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FERMENTABLE OLIGOSACCHARIDES, DISACCHARIDES, MONOSACCHARIDES AND POLYOLS AND THEIR ROLE IN FOOD DIGESTION

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ABSTRACT

Oligosaccharides containing fructose (fructans, inulin), galactose (galactans, stachyose, raffinose), disaccharides enclosing galactose (lactose), monosaccharides and mixtures of monosaccharides encompassing fructose (fruit sugar, honey) and saccharide polyols (mannitol, malbitol, sorbitol), are considered as safe to be consumed and beneficial to health. Gradually, however, their presence in the human diet reaches amounts that are indigestible by the small intestine, causing an osmotic load on the intestinal lumen. Subsequently, they pass into the large intestine, where they are fermented by intestinal bacteria to undesirable products such as gaseous carbon dioxide, hydrogen, methane, sulfane, and short chain fatty acids. Indigestible fermentable oligosaccharides, disaccharides, monosaccharides, and polyols may cause undesirable symptoms such as an increased flatulence, bloating, abdominal pain, alterations to the intestinal physiology, cessation of peristalsis, or diarrhea, which are manifested by a wide array of diseases of the gastrointestinal tract, such as the irritable bowel syndrome or small intestinal bacterial overgrowth. Fruits, vegetables, dairy products, legumes, some cereals, as well as honey or various sweeteners are among the most common food sources of these carbohydrates.

Keywords: FODMAP, irritable bowel syndrome, fructane, galactane

INTRODUCTION

Over the recent decades, human nutrition has been characterized by a shift from conventional foods to new types of foods, functional foods, or foods with a positive effect on the health and vitality. Prebiotics are also among healthy food ingredients. These are defined as substances of a carbohydrate nature that the human body cannot digest or degrades them only partially, while on the other hand, they serve as good substrates for the intestinal microorganisms. This heterogenous group includes the so-called fermentable oligo-, di-, mono- and saccharide polyols, abbreviated FODMAP. Their high intake may exhibit a negative effect on the human health, since the intestinal microflora produces various organic acids and gaseous substances in the large intestine, which may cause discomfort in the gastrointestinal tract. Historically, lactose, fructose and sorbitol have been the first to be associated with digestive problems. Gradually, and especially in connection with the development of the irritable bowel syndrome (IBS), the oligosaccharides galactans and fructans have also attracted the attention of the scientists and physicians.

The human digestive tract contains beneficial microorganisms that protect the body from pathogenic microorganisms and play an important role in the prevention of inflammatory diseases by stimulating the immune system. Through their metabolism, intestinal microorganisms help to break down and utilize food components that the human body cannot metabolize on its own. They also synthesize a variety of micronutrients, such as vitamins K, B2, B9 and B12, A, D and K **(Tojo *et al.*, 2014; Morrison and Preston, 2016).** Some intestinal bacteria are producers of short-chain fatty acids, which are a major source of nutrients for the colon cells. They support the formation of a sufficiently resistant intestinal barrier that prevents a possible entry of harmful substances, viruses, or bacteria, reducing the risk of inflammatory or tumorous processes. In an effort to support these defense mechanisms, an excessive consumption of fiber, including fructooligosaccharides (such as inulin) or galactooligosaccharides (such as pectins and various gums, cellulose and hemicelluloses) has been reported. These food components are not hydrolyzed by the digestive enzymes but act as suitable substrates for microbial fermentation in lower parts of the digestive tract. Consequently, an intensive development of microcenosis, called bacterial overgrowth may occur, leading to the development of IBS, dysbiosis, disruption of intestinal peristalsis, accompanied by water and nutrient malabsorption.

Characteristics and significance of intestinal microcenosis

The intestinal microcenosis is very rich in various types of microorganisms, dominated by bacteria representing the genera *Ruminococci*, *Bifidobacteria*, *Proteobacteria*, *Lactobacilli* and *Streptococci* **(O'Hara and Shanahan, 2006).** In addition, *Actinobacteria*, *Verrucobacteria* and *Fusobacteria* have been identified, as well as *Archaea* and eukaryotic microbioses **(Eckburg *et al.*, 2005; Scanlan and Marchesi, 2008).** The human intestinal microcenosis may include approximately 1 150 microbial species, out of which about 160 species are present in every individual **(Qin *et al.*, 2010; Orth *et al.*, 2011; Tilg and Kaser, 2011).** However, up to 80% of bacterial species of human origin cannot be cultured *in vitro* **(Eckburg *et al.*, 2005).**

Most of the bacteria present in human intestines are non-sporing anaerobes, out of which *Bacteroides* sp. and *Bifidobacterium* sp., *Eubacterium* sp., *Clostridium* sp., *Lactobacillus* sp., *Fusobacterium* sp. and various gram-positive cocci are the most predominant. A minor portion of bacteria is represented by *Enterococcus* sp., *Enterobacteriaceae* sp. and sulfate-lowering bacteria. Nevertheless, there are approximately 300 to 500 different bacterial species, the presence of which in the gut varies from individual to **individual (Guarner and Malagelada, 2003; Iannitti and Palmieri, 2010)**. Methanogenic *Archaea* are also present in the human gastrointestinal tract, whose interactions with the host may be beneficial as well as harmful **(Macario and Macario, 2009).** *Archaea* are typical representatives of anaerobic intestinal microbiota **(Million *et al.*, 2016)** and are already present in a child's digestive system **(Wampach *et al.*, 2017).** These microorganisms have been of interest for several decades. *Methanobrevibacter smithii*, *Methanosphaera stadtmanae* **(Miller and Wolin, 1983)**, members of the order *Methanomassiliicoccales* **(Mihajlovski *et al.*, 2008)** have been isolated from the intestinal contents of adults. *Methanomassiliicoccus luminyensis*, *Methanomethylophilus alvus* and *Methanomassiliicoccus intestinalis* have been identified as well **(Borrel *et al.*, 2012; Gaci *et al.*, 2014).**

An imbalance between beneficial and harmful microorganisms defined as dysbiosis, in which pathogenic bacteria predominate over commensal

microorganisms, leads to a dysfunction of the large intestine. Possible causes of these changes include the use of antibiotics, laxative abuse, excessive consumption of processed foods and diseases such as cancer, acquired immune deficiency syndrome or diverticulitis **(Cani and Delzenne, 2007).**

The body naturally defends itself against dysbiosis by the fact that the intestinal cells and beneficial microorganisms secrete chemicals that modulate the mucosal immunity and a subsequent inflammatory response as a strategy to combat various pathogens. For example, *Bacteroides fragilis* produces immunomodulatory and pro-inflammatory polysaccharides, such as polysaccharide A. This polysaccharide can induce a cascade of processes that leads to the production of interleukin IL-10 and promotes the colonization of *Bacteriodes fragilis* while at the same time limiting the intestinal colonization by competing microorganisms, including *Helicobacter hepatis* which causes colitis. Based on experiments in animal models, several authors have reported that oral administration of this polysaccharide may reduce the risk of colitis **(Mazmanian *et al.*, 2008; Round *et al.*, 2011; Mousa *et al.*, 2017).** Another example of a bacterial species that utilizes this strategy is *Lactobacillus plantarum*, which secretes amino acid derivatives that reduce the levels of the pro-inflammatory cytokine interferon INF-γ **(Zvanych *et al.*, 2014).** *Bifidobacterium longum* and *Bacteroides thetaiotaomicron* are also present in the gastrointestinal tract, being able to metabolize arachidonic acid and produce prostaglandins and leukotrienes that affect the immune response **(Eberhard *et al.*, 2002).**

Intestinal microorganisms produce bacteriocins that have a microbistatic or microbicidal effect. For example, the metabolic product of *Lactobacillus gasseri* is gassericin B, which exhibits antibacterial activity against *Listeria monocytogenes*, *Staphylococcus aureus* and *Bacillus cereus*. *Lactobacillus reuteri* produces reuterin, which has the ability to protect the host from pathological strains of *Escherichia coli* **(Mousa *et al.*, 2017).** *Lactobacillus plantrum* secretes lantipeptides called plantaricins that act against gram-positive bacteria such as *Streptococcus thermophilus* and *Enterococcus fecalis* **(Turner *et al.*, 2004).** *Pediococcus* produces pediocins that are effective against *Listeria* sp. **(Papagianni and Anastasiadou, 2009)**, while thuricin CD from *Bacillus thurigiensis* is effective against *Clostridium difficile* and *Listeria monocytogenes*. In the meantime, *Bacillus subtilis* produces amicoumacin A, which exhibits an antibiotic and anti-inflammatory activity against *Helicobacter pylori* **(Pinchuk *et al.*, 2020; Rea *et al.*, 2010).**

Food and nutrition have a significant effect on the composition and activity of the human gastrointestinal microcenosis **(Salonen *et al.*, 2014; Sonnenburg and Bäckhed, 2016).** Several studies have revealed links between the composition of the intestinal microcenosis and diseases of the body. The intestinal microcenosis may also significantly interfere with specific drug therapies, bringing attention of the pharmaceutical industry to these microorganisms **(Routy *et al.*, 2018).** The diagnostic approach is gradually changing, which also includes the identification of bacteria in the patient's gut **(Kåhrströmn *et al.*, 2016; Flemer *et al.*, 2018).**

Bacterial overgrowth

The upper gastrointestinal tract, comprising the stomach, duodenum, and lumbar region, is sparsely populated by microorganisms due to the microbicidal gastric acid barrier **(Mackie *et al.*, 1999).** Acid-resistant *Helicobacter pylori* and *lactobacilli* dominate this region of the gastrointestinal system **(Ghoshal *et al.*, 2012).** The distal part of the small intestine and the large intestine are inhabited by a larger number of microorganisms, such as coliform, gram-negative non-sporulating bacilli **(Mackie *et al.*, 1999).**

A proper intestinal microcenosis defined as eubiosis, is essential for the health of the body. Abnormalities such as dysbiosis, including a quantitative increase in the number of bacteria, such as small intestinal bacterial overgrowth (SIBO) or changes in the location of bacteria during which colon bacteria are found in the small intestine, cause various diseases **(Prakash *et al.*, 2011; Ghoshal and Srivastava, 2014; Nagao-Kitamoto *et al.*, 2016).** Bacterial overgrowth of the small intestine is defined as an excessive increase in the number of bacteria above 10^5 colony forming units (CFU) in 1 mL of jejunal aspirate **(Ghoshal and Srivastava, 2014; Ghoshal *et al.*, 2012).** Several authors consider overgrowth a condition in which SIBO is $>10^3$ CFU/mL jejunal aspirate. Determining this number is important in demonstrating the presence of coliform bacteria or in the diagnosis of IBS **(Khoshini *et al.*, 2008; Ghoshal *et al.*, 2012).** SIBO causes gastrointestinal dysfunction by several mechanisms, including a prolonged inflammation, activation of the immune system, changes in the intestinal peristalsis and permeability, deconjugation of bile acid salts, secondary lactase deficiency, malabsorption of water and nutrients with an increasing osmotic load on the luminal content of the intestine **(Pimentel *et al.*, 2004; Ghoshal *et al.*, 2012; Ghoshal and Srivastava, 2014).** In contrast to healthy individuals, the small intestine of subjects affected by SIBO contains bacteria of the colon, including gram-negative aerobes and anaerobes (e.g. *Escherichia coli*, *Enterococcus* spp., *Proteus mirabilis*) **(Bouhnik *et al.*, 1999; Sachdev and Pimentel, 2013)** which ferment carbohydrates with an intensive production of gases causing symptoms such as bloating, abdominal distension, pain, and cramps **(Posserud *et al.*, 2007; Sachdev and Pimentel, 2013).** The severity of the difficulties depends on the amount of carbohydrates consumed **(Shepherd *et al.*, 2008).**

Characteristics of FODMAP

Fermentable oligosaccharides, disaccharides, monosaccharides and polyols are short chain carbohydrates prevalent in foods such as fruits, vegetables, dairy products, cereals and legumes. They are also found in processed foods to which these raw materials have been added. From the point of view of human nutrition, the most frequently consumed FODMAP monosaccharides are fructose, glucose, and galactose, while the most eaten FODMAP disaccharides include sucrose, lactose, verbaskose, maltose and isomaltose. Plant food is also rich in the trisaccharide raffinose and the tetrasaccharide stachyose. The polysaccharides comprise various long fructans, galactans and galactomannans, agar, carrageenan, laminaran, hemicelluloses and cellulose **(Qi and Tester, 2019).** Fermentable polyalcohols are represented by sorbitol, mannitol, maltitol, and xylitol **(Tuck *et al.*, 2014)** (Tab. 1).

Table 1 Examples of fermentable di-, oligo-, polysaccharides and polyols

FODMAP	Name	Other name	Composition	Chemical formula
monosaccharides	glucose	grape	D-glucopyranose	$C_6H_{12}O_6$
		sugar	D-glucopyranose	$C_6H_{12}O_7$
		dextrose	D-glucopyranose	$C_6H_{12}O_8$
	fructose	fruit sugar	D-fructofuranose	$C_6H_{12}O_6$
		levulose	D-fructofuranose	$C_6H_{12}O_7$
	galactose	cerebrose	D-galactopyranose	$C_6H_{12}O_6$
	mannose	carubinose	D-mannopyranose / D-mannofuranose	$C_6H_{12}O_6$
	ramnose	isodulcit	6-deoxy-L-mannose	$C_6H_{12}O_5$
disaccharides	saccharose	sugar	D-glucose(1→2)D-fructose	$C_{12}H_{22}O_{11}$
	lactose	milk sugar	D-galactose(1→4)D-glucose	$C_{12}H_{22}O_{11}$
	maltose	malt sugar	D-glucose(1→4)D-glucose	$C_{12}H_{22}O_{11}$
	isomaltose	palatinose	D-glucose(1→6)D-glucose	$C_{12}H_{22}O_{11}$
	trehalose		D-glucose(1→1)D-glucose	$C_{12}H_{22}O_{11}$
	cellobiose		D-glucose(1→4)D-glucose	$C_{12}H_{22}O_{11}$
trisaccharides	raffinose	melitose	D-galactose(1→6)D-glucose(1→2)D-fructose	$C_{18}H_{32}O_{16}$
	kestose		D-fructose(2→1)D-fructose(2→1)D-glucose	$C_{18}H_{32}O_{16}$
tetrasaccharides	stachyose		D-galactose(1→6)D-galactose(1→6)D-glucose(1↔2)D-fructose	$C_{24}H_{42}O_{21}$
pentasaccharides	verbascose		D-galactose(1→6)-[D-galactose]$_2$(1→6)D-glucose(1→2)D-fructose	$C_{30}H_{52}O_{26}$
polysaccharides	agar		[D-galactose(1→3)D-galactose]$_n$(1→4) / [3,6-anhydro-L-galactose]$_m$	
	carrageenan		sulfated or nonsulfated [D-galactose(1→3)D-galactose]$_n$(1→4)[3,6-anhydro-L-galactose]$_m$	
	laminaran	laminarin	D-glucose linear polysaccharide with (1→3):(1→6) ratio of 3:1	$(C_6H_{10}O_5)_x$
polyols	mannitol	mannite	hexane-1,2,3,4,5,6-hexol	$C_6H_{14}O_6$
	sorbitol	D-glucitol	hexane-1,2,3,4,5,6-hexol / izomer of mannitol	$C_6H_{14}O_6$
	xylitol	xylite	1,2,3,4,5-pentahydroxypentane	$C_5H_{12}O_5$
	maltitol		D-glucopyranosyl-D-glucitol	$C_{12}H_{24}O_{11}$

Negative effects of FODMAP on the human digestive tract

Currently, the effects of malabsorption and intolerance to carbohydrates are increasingly evident in the human population. Their exact prevalence is unknown. This intolerance often leads to various, as yet unexplained difficulties in the gastrointestinal tract, such as flatulence, gas production, pain, distension, nausea, and diarrhea. Patients with such gastrointestinal symptoms are often subjected to an examination including endoscopy, blood tests and stool collection to determine a specific disease. However, the test results may be negative, in which case the gastrointestinal disorders may include IBS **(Fedewa and Rao, 2014).** One of the causes of IBS may lie in a high intake of FODMAP. It has been found that in developed countries, the disease affects one in five adults, with a higher prevalence in women.

Lactose has been described as the first carbohydrate associated with indigestion. A strict elimination of lactose from the diet, small bowel biopsy alongside with the determination of lactase activity and hydrogen in the breath have become the basis for the recognition of lactose malabsorption and intolerance **(Gibson, 2017).** While lactose-free diet has been very successful in some patients, it did not completely eliminate the undesirable and painful symptoms after consuming carbohydrates in most subjects (Vernia et al., 1995). In the 1990s, suggestions began to emerge that not only lactose but also fructose and sorbitol may play an important role in the development of IBS, since their elimination from the diet has led to a stabilization of digestive issues **(Rumessen and Gudmand-Høyer, 1988; Nelis *et al.*, 1990; Symons *et al.*, 1992).**

Nevertheless, foods do not only contain these carbohydrates in their free form, but also as part of oligosaccharides and polysaccharides. Therefore, fructooligosaccharides (fructans), galactooligosaccharides (galactans) and carbohydrate polyols, which are not completely absorbed in the gastrointestinal tract, have been included among the food components that can cause typical digestive problems.

Irritable bowel syndrome is characterized by abdominal pain, an unpleasant bloating, flatulence, and changes in the intestinal microcenosis, which may result in diarrhea or constipation. Mucus often occurs in the stool **(Spiller and Garsed, 2009).** Triggers of this syndrome are foods containing FODMAP. The condition is worsened especially by those containing spices, chocolate, beans, cabbage, fermented vegetables, and fruits. Changes in the intestinal microbiota or dysbiosis after ingestion of antibiotics or following gastrointestinal viral, bacterial, and parasitic infections may also contribute to the pathogenesis of IBS. Genetic predisposition also plays a role in IBS, since a family history is found in approximately 30% of patients **(Spiller and Garsed, 2009).** Recurrent abdominal pain is associated with advanced IBS and comes along with at least two of the following symptoms: defecation accompanied by pain, changes in the stool frequency, and alterations in the stool pattern. These symptoms reduce the quality of life, which is why it is necessary to pay attention to FODMAP, so that these can be identified in the diet and subsequently excluded in affected patients. In this sense, several authors point to the role of the intestinal microcenosis and subsequent changes in the gut microbial diversity **(Lacy and Patel, 2017; Losurdo *et al.*, 2018).**

Fermentable monosaccharides

Monosaccharides are absorbed from food in the human small intestine, which contains specific monosaccharide transporters **(Röder *et al.*, 2014).** According to **Wright *et al*. (2003)** the majority of carbohydrate uptake is mediated by specific carbohydrate-transporting proteins through the basolateral membranes of small intestinal enterocytes. These transporters are in particular glucose transporters (GLUT), which transport monosaccharides as follows: fructose is facilitated by diffusion through GLUT2 and GLUT5, galactose is delivered by co-transport with sodium ions via SGLT1 or by facilitated diffusion via GLUT2, while glucose alone is transported via sodium glucotransport and GLUT2 **(Le Gall *et al.*, 2007).** In some individuals, the availability of the GLUT5 transporter is limited in the presence of glucose, leading to fructose malabsorption **(Riby *et al.*, 1993).** This condition is typical for patients with IBS, occurring in up to 45% of all cases.

Fruit sugar - fructose

Fructose is a simple carbohydrate present in fruits and honey; however, it is also a major ingredient in two of the most commonly used food sweeteners, sucrose (fructose and glucose disaccharide) and syrup made from corn starch and considered a condiment with a high fructose content (HFCS, high fructose corn syrup). At present, the intake of fructose as an added sugar is close to 15% of the total energy intake from food in families with higher incomes, especially among younger individuals **(Lanaspa *et al.*, 2014; Yracheta *et al.*, 2015)** due to a high consumption of soft drinks. While sucrose-containing beverages have the same amount of glucose and fructose, HFCS-containing beverages have a fructose and glucose content oscillating from 55:45 to 65:35 **(Ventura *et al.*, 2012).** Fructose is absorbed in the small intestine by specific transporters expressed in both the apical and basolateral membranes of enterocytes **(Manolescu *et al.*, 2007).** After absorption, fructose is primarily metabolized in the liver **(Schalkwijk *et al.*, 2004).** Excess fructose passes into the large intestine, where it becomes a fermentable substrate for microorganisms. High fructose intake has been reported to alter the composition of microcenosis, leading to a reduced bacterial diversity and changes in the expression patterns of genes involved in specific metabolic pathways **(Payne *et al.*, 2012).**

Fructose is considered to be one of the most important fermentable carbohydrates within the FODMAP group **(Chumpitazi and Shulman, 2016; Giorgio *et al.*, 2016).** Any fructose not absorbed by the small intestine is fermented by colon bacteria producing short-chain fatty acids and gases, such as hydrogen and carbon dioxide, which may cause bloating, abdominal discomfort, and/or diarrhea in some individuals **(Skoog *et al.*, 2004; Shepherd and Gibson, 2006).** Hydrogen produced during the fermentation process is partially absorbed into the bloodstream and enters the lungs, allowing it to be detected in the exhaled air. This process is used in the diagnosis of fructose malabsorption, and is called the hydrogen breath test **(Gomara *et al.*, 2008).** Fructose intolerance, manifested by abdominal pain, flatulence, diarrhea, nausea, and vomiting, has also been diagnosed in some patients with indigestion **(Gomara *et al.*, 2008; Medeiros *et al.*, 2012).**

Honey - a mixture of monosaccharides containing fructose

Honey is a natural sweet substance produced by *Apis mellifera* from the nectar of plants, secretions from live parts of plants or secretions from insects sucking on live parts of plants, which bees collect, transform, and enrich with their own specific substances, thicken, store and leave in honeycombs to mature. The most commercially important types of honey are nectar and honeydew **(Kaškoniene and Venskutonis, 2010).** Honey is primarily a sweetener, but it is also consumed as a prebiotic as it contains oligosaccharides that can promote the growth of lactobacilli and bifidobacteria. However, this prebiotic potential is not as significant in comparison with the consumption of pure fructooligosaccharides **(Sanz *et al.*, 2005).**

Honey is an oversaturated solution of sugars, particularly fructose and glucose, which contains several minor components **(Viuda-Martos *et al.*, 2008).** Among the disaccharides sucrose and maltose make up 5 to 9%, followed by oligosaccharides, which represent 3 to 10% depending on the type of honey. A more detailed overview of carbohydrates found naturally in honey is provided in Table 2 **(Astwood *et al.*, 1998; Viuda-Martos *et al.*, 2008).** Honey contains carbohydrates, which are included in FODMAP, particularly fructose and fructooligosaccharides inulin and oligofructose that promote the growth of lactic acid bacteria from the genera *Lactobacillus* and *Bifidobacterium*. These bacteria are considered to be probiotic bacteria with an intensive saccharolytic metabolism **(Gibson and Roberfroid, 1995; Gibson and Shepherd, 2010).** Nevertheless, an increased number of these bacteria in the colon may result in the production of short-chain gases and fatty acids due to their anaerobic fermentation metabolism **(Roberfroid *et al.*, 2010; Flint *et al.*, 2012).**

Table 2 Average carbohydrate content in honey (**Doner, 1977; Bogdanov *et al.*, 2007)**

Carbohydrate		Nectar honey	Homeydew honey
monosaccharides, %	fructose	38.2	31.8
	glucose	31.3	26.1
disaccharides, %	saccharose	0.7 - 1.31	0.5 - 0.8
	maltose and others	5 - 7.31	4 - 8.8
trisaccharides, %	melezitose	<0.1	4.0
	erlose and others	1 - 1.5	4 - 4.7
oligosaccharides, %	non specific	3.1	10.1

Fermentation of fructose

Fructose currently accounts for 1/6 to 1/3 of the total carbohydrate intake **(Bhagan and Ha, 2011).** It is the sweetest monosaccharide with a low glycemic index **(Hedayat and Lapraz, 2019).** Fructose is absorbed by the small intestinal epithelial cells **(Douard and Ferraris, 2012)** through two mechanisms: if glucose and fructose are absorbed in an equimolar ratio by simultaneous transport with glucose (GLUT-2 transporter), in case of excess fructose the molecule is absorbed into the apical membrane of the enterocyte specific carrier using GLUT-5. The concentration of fructose is higher in the lumen than in the epithelium of the cells, which allows the molecule to use a concentration gradient and thus pass with the help of the transport proteins; however, this mechanism has a low capacity.

The first step in the metabolism of fructose lies in the formation of fructose-1-phosphate, which is cleaved to form two tricarbon molecules, namely glyceraldehyde and dihydroxyacetone phosphate (Fig. 1). These trioses will form pyruvate (further reduced to lactate), glycerol and, glucose in the case of dihydroxyacetone phosphate **(Geidl-Flueck *et al.*, 2021).**

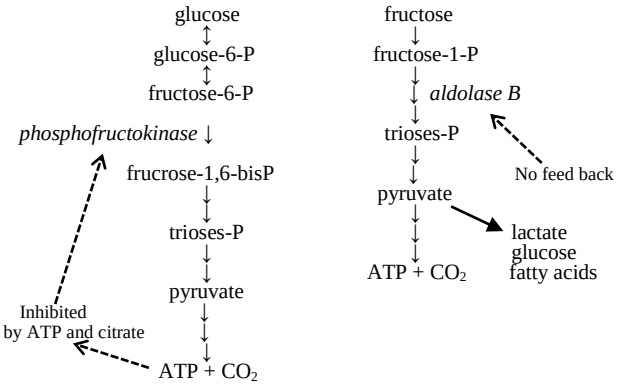

Figure 1 Metabolism of glucose and fructose in small bowel enterocytes, hepatocytes, and proximal tubule cells of the kidneys **(Geidl-Flueck *et al.*, 2021)**

Approximately 3% of fructose is used for the synthesis of triacylglycerols, ketone compounds and sorbitol **(Macdonald, 2003).**

Intestinal microorganisms involve fructose in their metabolism through glycolysis. As such, a mixed acid fermentation is typical for the genera *Citrobacter*, *Escherichia*, *Proteus*, *Salmonella*, *Shigella*, *Yersinia* and *Vibrio* and several *Aeromonas* species (Fig. 2). Some of these microorganisms are representative of a normal intestinal microcenosis in mammals, while others are pathogens **(Ciani *et al.*, 2013).** They produce lactic acid, formic acid, succinic acid, acetic acid and ethanol. The final amounts of each product vary depending on the microorganism and conditions suitable for their growth and reproduction. Due to the formate-hydrogen lyase complex, the mixed acid fermentation provides equimolar amounts of CO_2 and H_2. Pyruvate-formate lyase and lactate dehydrogenase enzyme complexes are sensitive to the presence of oxygen, which is why this fermentation requires an anaerobic environment. Some microorganisms can metabolize pyruvate via acetoin to butanediol **(Ciani *et al.*, 2013).**

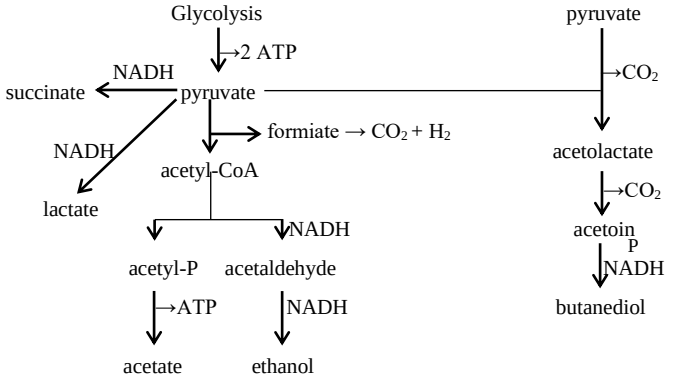

Figure 2 Mixed acid fermentation **(Ciani *et al.*, 2013)**

It has been mentioned on several occasions that the metabolism of microorganisms present in the intestines takes advantage of FODMAP to produce short-chain fatty acids. By-products of this process include many gases, containing mainly hydrogen, methane, and hydrogen sulfide, which has a number of consequences on the health. Hydrogen is then used by the microorganisms in the gastrointestinal tract as a reducing agent **(Nakamura *et al.*, 2010).** Hydrogenotrophic microorganisms are primarily methanogenic bacteria, followed by sulfate-reducing bacteria that convert sulfate to sulfide compounds as well as acetogens that produce acetate. Each of these species uses hydrogen to varying degrees and all are present in the human digestive tract **(Doré, 1995; Nava *et al.*, 2012; Wolf *et al.*, 2016).** Out of the methanogenic species, *Methanobrevibacter smithii*, *Methanobrevibacter oralis*, *Methanosphaera stadtmanae*, *Methanomassiliicoccus luminyensis* and *Methanomassiliicoccus intestinalis* have been detected in the human gut. Their presence has been linked to colon diseases **(Chaudhary *et al.*, 2018).** *Methanobrevibacter smithii* is the most common or in some cases the only methanogen found in the human colon **(Eckburg *et al.*, 2005).** Hydrogen and CO_2 generated by the FODMAP fermentation are converted to methane as follows: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$ **(Moss *et al.*, 2000).** Sulfur-reducing bacteria, especially the genus *Desulfovibrio*, may be present in very small amounts in the large intestine **(Nava *et al.*, 2012).** These present with the ability to reduce sulphates to hydrogen sulphide and at the same time convert lactate to acetate **(Marquet *et al.*, 2009; Keller and Wall, 2011).** Sources of sulphates are foods high in amino acids cysteine, methionine and taurine or inorganic sulphates, particularly plants of the *Brassicaceae* family **(Magee *et al.*, 2000).** Hydrogen and carbon dioxide produced by FODMAP fermentations may be used by some microorganisms in the large intestine for the so-called reductive acetogenesis: $4\ H_2 + 2\ CO_2 \rightarrow CH_3COO^- + H^+ + 2\ H_2O$ **(Gibson *et al.*, 1993).** Such microorganisms include, for example, *Ruminococcus hydrogenotrophicus* **(Bernalier *et al.*, 1996)** which uses the metabolic products of a number of mono- and disaccharides to generate acetate. Acetate has a beneficial impact on the colon health since it lowers the pH, transforming the environment into unsuitable for pathogens while being a source of energy for the microcenosis **(Morrison and Preston, 2016).**

Fermentable disaccharides

The most consumed FODMAP disaccharides are sucrose, containing glucose and fructose, the metabolism of which has been described above, followed by lactose (β-D-galactopyranosyl- (1 → 4) -D-glucose), which is normally hydrolyzed by the enzyme ß-galactosidase in the small intestine to the monosaccharides glucose and galactose. Reduction or loss of β-galactosidase activity, e.g., with an increasing age or due to active gastrointestinal diseases, drugs or a pathologically rapid intestinal peristalsis leads to lactose malabsorption. Undigested lactose enters the large intestine, where it is fermented by the bacteria present in the large intestine into short-chain fatty acids and gases (hydrogen, methane, and carbon dioxide). Excessive gas production causes abdominal pain, cramps, bloating or vomiting, while a high osmotic loading of the colon causes diarrhea. Nevertheless, lactose intolerance occurs only in a relatively small number of people with lactose malabsorption. In other cases, bacterial fermentation of lactose as a carbohydrate belonging to FODMAP is associated with IBS. In the case of lactose, this condition is accompanied by a chronic diarrhea lasting longer than 4 weeks **(Zheng *et al.*, 2015; Lacy and Patel, 2016; Xiong *et al.*, 2017).**

Lactose fermentation

Following hydrolysis of lactose to glucose and galactose, glucose is directly metabolized by glycolysis, while the major metabolic pathway for galactose utilization is the Leloir pathway (Fig. 3). Galactose is converted to glucose-1-phosphate (glc-1P), which subsequently enters glycolysis, or to UDP-galactose (UDP-gal). In addition to converting UDP-glucose (UDP-glc) to UDP-galactose (UDP-gal), the enzyme UDP-galactose epimerase catalyzes the conversion of UDP-N-acetylgalactosamine (UDP-galNAc) and UDP-N-acetylglucosamine (UDP-glcNAc) **(Leslie, 2003).**

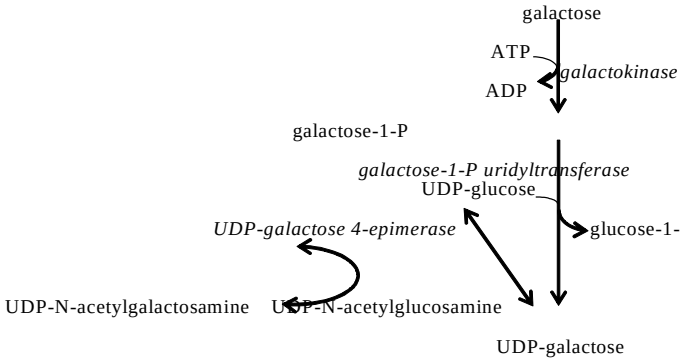

Figure 3 Leloir metabolic pathway **(Qi and Tester, 2019)**

Pyruvate as the glycolysis product, is fermented to lactate by probiotic bacteria **(Pascual, 2008).** Furthermore, microorganisms provide products of homofermentative (lactate) or heterofermentative (lactate, ethanol, acetic acid) lactic fermentation **(Ciani *et al.*, 2013).**

Fermentable oligosaccharides

Oligosaccharides are generally poorly absorbed by the digestive tract, leading to them being fermented as undigested carbohydrates by the intestinal bacteria **(Gibson and Shepherd, 2010; Barrett and Gibson, 2012; Barrett, 2013).** This results in gas production and subsequent adverse events such as flatulence in both healthy and hypersensitive individuals **(Ong *et al.*, 2010).**

Oligosaccharides are saccharides with a low degree of polymerization (3 - 10 monosaccharides, or in some cases up to 19 monosaccharides) and a low relative molecular weight, composed of monosaccharides. The structural properties of oligosaccharides determine the present monosaccharides and their bonds. For example, in fructooligosaccharides, D-fructose units are bound by β- (2-1) bonds with a terminal D-glucose bound by an α- (1-2) bond. In xylooligosaccharides, β-xylose phosphates are bound by 1-4 bonds and contain arabinose or 4-methyl-glucuronic acid. Specific types of oligosaccharides, called indigestible oligosaccharides, resist hydrolysis and absorption in the upper gastrointestinal tract, but these can be fermented in the large intestine by intestinal bacteria. Indigestible oligosaccharides have a prebiotic activity that can promote human health by increasing populations of beneficial microorganisms and/or their metabolic activity **(Wang *et al.*, 2019).** Naturally occurring oligosaccharide species and their sources are listed in Table 3 **(Mussatto and Mancilha, 2007).**

Table 3 Naturally occurring oligosaccharides (**Wang *et al.*, 2019)**

Naturally occurring oligosaccharides	Food source
fructooligosaccharides	artichokes, sugar cane, garlic, chicory, onion, Jerusalem artichokes, wheat, honey
xylooligosaccharides	bamboo shoots, fruits, vegetables, honey
galactooligosaccharides	milk
raffinose oligosaccharides	lentils, peas, beans, chickpeas, mallow, mustard
cyclodextrins	water-soluble glycans

Prebiotic oligosaccharides are in particular fructooligosaccharides, galactooligosaccharides, xylooligosaccharides and soy oligosaccharides. Intestinal microorganisms metabolize these producing acetate, propionate, and butyrate by fermentation **(Mussatto and Mancilha, 2007; Rivière *et al.*, 2016).** Their presence decreases the pH value in the large intestine, which can inhibit the growth of pathogenic bacteria as well as increase the resorption of minerals **(Mussatto and Mancilha, 2007)**. In addition, they have mild anti-inflammatory effects and are involved in the regulation of lipogenesis **(Flint *et al.*, 2015)** which contributes to their benefits for human health. Butyrate is the primary energy source for colonocytes, stimulates the growth of colonic epithelial cells and increases the absorption of salts and water, thereby alleviating constipation **(Mussatto and Mancilha, 2007; Rivière *et al.*, 2016).** In addition, butyrate has also been found to be associated with the inhibition of colon and rectal cancer cell proliferation **(Lim *et al.*, 2005).** Depending on the type of prebiotic oligosaccharides, the composition of these acids varies. For example, bifidobacteria produce acetate, lactate and formate but not butyrate **(Sarbini and Rastall, 2011).** Butyric acid is thus produced mainly by *Faecalibacterium prausnitzii* and *Eubacterium rectale* **(Rivière *et al.*, 2016).**

Although indigestible oligosaccharides have health benefits, high consumption of these may cause flatulence, excessive gas production or diarrhea **(Mussatto and Mancilha, 2007).** Therefore, they are classified as FODMAP, which may worsen the symptoms of IBS **(Rao *et al.*, 2015).**

In vivo studies from the last decade have shown that some indigestible oligosaccharides alter the composition of the intestinal microbiota at the species level **(Scott *et al.*, 2013; Flint *et al.*, 2015).** This is mainly because intestinal bacteria prefer different sources of carbon and energy in the environment, and present with different processes of oligosaccharide metabolism. The composition, structure of oligosaccharides and types of glycosidic bonds impact the selective use of these substances by intestinal bacteria at the strain level **(Sarbini and Rastall, 2011; Hamaker and Tuncil, 2014).**

Low molecular weight oligosaccharides are more rapidly fermented by *Bifidobacterium* sp. and *Lactobacillum* sp. This is because these oligosaccharides have more non-reducing ends, which are preferentially attacked, for example, by the bifidobacterial exoglucanase. However, the low molecular weight of oligosaccharides is also the reason for their complete decomposition before reaching the distal regions of the colon, which leads to an undesirable phenomenon typical for FODMAP **(Sarbini and Rastall, 2011).**

Nevertheless, in some cases, even large oligosaccharide molecules have been found to be fermented. Microorganisms may cooperate in their degradation **(Scott et al., 2013; Rivière *et al.*, 2016).** For example, during *in vitro* co-culture experiments, *Bifidobacterium longum* (LMG 11047) was able to consume even fructose released from inulin, while *Bacteroides thetaiotaomicron* (LMG 11262) had a high digestive capacity for oligofructosan from inulin and therefore was identified as the dominant species in the environment **(Sarbini and Rastall, 2011).** In another case, fructose was released by *Bifidobacterium longum* (BB 536), which was then used by the bacterium *Anaerostipes caccae* (DSM 14662) **(Sarbini and Rastall, 2011)** in an oligofructosan environment. Such coexistence of bacteria has been defined as "the mechanism of cross-feeding" (**Flint *et al.*, 2015).**

Fructose-containing oligosaccharides

There are three main types of fructans: inulins, levans (or fleins) and graminans. Linear inulin consists of ß-1,2-linked fructose residues attached to the sucrose core. A typical source of such oligosaccharides are plants of the family *Asterales*, such as chicory. Inulins of the family *Liliacae*, which includes onions, contain two ß-1,2-linked fructose chains attached to a sucrose core. Levan-fructans, in turn, are found in grasses and consist of a fructose chain attached by a ß-2,6 bond to sucrose. A mixture of fructans formed from ß-2,6-linked fructose residues with ß-1,2-branches is called a graminan and is also found in grasses.

Fructans are widely used in the food industry. They are defined as soluble fiber and are available as a dietary supplement. Chicory inulin is an additive that emulsifies with water and is used as a fat substitute **(Ritsema and Smeekens, 2003).**

The most important FODMAP are inulin-type fructans, which have a linear chain with β-2,1 glycoside bonds, and which occur naturally in plant foods such as onions, garlic, leeks, asparagus, chicory root, artichokes and others **(Franco-Robles and López, 2015).** These fructans modulate the intestinal biocenosis by increasing the number of *Bifidobacteria* sp. and *Lactobacilli* sp. **(Ortega-González *et al.*, 2013).** Fructans selectively stimulate the activity and growth of beneficial microorganisms and at the same time inhibit the development of pathogenic microcenosis. The main products of fructan fermentation are short-chain fatty acids (especially acetate, propionate and butyrate) as well as gases including H_2, CO_2 and methane **(Wong *et al.*, 2006; Roberfroid, 2007; Roberfroid *et al.*, 2010).** These gases cause flatulence and convulsions, typical for the conditions caused by an increased consumption of FODMAP.

Galactose-containing oligosaccharides

Following dietary fiber consumption, galactan is usually fermented in the large intestine, where it is broken down into galactooligosaccharides by the extracellular endo-β-1,4-galactanase encoded by the intestinal bacteria **(Lammerts van Bueren *et al.*, 2017).** Galactooligosaccharides are prebiotic carbohydrates that are generally considered safe for consumption **(Rastall, 2010; Lammerts van Bueren *et al.*, 2017).**

Plant galactans usually contain arabinose units **(Zykwinska *et al.*, 2008; Mohnen, 2008).** According to the type of glycoside bond in the galactan backbone, arabinogalactans (AG) are divided into type AG-I with a 1,4-linked galactan backbone and type AG-II with a 1,3- and 1,6-linked backbone **(Yapo, 2011).** In plants, galactan is usually also associated with other structural molecules, such as ramnogalacturonan I. Hence, by different side chain substitutions, different chain lengths and overall structure, galactans form substances known as pectin **(Mohnen, 2008).**

In addition to prebiotic properties, galactans have gastroprotective effects **(Cantu-Jungles *et al.*, 2014)**, arabinogalactans from *Cereus triangularis* possess antioxidant activities **(Petera *et al.*, 2015)**, galactans isolated from *Cereus peruvianus* exhibit protective effects against the formation of gastric ulcers **(Tanaka *et al.*, 2010)** and green tea arabinogalactans present with an insulinotropic effect **(Wang *et al.*, 2015).**

Oligosaccharides containing raffinose

Raffinose oligosaccharides are a group of soluble sucrose derivatives found in the seeds, roots, tubers, and bulbs of several plants. They represent a storage form of carbohydrates for plants and are considered as substances with a protective effect against abiotic stress. The main representatives are trisaccharide raffinose (galactosylsucrose) and tetrasaccharide stachyose (β-D-fructofuranosyl-O-α-D-galactopyranosyl- (1 → 6) -O-α-D-galactopyranosyl- (1 → 6) -α-D-glucopyranoside).

Raffinose oligosaccharides are generally considered to be of low nutritional value due to their indigestibility. However, they have been found to have a beneficial effect on the intestinal microcenosis, and therefore their dietary intake is recommended in particular as a protection against intestinal oncological diseases **(Chibbar and Båga, 2003).** On the other hand, raffinose is a useful substrate for *Escherichia coli*, *Enterococcus faecium*, *Streptococcus macedonicus*, *Streptococcus pasteurianus* and *Enterococcus avium*, whose fermentation metabolism has been characterized by an intensive gas production **(Mao *et al.*, 2018).**

Oligosaccharides containing stachyose

Stachyose, which consists of one glucose, one fructose and two galactose units, occurs naturally mainly in numerous vegetables, as well as in rice **(Yin *et al.*, 2006).** Although stachyose is not digestible for the human body due to α-galactoside bonds **(Baucells *et al.*, 2000)**, its consumption is recommended as a prebiotic for several healthy intestinal bacteria **(Li *et al.*, 2013).** Legumes are the most important food sources of stachyose. Fermentation of these indigestible oligosaccharides leads to the production of short chain gases and acids, which is why stachyose is classified among FODMAP.

Fermentable polysaccharides

Humans consume a wide range of dietary polysaccharides in the form of plant foods, animal connective tissue, food additives, and higher mushroom products **(Martens *et al.*, 2014).** However, the human body can only cleave α-1,4-linked polymers of glucose (including starches, maltodextrins, maltotriose and maltose), lactose and sucrose **(Kaoutari *et al.*, 2013)** which is why the intestinal microcenosis has an irreplaceable role in the polysaccharide metabolism. Microorganisms produce a wide range of glycolytic enzymes **(Gill *et al.*, 2006; Turnbaugh *et al.*, 2009; Turnbaugh *et al.*, 2010)**, capable of cleaving bonds in β-glucans, cellulose, or hemicelluloses. In addition to the positive prebiotic effect, polysaccharides are fermented by microbial metabolism to produce short-chain fatty acids and gases. For example, *Plantago asiatica* polysaccharides are fermented by the microcenosis to acetic, propionic, and butyric acids. These are the products of acetic, propionic and butane fermentation, which, however, also release large amounts of carbon dioxide and hydrogen **(Hu *et al.*, 2013)**. A frequently used food additive is guar gum (from the seeds of *Cyamopsis tetragonoloba*). It is used as a thickener, increases the feeling of satiety, and reduces the absorption of monosaccharides. It is an indigestible fiber and is fermented by intestinal microorganisms accompanied by an intensive production of propionate, butyrate, and gases **(Yang *et al.*, 2013).**

Carbohydrate polyols

Carbohydrate polyols are alcohols formed by the reduction of carbohydrates. In the food industry, they are used as thickeners and sweeteners, which have a low glycemic index. They are either obtained by an extraction from raw plant materials or by a reduction of monosaccharides, particularly glucose and fructose. These are used as a sugar substitute in low-calorie drinks, confectionery, pastries, yoghurts, or separately as low-calorie sweeteners. The most important representatives are sorbitol and mannitol.

Both sorbitol (D-glucitol) and mannitol (an isomer of sorbitol) occur naturally in fruits such as apples, cherries, and apricots; commercially available polyols for food purposes are prepared by hydrogenation of monosaccharides. Sorbitol has a relative sweetness of about 55% and mannitol about 50% when compared to sucrose **(Featherstone, 2015)**. In soft drinks, a 1-2% sorbitol solution is usually used to ensure a cool and sweet mouthfeel, as well as to enhance the taste. Sorbitol is also used to mask a typical bitter taste of saccharin in beverages containing this sweetener. One of the main differences between sorbitol and mannitol lies in their solubility. Sorbitol is highly soluble in water and is an excellent hygroscopic agent. Mannitol is significantly less soluble and is used as a carrier for flavorings in e.g., powdered beverage bases **(Featherstone, 2015)**.

Fermentation of mannitol and sorbitol

Enterobacter aerogenes ferments mannitol via glucose and pyruvate with a simultaneous intensive H_2 production **(Tanisho and Suganuma, 1999).** Mannitol-based fermentation is twice as intense as fermentation, in which glucose is the starting substrate when it comes to the production of hydrogen **(Tanisho and Ishiwana, 1994; Hongo, 2014)** (Fig. 4).

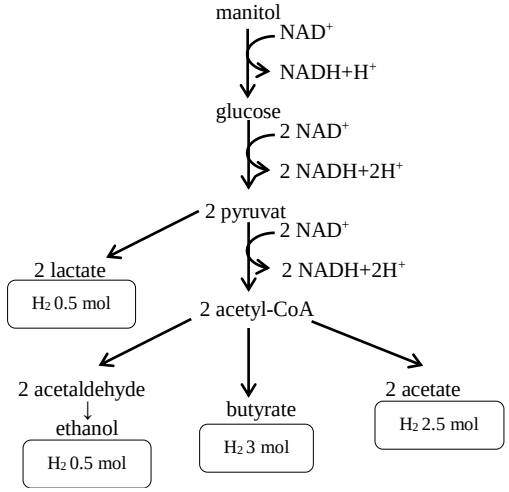

Figure 4 Mannitol fermentation **(Hongo, 2014)**

Due to a long tradition of using these sweeteners and research on them, it was found as early as 1986 that sorbitol altered the fecal microcenosis in rats by displacing gram-negative bacteria and promoting the growth of gram-positive bacteria **(Salminen *et al.*, 1986).** For example, sorbitol promotes the growth and reproduction of *Lactobacillus reuteri* in the digestive tract of rats and is metabolized with a marked increase in butyrate concentration in the colon **(Sarmiento-Rubiano *et al.*, 2007).** However, butane fermentation also produces gases, which is why flatulence and colicky pain are an undesirable side effect of polyol consumption. Therefore, both sorbitol and mannitol have been classified as FODMAP.

FODMAP food sources

To alleviate IBS and the inconveniences associated with bacterial overgrowth in the intestine, in which gaseous substances are produced by fermentation, it is necessary to describe the FODMAP food sources (Tab. 4) as well as foods that can be consumed since they contain little or no FODMAP.

Table 4 Foods high in FODMAP (**Gibson and Shepherd, 2005, 2010, 2012)**

FODMAP	Subcategory	Food
fructooligosaccharides	fructans	Cereals: wheat, rye, barley Vegetables: onion, garlic, artichoke, leek, beet and cabbage Fruit: melon, peaches, hurmikaki, plums, nectarines and most dried fruit
galactooligosaccharides	galactans	Legumes: beans, soybeans, peas, chickpeas Vegetables: beet
disaccharides	lactose	Dairy products from cow's and goat's milk
monosaccharides	fructose in excess of glucose	Fruits: apples, pears, melon, mango, cherries, blackberries, fruit juices, honey Sweeteners: high-fructose corn syrup Vegetables: asparagus, sugar peas
carbohydrate alcohols	polyols	Fruits: apples, pears, avocados, apricots, blueberries, nectarines, peaches, plums, prunes, and melon Vegetables: sweet potatoes, mushrooms, cauliflower and sugar peas

The importance of diet in the treatment of IBS was confirmed by a study in which 76% of patients diagnosed with IBS and fructose malabsorption experienced a significant remission of digestive issues following a well-defined diet without fructose and fructooligosaccharides **(Shepherd and Gibsond, 2006; Shepherd *et al.*, 2008).** A LOW-FODMAP diet significantly improved health in 75% of patients diagnosed with IBS **(Marsh *et al.*, 2015)**, and consequently, 60-70% of patients reported a worsening of symptoms after switching to normal eating habits **(Ahmad and Akbar, 2015; El-Salhy and Gundersen, 2015; Lacy and Patel, 2015).** However, there are also hypersensitive individuals who have not been diagnosed with any gastrointestinal diseases or syndromes and still have major problems after consuming HIGH-FODMAP foods. In these subjects, the consumption of foods rich in FODMAP followed by physical exertion, the movement of food through the upper gastrointestinal tract was intensified and carbohydrates were then fermented in the large intestine **(Peters, 2006; de Oliveira and Burini, 2009; Peters *et al.*, 2014).**

The sources of fructose are mainly fruits (apples, cherries, mangoes, pears, watermelon), vegetables (asparagus, artichokes, sugar peas), honey and HFCS syrup with a high fructose content (Tab. 5) **(Latulippe and Skoog, 2011; Douard and Ferraris, 2012).**

Table 5 Fructose content in fruits and vegetables **(Nookaraju *et al.*, 2010)**

Fruits	Fructose, g per 100 g	Vegetables	Fructose, g per 100 g
Apples	5.9	Tomatoes	1.4
Pears	6.5	Green peppers	1.0
Cherries	5.4	Red peppers	2.4
Plums	2.8	Cucumbers	0.7
Apricots	0.6	Broccoli	1.3
Peaches	1.2	Onion	1.8
Strawberries	2.4	Cauliflower	1.3
Raspberries	1.2	Carrot	1.9
Blackberries	2.5	Red cabbage	1.7
Black currants	5.0	Cabbage	2.0
Red currants	1.8	Brussels sprouts	0.8
Grapefruits	1.0	Watermelon	3.5
Grapes	7.1	Potatoes	0.1
Pineapple	1.4	Sweet potatoes	0.8
Bananas	3.8	Kidney bean	0.7

Lactose is considered a FODMAP when there is an insufficient amount of β-galactosidase in the digestive tract (estimated to be lacking in about 15% of the population), an enzyme required for its hydrolysis **(Carter and Attel, 2013).** Milk and milk products, ice cream, puddings and soft, unfermented cheeses are among the most prominent sources of lactose (Tab. 6).

Table 6 Lactose content in dairy products **(Agostoni *et al.*, 2010)**

Food	Lactose, g per 100 g
Cow milk	4.8
Goat milk	4.4
Sheep's milk	5.1
Human milk	7.2
Yoghurt	4.1
Kefir	3.8
Cream	3.1
Ice cream	6.0
Swiss cheese	0.0
Cottage cheese	2.2
Butter	0.7
Milk powder, full fat	38.0
Milk powder, without fat	52.0
Whey dried	74.0

FODMAP oligosaccharides are fructans and galactans whose digestion and absorption are not possible in the human body since the digestive juices do not contain the necessary enzymes **(Roberfroid and Delzenne, 1998; Ritsema and Smeekens, 2003; Sangwan *et al.*, 2011).** Fructooligosaccharides are found in various fruits, cereals and legumes, nuts, and vegetables. Peaches, hurmikaki, melons, artichokes, beetroot, brussels sprouts, chicory, fennel, garlic, leeks, onions, peas, wheat, rye, barley, oats, pistachios, lentils, chickpeas, and chicory drinks contain high amounts of fructans **(Roberfroid and Delzenne, 1998; Ritsema and Smeekens, 2003).** Wheat, containing 1-4% of these oligosaccharides, is also an important food source of fructans **(Roberfroid and Delzenne, 1998).** Therefore, wheat products such as bread, pasta, breakfast cereals, bakery and pastry goods are considered as foods containing FODMAP. Rye also contains fructans, which, however, have a longer chain length than wheat fructans and therefore present with a lower osmotic activity and are more slowly fermented, allowing them to pass through the digestive tract as undigested **(Roberfroid and Delzenne, 1998; Ritsema and Smeekens, 2003; Sangwan *et al.*, 2011; Van Loo *et al.*, 1995; Karppinen *et al.*, 2003).** Inulin crops are a frequently consumed source of fructans. Inulin, as a long-chain fructan with a degree of polymerization greater than 10, has a prebiotic effect **(Roberfroid, 1999; Boeckner *et al.*, 2001; Kaur and Gupta, 2002; Kelly, 2008).** Its food sources are chicory root, leeks, onions, garlic, artichokes, fennel, and asparagus (Tab. 7).

Table 7 Inulin content in inulin crops **(Fuchs, 2012)**

Source	Storage organ	Inulin content, % of fresh weight
Asparagus	root	10 - 15
Chicory	root	15 - 20
Dandelion	root, leaves	12 - 15
Garlic	bulb	9 - 16
Jerusalen artichoke	tuber	14 - 19

Table 8 Galactooligosaccharides in food **(Steggerda *et al.*, 1966)**

Food	Galactan, g per 100 g whole product
Jerusalem artichoke	7.5
Beans, baked	0.6
Beans, black-eyed	0.3
Beans, broad	0.2
Beans, butter	0.2
Beans, kidney	0.2
Bean, lima (dried)	2.9
Beans, red	0.8
Beetroot	0.1
Broccoli	0.1
Chickpeas	1.2
Fennel, bulb	0.1
Lentils, dried	3.8
Lettuce, radicchio	0.1
Onion, white	0.2
Peas, green (frozen)	0.2
Soy beverages	0.3 – 0.9

The primary food sources of galactans encompass legumes and their products, such as beans, chickpeas, lentils and soy products (Table 8), as well as cruciferous vegetables such as cabbage or kale **(Steggerda *et al.*, 1966).** Vegetarians have the highest intake of galactans, for whom legumes are a source of protein, alongside nations for which e.g. beans represent a traditional or national dish ("chili con carne" typical for Mexicans) **(Roberfroid and Delzenne, 1998).**

The polyols sorbitol and mannitol, as well as maltitol, xylitol, erythritol or polydextrose, are storage substances in plants and play an osmoregulatory role. Sorbitol is more common in fruits, while mannitol is more frequent in vegetables. Foods with a higher sorbitol content include apples, apricots, avocados, blackberries, cherries, nectarines, pears, plums, diet drinks, confectionery and chewing gums. Mannitol is found mainly in mushrooms, cauliflower, celery, and peas. Polyols are also used as artificial sweeteners such as E420 (sorbitol), E421 (mannitol), E965 (maltitol), E967 (xylitol) and E953 (isomalt) **(Hyams, 1983; Beaugerie *et al.*, 1990; Barrett and Gibson, 2012).**

Low FODMAP diet

The primary solution to the problems associated with the consumption of FODMAP lies in a strict elimination diet. A reduction of a high FODMAP food consumption in up to 70% of patients with irritable bowel syndrome has led to a significant health improvement **(Gearry *et al.*, 2016; Marsh *et al.*, 2015; Gibson, 2017).** Patients on a low FODMAP diet have presented with a significantly reduced abdominal pain and bloating **(Altobelli, 2017).** With respect to the irritable bowel syndrome, patients on a low FODMAP diet had lower serum levels of the pro-inflammatory interleukins IL-6 and IL-8, decreased concentrations of short-chain fatty acids and a reduced presence of *Actinobacteria, Bifidobacterium, Faecalibacterium prausnitzii* in their stool **(Staudacher *et al.*, 2012; Staudacher *et al.*, 2014; Staudacher and Whelan, 2016).** In addition to a low FODMAP diet, patients with irritable bowel syndrome are also advised to reduce their intake of fiber and foods that may cause bloating, as well as to reduce the consumption of alcohol, caffeine, and fatty foods. (Non)consumption of milk and dairy products is debatable, as not all patients present with a lactose intolerance **(Altobelli *et al.*, 2017; Tuck *et al.*, 2014).**

However, a low FODMAP diet may also come along with several negative side effects. Fructans and galactans are carbohydrates with a prebiotic effect. They act as substrates for the growth of a healthy microcenosis in the intestines and are a part of the so-called soluble fiber. Their presence enforces a proper function of the intestines. As such, elimination of FODMAP from nutrition may result in a disproportionately low fiber intake, a reduction of prebiotic substances, and thus undesirable changes in the composition of the intestinal microbiota towards a reduction of the beneficial bacteria **(Hill *et al.*, 2017).** Stool analysis has revealed that a very low FODMAP diet lasting for 3-4 weeks led to a reduction in *Bifidobacteria* **(Kerckhoffs *et al.*, 2009; Halmos *et al.*, 2014).** The number of butyrate-producing bacteria also decreased, while on the other hand the number of mucus degrading bacteria increased. This finding leads to the conclusion that if irritable bowel syndrome is associated with a dysbiosis, then a long-term low FODMAP diet is not an appropriate solution. As such, the diet is recommended for 2 - 6 weeks, or until pathological symptoms disappear. Subsequently, a professional dietary management with at least a partial return of FODMAP to food is required.

CONCLUSION

Fermentable disaccharides, oligosaccharides, polysaccharides and polyols are commonly found in a wide range of foods and play an important role in nutrition. They are a part of fiber, which contributes to a healthy function of the entire gastrointestinal tract. On the other hand, their ingestion may cause a variety of unpleasant difficulties to sensitive individuals. The possible solution lies in a low FODMAP diet, which, however, does not only come with benefits. Adverse side effects may occur after a long-term avoidance of these carbohydrates from food. Further studies are needed to assure a healthy functioning of the digestive tract.

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