Review Article

Implication of Fructans in Health: Immunomodulatory and Antioxidant Mechanisms

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Previous studies have shown that fructans, a soluble dietary fiber, are beneficial to human health and offer a promising approach for the treatment of some diseases. Fructans are nonreducing carbohydrates composed of fructosyl units and terminated by a single glucose molecule. These carbohydrates may be straight or branched with varying degrees of polymerization. Additionally, fructans are resistant to hydrolysis by human digestive enzymes but can be fermented by the colonic microbiota to produce short chain fatty acids (SCFAs), metabolic by-products that possess immunomodulatory activity. The indirect role of fructans in stimulating probiotic growth is one of the mechanisms through which fructans exert their prebiotic activity and improve health or ameliorate disease. However, a more direct mechanism for fructan activity has recently been suggested; fructans may interact with immune cells in the intestinal lumen to modulate immune responses in the body. Fructans are currently being studied for their potential as "ROS scavengers" that benefit intestinal epithelial cells by improving their redox environment. In this review, we discuss recent advances in our understanding of fructans interaction with the intestinal immune system, the gut microbiota, and other components of the intestinal lumen to provide an overview of the mechanisms underlying the effects of fructans on health and disease.

1. Introduction

Fructans are recognized as health-promoting food ingredients. They are found in a small number of mono- and dicotyledonous families of plants, such as Liliaceae, Amaryllidaceae, Gramineae, Compositae, Nolinaceae, and Agavaceae. Various fructan-containing plant species, including asparagus, garlic, leek, onion, Jerusalem artichoke, and chicory roots, are often eaten as vegetables [1–3]. Substantial variation in chemical and structural conformations makes fructans a flexible and appealing ingredient for different dietary products such as nutraceuticals.

Inulin-type fructans (ITFs) are among the most studied; ITFs are indigestible, fully soluble, fermentable food ingredients with known prebiotic properties. ITFs are linear fructose polymers with \( \beta(2 \rightarrow 1) \) linkages found naturally in chicory roots, wheat, onion, garlic, and other foods. In the scientific literature, ITFs are frequently referenced generically but inconsistently as "inulin," "oligofructose" (OF), and "fructooligosaccharides" (FOS) [4]. Agave fructans have a more complex, highly branched structure, including \( \beta(2 \rightarrow 1) \) and \( \beta(2 \rightarrow 6) \) linkages. Thus, Agave fructans can contain an external glucose, characteristic of graminans, and an internal glucose, characteristic of neofructans. For this reason, this type of fructans has been called "agavins" [5].

Fructans contribute to host health through multiple mechanisms. Fructans are selective substrates for probiotic bacteria stimulating probiotic bacterial growth, which can confer health benefits to the host through the several mechanisms, including immunomodulation [6–8]. Fructans may also act as scavengers of reactive oxygen species [9], decreasing inflammation and improving redox status. Fructans are fermented to short chain fatty acids (SCFAs), which have important implications in host health. In addition, direct interaction between fructans and intestinal immune cells has recently been suggested. The aim of this review is to summarize the latest findings on studies investigating fructans as prebiotics and to provide an overall image of the mechanisms underlying the health effects of fructans.
2. Fructans: Structure, Source, and Synthesis

Approximately 15% of flowering plants store fructans as reserve carbohydrates [10]. Worldwide, the most studied and marketed fructan is inulin, which is obtained primarily from chicory roots. However, some candidate fructans, such as galactooligosaccharides (GOS) derived from lactose and lactulose, have also demonstrated potential prebiotic effects [11].

In addition to chicory root, another potential fructan source includes the more recently investigated resistant galactooligosaccharides (FOS) derived from lactose and lactulose [11]. chicory roots. However, some candidate fructans, such as oligofructose (OF) is used for molecules with a DP of 3–10 derived from sucrose [22]; oligofructan (OF) is used for molecules with a DP of 3–10 derived from native inulin [23].

The biosynthesis of fructans begins with sucrose (Suc), to which fructose residues are added [4]. In plants, fructans are synthesized from Suc by the action of two or more enzymes known as fructosyltransferases. The first enzyme, 1-SST (sucrose:sucrose fructosyltransferase), initiates de novo fructan synthesis by catalyzing the transfer of a fructosyl residue from one Suc molecule to another, resulting in the formation of the trisaccharide 1-kestose. The second enzyme, 1-FFT (fructan:fructan 1-fructosyltransferase), transfers fructosyl residues from a fructan molecule with a DP of 2-10 to which fructose residues are added [4]. In plants, fructans are synthesized from Suc by the action of two or more enzymes known as fructosyltransferases. The first enzyme, 1-SST (sucrose:sucrose fructosyltransferase), initiates de novo fructan synthesis by catalyzing the transfer of a fructosyl residue from one Suc molecule to another, resulting in the formation of the trisaccharide 1-kestose. The second enzyme, 1-FFT (fructan:fructan 1-fructosyltransferase), transfers fructosyl residues from a fructan molecule with a DP of 2-10 derived from sucrose [22].

The length of fructosyl chains varies greatly in plants; plant fructosyl chains are much shorter than those of bacterial fructans. In general, the chain length or degree of polymerization (DP) is between 30 and 50 fructosyl residues in plants but can occasionally exceed 200 [13]. Fructans can also be classified according to their DP into small (2 to 4), medium (5 to 10), and relatively large chain lengths (11 to 60 fructose units). The term fructooligosaccharides (FOS) is used for fructans. The inulin neoseries are linear (2-1)-linked β-d-fructosyl units linked to both C1 and C6 on the glucose moiety of the sucrose (Suc) molecule. This results in a fructan polymer with a fructose chain ((mF2-1F2-6G1-2F1-2Fn); F (fructose), G (glucose)) on both ends of the glucose molecule. These fructans are found in plants belonging to the Liliaceae family (e.g., onion and asparagus (10–15% fructans)) [15, 21]. The smallest inulin neoseries molecule is called neokestose. The levan neoseries consists of polymers with predominantly β(2 → 6)-linked fructosyl residues on either end of the glucose moiety of the sucrose molecule. These fructans are rare, although they have been found in a few plant species belonging to the Poales (e.g., oat) [18].

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mented ingredients that allow specific changes, both in the
composition and/or activity in the gastrointestinal micro-
biosis of the host” [24]. Moreover, prebiotics may suppress pathogen growth to improve overall health [25]. Current evidence indicates that beneficial bacteria reduce the risk of diseases through diverse mechanisms, including modulation of gut microbiota composition or function, and regulation of host epithelial and immunological responses. These effects may be revealed through changes in bacterial populations or metabolic activity [26]. Bacterial metabolism can confer a number of advantageous effects to the host, including the production of vitamins, modulation of the immune system, enhancement of digestion and absorption, inhibition of harmful bacterial species, and removal of carcinogens and other toxins. The resident microbiota is also known to consist of pathogens that can disrupt normal gut function and predispose the host toward disease if allowed to overgrow [27].

Fructans play protective roles in plants subjected to drought, salt, or cold stress [14]. However, the therapeutic potential of fructans in human health has only recently been explored. As described above, fructans are the most widely known and used prebiotics [28]. Of the many nondigestible food ingredients studied for their prebiotic potential, human trials favor ITFs, FOS, OF, and GOS [29–32]. Fructans have been proposed as modulators of the microbiota of the normal gastrointestinal environment [33, 34]. Although they are subjected to minor hydrolysis in the stomach, the human gut lacks the hydrolytic enzymes capable of digesting β linkages [35]. Therefore, fructans reach the colon relatively intact and eventually trigger a decrease in the pH, thereby altering the colonic environment [36]. The rate and extent of ITFs fermentation appear to be strongly influenced by the DP. FOS (low DP) are rapidly fermented in the proximal colon [37], whereas inulin (high DP) appears to have a more sustained fermentation profile that potentially enables protective effects in the distal colon [4, 38]. Acting as prebiotics, inulin, FOS, and GOS improve glucose, reduce triglycerides, modify lipid metabolism, and reduce plasma LPS. Additionally, they stimulate Lactobacillus and Bifidobacterium species to reduce the presence of pathogens in the gut and relieve constipation (Table 1). One other fructan, including soluble gut oligosaccharides, mimic the sugar chains found in the glycoproteins and glycolipids of gut epithelial cells, thereby preventing the adhesion of pathogenic microorganisms [39] and exerting direct antimicrobial effects [40] (Table 1).

Interestingly, fructans from Dasylium spp. (Das) and A. tequilana Gto. (TEQ and DAS) have been shown to increase secretion of satiogenic/incretin peptides in the lower part of the gut [41] (Table 1). Moreover, Agave fructans have been shown to have physiological effects on lipid metabolism [41, 42] and reduce oxidative stress in conjunction with phenolic compounds in in vitro and in vivo assays [42] (Table 1). For the first time, the effect of agavins from Agave angustifolia and Agave potatorum as prebiotics has been reported showing satiety effect as well as an increment on GLP-1 and a decrement on ghrelin in an animal model [43] (Table 1).

Studies have been performed to determine whether prebiotics reduce cancer risk. To maximize the effect of a prebiotic compound, the prebiotic would need to ferment in the distal colon, where proteolytic fermentation predominates and toxic metabolites such as ammonia, hydrogen sulfide, and cresol are produced [44, 45]. A recent study by Gomez et al. was the first to investigate the effect of Agave fructan fermentation on complex fecal microbiota in vitro [46] (Table 1). The first clinical trial in humans with Agave fructans was very promising, as Agave treatment improved laxation [47]. Other carbohydrates, including glucooligosaccharides, isomaltooligosaccharides, lactulose, mannanooligosaccharides (MOS), nigerooligosaccharides, oat β-glucans, raffinose, soybean oligosaccharides, transgalactooligosaccharides, and xylooligosaccharides, are considered candidate prebiotics [31, 48]; however, more research is required.

4. Immunomodulatory Effects of Fructans

The consumption of prebiotics can modulate immune parameters in gut-associated lymphoid tissue (GALT), secondary lymphoid tissues, and peripheral circulation [70]. GALT functions to distinguish between harmful and innocuous agents and protects against infections while simultaneously avoiding the generation of hypersensitivity reactions to commensal bacteria and harmless antigens [71–73]. In inductive GALT, more structured and localized sites of antigen processing and presentation are distinguished in areas such as Peyer’s patches (PPs), mesenteric lymph nodes (MLNs), the appendix, and isolated lymph nodes. GALT also contains effector sites with more diffuse organization, containing previously activated and differentiated cells that performed effector functions (Figure 2). Joint activity of the inductive and effector sites generates a rich response in immunoglobulin A (IgA) and cellular immunity, with robust cytotoxic regulatory functions and memory at the level of the mucosa and serum [74]. The intestinal epithelium provides a physical barrier that separates the trillions of commensal bacteria in the intestinal lumen from the underlying lamina propria (LP) and the deeper intestinal layers. Microfold cells (M cells), B cells (especially IgA-producing plasma cells), T cells, macrophages, and dendritic cells (DCs) in the LP are located...
| Effect                                      | Type of fructan | Dose/duration                  | Model                        | Results                                                                 | Reference |
|---------------------------------------------|-----------------|--------------------------------|------------------------------|-------------------------------------------------------------------------|-----------|
| Decreasing blood glucose                    | FOS, inulin     | 8 g/d for 14 days; 10% for 4 weeks | Diabetic subjects; animal models | Significant reduction of mean fasting blood glucose levels. Improving glucose tolerance | [49–51] |
| Reduction in blood serum triacylglycerol levels | FOS, inulin     | 4–34 g/d for 21–60 days; 10% for 3–5 weeks | Healthy humans; obese animal models | Significant reduction in blood serum triacylglycerol levels | [52–54] |
| Improved lipid metabolism                   | FOS, GOS, inulin, and agavins | 5%–10% for 21 day to 8 weeks | Obese animal models | Decrease in body weight gain. Decrease in epididymal adipose tissue, inguinal adipose tissue, and subcutaneous adipose tissue. Reducing fat-mass development | [41, 50, 51, 55–59] |
| Stimulation of lactobacilli and bifidobacteria and decreasing pathogens | FOS, GOS, inulin, and agavins | 2.5–34 g/d for 14–64 days | Healthy subjects and animal models | Stimulating the growth of bifidobacteria and contributing to the suppression of potential pathogenic bacteria | [46, 60, 61] |
| Relief of constipation                       | Inulin, FOS, and GOS | 20–40 g/d for 19 days | Constipated humans and animal models | Inulin showing a better laxative effect than lactose and reducing functional constipation with only mild discomfort | [62, 63] |
| Increased production of SCFAs and decreasing colon pH | Inulin, FOS, and agavins | 24 g/d for 5 weeks; 10% for 28 days | Healthy subjects; animal models | Significant increase of acetate, propionate, and butyrate. Significantly increasing activity of bacterial enzymes and decreasing the pH of digesta | [36, 64, 65] |
| Improving mineral uptake                     | Inulin, FOS, and agavins | 1–40 g/d for 9 days; 50–100 g/kg diet for 4 weeks | Male healthy adolescents; animal models | FOS stimulating fractional calcium absorption in male adolescents. A combination of different carbohydrates showing synergistic effects on intestinal Ca absorption and balance in rats | [66–69] |
| Regulated gut peptides                       | Inulin, FOS, and agavins | 24 g/d for 5 weeks; 10% for 5 weeks | Healthy subjects; animals models | Increasing plasma glucagon-like peptide-1 (GLP-1) concentrations and reducing ghrelin. Increasing endogenous GLP-2 production and consequently improving gut barrier functions | [36, 41, 50, 57, 59] |
| Reducing body weight and energy intake      | Agavins         | 10% for 5 weeks | Male healthy animal model | Agave fructans showing indications of prebiotic activity, particularly in relation to satiety and GLP-1 and ghrelin secretion. In this same study, the levels of butyric acid were higher for Agave potatorum fructans | [43] |
| Growth inhibition and prevention of adhesion of pathogenic microorganisms | FOS             | 170 mg/kg, 2 weeks of lactation | Breast-fed infant; cocultures of Pseudomonas aeruginosa | Oligosaccharides in human milk interfering with microbial adhesion. Reduction of exotoxin A in cultures of P. aeruginosa | [39, 40] |
| Reduction of oxidative stress by reducing ROS levels | FOS, agavins    | 10% for 4–8 weeks | Male obese animal models | FOS reducing TBARS urine. Lipopolysaccharides reduction in plasma. Improving the redox status by reducing the malondialdehyde serum levels and protein oxidative damage | [9, 42, 65] |
| Stimulation of the immune system            | FOS, GOS, and inulin | | | | See Table 2. |

FOS: fructooligosaccharides; GOS: galactooligosaccharides; SCFAs: short chain fatty acids.
directly below the intestinal epithelium (Figure 2). M cells are part of the epithelial layer covering the PP and specialize in transporting antigens from the lumen to GALT [75].

T and B cells are activated after initial contact with the antigen at inductive sites. These cells then proliferate, differentiate, and migrate to various effector sites, such as the LP or the intestinal epithelium, where a single population of iIELs (intestinal intraepithelial lymphocytes) and some DCs are located between the enterocytes [76–78] (Figure 2).

In fact, iIELs provide a cellular defense against any individual antigen [79]. Meanwhile, DCs are potent antigen-presenting cells critical for the induction of downstream adaptive immune responses [80]. For instance, several subsets of DCs have been identified within the PP that possess either Th1- or Th2-polarizing ability [81]. The CD103+ subset has been found within the small intestinal LP, MLN, and PP, as well as the colonic LP. CD103+ DCs have FoxP3+ Treg-polarizing ability, as well as the ability to imprint gut-homing T cells; expression of the a4b7 integrin on conventional T cells and Treg cells involved in directing gut tropism ensures their ability to be imprinted [82, 83]. CD103+ DC subsets have also been shown to induce Th17 polarization and IgA class switching [84, 85]. Moreover, all DC subsets and antigen-presenting cells, including macrophages, are equipped with a battery of pattern recognition receptors (PRRs). These receptors can detect molecular patterns of invading microorganisms or endogenous “danger” signals and stimulate the immune response. PRRs are expressed on the cell surface and intracellularly are extremely diverse and capable of detecting a wide range of molecular species, including proteins, carbohydrates, lipids, and nucleic acids [86]. The Toll-like receptor (TLRs) family is the most intensely studied family of PRRs on DCs. Triggering TLRs on DCs is thought to be critical for their functional maturation to immunogenic DCs and for their ability to prime naive T cells in response to infection. Therefore, TLR activation couples innate and adaptive immunity [87]. TLR-mediated recognition of commensal microorganisms may also play important roles in tissue homeostasis, as recent studies have shown that TLR signaling by DCs was required to maintain immune homeostasis and tolerance to gut microbiota [88].

Interestingly, Tregs are also abundant at host-microbiota interfaces. Studies have suggested that commensal microbiota can stimulate the generation of Tregs and Th17 cells [89]. These results highlight the importance of diet and the microbiota in the establishment and configuration of the immune system of the intestinal mucosa. However, whether prebiotic compounds directly affect immune components or whether they act exclusively through the modulation of the endogenous intestinal microbiota remains unclear.

4.1. Indirect Mechanisms of Fructan Health Effects. Prebiotics and probiotics may have indirect immunomodulatory functions through their actions on nonimmune cells, such as epithelial cells. However, they may also exert immune system-independent effects by selectively stimulating
the growth and/or activity of beneficial intestinal bacteria, such as *Lactobacillus* and *Bifidobacterium* species, which results in the restoration of the normal composition of the intestinal microbiota [90]. Mutualism between the host and its microbiota is fundamental for maintaining homeostasis in a healthy individual [91]. Commensal bacteria provide the host with essential nutrients. They also metabolize indigestible compounds, defend against the colonization of opportunistic pathogens, and contribute to the development of intestinal architecture in addition to stimulating the immune system [92]. In fact, intestinal immune and metabolic homeostasis in mammals is largely maintained by interactions between the gut microbiota and GALT [93]. The host actively engages the gut microbiota and controls its composition by secreting antimicrobial peptides and immunoglobulins. Conversely, commensals shape the gut-associated immune system by controlling the prevalence of distinct T cell populations [94]. *Bacteroides fragilis* protects mice from infection by *Helicobacter hepaticus* through several immunological mechanisms, including suppression of IL-17 production [95]. These commensals also express capsular zwitterionic polysaccharide A, which is a cognate antigen to effector CD4⁺ T cells [92]. Other zwitterionic polysaccharides, such as type 1 capsule of *Streptococcus pneumoniae*, can also modify inflammatory responses in animal models by stimulating IL-10-producing CD4⁺ T cells [96]. Moreover, bacterial symbionts, such as *Bacteroides*, *Barnesiella*, and *Turicibacter*, interact with CD8⁺ cytotoxic T cells in the mucosal compartment of the small intestine and colon [97].

Other indirect pathways by which fructans exert immunomodulatory effects include the production of SCFAs, which are the fermentation products of fructans. Inulin fermentation increases the production of SCFAs (acetate, propionate, and butyrate), lactic acid, and hydrogen (H₂), while decreasing the pH of the colonic environment [36]. *Bifidobacterium* species are able to use some monosaccharides in a unique manner to ultimately generate SCFAs [98] and acidify the colonic environment. The increase in SCFAs antagonizes the growth of some pathogenic bacterial strains [99] and favors mucin production in the colon [100]. SCFAs bind to SCFAs receptors on GALT immune cells [101–103], activating G protein-coupled receptors (GPR) [104], such as GPR41 and GPR43 [101, 102, 104]. This binding affects the recruitment of leukocytes to inflammatory sites [105, 106] and suppresses the production of proinflammatory cytokines and chemokines [106–108]. GPR43 is highly expressed in polymorphonuclear cells (PMNs, i.e., neutrophils) and is lowly expressed in peripheral blood mononuclear cells (PBMCs) and purified monocytes. Conversely, GPR41 is expressed in PBMCs but not in PMNs, monocytes, or DCs [102]. Importantly, butyrate decreases the glutamine requirement for epithelial cells and alters epithelial cell gene expression [71, 109]. The mechanism for the indirect effect of fructans on the immune system is shown in Figure 3.

4.2. Direct Mechanism: Pattern Recognition Receptors. In addition to the indirect effects of fructans and their fermentation products on the microbiota, the direct effects of fructans on the signaling of immune cells have gained attention as an additional pathway of immunomodulation. ITFs have been reported to interact directly with GALT components, such as gut dendritic cells (DCs) and intraepithelial lymphocytes (iIELs), through receptor ligation of PRRs [7]. Signaling through PRRs, such as TLRs (Toll-like receptors), is considered the starting point of innate immune system activation against various environmental factors, including microbes and antigens. The innate immune system enables appropriate adaptive immune responses to be generated through the activation of multiple specific immunocompetent clones [110]. TLRs play an important role in initial innate immune responses, which includes cytokine synthesis and activating acquired immunity. The β(2 → 1)-linked fructans can provide a direct signal to human immune cells primarily by activating TLR2 and to a lesser extent TLR4, TLR5, TLR7, TLR8, and NOD2. β(2 → 1)-linked fructans stimulation results in NF-κB/AP-1 activation, further suggesting that β(2 → 1)-fructans are specific ligands for TLR2. However, chain length is important for the induced activation pattern and IL-10/IL-12 ratios stimulated by β(2 → 1)-fructans [111, 112]. In fact, ITFs increase the proportion of DCs in PPs and increase the secretion of IL-2, IL-10, and interferon-γ from the spleen and MLNs. Additionally, ITFs reduce the number and proportion of T cell receptor (TCR-) αβ⁺ CD8⁺ cells in the spleen and CD45RA⁺ cells in the MLNs [113] (Table 2). Furthermore, TLR4 appears to be involved in levan β(2 → 6)-fructans pattern recognition. Oral administration of levens in vivo significantly reduced IgE serum levels and Th2 response in mice immunized with ovalbumin [8].

A fructose receptor may exist on immune cells, as receptors for β-glucan [114] and mannose [115] have been identified on the surface of immune cells. Oligofructose has also been shown to bind to receptors on pathogenic bacteria, preventing them from attaching to the epithelial membrane [116]. Furthermore, ITFs treatment of gut epithelial cells can modulate the innate immune barrier by modifying the integrity of epithelial tight junctions or by altering signals from the epithelial cells to the underlying immune cells [117]. Thirty-six fructan studies reporting immune outcomes have been conducted in mice, rats, pigs, dogs, and humans, and these investigations are summarized in Table 2. These reports show that fructans may have specific effects on different immune system components.

5. Fructans Act as ROS Scavengers

Because inulins and agavins have health benefits, improve blood metabolic parameters [41, 52], reduce colonic pH [152], increase SCFAs production [36, 43, 69], and stimulate the immune system [48], interest has developed in the antioxidant capacity of fructans. As in plants, fructans and other carbohydrates have been shown to scavenge ROS [153–157]. ROS include free radicals such as the superoxide anion (O₂⁻), hydroxyl radical (‘OH), and nonradical molecules such as hydrogen peroxide (H₂O₂) and singlet oxygen (¹O₂). These molecules attack DNA, lipids, and proteins resulting
in cellular damage [158]. Fructans, galactooligosaccharides (GOS), arabinoxylans, β-glucans, and fructooligosaccharides (FOS) might act as ROS scavengers in plants [159] because they have strong antioxidant activity in vitro. Raffinose appears to be a moderate ROS scavenger [160].

Recently reports have suggested that fructans possess antioxidant activity in vivo models. A putative role for oligofructoses in counteracting the prooxidative effects of a high fructose diet has been demonstrated in rats. The addition of fructans to the diet may provide an early defense against oxidative stress and may act before the activation of the endogenous ROS detoxification systems [65]. In an indirect mechanism, these nondigestible carbohydrates might serve as ROS scavengers, which suggests that inulin can protect the colonic mucosa by acting as a barrier against oxidative stress in addition to its positive prebiotic effect. This hypothesis is consistent with the recently proposed ROS scavenging capability of inulin [65, 161] and the reported effects of SCFAs, which induce the expression of crucial antioxidant enzymes, such as glutathione S-transferases (GSTs) [162]. Li et al. showed that, in aged mice, synthetic oligosaccharides increase the activity of antioxidant enzymes [161]. By contrast, oligofructose has been shown to reduce the expression of NADPH oxidase in the colons of obese mice [51]. Moreover, intraperitoneal administration of synthetic oligosaccharides stimulates a dose-dependent decrease in lipid peroxidation, which supports the in vivo ROS scavenging capability of certain sugars [161]. Furthermore, agavins from Agave tequilana have been shown to improve the redox status in hypercholesterolemic mice by reducing malondialdehyde serum levels and oxidative protein damage. These results could be attributed to a reduction in the generation of oxidative products during digestion and colonic fermentation [42]. Additionally, polyphenol studies have indicated that metabolism in the large intestine is positively affected by prebiotic fructooligosaccharides, which have a synergistic effect with polyphenol to counteract oxidative stress in vivo models [163].

6. Conclusion

Prebiotic consumption is undoubtedly associated with several health benefits. In this review, we assessed the potential immunomodulatory and antioxidants mechanisms of the prebiotic fructans as well as the impact of fructans on immune health. Some preliminary data have convincingly suggested that fructan consumption can modulate immune parameters in GALT. Additionally, fructans may act as ROS scavengers providing an increase in antioxidant defenses...
Table 2: Effect of fructans on the immune function in healthy animal and human models.

| Effects of fructans | Dose fructan/duration | Model | Reference |
|---------------------|------------------------|-------|-----------|
| ↑ DC and γδ T cells in lamina propria of the caecum and ↓ PGE2 in small intestine, colon, and caecum | 3% FOS for 12 days | Mice treated with antibiotics and conventionalized with *Clostridium difficile* | [118] |
| In peripheral blood: ↑ CD4⁺/CD8⁺ ratio and ↓ B cells. In GALT: ↑ proportion of CD4⁺ cells and CD8⁺ cells, PP, and lamina propria cells and ↓ CD4⁺/CD8⁺ ratio in lamina propria | 0.87% FOS for 14 days | Adult dogs | [119] |
| Synbiotics ↑ whole blood phagocyte activation level. | 1% FOS for 28 days | Piglets infected with *S. typhimurium* | [120] |
| ↑ counts of leucocytes, lymphocytes, neutrophils, CD2¹ T cells, CD4⁺ T cells, CD8⁺ T cells, B cells, and macrophages in blood, ↑ % phagocytic activity of leucocytes and neutrophils in blood. | 3 g/d OF for 20 days | Newborn piglets | [121] |
| ↑ ileal IgA concentration. | 2 g/d FOS and/or MOS for 14 days | Adult dogs | [122] |
| ↓ blood neutrophils and ↑ blood lymphocytes. | 2 g FOS plus/1 g MOS for 14 days | Adult dogs | [123] |
| ↑ rotavirus-specific IgA levels in serum and ↓ duration of a strong rotavirus-specific IgA response in faeces and % IgA and IgG positive B cell in the PP, ↑ serum rotavirus-specific IgG and Rhesus rotavirus antigen concentration in stools. | 1.25 g/L OF for 7 weeks | Mice (pups) infected with *Rhesus rotavirus* | [124] |
| No change in protein, alb, serum Ig, secreting IgA, and IL-4 and IFN-γ secretion, ↑ antibodies against influenza B and pneumococcus. | 6 g OF/ITFs for 28 weeks | Healthy elderly (>70 years) | [125] |
| ↑ % CD4 and CD8 lymphocytes, ↑ phagocytic activity in granulocytes and monocytes and IL-6 mRNA expression in PBMCs. | 8 g/day FOS, 3 weeks | Nursing home elderly (77–97 years) | [126] |
| ↑ total faecal IgA, size of PP, total IgA secretion by PP cells and IL-10 and IFN-δ production from PP CD4⁺ T cells. | 0–75% FOS for 6 weeks | Female mice | [127] |
| ↑ leucocyte counts, ↑ NK activity of splenocytes and peritoneal macrophage phagocytosis of *Listeria monocytogenes*. | 2.5–10% FOS or OF for 6 weeks | Female mice | [128] |
| ↑ total number of immune cells in PP, B lymphocytes in PP and T lymphocytes and CD4⁺/CD8⁺ ratio in PP in endotoxemic mice only. | 10% FOS for 16 days | Female mice healthy or endotoxemic | [129] |
| ↓ peripheral blood lymphocyte concentration. | 1% ITFs/MOS for 4 weeks | Senior dogs | [130] |
| ↑ total intestinal IgA, ileal and colonic polymeric Ig receptor expression, ileal IgA secretion rate, IgA response of PP cells, and % of B220⁺ IgA⁺ cells. | 5% FOS for 23–44 days | Newborn mice | [131] |
| ↑ IL-10 and IFN-δ production in PP, secretory IgA concentration in ileum and caecum. | 10% FOS-enriched ITFs for 4 weeks | Male rats | [132] |
| ↑ NK activity. Prevention of the decrease in proportion of T cells with NK activity. | 6 g/d OF and ITFs (2:1 ratio) for 1 year | Elderly free-living adults (age ≤ 70 years) | [133] |
| Improved response to some vaccine components and increased lymphocyte proliferation to influenza vaccine components. | 4.95% FOS for 183 days | Healthy adults (age ≤ 65 years) | [134] |
| ↑ T cells, MHCII on antigen-presenting cells in spleen, MLN, and thymus, IL-2 and IL-4 in blood. | 10% FOS/ITFs for 4 months | Male rats | [135] |
| Trend towards higher fecal slgA. | 0.6 g (GOS/FOS)/100 mL formula for 32 weeks | Newborn non-breast-fed infants | [136] |
| Improved response to ↑ B cells, ↓ memory cytotoxic T cells, ↑ influenza-activated lymphocytes (CD69 and CD25) and IL-6 and ↓ IL10. | 4.95% FOS for 4 weeks | Healthy adults (age ≤ 65 years) | [137] |
### Table 2: Continued.

| Effects of fructans                                                                 | Dose fructan/duration | Model                                      | Reference |
|----------------------------------------------------------------------------------|-----------------------|--------------------------------------------|-----------|
| In pregnant females and pups no effect on serum IgG1, IgG2, IgA, or IgM. In colostrum and milk ↑ IgM. | 0.1% OF during lactation | Pregnant female dogs and pups              | [138]     |
| ↓ severity of enterocyte sloughing.                                              | 1% FOS or ITFs for 14 days | Puppies                                   | [139]     |
| ↑ % CD19 (B) cells, CD3⁺ HLA-DR⁺ (activated T cells) and ↓ % ICAM-1⁻ bearing lymphocytes and % CD3⁺ NK⁺ cells. | 9 g/d ITFs for 5 weeks | Adults smokers and nonsmokers              | [140]     |
| ↑ vaccine-specific faecal IgA and plasma IgG levels, peritoneal macrophage activity, mean fluorescence intensity of MHCII⁺ cells in spleen, IL-12 and IFN-γ production by splenocytes, and survival from Salmonella infection when given vaccine. | 5% mix (ITFs, FOS, and OF) for 1 week | Female mice                                | [141]     |
| ↑ fecal sIgA.                                                                   | 6 g/L GOS/FOS (9:1) for 26 weeks | Newborn healthy infants                    | [142]     |
| ↑ NK activity, and IL-10, ↓ IL-6, IL-1β, and TNF-α.                              | 5.5 g GOS/d for 10 weeks | Elderly (64–79 years)                      | [143]     |
| ↑ DCs in PP, ↑ IL-2, IL-10, and IFN-γ from spleen and MNL. cells. ↑ number and proportion of T cell receptor (TCR-αβ) CD8⁺ cells in spleen and CD45RA⁺ cells in MNL. | 5% ITFs for 4 weeks | Female rats                                | [113]     |
| ↓ total IgE, IgG1, IgG2, and IgG3; ↓ cow’s milk protein-specific IgG1.           | 8 g/L GOS/FOS for 6 months | Newborn infants at risk for allergy        | [144]     |
| ↓ intestinal sIgA.                                                              | 2.51–0.42 g/kg/d mix of GOS, XOS, OF, and ITFs (3.6 : 1 : 0.4 : 5) for 12 days | Female rats induced with diphenoxylate    | [145]     |
| ↓ IL-1β in macrophage cultures and ↑ fecal IgA.                                  | 3–5% FOS for 30 days | Female mice                                | [146]     |
| ↓ LPS in blood and ↓ LPS-induced increases in gene expression in IL-1β and LPS-induced decreases in gene expression in IL-13 in blood. | 5 g XOS, ITFs–XOS (3:1) for 4 weeks | Healthy volunteers                        | [147]     |
| ↓ serum cortisol, TNF-α and IL-6 after a LPS injection.                          | 0.10% levan-type fructan for 42 days | Growing pigs                              | [63]      |
| ↑ fecal secretory IgA and ↓ fecal calprotectin and plasma C-reactive protein.   | 5.5 g/d B-GOS (Bi2muno) for 12 weeks | Overweight adults                          | [148]     |
| ↑ TGF-β secretion by splenocytes and IFN-γ production and ↓ IL-5.                 | GOS/ITFs (dose and duration data not shown) | Healthy mice                              | [149]     |
| ↓ CD16/56 on natural killer T cells and ↓ IL-10 secretion, XOS and Bi-07 supplementation ↓ CD19 on B cells. | 8 g XOS or with 10⁵ CFU Bi-07/d for 21 days | Healthy adults (25–65 years)              | [150]     |
| ↓ cell-mediated immunity in terms of skin indurations and CD4⁺ T-lymphocyte population. | 20–60 g/kg FOS/ITFs for 12 weeks | Healthy rats                               | [151]     |

FOS: fructooligosaccharides; PGE2: prostaglandin E2; GALT: gut-associated lymphocyte tissue; CD: cluster of differentiation; PP: Peyer’s patch; OF: oligofructose; MOS: mannanooligosaccharides; IgA: immunoglobulin A; lgG: immunoglobulin G; ITFs: inulin-type fructan; IL: interleukin; PMBCs: peripheral blood mononuclear cells; NK: natural killer cells; MHC II: major histocompatibility complex II; GOS: galactooligosaccharides; HLA: human leukocyte antigen; ICAM-1: intercellular adhesion molecule 1; IFN-γ: interferon gamma; DC: dendritic cell; TCR: T cell receptor; MLN: mesenteric lymph nodes; XO: xylooligosaccharides; LPS: lipopolysaccharides.

Partially through the activation of endogenous ROS detoxification systems. Further studies will be required to fully understand and elucidate the mechanisms of action for fructans on GALT in various disease models.

### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.
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