Review

Pectin and Pectin Oligosaccharides Obtained from Agro-Wastes as a Constituents of Soluble Dietary Fibre: Effect on the Stabili-Zation of Intestinal Microbiome and Immunity of Humans and Animals – a Review

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Pectin and Pectin Oligosaccharides Obtained from Agro-Wastes as a Constituents of Soluble Dietary Fibre: Effect on the Stabilization of Intestinal Microbiome and Immunity of Humans and Animals—A Review

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Abstract: Regulation of the diet in terms of the content of soluble and insoluble fibre is of great importance from the point of view of dietetics, microbiology of the gastrointestinal tract and immunology of the organism. Dietary fibre plays an important role in maintaining the balance between the continuity of gut mucus production (intestinal mucosa), the stability of the intestinal microbiome composition, the regeneration of the intestinal epithelium and the immune status within the gut-associated lymphoid tissue (GALT) are played by pectin and their metabolic products in the form of pectin oligosaccharides. The main purpose of this review was to focus on pectin, their functions, their impact on the human's health and on some of the most promising prebiotics due to their solubility in the gastrointestinal tract in the form of pectin oligosaccharides. They have the properties of pectin, but have also additional features and postbiotics obtained in fermentation process can affect the intestinal microbiome and GALT-related immunity. They can be obtained from plant agro-wastes.

Keywords: dietary fibre; pectin; pectin oligosaccharides; microbiome; GALT

1. Introduction

Dietary fibre is one of the components of food products. The foods richest in this dietary ingredient include: fruits, vegetables, cereals, nuts, beans, and algae [1–3]. Important source of dietary fibre are also fruits and vegetable by-products [4]. The classic definition of dietary fibre defined it as 'plant parts that are resistant to the digestive enzymes of humans and animals', mainly concerned with structural carbohydrates and lignin [5,6] However, in the case of humans and monogastric animals, a more current definition divides dietary fibre (TDF) into soluble (SDF - viscous or fermentable, such as e.g. pectin) undergoing the process of complete or partial fermentation mainly in the large intestine. Insoluble fibre (IDF) can be also subject only partially fermentation process conducted by *Lactobacillus* spp. or *Bacillus* spp. strains [7–9]. However SDF is easier fermented than IDF, that is why cellulose, lignin or other insoluble elements of dietary fibre mainly functionate as a ballast and having a beneficial effect on intestinal peristalsis, as well as a "diluent of the digestive content" limiting the absorption of nutrients from the gastrointestinal lumen [10,11]. Table 1 presents physical properties of five individual carbohydrates [12–17]. Other important factor is particle size of dietary fibre which also can have influence on gut fermentation and SCFA profile [18].

Table 1. Physical properties of individual carbohydrates in comparison with cellulose.

Item	Solubility	Fermentability	Viscosity
Cellulose	-	slow	-
β-glucan (cereals)	high	rapid	high
Inulin	variable	rapid	low
FOS	high	rapid	-
Pectin	high	rapid	high
POS	high	rapid	low

According to the conception of functional fibre it is defined as a nondigestible carbohydrates found in fibre supplements which must show clinical evidence of a health benefit [19]. Dietary fibre can also be supplied as a result of supplementation and have prebiotic properties, act as a ballast or diluent and can also increase the viscosity of the chyme, reducing the absorption of nutrients [20,21]. This type of fibre containing sources for production fructo oligosaccharides (FOS) and pectin oligosaccharides (POS), can be obtained from by-products of the agri-food industry [22–25]. Pectin plays an important role during the inflammatory process in the gut, but its effect is also important when this process not occurred in terms of keeping overall gut health [26]. Long-term pectin supplementation modulates gut microbiome composition and affect positively on health [27,28]. From the other side pectin is able to modified redox potential which is important factor in case of metabolic and bacterial activity in gut [29]. Additionally last researches emphasize better bioactivities modified (with changes in functional groups) then natural pectin [30]. Nowadays interest in pectin, and POS, has increased significantly in recent years due to their mucus gut layer modulation properties and the prebiotic properties of pectic oligosaccharides utilized selectively mainly by *Eubacterium eilgens* and *Faecalibacterium prausnitzi* [31,32]. They consequently affects the maintenance of gut mucus layer continuity and counteracting inflammation of the intestinal epithelium, preventing the uncontrolled increase in the number of pathogens and their adhesion to the epithelial receptors [33]. This process maintaining the intestinal barrier and the efficient action of gut-associated lymphoid tissue (GALT), which affects the immunity of the entire organism human and animals [34–36].

2. Dietary Fibre and Its Importance in the Diet

2.1. Dietary Fibre Consumption

Due to the significant degree of urbanization of society and economic growth, many countries are experiencing changes in dietary habits towards the consumption of high-calorie food rich in refined carbohydrates and fats and low in dietary fibre [37]. This type of diet significantly increases the incidence of lifestyle diseases in high-income group of people without awareness from nutritional knowledge and choosing quick prepared meals what in consequence increases the costs of hospitalization in society [38,39].

Dietary fibre consumption varies significantly depending on the degree of industrialization of a given region of the world. Data up to 2015 indicate that the average dietary fibre intake by adults is 12-18 g/day in the USA, 14 g/day in the United Kingdom and 16-29 g/day in Europe [40]. However, in the last decade dietary patterns in development countries changes towards a significant increase in the consumption of processed food due to its lower costs, especially due to the savings in time needed to prepare this type of meal in home [41,42]. This is indicated by greater diversity of the microbiome intestinal in case of increasing the intake of dietary fibre in the diet, but also leading to insulin resistance and antioxidant stress when diet contains high amount of sucrose or refined carbohydrates [43]. The consumption of protein and animal fat in meat increases the number of Bacteroides in its composition, in turn, the high share of dietary fibre in agrarian societies affects the growth of *Prevotella* sp. [44]. This is especially easy to notice between populations from industrialized and non-industrialized areas [45].

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2.2. Properties of Dietary Fibre

The physiological and biochemical properties of dietary fibre in the small and large intestine have important implications for public health in a given population [46]. The most important include: solubility in water, influence on the viscosity of food content, increasing the volume through water absorption, influence on the absorption of nutrients, ability to ferment and binding other chemical compounds [39,47]. As a result of this, the action of dietary fibre in the digestive tract of humans and animals has a number of benefits: reducing cholesterol levels, lowering blood glucose levels, gut transit time, maintaining the health of the digestive tract by influencing peristalsis and mucus, having a positive effect on the bioavailability of calcium, microbial specificity and gut-associated immune function lymphoid tissue (GALT) [46,48].

2.3. Dietary Fibre in Diet and Its Effect on a Health

A diet low in dietary fibre favours the occurrence of inflammatory bowel disease, colon cancer, allergies, autoimmune diseases and obesity, which can be prevented by including an appropriate level of dietary fibre in the diet [49]. This ingredient contained in food affects the proper functioning of the digestive tract, maintaining the continuity of the epithelial structure and the balance of the digestive tract microbiome [45]. As a result, it affects the body's immunity, playing an important role in maintaining the proper functioning of the digestive tract and, therefore, good health of the patient [50]. In addition to the above-mentioned advantages of its use in the diet, dietary fibre also has a number of benefits, reducing the risk of developing ischemic heart disease, stroke, hypertension, diabetes, obesity and digestive problems [51]. Moreover, dietary fibre reduces the concentration of fats in the blood plasma and the level of glucose in the blood, which also has a positive effect on blood pressure [52].

Research by Thompson et al. [53] indicate that the avocado is an important source of dietary fibre in the diet, especially of overweight and obese adults. In addition to the fibre, which in the case of avocados in the diet (175 g in men and 140 g in women) increased the concentration of metabolites of microbial origin in faeces over a 12-week period, it also contains MUFA acids that reduce the pool of bile acids in faeces. As a consequence, regular consumption of avocado in the diet reduces the body weight of overweight and obese people and increases the number of commensal and symbiotic bacteria responsible for the production of postbiotics, including butyric acid, which is important in the process of nourishing the intestinal epithelium and preventing colon disease [53,54]. Walnuts and walnut meals rich in SDF and unsaturated fatty acids have a similar effect on increasing the number of microorganisms producing butyric acid [55,56]. Moreover, like avocados, they lower the state of pro-inflammatory secondary bile acids and LDL cholesterol, reducing the risk of metabolic syndrome. Additionally, Wang et al. [57] in their research, a predictive tool based on the deep learning method based on the metabolic response predictor using Multilayer Perceptrons (McMLP). It allows for more accurate diet selection compared to previously used machine learning methods for a given person, depending on the type of dietary fibre and unsaturated fatty acids content, based on information from the microbiome and metabolome, which will allow in the future to more precisely reduce the risk of obesity and metabolic problems with bound by it.

3. Types of Dietary Fibre and the Specificity of Their Action

3.1. Dietary Fibre Types and Its Action in Gastrointestinal Tract

Dietary fibre is divided into two groups based on solubility. Insoluble fibre consists of cellulose, lignin and part of hemicelluloses. IDF is insoluble in water and slightly fermentable, but mainly is responsible for accelerating the rate of content flow in the digestive tract and increases the frequency of peristaltic movements in the intestines [16]. Dietary fibre and its soluble fraction also influence the body's immune functions by stabilizing the mucus layer in the intestines, increase of flora diversity and reduce intestinal inflammation [58]. Goblet cells of the intestinal epithelium are responsible for the production of mucin, which has the form of a hydrated gel, which is a component of the mucus

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that prevents most bacteria from lumen to entering through the layer formed by it and contacting the receptors of the intestinal epithelium [59,60]. When the composition of the intestinal microbiome is disturbed and the barrier mechanism of the epithelium in the form of mucus disappears, we talk about "leaky gut" and the associated inflammation [61]. An important role in the process of stabilizing the protective barriers within the GALT is played by substances produced by microorganisms that restore the stabilization of the mucus layer, collectively called postbiotics [62,63].

3.2. Soluble Dietary Fibre and Its Action in Hindgut

Soluble fibre consists of pectin, gums and mucilage. It is characterized by very good solubility in water and is easily fermented in the gastrointestinal tract [64]. The viscosity effect of chyme caused by soluble dietary fibre limits the access of digestive enzymes to food/feed particles, as a result of which, in combination with the increased amount of insoluble fibre in the diet [65]. Consequently by this the phenomenon of limiting the absorption of nutrients is strengthened, which in combination with physical activity allows to counteract the occurrence of overweight or promotes weight reduction when a given person is overweight or obese [66,67].

Looking at this fact from the point of view of chemical compounds, cellulose, as an insoluble dietary fibre, is poorly fermented by the bacteria of the large intestine due to the linear structure of the chain composed of glucose residues of the molecules of this compound, while pectin, especially in highly branched molecules, is well fermentable [68]. Although, on the other hand, soluble fibre, depending on the type of compounds that compose it, may have a different degree of fermentation and then it tends to increase the viscosity of the food content, which will not be a beneficial solution when used in prebiotic preparations [3]. Table 2 presents content of IDF and SDF in food and amount of those types of dietary fibre in percentages [64,69–73].

Table 2. Dietary fibre content in different products.

Item	DF (g /100 g edible portion)			Percentage of TDF (%)		For 30 g TDF, person must eat in kg (single component of diet)
	Total	IDF	SDF	IDF	SDF	
Flaxseed	22.3	10.1	12.2	45	55	0.13
Soybean	21.5	19.4	2.1	90	10	0.14
Barley	19.5	15.7	3.8	81	19	0.15
Raw white beans	17.7	13.4	4.3	76	24	0.17
Wheat grain	12.6	10.2	2.3	81	18	0.24
Corn	11.9	10.5	1.4	88	12	0.25
Raw lentils	11.4	10.3	1.1	90	10	0.26
Almond	11.2	10.1	1.1	90	10	0.27
Oats	10.3	6.5	3.8	63	37	0.29
Raw coconut	9.0	8.5	0.5	94	6	0.33
Dry roasted peanut	8.0	7.5	0.5	94	6	0.38
Beetroot	7.8	5.4	2.4	69	31	0.38
Sesame seed	7.8	5.9	1.9	76	24	0.38
Frozen green peas	3.5	3.2	0.3	91	9	0.86
Kiwi	3.4	2.6	0.8	76	24	0.88
Pear	3.0	2.0	1.0	67	33	1.00
Raw spinach	2.6	2.1	0.5	81	19	1.15
Raw carrot	2.5	2.3	0.2	92	8	1.20

Strawberry	2.2	1.3	0.9	59	41	1.36
Unpeeled apple	2.0	1.8	0.2	90	10	1.50
Green beans	1.9	1.4	0.5	74	26	1.58
Peach	1.9	1.0	0.9	53	47	1.58
Raw cauliflower	1.8	1.1	0.7	61	39	1.67
Mango	1.8	1.1	0.7	61	39	1.67
Oranges	1.8	0.7	1.1	39	61	1.67
Bananas	1.7	1.2	0.5	71	29	1.76
Plums	1.6	0.7	0.9	44	56	1.88
Raw celery	1.5	1.0	0.5	67	33	2.00
Rice dry	1.3	1.0	0.3	77	23	2.31
Potato without skin	1.3	1.0	0.3	77	23	2.31
Raw tomato	1.2	0.8	0.4	67	33	2.50
Pineapple	1.2	1.1	0.1	92	8	2.50
Grapes	1.2	0.7	0.5	58	42	2.50
Rice cooked	0.7	0.7	0.0	100	0	4.29
Peeled cucumber	0.6	0.5	0.1	83	17	5.00
Watermelon	0.5	0.3	0.2	60	40	6.00

That makes it an effective remedy in the fight against constipation, and is also a diluent of the diet, which means that, per unit volume, it contains a smaller amount of nutrients available to the body [74,75]. On the other hand, the appropriate level of soluble and insoluble dietary fibre is responsible for slowing down the flow of food and the feeling of satiety.]. That affects intestinal peristalsis and additionally limits the absorption of nutrients, preventing overweight and obesity and reducing the level of cholesterol in the blood serum, especially the LDL fraction [76,77]. Figure 1 presents classification of dietary fibre proposed by EFSA with added kinds of resistant starch from Cione et al. [78,79].

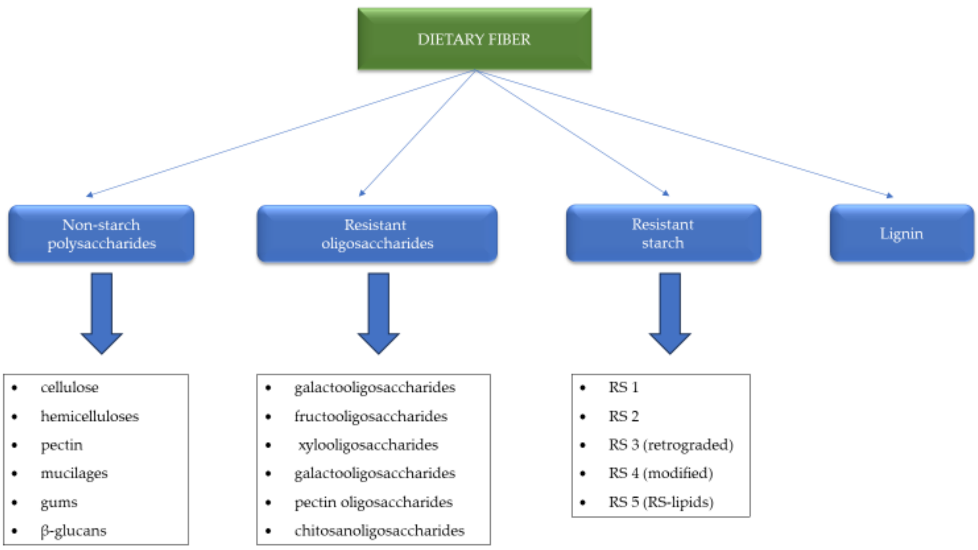

Figure 1. Classification of dietary fibre.

Soluble dietary fibre is characterized by properties that increase the viscosity of the food content, which results in a decrease in the absorption of nutrients from the gastrointestinal tract [80].

Moreover, this type of fibre has hypocholesterolemic properties related to limiting the digestion and absorption of fat and limiting the process of cholesterol synthesis in the liver through the production of propionic acid and other bacterial transformation products by microorganisms and as a result of the increase in the viscosity of the food content and its effect on the level of insulin and other hormones [6].

3.3. SDF and Changes in Microbiome of Hindgut

Additionally microbiome using SDF with a prebiotic effect increases the concentration of SCFA, what resulting in a lower pH and the production of end products in the form of butyrate, which influences the growth of epithelial cells, and soluble fibre is able to influence the thickness of the mucous layer, which makes it a favourable medium for the existence of symbiotic bacteria and facilitates their adhesion to epithelial receptors [81,82].

Synthesis of SCFA by microorganisms affects the stabilization of the microbiome in a given region of the gastrointestinal tract, prevents disruption of the continuity of the epithelial structure and supports the action of GALT [83,84]. A high level of dietary fibre, including soluble fibre in the diet, prevents the development of inflammation bowel disease [85].

Dietary fibre affects the growth of specific groups of microorganisms and serves as a substrate for the production of short-chain fatty acids SCFA, which play an important role in metabolism and immune processes and are included in the definition of postbiotics [50,86]. Dysbiosis in the intestinal microbiome environment may disturb the host's interaction with the microbiome, limit the thickness and quality of the mucous layer and contribute to the development of pathogenic microorganisms, as well as lead to the occurrence of a disease process [87]. Dietary fibre has an impact on maintaining the balance of the microbiome in the gastrointestinal tract of humans and animals and is necessity in rebuilt its status [88,89].

4. Pectin Structure and Their Properties

4.1. Occurrence of Pectin and Its Amount in Various Fruits and By-Products

Water-soluble pectin is an important element of dietary fibre, playing an important role in modulating the immune barrier of the gastrointestinal tract. They are isolated from the cell walls of fruits and vegetables and are found mainly in the peel or shell of: apples, citrus fruits, and potatoes, passion fruit, mango, bergamot, olives and the exception is sugar beets [90–95]. However, the share of pectin in individual plants varies and also depends on the plant parts that are taken into account during the analysis and used for the industrial production of pectin or POS (Figure 2) [96,97].

Orange peel contains 30% pectin, apple peel 15%, and onion peel 12% [14,98]. In turn, raw sugar beets contain approximately 18% pectin, 19% cellulose, 28% hemicelluloses and 8% total protein [99]. Mango peel contains 5-11% of pectin [100]. Of course, taking into account the possible prebiotic effect of pectin or oligosaccharides with typically prebiotic properties are isolated from it. They do not have a viscous effect, do not form gels, but are highly fermentable and affect the profile of fatty acids in the colon [101].

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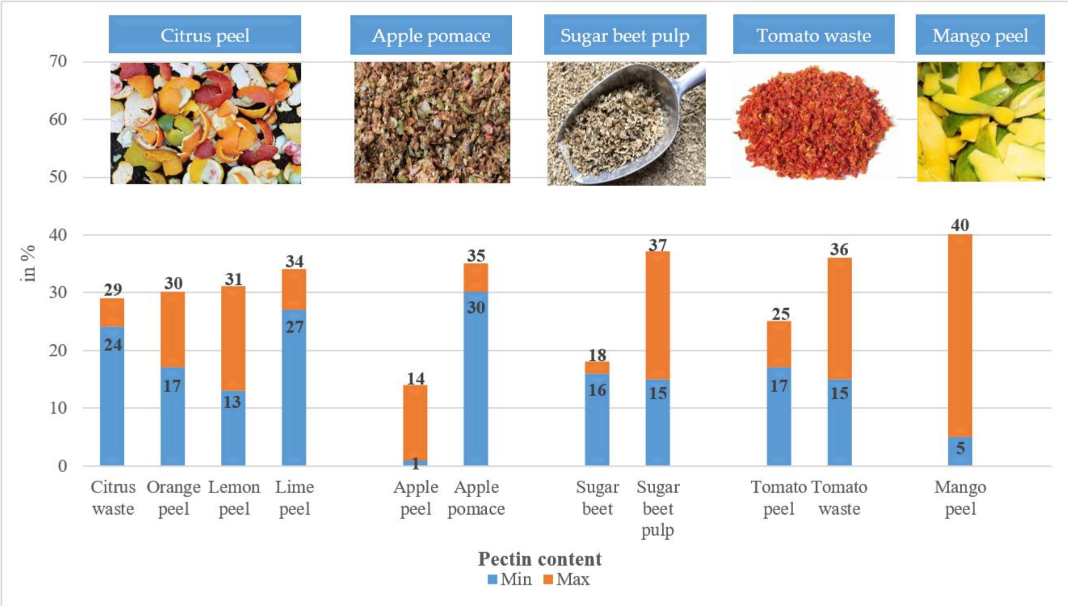

Figure 2. Pectin content from various agro-waste sources.

Citrus peel is a rich source of pectin and is also a sustainable source of raw material for the production of high-quality pectin and its derivatives [102]. The production of citrus products is associated with the formation of a large amount of by-products in the form of peels and seeds (up to 50% of the fruit weight), which can be used to produce pectic oligosaccharides with prebiotic properties [22]. In turn, during the production of mango products, peel and seeds constitute 35-60% pectin, which can also be used to produce pectic oligosaccharides, especially due to the fact that peel has antioxidant properties and low fat and protein content [103]. Wande et al. [104] after their analysis also confirm the presence of several types of POS in different concentrations in pomelo peel. Gamonpilas et al. [105] after analysing the solubility of dietary fibre found: 86 g TDF/100 g DM, 20 g SDF/100 g DM and 66 g IDF/100 g DM. Valuable source of pectin are also by-products from avocado (*Persea americana)*, from which in biorefineries this product is obtained with efficiency from 75 to 85% [106].

4.2. Pectin in Cell Wall

Pectin is a component of the cell wall and are located between cellulose and hemicellulose microfibrils which support the functioning of the cell wall by combating external stresses, give it elasticity together with hemicelluloses, which allows it to withstand turgor pressure and maintain the cell shape [107,108]. They act as cementing substances in the cell wall, and thanks to their gelling properties, pectin can reduce the rate of gastric emptying and influence the rate of content flow in the small intestine [67]. Like gums and mucilages, pectin are substances that are soluble in water and are easily fermentable in the large intestine [68]. Pectin has the ability to bind metals in the digestive tract, limiting their absorption from light, thus removing heavy metals from the body in urine, reducing the absorption of lead into the blood and lowering the level of strontium in bones and blood, which may be of great importance in people living in industrial or post-industrial areas [109,110].

4.3. Structure of Pectin

Pectin are polymers composed mainly of homogalacturonan, rhamnogalacturonan I, rhamnogalacturonan II and xylogalacturonan [111]. These compounds belong to heteropolysaccharides consisting primarily of galacturonic acid (GaIA) residues connected by α-1,4 bonds [112]. Pectin molecules consist of approximately 70% of glucuronic acid residues which is a part of hairy and smooth regions in molecule (Figure 3). The remaining part are branched elements:

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xylogalacturonan, apiogalacturonan, rhamnogalacturonan I. Those branched structures additionally consisting of galactose, arabinose, rhamnose molecules, and rhamnogalacturonan II. Molecules in the side chains are composed of: rhamnose, apiose, galacturonic acid, glucuronic acid, fructose, 3-deoxy-D-*lyxo*-2-heptulosaric acid (Dha), 3-deoxy-D-*manno*-2-octulosonic acid (Kdo), acetyl and methyl esters. Due to the degree of branching, pectin with low and high dry matter content are distinguished.

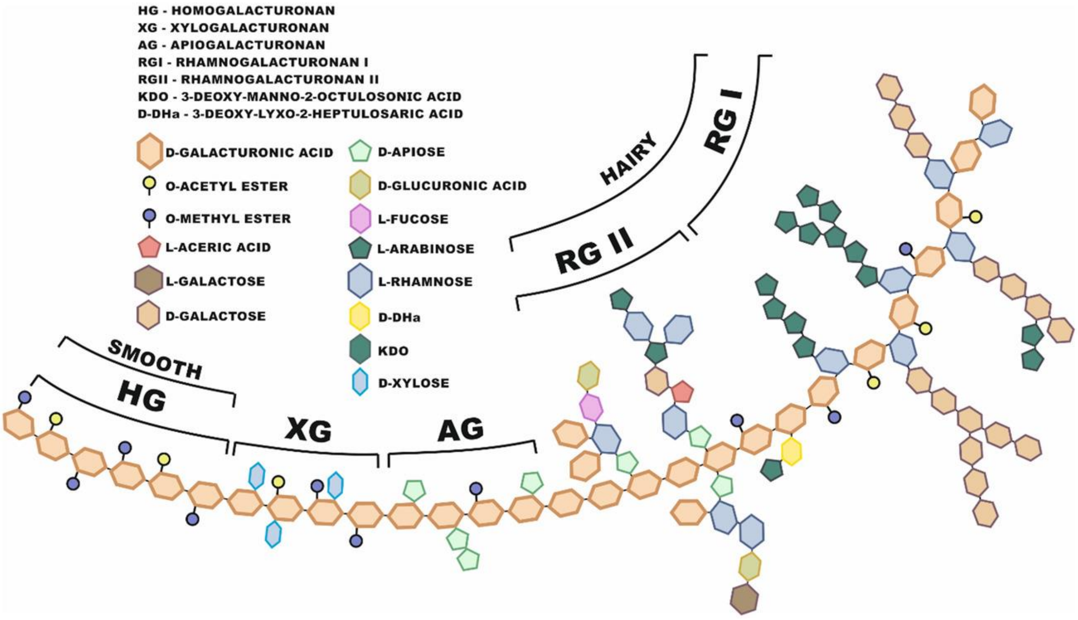

Figure 3. Structure of pectin with characterization of smooth and hairy region [113].

Pectin is broken down by the action of bacterial pectinase, which is a mixture of endo and exoenzymes:

- polygalactouronases and polymethylgalactouronases hydrolyzing α-1,4-glycosidic bonds of pectin molecules,
- polygalactouronate lyases and polymethylgalactouronase Lyases break down α-1,4-glycosidic bonds by a trans-elimination mechanism
- pectinoesterases hydrolyzing methyl-ester groups of pectin, resulting in the formation of polygalacturonic acid and methanol [114,115]

Homogalacturonan is digested with the participation of polygalactouronase , pectin methyl esterase, pectin lyase and pectin acetyl esterase. RG I is degrade by RG lyase, hydrolase and RG acetylesterase. Pectin galactan by β-1,4-galactanase, β-1,6-galactanase and α- arabinosidase. Arabinogalactan is degrade by the action of β-1,3-galactanase, β-1,6-galactanase, α-(1,5) arabinanase and α- L - arabinofuranosidase. Arabinate in the case of α-(1,5) arabinanase and α- L - arabinofuranosidase activity towards to RG II is not precisely defined in terms of families of enzymes that degrade its structures [116].

Pectin consists of linear α-1,4-linked D-galacturonic acid (homogalacturonan) segments and branched rhamnogalacturonan segments [117]. Homogalacturonan pectin are most often isolated from: sunflowers, citrus fruits, apples and rice endosperm cell walls. Homogalacturonan chains in sugar beet pectin are shorter compared to those found in citrus fruits and apples, but beet pulp has a higher share of type I rhamnogalacturonan than apple pomace and citrus peels [118]. The desirable properties of citrus pectin are related to the high degree of branching of their structure, heterogeneous distribution of the galacturonic acid residue and the presence of neutral sugars and acetyl groups in the side chains [102]. Studies in humans and animals have shown that pectin protects intestinal epithelial barrier indirectly by the modulation of microbiome and its activity, and directly blocking

Tool-like receptor 2-1 by which preventing doxorubicin-induced ileitis [119,120]. Additionally products of it degradation, especially butyrate can protect and repair intestinal barrier function controlling mechanism synthesis of junctional proteins and molecular cascade of their secretion [36,121].

Pectin is one of the most important hydrocolloids, primarily in the food industry, but it is also used in other sectors of the economy, including pharmaceutical applications for the production of medicines and hydrocolloid dressings [122]. From the point of view of industry and raw materials for further processing, the methoxyl content in such components is important. Citrus and apple pectin contain over 50% of this compound, while sunflower pectin has a low content of this ingredient [123]. Most natural pectin contains pectin with a high methoxyl content with a level of esterification (HM, above 50%), while processed pectin are dominated by pectin with a low methoxyl content (LM, below 50%) due to the fact that it is easier to obtain homogalacturonan in the technological process , as the unbranched part pectin molecules [124,125]. HMs are used as gelling substances in jams, marmalades and jellies, while LMs mainly act as stabilizers in acidified silent drinks, sour dairy products and mixtures of fruit juice and milk [126].

There is also a division according to the degree of branching of pectin into "smooth" and "hairy", corresponding to unbranched and branched forms, respectively [127]. Commercially produced pectin is rich in smooth pectin and is widely used in the food and pharmaceutical industries due to its excellent hydrocolloid properties [128]. It is produced mainly from citrus peels, beet pulp and apple pomace [127]. However, recent studies indicate that the branched form has a beneficial effect on the human microbiome by increasing the number of *Bifidobacterium* spp., *Lactobacillus* spp., *Faecalibacterium* spp. and inhibiting the adhesion of pathogenic bacteria and toxins [129]. This type of form is difficult to obtain in the technological process, but it has greater prebiotic potential compared to pectin [93,130].

5. Prebiotics

5.1. Oligosaccharides

Oligomers are obtained on an industrial scale from dietary fibre and have great potential for use in various industries. The high bioactivity of this type of compounds creates the possibility of their use in the production of foodstuffs and medicines, cosmetology, prebiotics and symbiotics , antioxidants, they can also be used as a source of anticarcinogenic ingredients [99,131]. Enzymatic hydrolysis of pectin using pectin lyase results in obtaining POS with various structures and degrees of polymerization [132,133]. However, in the case of beet pulp, better results by 20% in terms of the amount of POS obtained are obtained in the case of hydrothermal processing [31].

The most commonly used to modulate the body's immunity and microbiome are: FOS, GOS, XOS [134]. In recent years, attention has also been paid to other water-soluble oligosaccharides with probiotic properties: GalOS, COS and the previously mentioned POS [135]. POS is an addition to dietary fibre in the form of functional fibre. It is extracted in an industrial process towards selected beneficial chemical compounds contained in pectin, which affect the health of the organism [136]. The functional fibre includes: vicus fibre - lowering glucose and cholesterol levels and fermentable fibre - affecting colon health and insoluble fibre stimulating peristalsis and reducing the number of constipations [137]. Research by Kang et al. [138] confirms the beneficial effect of pectic oligosaccharides on reducing the level of triglycerides in blood serum and total cholesterol and LDL fraction in the blood.

5.2. Pectin Oligosaccharides

Pectin oligosaccharides, like pectin, have a prebiotic effect in the digestive tract of humans and animals against lactic acid bacteria: *Lactobacillus* sp., *Bifidobacterium* sp. [139]. On an industrial scale, they are obtained as a by-product from agri-food waste contained in fruit and vegetable peels: orange peel, onion peel, beet pulp, *Actinidia alifolia* and fresh artichokes [92,140] . Oligosaccharides obtained from pectin may have similar or additional applications, but they are characterized by a higher degree

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of fermentation compared to pectin (lower viscosity), hence they may have a greater selective effect on the profile of fatty acids produced in the hindgut [141]. POS also has antioxidant and anti-carcinogenic properties against several types of cancer, causing apoptosis of cancer cells, preventing colon ulcers and inflammation [142]. In addition, like other oligosaccharides not digested in the host organism, they stimulate the growth of beneficial bacteria in the colon and, on the principle of competitive exclusion [143]. Therefore limit the number of pathogens in the mucus layer, preventing their nesting on epithelial receptors and thus preventing the occurrence of inflammation of the large intestine [118].

Pectin oligosaccharides are obtained on an industrial scale as a result of: enzymatic hydrolysis of pectin, acid hydrolysis, hydrothermal treatment and physical decomposition. However, purification of raw POS mixtures occurs through membrane filtration [131]. Oligosaccharides obtained from pectin may include products such as: oligogalactouronides (OGalA), galactooligosaccharides (GalOS), arabinooligosaccharides (AraOS), rhamnogalacturonooligosaccharides (RhaGalAOS) and arabiongalactooligosaccharides (AraGalOS), which may be additionally replaced with a methyl or acetyl group or an esterified ferulic acid [130].

Scholz-Ahrens et al. [144] is available raising the issue of the impact of probiotics, prebiotics and synbiotics on calcium absorption, the mineral composition of bones and their structure, we may assume that the use of oligosaccharides has a beneficial effect on increasing the level of calcium in the body. This effect was confirmed by Chawla and Patil [6] in their review article, pointing to numerous studies using inulin, oligofructose and FOS, in which increased absorption of Ca, Mg and Zn from the gastrointestinal tract was found in the participants.

In addition, POS has a positive effect on lipid metabolism in white adipose tissue in studies on mice fed a high-fat diet. Fan et al. [145] in their experiment using POS derived from hawthorn found a reduction in inflammation of adipose tissue when animals were on a high-fat diet. Moreover, POS had a positive effect on the metabolism in adipose tissue by blocking the formation of triglycerides and fatty acids and facilitating fatty acid oxidation and triglyceride catabolism. In turn, Li et al. [146] in their experiment with POS contained in hawthorn fruits found their very strong antibacterial activity in vitro. POS also have antioxidant and anti-carcinogenic properties against several types of cancer, causing apoptosis of cancer cells, preventing ulcers and inflammation in the colon [131].

Oligosaccharides obtained from pectin are also the subject of the research from the point of view of formulas of milk replacers for infants [147,148]. POS extracted from pectin are acidic, while oligosaccharides found in human milk consist of 75-85% of neutral oligosaccharides and 15-25% of them acidic. However, as research by Fanaro et al. [149] use 0.2g/dL acidic oligosaccharides gave similar results to the standard preparation based on milk proteins (in a 60/40 ratio for whey and casein, respectively), and they also found no difference between the total number of bifidobacteria in feces. However, much better results were achieved by combining pectic oligosaccharides in the amount of 0.2 g/dL with the GOS/FOS mixture in the amount of 0.6 g/dL. Newborns showed greater weight gain, although not statistically significant ($p>0.05$), whereas a significantly higher number of Bifidobacterium was found in their stools.

Additionally, pectin and POS block the formation of advanced glycation end products (AGE's), which is associated with the occurrence of diabetic complications, the aging process and atherosclerosis [150,151]. Additionally, research by Zhu et al. [147] showed that the content of AGE's in milk replacers in infant formulas based on cow's milk designed to meet the nutritional requirements of infants was up to a thousand times higher than in raw human or cow's milk. For these types of infant formulas, the use of POS at 1.5 mg/ml yielded comparable results compared to the same amount of aminoguanidine. These results were significantly higher compared to the participation of these two ingredients in the amount of 1 and 0.5 mg/ml and the blank sample containing no active substances in relation to AGE's .

6. Pectin and POS - Prebiotic Effect on Intestinal Microbiome

6.1. Prebiotics

The definition of prebiotics used today developed over an 8-year period (from 1995 to 2004) and initially described them as: non-enzymatically digestible dietary components that beneficially affect the host by selectively stimulating the growth and activity of one or a specific number of bacterial strains in the colon that improve the health of the host. Subsequently, it was slightly modified and prebiotics were defined as: selectively fermented ingredients that allow specific changes in both the composition and activity of the gastrointestinal microflora that benefit the host organism [152,153]. From this time definition was subject of gradual modifications and her the most current sound left, proposed by Bindels et al. [154] defines prebiotics as: "A nondigestible compound that, through its metabolism by microorganisms in the gut, modulates the composition and/or activity of the gut microbiota, thus conferring a beneficial physiologic effect on the host."

Pectin and POS directly influence the intestinal microbiome, similarly to other prebiotics. Comparison between effect on microbiota and SCFA production from pectin source and POS obtain from the same source is presented in a Table 3. Four main types of bacteria dominate the human intestinal microbiome are: *Firmicutes*, *Bacteroidetes*, *Actinobacteria*, *Proteobacteria*. In western populations, the ratio of *Bacteroidetes* to *Firmicutes* is 1:1 [155].

Table 3. Effect of pectin and pectin oligosaccharides from similar sources on specific microorganisms growth and SCFA production.

Research					
with pectin	**Microbiota**	**SCFA**	**with POS**	**Microbiota**	**SCFA**
Apple pectin [156]	↑Bacteroidetes ↑Firmicutes ↑*Eubacterium eligens*	*Acetate *Propionate *Butyrate	Apple POS [157]	↑Bifidobacteria ↑Lactobacilli ↓Bacteroides ↓Clostridia	↑Acetate ↑Propionate
Citrus pectin [111,150–160]	↑Bifidobacteria ↑Bacteroides ↑*Eubacterium rectale* ↑Lachnospira ↑Dorea ↑Clostridium ↑Sutterella	↑Acetate ↑Propionate *Bytyrate	Orange POS [161]	↑Bifidobacteria ↑Lactobacilli	*Acetate *Propionate *Butyrate
Sugar beet Pectin [162]	↑Prevotella ↑Bacteroides		Sugar beet POS [163]	↑Bacteroidetes	↑Acetate

	↑Bacteroidales ↑Clostridium ↓Lachnospiraceae ↓Ruminococcus	↑Acetate			↑Propionate ↑Butyrate ↓Valerate
Apple and Citrus pectin [164]	no available data	↑Acetate ↑Propionate ↑Butyrate	Apple POS and Citrus POS	no available data	no available data
Apple and sugar beet pectin [165]	↑Bifidobacteria	↑Butyrate ↑Acetate	Apple POS and sugar beet POS	no available data	no available data
Citrus and sugar beet pectin [81]	↑Bacteroidetes ↑Enterobacteriaceae	↑Propionate	Citrus POS and sugar beet POS	no available data	no available data

with pectin and POS	Microbiota	SCFA
Citrus pectin, sugar beet pectin and POS from lemon peel [Gomez 2016 JFF]	↑Bifidobacteria ↑Lactobacilli ↑Faecalibacterium ↑Roseburia	↑Acetate ↑Propionate ↑Butyrate

↑Increase number of bacteria or individual SCFA level. ↓ Decrease number of bacteria or individual SCFA level. *Change of individual SCFA level.

Obesity and irritable bowel syndrome are associated with an increase in *Firmicutes* and a decrease in *Bacteroidetes* in the gut microbiome [162,166] Wang et al. [167] highlight three important functions in the modulation of the microbiome through the use of pectin and their derivatives: prebiotic effect by selectively increasing *Bifidobacterium* and *Lactobacillus* strains in the colonic microbiome, modifying the ratio of the number of *Bacteroidetes* and *Firmicutes* , and reducing the potential of *Proteobacteria* associated with mucosa, especially the enteric pathogens present in this group of microorganisms.

6.2. Pectin and Its Effect on Microbiome

Pectin in the gastrointestinal tract is responsible for limiting the absorption of glucose from the intestinal lumen, causing hypercholesterolemia and prolonging the gastric emptying time [168]. Additionally, oligosaccharides obtained from pectin are a prospective addition to the diet as new generation prebiotics, characterized by high efficiency and relatively low production costs [90]. By many years there was a conviction that pectin does not have a direct antibacterial effect, it is only a source of substrates for bacteria, which degrade it into oligosaccharides, activating the antibacterial properties of these compounds [169]. However, this is not entirely true because the research by Ishisono et al. [85] and Sahasrabudhe [120] showed that pectin also have a direct effect on antibacterial activity within the intestines by blocking Tool-like signalling receptors in Peyer's patches. Hence, the antibacterial effect is visible on two levels.

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The diversity of microorganisms in the intestines plays an important role in the development of inflammatory disease processes, similarly, the occurrence of allergies is related to the disruption of the intestinal colonization process by microorganisms or to the limitation of the diversity of the microbiome in this part of the digestive tract [170]. Additionally, Chung et al. [156], comparing the effect of inulin and pectin on the diversity of the microbiome, found a significantly higher Shanon value diversity index in the case of the microbiome whose substrate was pectin ($p = 0.001$). Inulin increased the replication of the selected type of bacteria, which is a reason to use functional fibre in the form of both types of probiotics.

Pectin, depending on its structure and the number of branched chains, affects different profiles of fatty acids: acetate, propionate and butyrate. Additionally, the high content of dry matter in pectin was positively correlated with the level of propionate produced by microorganisms. Gram-negative *Bacteroidetes*, which are part of the native flora of the intestinal microbiome , are mainly responsible for the degradation of pectin [171]. Another interesting species of bacteria that participate in the pectin decomposition process is *Eubacterium eligens*, belonging to *Firmicutes*. This bacterium has the ability to reduce the occurrence of inflammation within the intestinal mucus and epithelium by stimulating the production of IL-10 in the intestinal epithelial layer, which affects the stabilization of the microbiome in the colon, but also has a positive impact on the health of patients [172]. Pectin contained in beet pulp contain mainly arabino -oligosaccharides with polymer numbers ranging from 2 to 6. Holck et al. [173] indicate that arabino-oligosaccharides with a polymer number of up to 8 influence the selective stimulation of Bifidobacteria in relation to Clostridia, Lactobacilli and Bacteroides in the case of in vitro fermentation. However, a precise determination of the effect of pectin on the microbiome, and in particular on the entire mechanism of maintaining the balance of the microbiome and developing immunity, requires more research, meta-analyses and systematic reviews.

6.3. Pectin Oligosaccharides - Effect on Microbiome

The increase in the microbiome population is associated with the production of SCFAs in the hindgut, and in addition, the presence of dietary fibre not digested by the host affects its blood lipid profile [174]. Additionally, Wilkowska et al. [32] conducted studies on two age groups of healthy volunteers who used the addition of functional fibre to Western diets in the form of POS obtained from apple fibre. Researchers found that as in the case of the microbiome and animal model studies, also in humans POS work more effectively in the case of younger people leading to a more favourable SCFA profile. However, research of Gu et al. [175] emphasize that influence of different types of pectin on the gut microbiome composition and SCFA profiles of elderly is compared to younger adults. This fact is emphasized by Williams et al. [47], who points out that the criterion for selecting dietary fibre in the diet should be not only its solubility, but also the ability to ferment and thus influence the obtained SCFA profile, what consequently affects the maintenance of the homeostasis of the intestinal microbiome and positively interacts with an increase in immunological resistance in humans and animals. In vitro studies Yang et al. [176] show that pectin are fermented in about 60%, β- glucan , resistant starch in about 50%, inulin in 40%, and guar gum and arabinoxylans in 30%. Of course, obtaining dietary fibre in the form of oligosaccharides from these types significantly increases the efficiency of fermentation in the intestines.

POS influences the composition and diversity of intestinal microbiome [177]. The main bacteria responsible for the degradation of this type of oligosaccharides are *Bacteroides* and *Prevotella*, the latter type of bacteria showing an affinity for pectin with a higher methoxyl content, and the profile of SCFA resulting from microbiological transformations contains more propionic acid [139]. Pectin seems to be a better substrate for *Bacteroides* present in the large intestine than inulin, and 70% of bacteria from this genus use HG and galactan for growth, the breakdown of dietary fibre occurs thanks to enzymes such as: lyases, methylesterases and acetylases [178]. Products resulting from the action of these bacteria increase their number and that of Lactobacilli [179]. Although, on the other hand in studies on: rats, mice and piglets, a reduction in the number of *Lactobacillus* sp. and *Bacteroides* spp. was observed [142,180]. Some studies also show a positive correlation between *Bacteroidetes* and

Firmicutes ratios, and the amount of SCFAs [181,182] However, Hu et al. [183] indicate a correlation between the number of Bifidobacterium , Bacteroidetes and Lactobacillus and the level of SCFA, total cholesterol and LDL fraction.

In terms of the overall SCFA profile for pectin, many microorganisms are responsible for the production of acetic acid, but especially those of the Bifidobacteria and Lactobacilli genera. Propionic acid is mainly produced by Bacteroidetes and Firmicutes, while butyric acid is synthesized by *Eubacterium rectale*, *Roseburia intestinalis*, *Faecalibacterium prausnitzii* [184,185]. Butyric acid plays a very important role in the colon related to the nutrition of intestinal epithelial cells, as well as in the prevention and treatment of colon diseases [54,186]. The prebiotic potential of POS has been confirmed in experiments in which they selectively increased the number of beneficial bacteria in the human gastrointestinal tract, such as *Bifidobacteria* or *Eubacterium rectale* [141,159]. However, the effect of POS and their probiotic potential depends on the type of plants from which they are obtained and the production process. They can be obtained as a result of physical, chemical and enzymatic processes, which affects their degree of polymerization and thus their properties [15]. Therefore, in the case of large-scale use of POS, it is necessary to standardize the obtained product or obtain a uniform product from POS with different atomic weight on the basis of masterbatches. Of course, in the case of prebiotic properties and the impact on the stabilization of gut mucus layer, intestinal epithelium and immunity, branched forms with a significant share of rhamnogalacturonans I and II, due to high solubility in water and easier access of microorganisms to the structure of the POS molecule.

6.4. Antibacterial and Immunomodulatory Effect of POS

The antibacterial effect of POS was first confirmed by Takenaka et al. [187] using pectin hydrolyzate contained in lemons due to the action of galacturonan oligomers. Foti et al. [188] also demonstrated the antibacterial effect and modulatory effect of POS obtained from citrus pectin on the intestinal microbiome. Wang et al. [58] in their studies demonstrated strong antibacterial activity of POS contained in citrus peels and apple pomace against gram-bacteria. In turn, Gullón et al. [118] showed a very high ability of pectin and POS in modulating the microbiome (especially *Faecalibacterium prausnitzii* bacteria and *Roseburia intestinalis*) compared to other FOS or GOS oligosaccharides. Which is especially important in the case of *Faecalibacterium prausnitzii* , because as one of the main bacteria from the entire group of microorganisms it is responsible for the health of the organism within the biofilm colonic microbiome [129]. The remaining bacteria include: *Bacteroides* spp., *Coprococcus*, *Dorea*, *Ruminococcus*, *Blautia*, *Oscillospira*, *Sutterella*, *Bifidobacterium*, *Christensenellaceae*.

An important element in the stabilization of the microbiome, as well as the acquisition of immunity, is the combination of the effects of POS, FOS and GOS. Hence this type of research has been carried out in infants and the studies have shown that the combination of ScGOS, lc FOS and pectin results in a higher number in their microbiome: *Bifidobacterium* sp. and Lactobacilli compared to groups of newborns who received only pectin in the formula or the control group [148,149]. What is important in this case is the number of Lactobacilli and Bifidobacteria, the reduced level of which in the digestive tract of children under 5 years of age resulted in a greater risk of allergies [189]. Stabilization of the microbiome by prebiotics (including pectins and POS) also affects the amount and type of metabolites produced by microorganisms, including SCFA: which is a source of energy for colonocytes, regulators of gene expression, cell differentiation and inflammatory agent [183,190]. This allows for the creation of a cross-feeding network, thanks to which, using metagenomics and metabolomics methods combined with machine learning methods (GutCP) or deep learning, it is possible to modulate the composition of the diet, and thus influence changes in the microbiome and control the health status of a given person. people based on methods of inferring and predicting cross-feeding interactions in the human gut microbiome [57,191]. Similar studies on intestinal microflora and its metabolites collected in the form of a global metabolic interaction network were performed by [190]. Like the others, it allows predicting changes in the composition of the intestinal microbiome, and thus the concentrations of metabolites produced by microorganisms, which allows, based on changes in groups of metabolites, to predict changes that may lead to the occurrence of a disease in order to avoid it.

7. Interaction of Pectin and POS with GALT

7.1. Dietary Fibre and Its Effect on GALT

Dietary fibre is broken down mainly in the human large intestine and its decomposition products are obtained there [192]. However, in the small intestine, it has the ability to directly interact with the cells of the immune barrier in the small intestine, due to the interaction between intestinal epithelial cells and immune cells (Figure 4).

The consequence of these interactions is the strengthening of the mucous layer, the barrier function of epithelial cells and the modulation of the intestinal immune response [193,194]. The direct interaction between dietary fibre and the intestinal immune system may improve health and reduce the occurrence of diseases [195].

Dietary fibre is correlated with reducing the occurrence of diseases, immune disorders and mortality, a special role in this case is played by maintaining the immune barrier of the gastrointestinal tract by stabilizing the microbiome and their metabolites, especially in case use inulin in relation with type 2 inflammation [196]. Additionally, research indicates the immuno-modulatory function of short-chain galactooligosaccharides (scGOS) and long-chain fructooligosaccharides (lcFOS) also supporting the function of human milk oligosaccharides (HMOS) [197]. Additionally, Bernard et al. [198] when used in the diet of mice (pAOS) found stimulation of immune polymerization of Th1 lymphocytes as a result of increasing the release of interferon γ, upregulating the expression of the t-bet gene, decreasing the secretion of interleukin 4 and downregulating the expression of the GATA3 gene.

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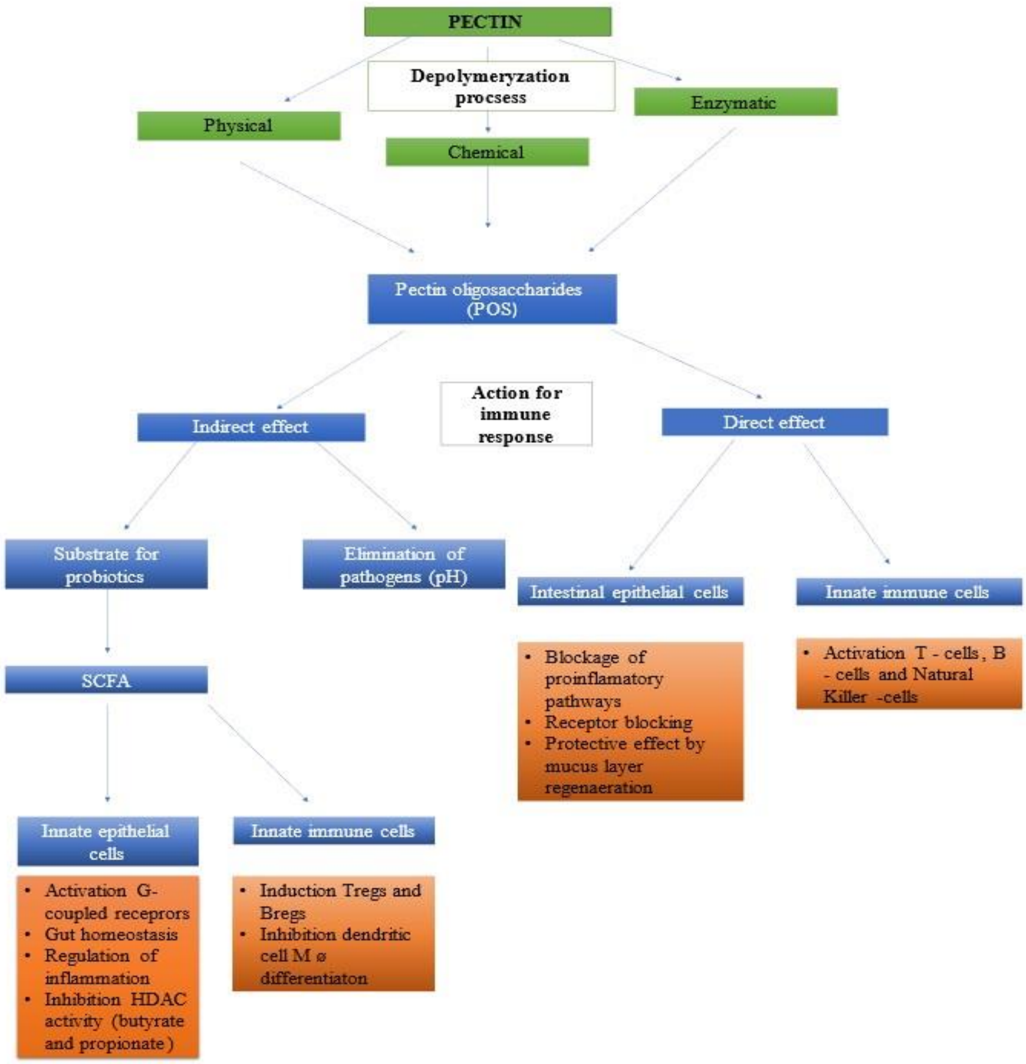

Figure 4. Pectin oligosaccharides production and its effect for guts and GALT.

7.2. Pectin Effect on GALT

Pectin have a large impact on the health of the body by modulating the intestinal immune barrier [199]. The mucosal layer is a protective barrier separating the intestinal epithelium from the microbiome and digestive content [200]. Metabolic products synthetized by microorganisms change the composition and properties of the mucous layer [201]. In the colon mucus is divided on two layers: inner free from bacteria and outer composed from mucus, gut bacteria and dietary material [202].

Citrus pectin exhibit immunomodulatory properties in two ways: neutral RG-1 or RG-2 side chains inhibit the activation of lipopolysaccharide (LPS) induced by pattern recognition receptors tool like receptors 4 (TLR-4), while homogalactouronate (HG) has an immunostimulatory effect through the TLR-4 pathway and the MyD88 protein [183]. Additionally, modified citrus pectin has strong anticancer properties [203].

The immunomodulatory effect of pectin depends mainly on the content of galacturonic acid and methoxyl residues, the percentage of which is most abundant in the parts of pectin composed of RG-I and RG-II that are intact during the POS extraction process [110]. The effect of increasing the thickness of the mucous layer is visible after the use of pectin in the diet by stimulating mucin secretion in the small intestine [204]. Regulation mucus secretion and homeostasis occurs with the

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participation of Forkhead box protein O1 (Foxo1) [205]. These compounds are produced in goblet cells in response to microorganisms in the intestinal lumen and dietary ingredients as a result of activation of pattern recognition receptors (PRRs), simulation of SCFA production and as a result of cytokine secretion from immune cells [206].

7.3. POS Effect on GALT

Oligosaccharides FOS, POS and GOS are broken down by the intestinal microbiome into SCFAs, the concentration of which affects the functions of leukocytes and the differentiation of T lymphocytes and their functions, allowing SCFAs to be classified as postbiotics [139,207]. POS, like other oligosaccharides, is responsible for reducing the response dependent on Th2 lymphocytes in the course of allergic diseases, limiting the excessive response of the immune system to allergens [208]. The use of POS also affects the regulation of Treg /TH17 levels [167]. Additionally, the results of studies conducted in children and infants indicate a reduction in the frequency of viral and bacterial infections requiring antibiotic treatment [203]. Therefore, in recent years, the administration of prebiotics in the form of oligosaccharides has become a new strategy for preventing acute or chronic infectious diseases , and thus reducing the phenomenon of antibiotic resistance in bacteria. However, Montilla et al. [209] point out that when using pectin and POS, the level of pro-inflammatory biomarkers is reduced and the body's immunity increases. Xie et al [210] noted lack differences in thickness of mucus layer when inulin and POS was used. The mucous layer also contains immunoglobulin A, which counteracts the increase in the number of pathogenic microorganisms, important role in this process plays eosinophils [211].

Oligosaccharides plats also important role in decrease of allergic reaction of organism. Jeurink et al. [212] described the impact of the use of oligosaccharides on immune processes and mechanisms responsible for shaping the body's resistance in connection with exposure to allergens. Cohort studies indicate that one of the factors contributing to the occurrence of food allergies is intestinal dysbiosis [213,214].

Fecalibacterium prausnitzii and *Akkermansia muciniphilla* play an important role in maintaining the balance of the colon's microbiome and thus improving its health, belong to bacteria that degrade mucin and pectic oligosaccharides, which constitute substrates for the production of butyric acid, which influences the nutrition of intestinal epithelial cells [195]. The first bacterial species reduces inflammation of the epithelium, while the second one strengthens the barrier function of the mucus Wang et al. [132] in their studies confirm the beneficial effect of POS obtained as a result of enzymatic degradation of pectin in restoring the balance of the microbiome and immunological homeostasis in the intestines, both to prevent uncontrolled changes, as well as after ulcerative colitis. Additionally, POS causes an increase in the number of beneficial microorganisms: *Bifidobacterium* , *Lactobacillus* and *Eubacterium*, which ferment carbohydrates without producing toxins, increasing immunity and acting on the principle of competitive exclusion in relation to pathogens. In the study by Guevara-Arauza et al. [215] found an increase in Lactobacilli in response to mucilage oligosachides from *Opuntia ficus-indica* by 23.8% and Bifidobacteria by 25.0% when POS derived from this plant was used

Pectin and POS have the ability to block the adhesion of pathogens to intestinal epithelial cells [216]. POS reduces the adhesion of pathogenic bacteria: *E. coli*, *Listeria monocytogenes*, *Salmonella typhimurium*, *Campylobacter jejuni*. However, pectin with lower molecular weight is mainly responsible for this type of effect Moreover, pectin and mainly pectin oligosaccharides enhance the action of commensal and probiotic Lactobacilli strains to the intestinal epithelium, but the final effect in these authors' studies depended on the species and conditions of their performance, which were most often in vitro studies [50]. The mucus layer of the intestinal epithelium is favourable medium for symbiotic bacteria, which promotes their multiplication in this place and also facilitates adhesion to the receptor of the intestinal epithelium, Ouwerkerk et al. [217] defined interaction between those three elements as a glycobiome.

8. Conclusions

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The change in eating habits, especially in urbanized societies in the last decade, requires paying more attention to supplying the organism with dietary fibre present in the diet. Insoluble dietary fibre constitute ballast and dietary diluent in both humans and animals GIT, it is also object of partially fermentation. Soluble fibre is divided into fermentable as a source of SCFA) and viscous (limiting the absorption of nutrients). Pectin as an element of SDF contained in agri-food products is an important source of pectin in food industry and pectic oligosaccharides, varied in terms of branching of the side chains of pectin molecules, which affects their properties. Pectin-oligosaccharides have a prebiotic effect in the gastrointestinal tract mainly promoting *Lactobacillus* sp., *Bifidobacterium* sp., *Bacteroidetes*, *Firmicutes* and *Prevotella*. Adhesion of pathogens is blocking by: indirect effect as a component, in regeneration of mucus layer in GIT as a barrier for pathogenic bacteria, and synthesis of SCFA by bacteria present in intestines and also in mucus layer. Direct effect on antibacterial activity within the intestines by blocking Tool-like signaling receptors in Peyer's patches. Additionally in organism POS have a positive effect on lipid metabolism (supporting their catabolism), have antioxidant properties by blocking advanced glycolysis products and anti-cancer properties by activating the apoptosis mechanism of cancer cells. Immunomodulation effect is induced by HG, RG-1 and RG-2 mainly by SCFA production from oligomers and stabilization of mucus layer in guts. This type of oligosaccharides is new aspect in science, that is why more research is necessary to find an easier way to obtain POS and to precisely determine their mechanism of action in humans and animals, as well as in synergy with other types of oligosaccharides.

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