon, thereby enhancing the solubility of minerals like calcium, magnesium, and iron. The acidic environment created by SCFAs improves the efficiency of mineral absorption in the large intestine, which is beneficial for bone health and reduces the risk of deficiencies (Mondal et al., 2024).

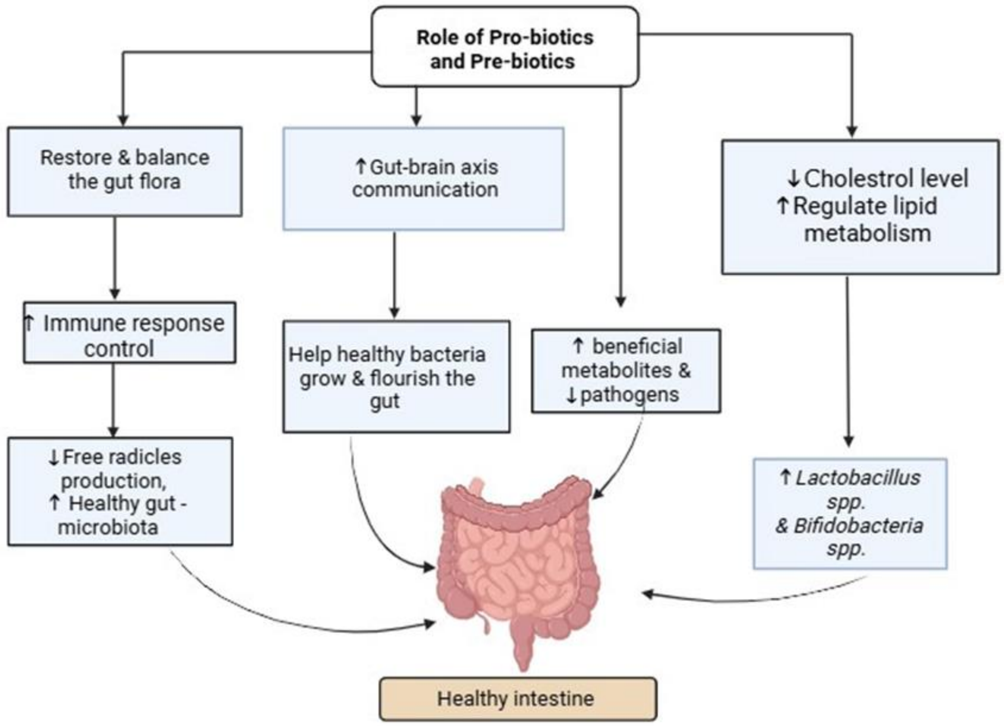

Fig. 3: Role of Probiotics and Prebiotics in maintaining healthy guts.

Role of Probiotics and Prebiotics in gut Symbiosis

Probiotic bacteria function through gut colonization, competing with other harmful pathogenic bacteria, causing proliferation and disruption of the normal microbial balance that otherwise would have caused dysbiosis or an imbalance in the gut microbiome associated with various diseases. Selective prebiotics feed and activates advantageous bacteria, with special emphasis being placed on advantageous bacteria that tend to be central in the balanced gut ecosystem shown in Figure 3. A nutrient selective for beneficial bacteria creates an indirect inhibition of the pathogenic microbes, providing long-term microbial stability and leading to a symbiotic condition (Leach, 2024).

1. Gut Barrier Integrity Enhancement

Some strains of probiotics fortify the gut barrier by tightening the junctions between intestinal cells. This diminishes the gut permeability or "leaky gut," which is the opening that allows toxins, pathogens, and undigested food particles to be passed into the bloodstream to provoke inflammation or an immune reaction. A healthy gut barrier is crucial in order to maintain a stable and protective interface between the microbiome and the body (Mohanty et al., 2018).

2. Producing SCFA's and other useful Metabolites

The probiotics and prebiotics both produce SCFA's including acetate, propionate, and butyrate through fermentation. It also lowers the pH in the gut and thus creates an environment not helpful for pathogenic bacteria but helps the beneficial species (Blaak et al., 2020).

3. Maintenance of Immune System Homeostasis

Probiotics may interact with various cells involved in the gut-associated lymphoid tissue (GALT). They induce immune response control by regulatory T cells and counteract excessive immunity towards irrelevant antigens. Additionally, probiotics boost immunoglobulin A, a predominant antibody responsible for pathogens degradation (Okumura & Takeda, 2016).

4. Inhibition of Overgrowth of Pathogens

In direct action against pathogens, probiotic strains produce several antimicrobial compounds, such as bacteriocins, lactic acid and hydrogen peroxide. These inhibit the growth of harmful bacteria. Furthermore, prebiotics help ensure pathogen suppression through the growth of naturally antagonistic populations of bacteria, which populate the gut in a way that allows little or no space for the pathogens, hence further in support of the protective role of gut symbiosis (Piatek et al., 2020).

5. Risk Minimization and Protection against Dysbiosis-Associated Disorders

Probiotics help to prevent dysbiosis that has been recently associated with several other diseases, such as IBD, obesity and mental disorders. After antibiotic consumption or any kind of microbiota disruption, probiotics ensure the recovery of balance to the microbiome; thereby, it also reduces the probability of dysbiosis (Duan et al., 2022).

Prebiotics feed the stable growth of beneficial bacteria, thus ensuring a strong and harmonious microbiota that is resistant to disruption and imbalance in a way that may lead to dysbiosis (Konstantinidis et al., 2020).

6. Synergistic Effects

This might enable probiotics with prebiotics to develop enhanced gut symbiosis when administered together with a synergistic impact during its consumption. A function of the prebiotic is to enhance their fuel for probiotic cells for survival and growth activities within the gut for multiplication as they increase the impacts by them on the host in improving beneficial effects (Rossi et al., 2016).

Conclusion

Large number of microbes are present inside the intestine known as gut microflora. The imbalance of microbes results in several chronic diseases like obesity, inflammatory bowel disease, and cardiovascular problems. Therefore, maintaining a healthy microbial community in the body is important for overall health and wellbeing. Functional foods are essential to include as a part of balanced meals to improve physiological processes of the body such as digestion and immunity. The recent literature reported that probiotics stimulated immune function, inhibited the growth of pathogens and lowered the risk of gastric issues by modifying the gut barrier. Moreover, the prebiotics produced short chain fatty acid through the process of fermentation, improved the absorption of nutrients and enhanced the proliferation of good bacteria. Further, there is a dire need for new researches to understand the long-term impact of probiotics and prebiotics in relation to health and disease.

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