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Unveiling the role of functional foods with emphasis on prebiotics and probiotics in human health: A review

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ABSTRACT

Functional foods particularly prebiotics and probiotics have attracted a lot of attention due to their ability to alter gut microbiota and have an impact on a number of health and disease-related factors, in relation to human health in recent years. Functional foods are foods that provide benefits to health beyond simple sustenance. They contain biologically active ingredients that offer additional health benefits when consumed on a regular basis as part of a balanced diet. Prebiotics, which are indigestible fibers that specifically promote the growth and activity of beneficial bacteria, and probiotics, which are live microorganisms that offer health benefits upon consumption of sufficient amount, have shown great promise in modifying the composition and function of the gut microbiota. The identified review problem involves clarifying the precise impacts of prebiotics and probiotics on immune system function, gut microbiota composition, metabolic health, and disease prevention. This review emphasizes the numerous advantages of probiotics and prebiotics in preserving the balance of gut microbiota, boosting immunity, enhancing metabolic parameters, and reducing the risk of a number of diseases. The review also insight to recent advances in the formulation of functional foods in mitigating health conditions and synergy between probiotics and prebiotics.

1. Introduction

The growing recognition of the significance of gut microbiota in preserving general well-being has spurred research into the role of functional foods, specifically, prebiotics and probiotics, in human health in recent years. Food items that offer more health benefits than just basic nourishment is referred to as functional foods (Olaniran et al., 2023). These foods are enhanced or prepared with biologically active ingredients, like vitamins, minerals, herbs, or other materials, with the intention of providing particular health advantages over and above their basic nutritional content (Gul et al., 2016). Functional foods are made to increase general well-being, lower the risk of disease, or promote optimal health. They frequently target particular physiological processes or deal with specific health issues (Birch & Bonwick, 2019). Fortified foods (like orange juice fortified with calcium), probiotics (live bacteria that support gut health), prebiotics (fiber that promotes probiotic growth), omega-3 enriched products, and foods high in antioxidants, like some fruits and vegetables, are a few examples (Gul et al., 2016). As more people look to improve their health through diet, the idea of functional foods has gained traction. These foods can be included into a holistic approach to wellness and preventive healthcare (Visen et al., 2022). Functional foods are a broad category of goods that provide particular health advantages over just basic sustenance. These foods may be found naturally or may have been enhanced or altered to include health-promoting bioactive substances. Their functionalities are the basis for their categorization and based on functionality, they have been categorized as fortified food, (Gul et al., 2016). Foods that have had extra nutrients added to them that were not previously present or were not present in sufficient amounts are known as fortified foods. This procedure is carried out to improve the food's nutritional value and address any deficiencies or health issues that may exist within a population (Delfanian & Sahari, 2020). Vitamins like D, A, B-vitamins (like folic acid, niacin, and B12), and vitamin C, along with minerals like iron, calcium, zinc, and iodine, can be added to food to fortify it (Nagar et al., 2018). Cereals, grains, and their byproducts, including rice, bread, pasta, and breakfast cereals, are frequently fortified with a variety of vitamins and minerals (Saleh et al., 2019). Dairy products like cheese, yogurt, and milk can have calcium and vitamin D added to them (Zahedirad et al., 2019).Vitamin additions may be present in certain bottled waters, fruit juices, and energy drinks. Nutrients are added to

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snack foods like chocolate and bars that have been fortified. Food can be fortified for a number of purposes, including addressing deficiencies, enhancing health, and satisfying dietary needs (fortified products for athletes or expectant mothers, for example) (Nair et al., 2016). Deficits have been successfully addressed by fortification. For example, iodine deficiency disorders have been dramatically reduced in many parts of the world when iodine has been added to salt (Santos et al., 2019). Infants' neural tube defects have decreased as a result of folic acid fortification (Dean et al., 2020).

Medical foods are a specific type of therapeutic product meant to be used in the diet to manage certain diseases or conditions that have unique nutritional requirements. These products provide targeted nutrients that are not adequately supplied by a regular diet, nutritional deficiencies or imbalances linked to specific medical conditions (Aronson, 2017). Medical foods are defined in the US by the Orphan Drug Act (ODA) as foods meant to be consumed by people with particular illnesses or ailments (Thomas & Caplan, 2019). Medical foods are regulated by the FDA differently than regular foods and dietary supplements. A product has to fulfill certain requirements listed in the ODA in order to be considered a medical food (Bailey, 2020). A specific disease or condition's nutritional needs must be managed in the formulation of medical foods. They have components or nutrients that contribute to fulfilling these specific dietary needs. They are applied under medical supervision and according to accepted scientific theories (Cederholm et al., 2017). Medical foods are used in the treatment of a number of illnesses where dietary changes are very important. Among the noteworthy applications are Inborn Metabolism Errors, Digestive Disorders, Renal Disorders, and Neurological Disorders (Makkar et al., 2020). Nutritional foods designed for particular metabolic pathways assist in meeting these requirements. To treat their condition, patients with inborn errors of metabolism (IEM) frequently need to follow special diets (Berry et al., 2020). Phenylketonuria (PKU), for example, requires a low-phenylalanine diet, which is controlled with prescription foods (Stroup et al., 2017). Certain nutritional support is often necessary for conditions such as short bowel syndrome, celiac disease, and inflammatory bowel disease (IBD). Nutrition from medical foods can help those with weakened digestive systems absorb or tolerate nutrients more easily (M.-S. Hsieh et al., 2020). Individuals receiving dialysis or suffering from chronic kidney disease (CKD) have specific dietary needs. These conditions can be managed with the help of medical foods made to control intake of protein, phosphorus, and potassium (Kelly et al., 2018). Certain neurological conditions, like Alzheimer's disease, necessitate nutritional assistance. Nutrients thought to support cognitive function and overall brain health may be present in some medicinal foods (Abate et al., 2017). A common feature of contemporary life are dietary supplements, which provide a practical way to meet nutritional requirements (Kantor et al., 2016). These supplements cover a wide range of goods, such as vitamins, minerals, amino acids, herbal extracts, and other substances, with the intention of enhancing or supplementing the diet (Mishra et al., 2021). Their appeal arises from the wish to close nutritional gaps, encourage well-being, and deal with particular health issues. But in order to use them wisely, one must be aware of their safety, effectiveness, and legal and regulatory environments (Kantor et al., 2016). Vitamins (A, B, C, D, E, and K) and minerals (iron, calcium, magnesium, and zinc) are among the most widely used supplements and are vital for a variety of body processes, from immune system support to bone health. These are frequently eaten to make up for deficiencies brought on by insufficient food intake (Godswill et al., 2020). Made from plants, herbal and botanical supplements include ginseng, turmeric, and echinacea, among other products. They are used for a variety of purposes, including enhancing digestion, lowering inflammation, and boosting immunity (Dasgupta, 2019). Since amino acids are the building blocks of proteins, athletes and fitness enthusiasts frequently take supplements containing these molecules to promote muscle growth and recovery (Zielińska & Pankiewicz, 2023). Specialty supplements address specific wellness needs with a range of products such as glucosamine for joint health, fish oil for omega-3 fatty acids, and probiotics for gut health (Raja et al., 2024).

The health benefits of functional foods are derived from a variety of bioactive substances, including omega-3 fatty acids, antioxidants, probiotics, prebiotics, and phytochemicals (Peng et al., 2020). Fruits, vegetables, and whole grains are rich sources of antioxidants, which work in the body to counteract harmful free radicals. This reduces oxidative stress and lowers the risk of chronic diseases like cancer and heart disease (Jideani et al., 2021). Live beneficial bacteria, or probiotics, are found in fermented foods like kefir, kimchi, and yogurt. They support a healthy gut microbiome, which helps with immunity, digestion, and may even reduce inflammation (Sanap et al., 2019). Prebiotics are non-digestible fibers found in foods like bananas, garlic, and onions that nourish the good bacteria in the stomach and promote probiotic growth and activity (Bhawana & Neetu, n.d.). Colorful fruits, vegetables, and herbs contain plant compounds called phytochemicals that have anti-inflammatory, antioxidant, and anti-cancer qualities that improve general health (Oz & Kafkas, 2017). The review aim is to elucidate the impact of functional food, specifically probiotics and prebiotics on immune function, gut microbiota composition, mental and digestive health.

2. Prebiotic

The importance of gut health for general wellbeing has come to light more and more in recent years. The gut microbiota, a diverse community of microorganisms found in the human gastrointestinal tract, is vital to immune system function, digestion, metabolism, and general health (de Vos et al., 2022). Diet is one of the key determinants of the composition and function of the gut microbiota among other factors. Prebiotics, in particular, are dietary components that have attracted a lot of attention due to their potential to support the growth of beneficial bacteria in the gut and improve overall gut health (Han et al., 2023). Several definitions have been used to describe prebiotics. In 1995, Gibson and Roberfroid popularized the term "prebiotics," defining them as "non-digestible food ingredients that beneficially affect the host by selectively stimulating the growth and/or activity of one or a limited number of bacteria in the colon, and thus improve host health" (Gibson & Roberfroid, 1995). As part of the process of updating the definition of prebiotics, in December 2016, the International Scientific Association for Probiotics and Prebiotics invited several scientific forums to convene a meeting. The change in the definition of prebiotic describes a prebiotic as a substrate that is utilized preferentially by the hosted microorganisms who provide a health benefit. This has broadened the definition to include non-carbohydrate compounds, utilization in other than GI tract, and in various other categories than just food. It retains the imperative need for selective biopsy-based mechanisms mediated through microbiota. Consensus also highlights that to be considered as a prebiotic a substance should show a documented positive health effect, and it should apply both to humans and animal uses, which has the objective of achieving better standardization, both in research, marketing, and regulatory points of view (Gibson et al., 2017; Hill et al., 2014).

Prebiotics are described as distinct fermentation component that alter the activity or composition of the gut microbiota to the host's advantage (Rossen et al., 2015). Prebiotics need to be able to withstand stomach acids while still being broken down by digestive enzymes, absorbed by the upper digestive tract, fermented by the gut microbiota, and encouraging the growth or activating beneficial species of the gut microbiota. Prebiotics have an impact on the types of bacteria already present in the colon (Slavin, 2013). According to Tabibian et al., (2013), prebiotics primarily target the species of *Lactobacilli* and *Bifidobacteria,* and their effects include enhancing the production of short-chain fatty acids and lowering pH. Consuming dietary fiber is crucial to preserving the mucosal barrier's functionality in the gut. Prebiotic fibers have been shown to influence the gut microbiota in a number of recent investigations (Dahiya et al., 2017; Gibson et al., 2017). According to studies, inulin supplementation can counteract the negative effects of high-fat diets on the mucus layer's permeability and metabolic processes (Schroeder et al., 2018; Zhou, 2017). Evidence links the Western diet with chronic diseases by showing that the low-fiber Western diet weakens the intestinal mucus barrier, which encourages the growth of microbiota, which increases pathogen susceptibility (Desai et al., 2016) and inflammation (Earle et al., 2015). Moreover, galacto-oligosaccharides alone boost *Lactobacillus*, the combination of galacto-oligosaccharides and fructo-oligosaccharides has the ability to increase *Bifidobacteria* and decrease *Clostridium* in the gut (Dinleyici et al., 2012). Further research revealed that inulin and *arabino*-xylooligosaccharides change the function of the intestinal barrier and immune response (Abbeele et al., 2018).

In Europe, the regulation of prebiotics is stringent, requiring thorough scientific validation and approval by the European Food Safety Authority (EFSA) and the European Commission. Health claims on food products must undergo scientific assessment by EFSA and subsequent authorization by the Commission. For instance, chicory inulin has been approved with the claim "Inulin improves bowel function" due to evidence of its effect on increasing stool frequency (EFSA Panel on Dietetic Products, Nutrition and Allergies (NDA), 2015). Prebiotics like inulin, FOS, and GOS used before 1997 are considered safe, but those developed post-1997, including specific human milk oligosaccharides (HMOs), are classified as novel foods and must undergo safety clearance. The regulatory process also considers the safe history of use in non-EU countries for novel foods (Turck et al., 2017). In contrast, the United States does not officially recognize the term "prebiotic" under the Food and Drug Administration (FDA). Instead, prebiotics are regulated based on their intended use, which can span food products, dietary supplements, medical foods, drugs, cosmetics, or devices. The FDA's 2016 guidance on the new dietary ingredient notification process outlines safety and efficacy requirements. Changes in fibre labelling regulations in 2014 redefined fibre to include non-digestible carbohydrates with beneficial physiological effects (FDA, 2016). For a prebiotic to be listed as fibre, it must demonstrate such effects, and this evidence must be submitted to the FDA through specific petition processes. The FDA is expected to provide further guidance to clarify prebiotic regulation and labelling (Gibson et al., 2017).

2.1. *Types of prebiotics*

The word "prebiotic" refers to a broad range of substances, each with distinct structures and modes of action. Prebiotics come in many forms, from resistant starches to oligosaccharides, and research has recently been able to identify and characterize them. Each type of prebiotic has unique qualities and advantages for health (Rezende et al., 2021). These prebiotic substances are able to withstand digestion in the upper gastrointestinal tract and make it all the way to the colon, where they act as substrates for fermentation by beneficial gut bacteria (Rawi et al., 2020). This fermentation produces metabolites that may be advantageous to health, such as short-chain fatty acids (SCFAs) and other compounds. Prebiotics typically contain oligosaccharides or short polysaccharides like inulin, oligofructose, galactofructose, galacto-oligosaccharides, and *xylo*-oligosaccharides, which are not digestible carbohydrates (Ray, 2018) as shown in Fig. 1.

2.1.1. *Inulin*

Prebiotics such as inulin are members of the fructans class of dietary fibers (Mudannayake et al., 2022). Numerous plants naturally contain it, but one of the richest sources is chicory root. Foods like garlic, onions, leeks, asparagus, bananas, and Jerusalem artichokes also contain substantial amounts of inulin (Mudannayake et al., 2022). A polymer of fructose molecules joined by beta (2–1) glycosidic bonds is called inulin. It is categorized as a fructan, meaning that fructose units with a terminal

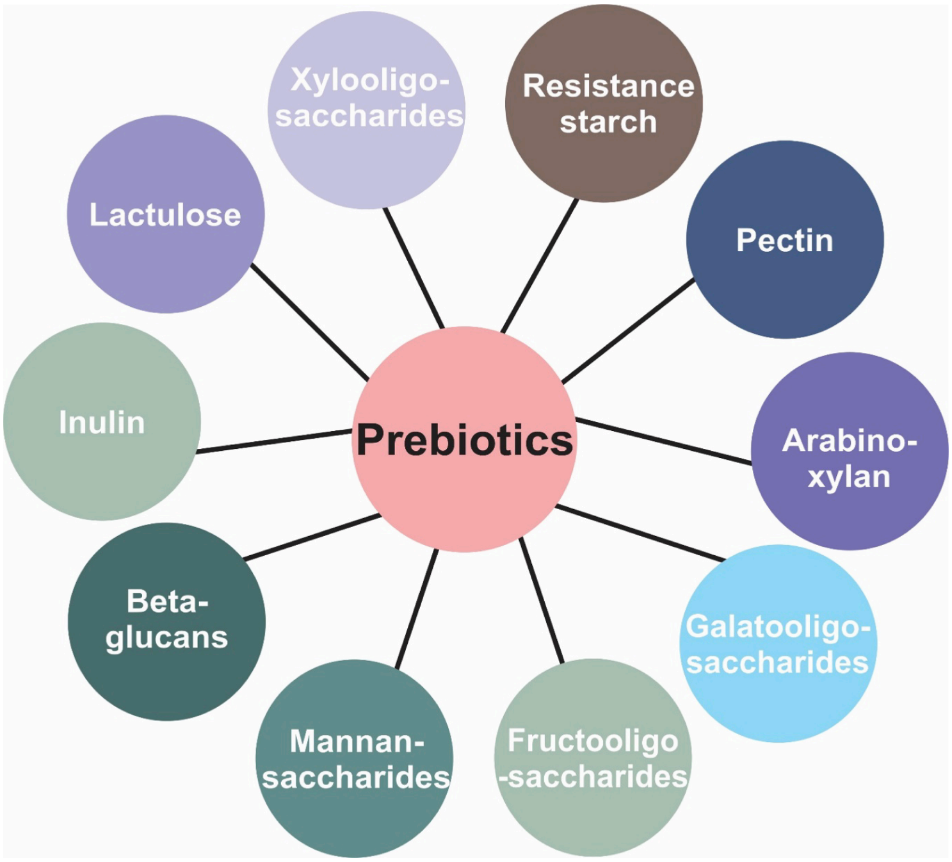

Fig. 1. Types of prebiotics.

glucose molecule make up its structure. Inulin chains come in different lengths; shorter chains are called oligofructans, and longer chains are called polysaccharides (Wan et al., 2020). Because it evades digestion in the upper gastrointestinal tract and enters the colon undigested, inulin is regarded as a prebiotic. There, it acts as a substrate for fermentation by beneficial bacteria. Particularly, bacteria that are known to improve gut health, such as *lactobacilli* and *bifidobacteria*, ferment inulin (Tawfick et al., 2022).The capacity of inulin to specifically promote the development and activity of advantageous bacteria, especially bifidobacteria, in the gut is one of its most important characteristics. Inulin aids in the proliferation of these bacteria by giving them a fermentable substrate, which creates a more diverse and well-balanced gut microbiota. Numerous health benefits, such as better immune system performance, better digestive health, and possibly lower risk of certain chronic diseases, have been linked to inulin consumption (Nazzaro et al., 2020). Short-chain fatty acids (SCFAs) like acetate, propionate, and butyrate are produced during the fermentation of inulin in the colon. These SCFAs have anti-inflammatory properties and provide colonocytes with energy (Huang et al., 2023). According to a research by Mitchell et al., (2021), inulin may enhance insulin sensitivity and lower postprandial glucose levels, which may help with blood sugar regulation. It is believed that the synthesis of SCFAs, which can affect insulin signaling pathways and glucose metabolism, is what mediates this effect.

2.1.2. *Fructooligosaccharides*

A type of prebiotic fiber known as fructooligosaccharides (FOS) is made up of short chains of fructose molecules with a glucose molecule at one end (Rahim et al., 2021). They are present in some fruits, vegetables, and grains in their natural form. The molecules that make up FOS are oligosaccharides, and they have a low sugar molecular weight. They consist of glucose molecules at the end and fructose units connected by beta (2–1) glycosidic bonds (Nobre et al., 2022). Depending on the source and processing technique, the FOS chain's length can change.

FOS, like other prebiotic fibers, is able to withstand digestion in the upper gastrointestinal tract and make it all the way to the colon, where it is utilized as a substrate by beneficial bacteria for fermentation. Certain bacteria, such as *lactobacilli* and *bifidobacteria*, selectively ferment fermented foods (FOS) and are thought to be good for gut health (D. Zielińska et al., 2021). FOS consumption has been linked to a number of health advantages, such as strengthened immunity, better digestive health, and possibly lower risk of developing certain chronic diseases.

FOS has been demonstrated to have a bifidogenic effect, which means that they specifically encourage the growth of gut-dwelling *bifidobacteria* (Costa et al., 2022). By increasing stool frequency and improving stool consistency, this can help control bowel movements and relieve constipation symptoms (McRae, 2020). It has been demonstrated that FOS has antimicrobial properties against *Salmonella spp*. and *Escherichia coli*, among other pathogenic bacteria (Balta et al., 2021).

2.1.3. *Galactooligosaccharides*

Another type of prebiotic fiber is called galactooligosaccharides (GOS), and it is made up of short chains of galactose molecules. GOS aids in the preservation of a balanced gut microbiota by encouraging the growth of bifidobacteria. It was reported by Wang et al., (2021) that GOS supplementation alters the gut microbiota's composition and activity, resulting in a more varied and harmonious microbial community. This may help prevent gastrointestinal illnesses and disorders and have a positive impact on gut health in general.

2.1.4. *Resistant starch (RS)*

A form of starch known as resistant starch (RS) makes it past the small intestine's ability to break it down and into the colon, where it is used as a substrate by gut bacteria to ferment. It is made up of molecules of amylose and amylopectin, which are the two main parts of starch. Nonetheless, resistant starch's structure prevents human enzymes from breaking it down in the small intestine (BeMiller, 2020). Based on its physical characteristics and origins, resistant starch is categorized into various kinds. Physically inaccessible starch, such as that present in whole or partially ground grains and seeds, is referred to as RS1. RS2 are High-amylose granular starch that can be found in raw potatoes, green bananas, and high-amylose corn. RS3 are Retrograded starch, which is produced when starchy foods like pasta, rice, and potatoes are cooked and cooled. Starch that has undergone chemical modification in order to withstand digestion is known as RS4 (Tian & Sun, 2020). Because of the way it is structured, resistant starch evades digestion in the small intestine and makes it all the way to the colon. Short-chain fatty acids (SCFAs), like acetate, propionate, and butyrate, are produced during this fermentation process and offer a number of health advantages. They provide colonocytes energy (Chen et al., 2024).

The colon's fermentation of resistant starch yields SCFAs, which have osmotic qualities and attract water into the colon to soften and make it easier for stools to pass. According to a research by Kim et al., (2020), who investigated effect of the intake of a snack containing resistant starch on postprandial glucose levels, it was discovered that blood glucose levels was significantly reduced which means resistant starch may aid in better blood sugar regulation. It is believed that the synthesis of SCFAs, which can affect insulin signaling pathways and glucose metabolism, is what mediates this effect. Many foods, such as whole grains, legumes, seeds, green bananas, cooked and cooled potatoes, and some varieties of high-amylose maize, naturally contain resistant starch (Artavia et al., 2020). However, processing, cooking techniques, and storage conditions can all have an impact on how much resistant starch is present in a food.

2.1.5. *Beta-glucans*

Prebiotic fibers known as beta-glucans are polysaccharides made of glucose molecules bound together by beta-glycosidic bonds. They can be discovered in the cell walls of some bacteria, fungi, yeasts, algae, and grains. Although the main function of beta-glucans is to modulate the immune system, new studies indicate they also have prebiotic effects (Xin et al., 2022). Polysaccharides called beta-glucans are made up of glucose units joined by beta-glycosidic bonds. A beta-glucan's specific structure can change based on its molecular weight, degree of branching, and source. Oats, barley, yeast (*Saccharomyces cerevisiae*), mushrooms (shiitake and maitake), and some bacteria (*Lactobacillus* species) are common sources of beta-glucans (Singla et al., 2024). The bran and germ layers of oats and barley contain higher concentrations of beta-glucans, making them particularly rich sources of this dietary fiber. There are also supplements containing beta-glucan made from yeast or mushrooms. Frequently utilized as useful ingredients in a wide range of food items, such as bread, pasta, cereal, and dietary supplements, are beta-glucans (Lante et al., 2023).

2.1.6. *Arabinoxylan*

The hemicellulose polysaccharide known as arabinoxylan is present in the cell walls of cereal grains, including wheat, rye, barley, and oats, in addition to certain other plant sources (Barron et al., 2020). It is made up of side chains of arabinose joined to a backbone of xylose molecules. Xylose units make up the complex polysaccharide arabinoxylan's main backbone, to which arabinose side chains are attached (Pang et al., 2023). Depending on where the arabinoxylan is sourced from, the ratio of xylose to arabinose units can change (Wang et al., 2020).

Because arabinoxylan withstands being broken down by human enzymes in the small intestine and makes it all the way to the colon, it is categorized as a prebiotic (Dewanjee et al., 2023). It acts as a substrate in the colon for the fermentation of beneficial microbes like *Lactobacillus* species and *Bifidobacterium*. Short-chain fatty acids (SCFAs), like butyrate, propionate, and acetate, are produced during this fermentation process and offer a number of health advantages (Rauf et al., 2022).

2.1.7. *Mannan oligosaccharides*

Prebiotic fibers known as mannan oligosaccharides (MOS) are derived from the cell walls of yeast or specific plant materials, including some forms of seaweed or yeast (Liu et al., 2023). They are made up of brief mannose molecule chains joined by glycosidic bonds. Because MOS withstand digestion in the upper gastrointestinal tract and make it to the colon undigested, where they act as a substrate for fermentation by probiotic bacteria, they are regarded as prebiotics (Singh & Shaida, 2023). Mannan are made up of mannose units connected by β-(1–4) glycosidic bonds. Depending on where they come from and how they are processed, they might also contain side chains of other sugars like galactose or glucose. MOS can have a range of degrees of polymerization (DP), from short oligosaccharides to longer polysaccharides (Suryawanshi & Kango, 2021).

2.1.8. *Lactulose*

Galactose and fructose combine to form the artificial disaccharide sugar lactulose. Beta (1–4) glycosidic bonds bind galactose and fructose molecules together to form Lactulose, an indigestible disaccharide (Chen et al., 2021). In addition to being a popular laxative for constipation, it serves as a prebiotic by favorably promoting the development of healthy bacteria in the stomach. According to Ma et al., (2023), who investigated the effect of lactulose on constipation, in comparison to the healthy control group, the majority of the bacteria in the constipation group including *Bifidobacteria*, *Bacillus cereus*, *Prevotella*, *Bacillus*, *Anaerostipes, Oribacterium, and Mogibacterium* grew after receiving lactulose treatment. Following lactulose treatment, *anaerotruncus* decreased in the healthy control group. According to their research, lactulose can improve the intestinal microenvironment, boost probiotic abundance, and reduce constipation. Lactulose encourages the growth of these bacteria by giving them a fermentable substrate, which results in a more balanced and diverse gut microbiota (Biscarrat et al., 2023). It comes in a number of forms, such as tablets, powders, and oral solutions. Laxatives like lactulose can also be used as a prebiotic supplement to help maintain gut health (Hassan et al., 2022).

2.1.9. *Pectin*

One kind of prebiotic fiber that can be found in fruits is pectin, which is mostly present naturally in the peels of berries, citrus fruits, and apples. Pectin's structure can change depending on a number of variables, including the type of fruit and how ripe it is (Gamonpilas et al., 2021). It is a complex polysaccharide made up of side chains of other sugars like rhamnose, galactose, and arabinose joined by chains of galacturonic acid molecules (Kaczmarska et al., 2022). One of pectin's distinctive functional qualities is its capacity to congeal into a gel-like material when exposed to water, which is why it is used as a gelling agent to stabilize and thicken products like fruit preserves, jams, and jellies in the food industry (Alam et al., 2023). Pectin is a heteropolysaccharide, which means that different sugar units make up its composition.

Galacturonic acid, which makes up the majority of the molecule, is its main constituent. Other sugar side chains, including galactose, arabinose, and rhamnose, can also be found in pectin molecules (Sharma et al., 2021). Pectin enters the colon undigested, where it acts as a substrate for fermentation by helpful bacteria because it does not break down in the upper gastrointestinal tract. Pectin consumption has been linked to a number of health advantages, such as strengthened immunity, better digestive health, and possibly lower risk of developing certain chronic diseases (Wu et al., 2021).

2.1.10. *Xylooligosaccharides (XOS)*

Xylooligosaccharides (XOS) are oligosaccharides made of glycosidic bonds connecting xylose units. Oligosaccharides made up of two to ten xylose units connected by β-(1–4) glycosidic bonds are called xylooligosaccharides (Nsofor et al., 2022). They come from the hydrolysis of xylan, a hemicellulose that is present in plant cell walls, especially in agricultural residues and hardwoods (Marim & Gabardo, 2021). In the gut, XOS specifically promote the growth and activity of good bacteria, especially those that can ferment xylooligosaccharides. XOS encourage the growth of these bacteria by giving them a fermentable substrate, which results in a more balanced and varied gut microbiota (Marim & Gabardo, 2021). Certain plant foods, such as cereal grains, fruits, vegetables, and bamboo shoots, naturally contain XOS. But the most common way to make them is by enzymatic hydrolysis of xylan-rich materials like wood chips, sugarcane bagasse, and corncobs (Dyshlyuk et al., 2024). Functional ingredients called XOS are frequently found in a wide range of food products, such as dairy products, drinks, baked goods, and dietary supplements. Additionally, they are added to animal feed as additives to help livestock's digestive systems (Palaniappan et al., 2021).

2.2. *Mechanisms of action of prebiotics*

Recent studies have provided insight into the complex mechanisms by which prebiotics affect the composition of microorganisms, metabolic pathways, immune responses, and barrier function in the gut as shown is Fig. 2. Prebiotics act as substrates for the fermentation of beneficial bacteria, resulting in the production of metabolites like short-chain fatty acids (SCFAs). These metabolites are essential for preserving gut homeostasis and have effects that extend beyond the gastrointestinal tract (Marnpae et al., 2024). Determining the exact mechanisms by which prebiotics enhance gut health and reduce the likelihood of different gastrointestinal disorders and related comorbidities is crucial to realizing the full benefits of prebiotics. Prebiotics, such as inulin, fructo-oligosaccharides (FOS), and galacto-oligosaccharides (GOS), are non-digestible fibers that reach the colon intact (Kumari et al., 2024). These fibers serve as a selective food source for beneficial bacteria, including probiotics like *Lactobacilli* and *Bifidobacteria*. By nourishing these beneficial microbes, prebiotics promote their growth and proliferation in the gut microbiota (Limbu et al., 2024).

SCFAs produced through fermentation of prebiotics help to lower the pH in the gut to about 5.5 from 6.5, creating an acidic environment that is unfavorable for the growth of pathogenic bacteria. This acidic environment promotes the growth of beneficial bacteria, which thrive under these conditions, thus contributing to gut health (Roupar et al., 2023). In a study by Xie et al., (2024), where substrates such as inulin, lactose, galactooligosaccharides (GOS), and fructooligosaccharides (FOS) was used in an in vitro colon setup to examine the effects of pH gradients that correspond to levels normally found in the colon on gut microbiota(GM) composition and metabolite production. Low pH regimes were found to have a significant impact on GM, resulting in an increase in *Bifidobacterium spp*. relative abundance and a decrease in *Bacteroides spp*. The synthesis of SCFAs was stimulated by higher in vitro simulated colonic pH in a donor- and substrate-dependent manner. At higher pH values, butyrate production for inulin was also enhanced, leading to the enrichment of the *butyricimonas* butyrate producer. Higher colonic pH was also associated with an increase in the relative abundance of *Phascolarctobacterium, Bacteroides*, and *Rikenellaceae,* as well as an increase in propionate production using GOS and FOS as substrates.

A vital part of the immune system is the gut-associated lymphoid tissue (GALT). Prebiotics encourage the growth of good bacteria that interact with the GALT, which helps regulate the immune system's activity (Shokryazdan et al., 2017). This interaction promotes a balanced immune system and lowers inflammation by regulating immune responses in the gut (Zhou et al., 2024). In the gut, SCFAs are also involved in the regulation of immune responses. They can encourage immune tolerance and control the function of immune cells like T regulatory cells. The immune system as a whole and gut homeostasis are supported by this immunomodulatory effect (Ney et al., 2023). Prebiotics help to maintain the integrity of the gut barrier by encouraging the growth of good bacteria that make substances like tight junction proteins and mucins (Peredo-Lovillo et al., 2020). Tight junction proteins assist in sealing the spaces between epithelial cells to stop pathogens and dangerous substances from entering the bloodstream, and mucins coat the intestinal epithelium to provide protection. The colonocytes, which

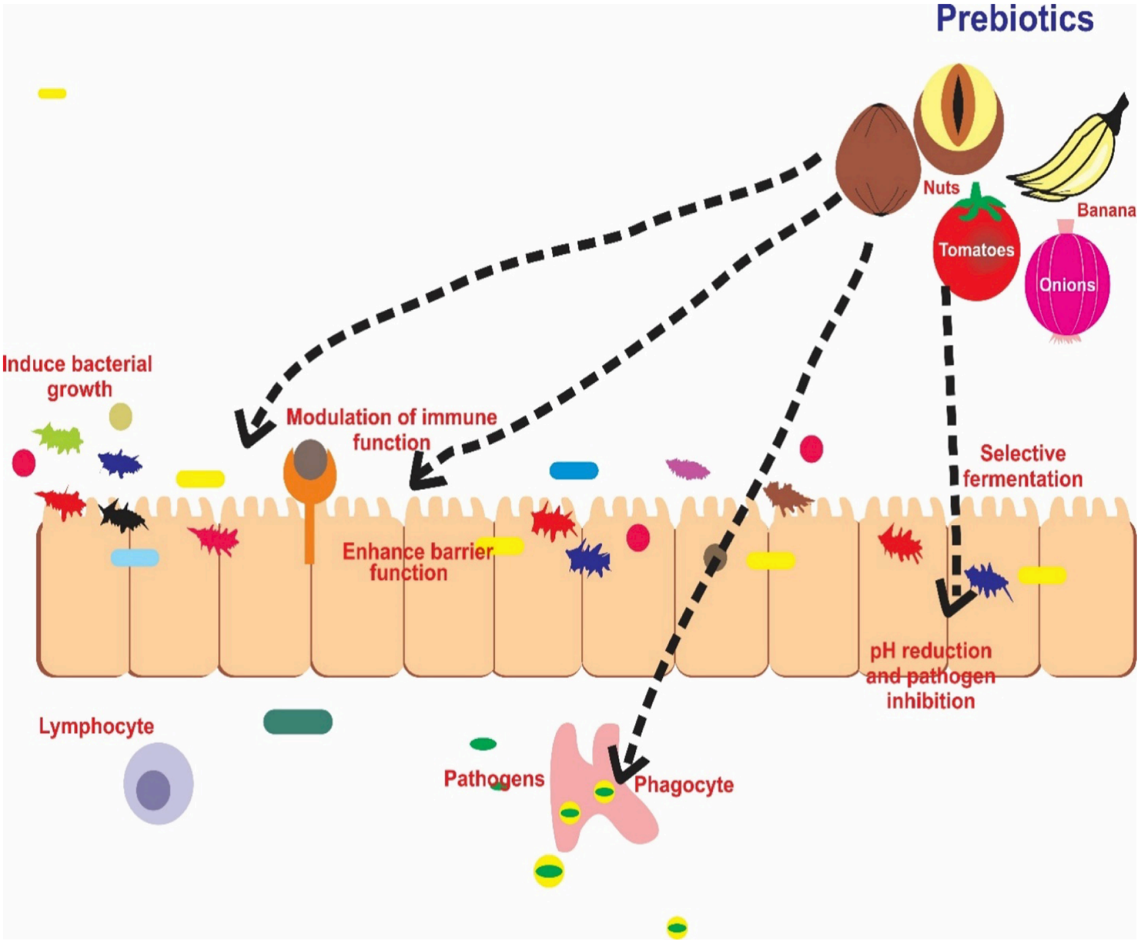

Fig. 2. Mechanism through which prebiotic exert benefit in the gut.

are the cells lining the colon, primarily obtain their energy from SCFAs, especially butyrate. SCFAs support the preservation of the integrity of the gut barrier and encourage the regeneration of the gut epithelium by supplying this energy (Fei et al., 2023). Prebiotics have the ability to improve the performance of phagocytes and lymphocytes, two important immune system cells that are involved in identifying and getting rid of pathogens (Nawaz et al., 2018). Prebiotics support the activity of these immune cells by encouraging the growth of beneficial bacteria and regulating immune responses, which improves the body's capacity to fight against infections and preserve gut health (Ashaolu, 2020). SCFAs produced via prebiotic degradation by the intestinal microbiota also act in defense of the immune system. Tarantino & Finelli, (2015) reported that prebiotic treatment had some varied impacts among NAFLD and obese individuals who had undergone gastric bypass surgery with intriguing hypothesis based on molecular and biochemical mechanisms. Processes like minor conversion of indigestible carbohydrates into SCFAs or decreased local alcohol production may reduce the risk of worsening NAFLD by ameliorating insulin resistance. By fostering the development of beneficial bacteria in the gut, prebiotics indirectly aid in the inhibition of the growth of pathogenic bacteria (Rousseaux et al., 2023). In the gut, beneficial bacteria fight pathogenic bacteria for nutrients and also attach themselves to the active sites, which inhibits the colonization and growth of dangerous pathogens (Plotniece et al., 2023).

3. Probiotics

Probiotics are described as "live microorganisms that, when administered in suitable proportions, confer a health benefit on the host" (Sanap et al., 2019). According to Ryabtseva et al., (2023) *Lactobacillus, Bifidobacteria*, and yeasts like *Saccharomyces boulardii* are the most often utilized probiotic species. The development of beneficial gut bacterium types is one of the hypothesized methods through which probiotics enhance health. According to a 2007 study (Stratiki et al., 2007) feeding preterm newborns a *Bifidobacter*-fortified infant formula reduced their intestinal permeability and raised the amount of fecal *Bifidobacterium.* For attachment sites, probiotics compete with pathogenic organisms. For instance*, E. coli Nissle* can migrate, fight, and hinder the adherence of pathogenic microorganisms (Pradhan and Weiss, 2020). Certain probiotics have the ability to create antimicrobial substances, such as *Lactobacillus reuteri*, which produces reuterin, which directly kills pathogenic bacteria and stimulates the host's immune system. *Bifidobacterium* can improve the way the mucosal intestinal barrier works, raise serum IgA levels, and lessen intestinal inflammation (Yang et al., 2021). Moreover, it has been observed that *Bifidobacterium* lowers the quantity of dangerous bacteria in stool samples (Yamamura et al., 2023).

The impact of probiotics on clinical outcomes was examined in a number of systematic reviews. The analysis revealed strong support for probiotic supplementation's beneficial effects on chronic periodontitis (Ikram et al., 2018), urinary tract infections (Schwenger et al., 2015), necrotizing *enterocolitis* (Rees et al., 2017), and a decrease in total cholesterol and low-density lipoprotein cholesterol (Wu et al., 2017). Probiotic therapy decreased cardiovascular risk, fasting blood glucose and HbA1 in type 2 diabetic patients (Akbari and Hendijani, 2016). An important index to measure insulin resistance in several diseases, such as prediabetes, diabetes mellitus type 2, and metabolic syndrome, was the homeostasis model assessment of insulin resistance score, which was significantly reduced in patients receiving probiotic therapy for type 2 diabetes (Zhang et al., 2016). The effectiveness of probiotics in treating vulvo vaginal candidiasis in non-pregnant women was reported by Xie et al., (2017). They found that probiotics raised the rate of mycological and clinical cure in the short term and decreased relapse rate at one month. The colonic mucus barrier erodes due to the gut microbiota's usage of mucins when there is a lack of dietary fiber (Desai, 2016). Recent research with mice showed that giving them *Akkermansia muciniphila*, a mucin-degrading organism, restored the intestinal barrier (Xue et al., 2023). Many metabolic problems can be prevented or treated by *A. muciniphila* due to its probiotic capabilities (Zhou, 2017). Recent research on mice on a chow diet revealed that supplements could lessen metabolic inflammation, which in turn would lessen body weight increase and fat mass (Zhao et al., 2017). Moreover*, A. muciniphila* functions as an energy sensor; its abundance rises with fewer calories and falls with more energy, enabling the uptake of energy when it is present (Chevalier et al., 2015). With all this evidence, probiotics might just be an answer to many health challenges.

The effects of probiotic products vary depending on the type and quantity of bacteria used, and many of these products use the microencapsulation approach to shield bacteria from environmental influences (Vivek et al., 2023). The probiotic products typically have 10^6–10^7 CFU or more. When the various probiotic doses used to treat antibiotic-induced diarrhea were examined, greater doses of probiotics proved to be more effective (Yang & Hu, 2023). This is due to the fact that a significant portion of probiotic organisms are destroyed in the stomach before reaching the colon. Probiotics' effectiveness in treating intestinal diseases is still up for debate among researchers, in large part because different probiotic doses and types have been used in different studies (Purdel et al., 2023). For instance, while some research suggests that probiotics can help prevent traveler's diarrhea, other studies have found mixed results (Islam et al., 2023). Probiotics with multiple health benefits include *Lactobacillus, Bifidobacterium, and Saccharomyces* (Kumar Bajaj et al., 2015). They are essential for preserving the equilibrium of gut microbes, fortifying the intestinal barrier, regulating the immune system, and generating metabolites that impact the physiology of the host (Sharifi-Rad et al., 2020). Table 1 shows the functions of specific strains of probiotics.

Table 1
Functions of specific strains of probiotics.

Functions	Strains	References
Cholesterol lowering activities	*Lactobacillus acidophilus,* *Lactiplantibacillus plantarum*	(Oh et al., 2021), (Tian et al., 2022)
Inflammatory bowel disease and syndrome	*Lactobacillus acidophilus,* *Bifidobacterium infantis,* *Saccharomyces boulardii,*	(Al-Sadi et al., 2021), (L.-Y. Zhou et al., 2022), (B. Li et al., 2022),
Urinary tract infections	*Lactobacillus rhamnosus*	(Daniel et al., 2020)
Treatment of diarrhea	*Bacillus subtilis,* *Saccharomyces boulardii,* *Bifidobacterium longum,* *Bifidobacterium bifidum,* *Lacticaseibacillus casei,* *Lactobacillus acidophilus*	(Ghosh et al., 2021), (Ivashkin et al., 2021), (Bhuyan et al., 2023), (K. Chen et al., 2020)
Anticancer and Antitumor	*Streptococcus thermophilus,* *Lactobacillus acidophilus*	(Al-Nabulsi et al., 2022), (Garbacz, 2022), (Isazadeh et al., 2020)
Antimicrobial activity	*Lactiplantibacillus plantarum,* *Lactobacillus rhamnosus*	(Ruiz et al., 2023), (Rose Jørgensen et al., 2020)
Belly weight loss	Lactobacillus gasseri	(S.-P. Jung et al., 2013)

3.1. Probiotics and gut health

The study of microbial ecology in the human gastrointestinal tract (GIT) is an intriguing and intricate field. Numerous microorganisms that make up a dynamic ecosystem and are essential to human health and disease are found in the gastrointestinal tract (GIT) (Yeoman & White, 2014). The collective genomes of the microbiota that live inside of us and also occupy the surfaces of our bodies, these include bacteria, viruses, eukaryotes, and protozoa, make up the human microbiome. These microbiotas are symbiotic and coexist on and in different parts of the human body. According to estimates, there are approximately 10^{13}–10^{14} microbial cells in the human microbiota, with a microbial cell to human cell ratio of 1:1 (Sender et al., 2016). Determining the role of these microbes in preserving homeostasis and averting various disorders requires an understanding of their distribution and dynamics throughout the gut. Eubiosis is interspecies balance of microbiota community, while a disturbance of eubiosis, is known as dysbiosis, that could cause infectious and non-infectious diseases (Al-Rashidi, 2022). Dysbiosis can also be refer to as microbial imbalance caused by qualitative and quantitative changes in the intestinal flora, their metabolic activities, and changes in their local distribution which exerts negative effects on the host changes (Talapko et al., 2022). The mouth, esophagus, stomach, small intestine, large intestine (colon), and rectum make up the long and complex GIT system. The GIT displays regional differences that are impacted by physiological circumstances specific to each segment. Different gut regions have different microbial compositions due to factors like peristalsis, mucus layers, immune responses, oxygen and nutrient availability, and variations in these factors (Lin & Zhang, 2017). Fig. 3 shows the microbial population and some biochemical and biological factors that influence them.

. It supports a heterogeneous microbial community that is shaped by host genetics, diet, and oral hygiene. This environment is home to numerous anaerobes and bacteria such as *Actinomyces* and *Streptococcus* (Simon-Soro et al., 2013). In addition to being beneficial to dental health, these microorganisms can lead to illnesses like periodontal infections and cavities. Microbial growth is restricted by the stomach's acidic environment. But here is also where some acid-tolerant bacteria, such as *Helicobacter pylori*, can grow and cause gastritis or ulcers (Miri et al., 2023). Bile and pancreatic secretions, which aid in regulating microbial growth, contribute to the small intestine's lower microbial load in comparison to other gut sections. But it is home to a wide variety of bacteria, such as Bacteroides and *Lactobacilli.* The microbial composition is impacted by the environment's gradual transition from anaerobic in the lower to aerobic in the upper part (Hegyi et al., 2018). The small intestine contains an increasing number of thousands to several hundred million of cells per gram of content with partly oxygen-tolerant *Firmicutes* and *Proteobacteria* as major phyla. The colon is the region of the GIT with the highest population density. Trillions of bacteria from various phyla, mostly *Firmicutes* and *Bacteroidetes*, but also *Proteobacteria, Actinobacteria*, and other types, are housed there. These microorganisms are important for immune modulation, fermentation, and the production of vitamins (Delgado et al., 2020). The microbial composition of the colon is greatly influenced by variables such as host genetics, pH, transit time, diet (especially fiber intake), and microbiology. The colonic microbiome is dominated by mainly anaerobic bacteria, including thousands of species and millions of genes, distributed among the major phyla of *Firmicutes* (predominantly *Ruminococcaceae and Lachnospiraceae), Bacteroidetes, Actinobacteria, Proteobacteria* and *Verrucomicrobia* (Akkermansia) (Seekatz et al., 2019). Broadly speaking, these start with mucus-degrading consortia that are usually dominated by the mucolytic and microaerophilic Akkermansia muciniphila and end with strictly anaerobic communities, including butyrate-producing and propionate-producing *Ruminococcaceae*, Lachnospiraceae and Bacteroidia as well as homoacetogens and methanogens (de Vos et al., 2022). The microbial community in the rectum is relatively similar to that in the colon, contributing to the final stages of digestion and fecal

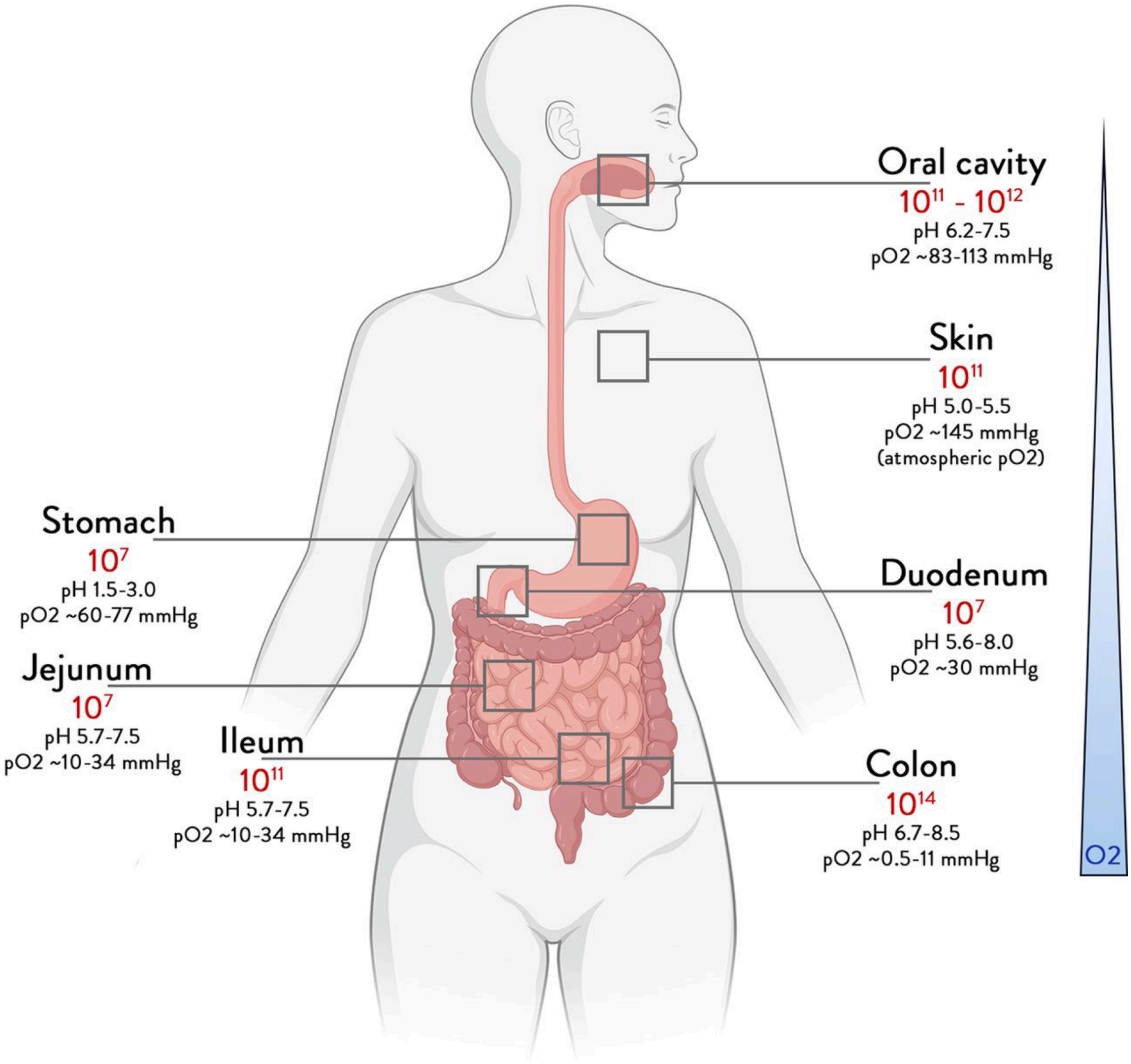

Fig. 3. Microbial population and some biochemical and biological factors that influence them (de Vos et al., 2022).

formation (Jones et al., 2018). The pictorial representation of the microbial ecology in the human GIT is shown in Fig. 4. As gut microbiota dysbiosis has been linked to metabolic disorders, targeted microbial composition manipulation through dietary intervention, such as the administration of prebiotics or probiotics, may be a promising treatment strategy. In animal models, administration of CLA produced by bacteria or CLA-producing bacteria such *Lactobacillus rhamnosus* resulted in significantly lower plasma cholesterol, triacyl glycerides, and white adipose tissue (den Hartigh, 2019). Prebiotics such arabinoxylan, which boosts the number of *Bifidobacterium, Roseburia,* and Bacteroides, and inulin-type fructans, which preferentially feed *Roseburia* and *Clostridium* cluster XIVa, have shown an anti-adipogenic impact in high-fat-induced obese mice (Schupfer et al., 2021). These results show a promising use of prebiotics and probiotics in the management of dysbiosis; however, stronger evidence from human models and clinical studies is needed to validate these therapy modalities and their corresponding success rates.

3.2. *Antitumor effects of probiotics*

Probiotics have been shown to have anti-tumor effects through a number of mechanisms. Probiotics alter the diversity and make-up of the gut microbiota, which makes the environment less conducive to the growth of tumors. Probiotics boost immune cell activity that is involved in tumor surveillance and eradication by stimulating the immune response (Sehrawat et al., 2021). Probiotics generate metabolites that have anti-tumor properties, like bacteriocins and short-chain fatty acids (SCFAs). Probiotics indirectly inhibit tumor-promoting pathways by lowering gut inflammation (Thananimit et al., 2022).

Probiotics may be used to prevent and treat tumors, according to a number of preclinical and clinical studies. Probiotics have been shown in preclinical models involving mice and other animal models to have inhibitory effects on tumor growth and progression (Chen et al., 2020). Human clinical trials have yielded encouraging results as well, but more investigation is necessary to determine the best strains, dosages, and lengths of treatment (Reid et al., 2003; Thomas et al., 2010).

3.3. *The role of probiotics in reducing cholesterol levels*

Lipid molecules like cholesterol are essential to the body's cellular composition, hormone synthesis, and bile acid production. On the other hand, high levels of low-density lipoprotein (LDL), sometimes known as "bad" cholesterol, are linked to a higher risk of cardiovascular illnesses (Schade et al., 2020). Probiotic strains that have bile salt hydrolase (BSH) enzymes, like Lactobacillus and Bifidobacterium, are able to hydrolyze bile salts. Because of the decreased reabsorption of bile acids as a result of this action, the liver uses more cholesterol for bile synthesis, which lowers the amount of cholesterol in the blood (Di Ciaula et al., 2018). Propionate, acetate, and butyrate are SCFAs that are produced

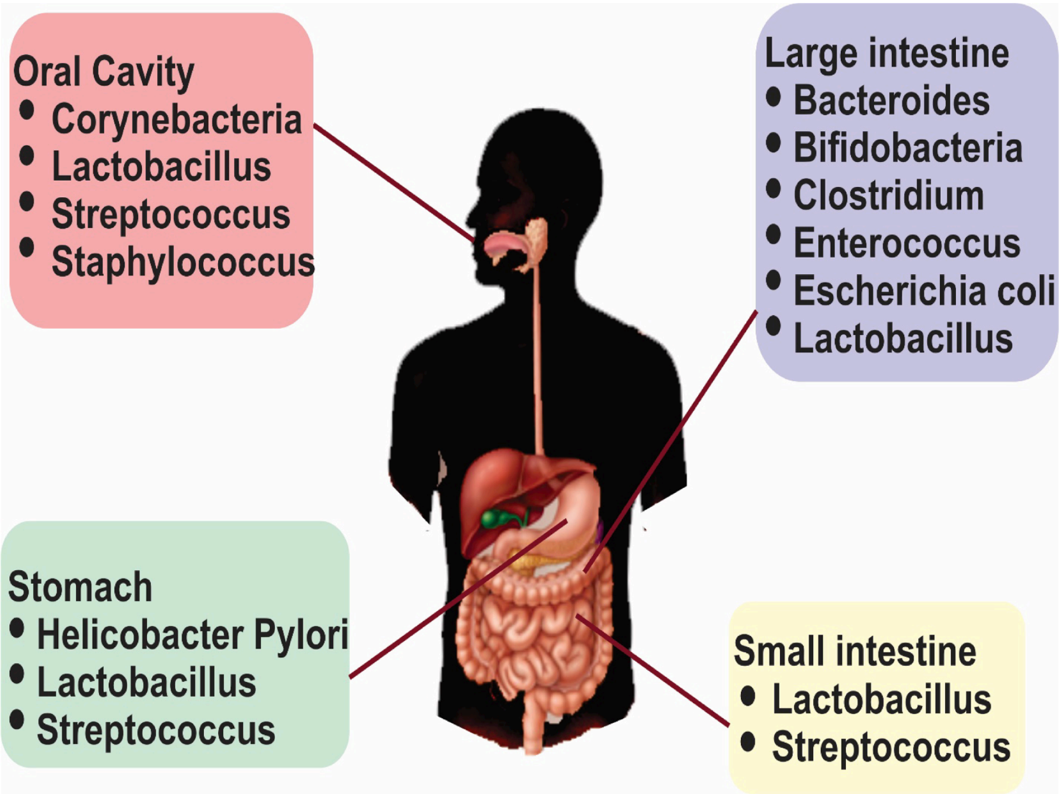

Fig. 4. Microbial ecological distribution along the human GIT.

when non-digestible fibers are fermented by probiotics. It has been demonstrated that SCFAs prevent the liver from synthesizing cholesterol, which lowers cholesterol levels (Zhang et al., 2021). Probiotics have been shown in numerous *meta*-analyses and systematic reviews to have cholesterol-lowering properties. Studies showing significant drops in LDL cholesterol levels with probiotic supplementation include those by Hossain et al. Research on the effects of particular probiotic strains on cholesterol levels has been conducted through controlled clinical trials (Hossain et al., 2023). For example, Shimizu et al.'s randomized controlled trial demonstrated that giving participants with mild to moderate hypercholesterolemia daily supplements of *Lactobacillus acidophilus* for 12 weeks led to a significant reduction in their LDL cholesterol levels (Shimizu et al., 2015).

3.4. *Improving digestive health*

Through a variety of mechanisms, including the production of short-chain fatty acids (SCFAs), the balancing of gut microbiota, the enhancement of gut barrier function, the improvement of digestive disorders, the enhancement of nutrient absorption, and immune system modulation, they significantly contribute to the improvement of digestive health (Markowiak-Kopeć & Śliżewska, 2020). A complex ecosystem of bacteria, fungi, and other microorganisms can be found in the gut. Lactobacillus and Bifidobacterium species are examples of probiotics that aid in preserving a balanced population of good bacteria in the digestive system (Yu et al., 2021). The intestinal barrier serves as a barrier against pathogens, and probiotics help to maintaining this equilibrium is essential for healthy digestion, nutrient absorption, and immunological response. By strengthening the intestinal lining, they aid in limiting the absorption of toxins and pathogens into the blood. This promotes general wellbeing and a healthier digestive system (Di Tommaso et al., 2021). Food fibers that the body is unable to digest are fermented with the help of probiotics. SCFAs like butyrate, acetate, and propionate are created during this fermentation process and support gut health, control inflammation, and nourish the cells lining the colon (Hijova, 2019). The potential of probiotics to treat digestive disorders such as diarrhea, constipation, inflammatory bowel disease (IBD), and irritable bowel syndrome (IBS) has been thoroughly investigated (Currò et al., 2017; Lacy et al., 2015). Through the regulation of gut flora and the reduction of inflammation, they can aid in symptom relief. Probiotics aid in the absorption of nutrients like vitamins, minerals, and fatty acids by enhancing the environment in the gut (Currò et al., 2017). This may be especially helpful for people who struggle with malabsorption. The gut contains a sizable portion of the immune system. Probiotics help control and enhance immune responses by interacting with immune cells in the gut-associated lymphoid tissue (GALT). This may help protect against autoimmune diseases and infections (Sanz & De Palma, 2009).

3.5. *Reducing antibiotic-associated issues*

Although antibiotics are meant to treat harmful bacteria, they can also upset the delicate balance of good gut flora (Dahiya & Nigam, 2023a). Probiotics can help restore the gut microbiota more quickly, either in conjunction with or after antibiotics, which lowers the risk of antibiotic-associated diarrhea or other digestive problems (Mekonnen et al., 2020). Maintaining a healthy balance of gut bacteria can be facilitated by taking probiotic supplements or by consuming foods high in probiotics, such as yogurt, kefir, sauerkraut, kimchi, and kombucha (Putta et al., 2018). Probiotics work in the gut, where trillions of bacteria live and a large percentage of the body's immune cells are found (Li et al., 2021). Enhancing the production of immunoglobulins, competitive exclusion and antimicrobial production, short-chain fatty acid (SCFA) production, indirect immune system support, metabolism and nutrient absorption, and gut barrier integrity are all maintained by probiotics through the promotion of tight junction proteins (Rose et al., 2021). By keeping dangerous pathogens and toxins out of the bloodstream, this barrier lessens the strain on the immune system. Probiotics affect mesenteric lymph nodes and Peyer's patches, two immune cell types found in the gut-associated lymphoid tissue (GALT) (Rodrigo, 2022). They influence T cells, macrophages, and dendritic cells to control the immune response. Probiotics have the ability to suppress the production of pro-inflammatory cytokines (TNF-alpha, IL-6) and increase the production of anti-inflammatory cytokines (IL-10) (Cong et al., 2022). Immunoglobulins (IgA) are produced in response to probiotic stimulation. IgA functions as an antibody, strengthening the mucosal barrier and attaching to pathogens to stop them from adhering to the intestinal lining (Guli et al., 2021). Probiotics compete with pathogenic bacteria in the gut for nutrients and available space. They generate antimicrobial agents (like bacteriocins) that stop the spread of harmful bacteria (Wan et al., 2019). Butyrate, acetate, and propionate are three SCFAs that are produced when probiotics ferment dietary fiber. SCFAs contribute to gut health maintenance, inflammation reduction, and immune cell regulation (Parada Venegas et al., 2019).

3.6. Control of autoimmune response

Probiotics help the body build immune tolerance, which stops the immune system from overreacting to things that are harmless. By regulating the immune response, they also assist in lowering the risk of autoimmune disorders (Xiang et al., 2023). The state of the gut affects how the immune system reacts. An immunological system in organs such as the skin, lungs, and other mucosal surfaces is indirectly supported by a healthy gut microbiome (Ipci et al., 2017). Probiotics facilitate the breakdown and assimilation of nutrients necessary for immunological function, including minerals (like zinc) and vitamins (like vitamin D) (Varvara & Vodnar, 2023).

3.7. Gut-brain axis communication

Probiotics aid Gut-Brain Axis Communication through various mechanisms which include, the regulation of brain inflammation, improving the microbiota-gut-brain axis, the synthesis of neurotransmitters, immune system modulation, anti-inflammatory effects, the regulation of stress hormones, antioxidant properties, neuroprotective properties, and the production of vitamins and neuroactive compounds (Suganya & Koo, 2020). Via neural, endocrine, and immunological pathways, the gut and brain exchange information back and forth (Yoo & Mazmanian, 2017). Probiotics affect this axis by changing the makeup and activity of the gut microbiota. Probiotics support the gut's synthesis of neurotransmitters like serotonin. The gastrointestinal tract is where serotonin is mostly produced and is well-known for its function in mood regulation (T. Liu & Huang, 2019). Probiotics alter immune responses by interacting with lymphoid tissue connected to the gut. This interaction affects the production of cytokines, which have an effect on behavior and mood. Probiotics for example *Lactobacillus plantarum* lessen intestinal permeability by supporting the integrity of the gut barrier. This action lowers systemic inflammation (Malomo et al., 2023), which has been linked to mental health disorders, by reducing the translocation of harmful substances into the bloodstream (Wang et al., 2018).

The hypothalamic–pituitary–adrenal (HPA) axis, which governs the stress response, may be regulated by probiotics. This adjustment may lessen the physiological impacts of stress on mental well-being (Frankiensztajn et al., 2020). When dietary fibers are fermented by probiotics, SCFAs like butyrate, acetate, and propionate are produced. In addition to supporting gut health, SCFAs have an impact on the central nervous system, which may have an impact on mood and cognition (Bruun et al., 2023). Certain strains of probiotics have antioxidant qualities that lessen the body's oxidative stress, lowering oxidative stress may positively impact mental health conditions (Feng & Wang, 2020). According to some research, certain probiotics produce substances that have neuroprotective effects, potentially shielding neurons from damage and supporting overall brain health (Hsieh et al., 2020). Probiotics might indirectly regulate neuroinflammation by modulating systemic inflammation, influencing the brain's immune response. Probiotics aid in synthesizing vitamins like B vitamins and producing neuroactive compounds, which can influence cognitive function and mood regulation (Rudzki et al., 2021).

3.8. Weight management

Probiotic consumption has been connected to weight management and control through various means such as short-chain fatty acid (SCFA) production, enhanced digestion and nutrient absorption, gut microbiota regulation, inflammation reduction (Aoun et al., 2020), appetite and satiety regulation, improving insulin Sensitivity energy modulation (Falcinelli et al., 2018). Probiotics support the proper balance of gut flora, while inhibiting harmful bacteria, they boost the population of advantageous bacteria like *Lactobacillus* and *Bifidobacterium* (Dahiya & Nigam, 2023b). Improved metabolic health and a lower chance of obesity are associated with a balanced gut microbiota (Obayomi et al., 2024). Probiotics aid in the breakdown of complex carbohydrates, fibers, and fats that the body might not be able to process on its own, better nutrient and energy absorption from food is made possible by this breakdown. (Ashaolu, 2020). Acetate, propionate, and butyrate are among the SCFAs that some probiotics generate when they ferment dietary fibers. The body uses SCFAs as an energy source and they also influence hormones linked to fat storage and satiety, which helps control metabolism (Morrison & Preston, 2016). Probiotics can lessen inflammation both internally and externally, including in the gut. Obesity and metabolic syndrome are associated with chronic inflammation (Aoun et al., 2020). Probiotics may be able to control hunger and satiety by modifying these hormones, which may aid in managing food intake and weight. Probiotics may affect how the body stores and uses energy by influencing the synthesis of specific proteins and enzymes involved in fat metabolism. This could have an impact on energy balance (Pizarroso et al., 2021). Certain probiotics have the potential to prevent the intestines from absorbing fat from food, which would lower total caloric intake (Jang et al., 2019). It has been demonstrated that some probiotics increase insulin sensitivity, which facilitates the body's better utilization of insulin. This may lessen the likelihood of severe blood sugar spikes and help with weight control (Kim et al., 2018).

4. Synergy between prebiotics and probiotics

The synergy between prebiotics and probiotics, often referred to as "synbiotics," is an area of growing interest and research in nutrition and gastrointestinal health. This synergy enhances the benefits of both prebiotics and probiotics, providing a more effective approach to improving gut health and overall well-being. While Prebiotics have been described as non-digestible food components, typically fibers, that selectively stimulate the growth and/or activity of beneficial microorganisms in the gut, Probiotics are live microorganisms that, when administered in adequate amounts, confer health benefits to the host. According to Roy & Dhaneshwar, (2023) the term synbiotic refers to synergism where the prebiotic component is selectively favoured by the live probiotic organism. The synbiotic combination is intended to enhance the in vivo survival and activity of proven probiotics to promote or enhance the beneficial properties of both products. Selectively, synergistic probiotics and prebiotics promote microbial growth or induce specific metabolism by means of gut flora. The presence of the readily fermentable substrate should help in increasing the survival rate of the probiotic. The prebiotic component should also have the ability to shield the probiotic from the effects of gastric acidity and action of proteolytic enzymes which could be by concealing the probiotic through steric-blocking. Hence, appropriate combinations of substrate and specific microorganisms in synbiotic products must be selected inorder to produce beneficial effects than that of containing either probiotics or prebiotic alone (Palai et al., 2020). Different prebiotics, the probiotics they selectively support, and their health benefits is shown in Table 2.

Table 2
Different prebiotics, the probiotics they selectively support and their health benefits.

Prebiotic	Specific selective microbial growth	Short chain fatty acid produced	Specific health Benefit	References
Inulin	Bifidobacterium longum, Lactobacillus acidophilus, Catenibacteria, Bifidobacteria and Collinsella	Increased acetate and butyrate production	Improved digestion, enhanced mineral absorption, immune support	(J. Yang et al., 2013), (Roberfroid, 2004), (Gibson et al., 2004)
Fructooligosaccharides (FOS)	Bifidobacterium lactis, Lactobacillus rhamnosus	Increased acetate and butyrate production	Increased satiety, reduced blood glucose levels, improved gut health	(W. Li et al., 2015), (Slavin, 2013), (T. Chen et al., 2017), (Cummings et al., 2001)
Galactooligosaccharides (GOS)	*Bifidobacterium, Lactobacillus*	Increased propionate and butyrate production	Enhanced immune function, improved calcium absorption, gut health	(W. Li et al., 2015), (Macfarlane, 2010), (Sako et al., 1999)
Type 2 Resistant Starch	Selectively supports the growth of Bifidobacteria; reduced Bacteroides, Dorea and Blautia growth. Fermented by Bifidobacterium adolescentis, Ruminococcus bromii.	Increased acetate and butyrate production	Improved insulin sensitivity, reduced appetite, enhanced gut health	(Plongbunjong et al., 2017), (Topping & Clifton, 2001), (Nugent, 2005)
Pectin	supports the growth of Sutterella, Lachnospira, Bifidobacteria and Clostridia; reduced Parabacteroides, Bacteroides and Dorea growth	Increased acetate and butyrate production; decreased propionate production	Lowered cholesterol levels, improved gut barrier function	(Bang et al., 2018), (Ferreira-Lazarte et al., 2018), (Dhingra et al., 2012),
Arabinogalactan	supports the growth of Faecalibacteria, Coprococci Bifidobacterium, Lactobacillus and Bacteroides	Increased acetate and butyrate production	Enhanced immune response, improved gut health	(Rumpagaporn et al., 2016), (T. Chen et al., 2017), (Goffin et al., 2011)
Beta-glucan	supports the growth of Lactobacillus, Enterococcus and Coprobacillus spp; reduced Dorea growth	Increased acetate and butyrate production	Reduced cholesterol levels, enhanced immune function	(J. Yang et al., 2013), (Volman et al., 2008)
Xylooligosaccharides (XOS)	supports the growth of Bifidobacteria, Bacteroides and Lachnospiraceae	increased propionate and butyrate production	Improved bowel regularity, enhanced immune response	(Tuncil et al., 2017), (Finegold et al., 2014)
Lactulose	Bifidobacteria, Lactobacillus	Increased acetate, lactate, propionate, butyrate	Treatment of constipation, improved gut health	(J. Wang et al., 2023), (Karakan et al., 2021), (Cui et al., 2021)
Soy Oligosaccharides	Support Lactobacilli and Clostridia, reduce the growth of Bifidobacterium and Bacteroides	Increased acetate, lactate, propionate, butyrate and BCFAs production	Improved lipid metabolism, enhanced immune function	(Ashaolu et al., 2019), (Du et al., 2023)
Type 3 Resistant Starch	Selectively supports the growth of Bifidobacteria	Increased acetate and butyrate production	colonocyte health, reducing inflammation and potentially lowering the risk of colorectal cancer	(D.-H. Jung & Park, 2023), (Plongbunjong et al., 2017), (J. Yang et al., 2013)

4.1. *Recent advances in the formulation of functional foods in mitigating health conditions*

Recent advances in the formulation of functional foods rich in dietary fibers have shown great promise in mitigating health conditions like celiac disease, colon inflammation, lactose intolerance, and other health challenges. The acceptability of functional foods rich in dietary fibers is crucial for their success. Factors influencing acceptability include taste, texture, and overall palatability (Maina, 2018). Recent advancements have focused on improving these aspects to ensure consumer satisfaction. Innovations in food processing technologies, such as microencapsulation and extrusion, have helped improve the taste and texture of high-fiber foods. This makes them more appealing to consumers who may be hesitant to try fiber-rich diets due to past experiences with less palatable products (Lazou, 2022). Increasing consumer awareness about the health benefits of dietary fibers has also improved acceptability. Educational campaigns and clear labeling on products help consumers make informed choices (Bollinger et al., 2022). offering a variety of fiber-enriched foods, from bread and pasta to snacks and beverages, has also contributed to greater acceptance. This variety allows consumers to easily incorporate these products into their daily diets. Functional foods for celiac disease focus on gluten-free fibers that enhance gut health without triggering adverse reactions (Mazzola et al., 2024). Recent advances have shown that the inclusion of fibers like psyllium husk, flaxseeds, and chia seeds in gluten-free products can improve bowel regularity and overall gut health. A study by Montemurro et al., (2021) demonstrated that gluten-free bread enriched with psyllium improved texture and had positive effects on gut microbiota in individuals with celiac disease. Research by Koleva et al., (2012) found that inulin and fructooligosaccharides (FOS) significantly reduced markers of inflammation in the colon. These fibers were incorporated into everyday foods like yogurt (Helal et al., 2018) and cereals products like bread (Miolla et al., 2023), making them more accessible and acceptable to consumers.

McFarlane et al., (2023), investigated the acceptability and experiences of prebiotic and probiotic supplementation in adults with Stage 3–4 chronic kidney disease (CKD). In this study, thirty adults, aged 41–80, with Stage 3–4 CKD, participated in a 12-month intervention involving prebiotics, probiotics, or placebo. Semi-structured interviews were conducted post-intervention and analyzed thematically. The findings indicate that pre- and probiotics are acceptable and beneficial for adults with Stage 3–4 CKD. Chen et al., (2023) also studied the optimal combination of *Lycium barbarum* L. polysaccharide (LBP) and *Laminaria japonica* polysaccharide (LJP) to develop a highly effective prebiotic for gut health. In the study, two LBPs (rhamnogalacturonan I enriched pectins) and two LJPs (fucoidans) were extracted using enzyme-assisted acid extraction at different temperatures. These were combined in four different ratios and evaluated for their prebiotic effects. The LBP and LJP combination extracted at 50 °C in a 4:1 ratio was the most effective. This optimal combination promoted the growth of beneficial bacteria *(Bifidobacterium, Lactobacillus, and Bacteroides*) and enhanced the production of short-chain fatty acids (SCFAs) and other health-associated metabolites. It also increased butyrate-producing bacteria, showcasing a complementary and synergistic effect. In another study by Fang et al., (2024) Ferulic acid was combined with different dietary fibers to improve glucose metabolism and intestinal barrier function by regulating gut microbiota in high-fat diet-fed mice. It was observed that compared to ferulic acid alone, ferulic acid combined with arabinoxylan or β-glucan significantly improved glucose tolerance and maintain intestinal homeostasis in high-fat diet-fed mice. Ferulic acid combined with β-glucan significantly increased serum GLP-1 level and tight junction proteins expression in colon. Ferulic acid combined arabinoxylan increased the abundance of *Bifidobacterium* and *Faecalibaculum*. Ferulic acid combined with β-glucan increased the abundance of *Akkermansia*, which were negatively correlated with impaired glucose tolerance. Therefore, ferulic acid combined with arabinoxylan or β-glucan ameliorates glucose metabolism and protects intestinal barrier integrity by regulating gut microbiota.

5. Conclusion

Probiotic- and prebiotic-enriched functional foods are at the forefront of promoting general health and wellbeing. The complex interactions among these components create a healthy environment in the gut, which is vital for digestion, immunity, and even mental well-being. The recognition of these components' potential to alleviate a variety of health concerns grows along with our understanding of them. Including these functional foods in our diets is a proactive way to take care of our bodies and create a balanced, harmonious environment inside of us, which will lead to a healthier future. Even though their advantages seem great, more research is still needed to completely understand their mechanisms and any possible effects on the well-being of an individual. Adopting a holistic lifestyle that includes these functional foods highlights their role as allies in our pursuit of improved wellness.

CRediT authorship contribution statement

Oluwatobi Victoria Obayomi: Writing – review & editing, Writing – original draft, Conceptualization. **Abiola Folakemi Olaniran:** Writing – review & editing. **Stephen Olugbemiga Owa:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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