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Review Article

Pectin as a Value-Added Biopolymer from Fruit Processing Waste: Structural Features, Extraction Methods, and Health Applications

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Abstract

Interest in valuing fruit processing by-products as sources of high-value biopolymers has increased due to growing concerns about environmental sustainability and the production of food waste. Because of its structural diversity, wide range of functional applications, and abundance in fruit wastes, pectin has emerged as one of these promising value-added polysaccharides. Higher plants the central lamella and main cell wall are largely composed of pectin, a complex heteropolysaccharide high in galacturonic acid. The fruit juice and canning industries produce large amounts of wastes that are rich in pectin, especially from apple pomace and citrus peels, which provide a cost-effective and environmentally friendly substrate for pectin extraction. An extensive summary of pectin's structural characteristics, compositional domains, and impact on functional properties is given in this review. The yield, efficiency, and environmental impact of several traditional and cutting-edge extraction methods including enzymatic, acidic, microwave-assisted, and ultrasound-assisted methods are examined critically. The review also emphasises the health benefits of pectin, which are primarily mediated through altering gut microbiota and metabolic pathways. These benefits include antihyperglycemic, antihyperlipidemic, anti-obesity, cardioprotective, immunomodulatory, and anticancer properties. Pectin's uses in industry, medicine, and nutraceuticals are also examined, with particular attention paid to its functions as a gelling agent, stabiliser, binder, controlled-release polymer, and prebiotic dietary fibre. Overall, this review highlights pectin's potential as a sustainable biopolymer made from fruit processing waste that can be used to develop functional foods, reduce waste, and improve drug delivery systems.

Keywords: Pectin; Biopolymer; Nano drug delivery; Prebiotic; Sustainable extraction

1. Introduction

Recovering useful compounds from horticultural waste is becoming more and more popular. The realisation that waste products may contain useful bioactive substances including polyphenols, pectin, carotenoids, and flavonoids is what is driving the recent spike in popularity. One-third, or around 1.3 billion tonnes, of the food produced each year for human use is wasted. Fruits and vegetables account for almost 45% of all food waste. Fruit processing produces a large amount of solid waste, particularly when fruit juice and canned fruit are produced[1]. A large portion of the garbage ends up in landfills, even though some of it can be used as animal feed or fertiliser. Waste can be divided into two categories: avoidable and unavoidable. The latter category includes edible fruit slices that are frequently discarded[2]. Untreated garbage adds to the "carbon footprint" and, consequently, climate change by releasing greenhouse gases into the environment. Pectinocellulosic materials are usually found in lignocellulosic wastes, including citrus wastes, this can be utilised as an inexpensive extracted pectin substrate. In the juice industry, citrus fruit peels are thought to be the main source of waste[3]. For example, pectin is abundant in the albedo, the white, porous part of an orange peel. Since fruit wastes are primarily composed of pectinocellulosic components, they can be utilised as a cheap substrate for the extraction of pectin[1,4].

One heteropolysaccharide that confirms a strong propensity to collect and agglomerate is pectin. Higher plants' cell walls include galacturonic acid (GalA), which is abundant in pectin. Pectin, a crucial structural and biocompatible polysaccharide, is mostly found in the main and middle lamellae for plant cell walls[5]. The Greek word pektos which means to solidify or coagulate, is where the word pectin originates. In plants, pectin mostly maintains the tissue's rigidity and structure while fostering turgidity, mechanical resistance, and intercellular adhesion. Pectin has several medical uses and is highly valued as a functional food element. Additionally, pectin enhances the texture of dishes prepared with them[6]. The nanostructural characteristics of pectin are influenced by both the crop source and the specific tissue segment from which it is isolated. Pectin also contributes significantly to the growth and progress of plants by offering mechanical resistance and acting as a barrier against external effects.

2. Pectin composition

In terms of both structure and function, pectin is the most complex polysaccharide present in plant cell walls. Covalent bonds firmly bind pectin molecules to a variety of cell wall polysaccharides, like cellulose and hemicellulose[1]. Pectin, which is believed to be a triad component of the homogalacturonan (HG), rhamnogalacturonan II (RG-II), and RG-I domains (Table 1), contains around 70% D-GalA[7].

Table 1:

No.	Sub-domain	Structural Composition	Key Properties	Approximate Amount (%)	Ref
1	Homogalacturonan (HG)	D-galacturonic acid units joined by α-1,4-glycosidic linkages form a linear polymer.	Considered a smooth region of pectin; carboxyl groups at C6 may be methyl-esterified and acetylated at C6 and C3 depending on plant source.	≈ 65	8,9
2	Rhamnogalacturonan I (RG-I)	Recurrent α-1,4-D-galacturonic acid and α-1,2-L-rhamnose disaccharide units	Side chains include neutral sugars like arabinose and galactose, which create arabinan, galactan, and arabinogalactan. This area is referred to as hairy.	20–25	10
3	Rhamnogalacturonan II (RG-II)	HG backbone containing at least eight α-1,4-linked D-galacturonic acid residues with complex side chains composed of multiple rare sugars.	Unique borate-binding polysaccharide discovered in the main cell wall of plants.	< 10	11,12
4	Xylogalacturonan (XG)	HG backbone substituted with β-1,3-linked xylose residues or additional xylose units.	Predominantly observed in reproductive tissues but also present in other plant tissues.	< 10	13

3. Sources of Pectin

Fruits and vegetables can be used as an industrial source of pectin extraction due to their substantial pectin concentration[14]. From the main cell membrane to the plasma membrane, the concentration of pectin in the cells progressively drops; the middle lamella has the highest concentration. Apples, citrus fruits, and their processing byproducts such as apple pomace and citrus peel are the primary sources of pectin. However, cocoa husk, sunflowers heads, sugar beet root, pumpkins, melon and water pears, and potato pulp also contain pectin.

While sugar beetroot and sunflower head residues have pectin concentrations of 10-15% on a dry weight basis, apple pomace and citrus peel have pectin contents of approximately 10-15% and 20-30% on a dry matter basis correspondingly. Non-traditional sources, such as fruits and vegetables like carrots, oranges, cherries, and apricots, have pectin concentrations of 1.4%, 0.4%, 0.5–3.5%, and 1% on a fresh weight basis. Pectin extraction finds appeal in industrial waste by-products as sugar beetroot pulp, amaranth, olive pomace, and mango waste [15–27]. It has been claimed that sugar beetroot can produce up to 23% pectin, depending on the extraction circumstances.

Compared to traditional sources like apples and citrus fruits, sugar beetroot pectin has a lower molecular weight, a higher concentration of acetyl and neutral sugars, and a worse gelling ability because of the proteins covalently bonded in the lateral chains. Consequently, sugar beetroot pectin is not frequently utilised as a texturizer despite being affordable, easily accessible, and having a high pectin recovery.

However, its exceptional emulsifying properties make it superior to and advantageous over pectin derived from traditional sources. The remaining residues from sunflower heads after oil extraction contain a high molecular weight, a high concentration of galacturonic acid, and good gelling properties[28–31].

To comprehend the uses for which we can presently only speculate, a thorough characterisation of pectins will be helpful. Table 2 shows the origins of pectin and its extraction procedure.

Table 2: Sources and methods of pectin extraction

Source	Yield of Pectin	Extraction techniques	Ref
Citrange	29% of dried albedos (w/w)	Acidic extraction with electromagnetism heating and 1 M H_2SO_4	32
Lime peel	5.20–23.59%	Acidic extraction utilising a microwave and traditional heating methods with hcl or citric acid	33
Grapefruit peel	23.44–26.74%	An acidic extraction using ultrasound-assisted heating and 0.5 M HCl	34
Sunflower heads	15–25%	Alkaline washing at 16 °C for 25 min (pH 5–7), solvent:solid ratio 28:1	17
Sugar beet	4.37–28.84%	Xylanase and cellulase enzymatic extraction (1-4 hours) with ultrasound assistance	35
Sugar beet pulp (pressed, ensiled, dried)	13–19%	Acid extraction or extraction with commercial cellulase assistance	36
Pumpkin	10.03 and 8.08 g/100 g	Enzyme extraction with α-amylase and cellulase	19
Watermelon rind	13.4%	Acidic extraction applying 1 M HCl	37
Watermelon	14.2–19.35%	Acidic extraction for one hour with 0.1 M nitric acid	20
Pear	68.40–42.00 g EIM/100 g (dry basis); 6.84–4.20 g EIM/100 g (processed material)	Enzymatic extraction using recombinant polygalacturonase	21
Potato pulp	4.08–14.34%	Acidic extraction uses HCl, H_2SO_4, HNO_3, citric acid, or acetic acid	22
Sugar beet pulp	6.3–23.0%	Citric acid–based acidic extraction	28,38
Banana peels	15.89–24.08%	Lactic acid-based acidic extraction	39
Mango peel	13.85%	Acidic extraction with microwave aid at pH 1.5 using 2 M HCl	40
Linseed seed	0.35–0.65%	Alkaline extract & pH 2 treatment with 0.1 M HCl	41
Pomegranate peel	8.5%	Employing 1 M nitric acid in acidic extraction	42
Palmyra palm	102.3–105.8 g kg^{-1}	Acidic extraction via 0.1 mol/L HNO_3	43
Cashew apple bagasse	10.7–25.3% (dry basis)	Acidic extraction in 1 N HNO_3	44
Gold kiwifruit	4.00–5.40% (dry basis)	Enzymatic extraction using Celluclast, Cytolase, Cellulyve, NS33048	45
Pista	10.3–12.0%	sulfuric acid extraction with ultrasound assistance	46
Mangosteen rind	1.16 ± 0.17%	Acidic extraction via H_2SO_4 at pH 2	47
Green artichoke	65.9 ± 2.1 mg/100 mg	Viscozyme® L enzyme-assisted separation	48
Apple pomace	5.7–16.8%	5% (w/v) citric acid during acidic extraction	49
Apple pulp	13.75–17.82 g% (dry basis)	acidic extraction with nitric or citric acid	50
Cocoa shell	2.0–9.0%	Acid extraction with microwave heat and HCl	16
Cocoa husks	3.38–7.62%	The acidic extraction at pH 2.5–4.0 using hydrochloric or citric acid	51

4. The Health Benefits of Pectin

4.1 Anti-diabetic Activity

Pectin may be able to regulate postprandial hyperglycemia and starch digestion by influencing metabolic pathways, physicochemically altering digesta, and inhibiting the activity of certain enzymes. Pectin may restrict the gastrointestinal system's ability to release glucose. The change in postoperative blood glucose levels is a good indicator of the the metabolism of type 2 diabetes, and fasting hyperglycemia is recognised as a reliable indicator of diabetes. Thus, it is essential for both nutrition and health to keep glucose levels within normal ranges. Pectin may have regulatory effects on postprandial blood glucose levels, fasting glucose levels, and the in vivo digesting of starch-rich diets in both humans and animals when consumed as a supplement to the diet or as an ingredient in whole foods [52].

4.2 Anti-Hyperlipidemic Activity

It's interesting to note that rhamnogalacturonan I demonstrated both antihyperglycemic and substantial antihyperlipidemic effects in laboratory animals with hyperlipidemia caused by a high-fat diet. Following 30 days of treatment with rhamnogalacturonan I, the ratio of monounsaturated to saturated fatty acids changed and hepatic fat deposition reduced, suggesting that pectin could restore healthy fatty acid metabolism[53].

4.3 Anti-Obesity Effect

Pectin decreased glucose and insulin reaction more in patients with normal weights than in those who were overweight or obese, according to studies based on body mass index data. Furthermore, compared to participants who were overweight, subjects of normal weight had a higher ratio of bacteria to Firmicutes, according to microbiota sequencing. It is commonly acknowledged that gut flora plays a major role in the development of obesity. The gut microbiota associated with obesity can be altered by pectin-containing rhamnogalacturonan I regions, which also encourage the production of fatty acid butyrate, an essential obesity preventive factor. Citric pectin is the main component when coupled with the prebiotic Bifidobacterium longum BB-46[54,55].

4.4 Preventing Heart Disease

Globally, the major causes of morbidity and mortality are cardiovascular illnesses, including stroke, coronary artery disease, and hypertension. Heart failure (HF) is the final stage of many cardiovascular illnesses. Patients' quality and functionality of life have not improved despite advancements in HF medical care and technology. One of the most crucial aspects of heart disease prevention and treatment is pectin's impact on lipid metabolism, namely on low-density lipoprotein. A potential mechanism has been suggested by observational studies that have identified the impact of Gal-3, a protein that serves multiple that binds carbohydrates, on the extracellular matrix synthesis of cardiac fibroblasts. Researchers have recently looked into how Gal-3 promotes cardiac inflammation and fibrosis by regulating oxidative stress[55].

According to a recent study, Gal-3 regulates cell growth, proliferation, and death through interactions between cells and between cells and the matrix. Its importance increases in people with heart failure (HF), and its part in the development and course of cardiovascular diseases is highlighted. Gal-3 promotes monocyte migration to the artery wall, which exacerbates inflammation and atheroma in atherosclerosis. Gal-3 expression is critical for inflammation, interstitial fibrosis through collagen synthesis, macrophage infiltration, and differentiation to the M1 phenotype. It increases in both infarcted and distant regions of acute myocardial infarction (AMI) from the onset of AMI. Gal-3 may be used as a therapeutic target to treat cardiovascular diseases and manage heart deterioration[56].

4.5 Butirate in Regulating the Myocardial Ischemia Reperfusion Injury (MIRI)

One of the leading causes of death globally is acute myocardial infarction. Cardiomyocyte damage and cardiac ischemia/reperfusion (I/R) injury, a following process including oxidative stress, inflammation, and apoptosis, are caused by the required event of reperfusion. However, there are very few options for preventing and treating myocardial I/R injury. Sodium butyrate enters the circulatory system, travels to the liver, and takes part in the tricarboxylic acid cycle (TCA) after being taken in by the intestinal mucosal cells. Butyrate combines with other metabolites in this cycle to generate energy. Butyrate is involved in cell development and differentiation in addition to providing energy and influencing energy balance.

It travels to the liver and takes part in the TCA cycle, where it combines with other metabolites to produce energy, after being soaked up by the cells of the intestine and accessing the bloodstream. Furthermore, prior research by Hu et al. demonstrated that pretreatment with sodium butyrate dramatically decreased the size of myocardial infarcts, which was in line with lower levels of the tissue damage markers lactate dehydrogenase and creatine kinase. Additionally, it was found that sodium butyrate significantly suppresses the expression of HMGB1, IL-6, and TNF-α produced by MIRI[57-59].

4.6 Antineoplastic Activity

Through tumour growth suppression, anti-metastasis action, gene expression modification, and immune system control, rhamnogalacturonan I and its produced branches have been shown in numerous studies to successfully limit the growth of cancer cells[60,61,62]. These days, a number of methods have been developed to improve the anti-tumor properties of pectin fractions and the rhamnogalacturonan I regions in pectin. Another use for RG-1 pectin was the application of modified citrus pectin, a Gal binder, as a new radiosensitizing agent for ionising radiation. To better understand the possible mechanism of RG-I pectin's anticancer effect, more thorough in vivo research is needed[63,64].

4.7 Gastroprotective Activity

Some altered pectin structures protect the digestive tract and help with stomach issues. Dietary fibers contain a wide range of rhamnogalacturonan I forms, which have been demonstrated to maintain intestinal integrity, enhance the health of the colonic mucus barrier, prevent bacterial invasion, and lessen inflammation. On the other hand, the body becomes more susceptible to infections when the microbiota breaks down the mucous barrier due to a lack of dietary fiber[65].

4.8 Immunoregulating Activity

Strong immunological effects of several rhamnogalacturonan I domains have been found, particularly in relation to lymphocytes, macro and the complement system[66].

5. Industrial, Pharmaceutical, and Nutraceutical Applications

Pectin is a naturally occurring heteropolysaccharide that is widely used in industrial, pharmaceutical, and nutraceutical formulations due to its biodegradability, non-toxicity, and functional flexibility. Because of its unique physicochemical characteristics, which include gelling ability, degree of esterification, molecular weight, and ion interaction, it can be employed as a stabilizer, binder, and controlled-release polymer. The increasing need for sustainable, plant-based excipients has further supported the usage of pectin in food, pharmaceutical, and functional nutrition products. Table 5.1

Table 3: Industrial, Pharmaceutical, and Nutraceutical Applications of Pectin

Application Domain	Function	Example Uses	Mechanism / Benefit	Ref
Food Industry	Gelling agent	Jams, jellies, marmalades	Forms a three-dimensional gel network in the presence of sugar and acid, improving texture and stability.	67,68
Food Industry	Stabilizer / thickener	Fruit drinks, dairy desserts	Enhances viscosity and prevents phase separation, leading to uniform consistency.	69,70
Pharmaceutical Industry	Tablet binder	Conventional and herbal tablets	Improves granule cohesion and tablet strength without compromising drug release.	71,72
Pharmaceutical Industry	Controlled release polymer	Colon-targeted formulations	Resists gastric digestion and undergoes microbial degradation in the colon for site-specific release.	73,74
Nutraceutical Applications	Prebiotic dietary fiber	Gut-health supplements	Short-chain fatty acids are produced by intestinal fermentation by microbes promoting gut health.	75,76
Functional Foods	Health-promoting ingredient	Fortified beverages, nutrition bars	Improves dietary fiber intake and supports metabolic and cardiovascular health.	77,78,79

6. Future perspectives

Because pectin has the GRAS designation in the US and is recommended as a great component by the European Food Safety Authority (EFSA), it is widely utilised as an essential food ingredient and a health-promoting component. The main cause of pectin's functional properties is its varied structure, which comprises neutral sugar side chains that are present in its source, different levels of esterification, and molecular weight. Under the concept of a biorefinery for environmental sustainability, this has raised the need for continued research into novel sources of pectin and the value-adding of fruits and veggies as agro-industrial by-products, where can be used to make customised food ingredients and minimise food waste.

Another important role of pectin is that of an emulsion stabiliser. Pectin is typically used in the cosmetic industry to stabilise creams and lotions or as an anti-aging ingredient for the skin, but it has numerous applications in the pharmaceutical industry, from delivering drugs to the treatment of various conditions and illnesses, such as blood cholesterol reduction, postprandial glycaemic response, or a potential cure of widespread diabetes. A new trend in food preservation is being supported by an increase in research on the encapsulation of bioactive substances. In order to produce more stable emulsions, nanoparticles, small capsules, hydrogels, or liposomes for targeted delivery systems, pectin interacts with various biopolymers such chitosan, animal protein, collagen, whey protein isolates, and others.

In vivo research is still needed to provide experimental proof of pectin's ability to function as a prebiotic, increasing the quantity of healthy gut bacteria and enabling medicinal uses. Pectin is a great biomaterial because it is low toxicity and biodegradable, however more research into tissue engineering and biofilm development is necessary. Another quickly expanding area of study is the potential application of pectin as an ingredient in edible food ink for 3D printing[80].

7. Conclusion

One extremely significant biopolymer that connects industrial, medicinal, and nutritional innovation with environmental sustainability is pectin. Under a circular bioeconomy framework, the quantity of pectin in fruit processing wastes like apple pomace, citrus peels, and other agro-industrial by-products presents a great opportunity for waste valorization. Its physicochemical behavior and functional performance in a variety of applications are determined by its heterogeneous structure, which is made up of discrete domains with differing degrees of esterification and branching. Pectin extraction is becoming more and more feasible on an industrial scale thanks to advancements in extraction methods that have increased recovery yields while lowering energy usage and environmental impact. Pectin has garnered significant attention for its pharmaceutical uses, especially as a natural excipient, controlled-release polymer, and colon-targeted drug carrier, in addition to its well-established function in food systems as a gelling and stabilizing agent. Furthermore, there is mounting evidence of its nutraceutical value, particularly in the areas of metabolic control, cardiovascular protection, and gut health modulation due to its prebiotic qualities and bioactive interactions. Notwithstanding these encouraging characteristics, more investigation is needed to thoroughly characterize structure function interactions, standardize extraction procedures, and confirm health advantages through carefully planned in vivo and clinical investigations. All things considered, pectin made from fruit processing waste has enormous promise as a multipurpose, environmentally friendly biomaterial that promotes sustainable development while tackling present issues in food technology, healthcare, and functional nutrition.

References

1. Freitas CMP, Coimbra JSR, Souza VGL, et al. Structure and applications of pectin in food, biomedical, and pharmaceutical industry: A review. Coatings. 2021;11:922. doi:10.3390/coatings11080922
2. Zdunek A, Pieczywek PM, Cybulska J. The primary, secondary, and structures of higher levels of pectin polysaccharides. Compr Rev Food Sci Food Saf. 2021;20:1101–1117. doi:10.1111/1541-4337.12689
3. Picot-Allain MCN, Ramasawmy B, Emmambux MN. Extraction, characterisation, and application of pectin from tropical and sub-tropical fruits: A review. Food Rev Int. 2022;38:282–312. doi:10.1080/87559129.2020.1733008
4. Dominiak M, Søndergaard KM, Wichmann J, et al. Application of enzymes for efficient extraction, modification, and development of functional properties of lime pectin. Food Hydrocoll. 2014;40:273–282. doi:10.1016/j.foodhyd.2014.03.012
5. Basak S, Annapure US. Trends in “green” and novel methods of pectin modification: A review. Carbohydr Polym. 2022;278:118967. doi:10.1016/j.carbpol.2021.118967
6. Chandel V, Biswas D, Roy S, et al. Current advancements in pectin: Extraction, properties and multifunctional applications. Foods. 2022;11:2683. doi:10.3390/foods11172683
7. Salima B, Seloua D, Djamel F, et al. Structure of pumpkin pectin and its effect on its technological properties. Appl Rheol. 2022;32:34–55. doi:10.1515/arh-2022-0124
8. Gawkowska D, Cybulska J, Zdunek A. Structure-related gelling of pectins and linking with other natural compounds: A review. Polymers. 2018;10:762. doi:10.3390/polym10070762
9. Humerez-Flores JN, Verkempinck SH, De Bie M, et al. Understanding the impact of diverse structural properties of homogalacturonan-rich citrus pectin-derived compounds on their emulsifying and emulsion stabilizing potential. Food Hydrocoll. 2022;125:107343. doi:10.1016/j.foodhyd.2021.107343
10. Mao Y, Lei R, Ryan J, et al. Understanding the influence of processing conditions on the extraction of rhamnogalacturonan-I “hairy” pectin from sugar beet pulp. Food Chem X. 2019;1:100026. doi:10.1016/j.fochx.2019.100026
11. Yapo BM. Pectin rhamnogalacturonan II: On the “small stem with four branches” in the primary cell walls of plants. Int J Carbohydr Chem. 2011;2011:964521. doi:10.1155/2011/964521
12. Begum RA, Fry SC. Arabinogalactan-proteins as boron-acting enzymes, cross-linking the rhamnogalacturonan-II domains of pectin. Plants (Basel). 2023;12:3921. doi:10.3390/plants12233921
13. Jensen JK, Sørensen SO, Harholt J, et al. Identification of a xylogalacturonan xylosyltransferase involved in pectin biosynthesis in Arabidopsis. Plant Cell. 2008;20:1289–1302. doi:10.1105/tpc.107.050906
14. Thakur BR, Singh RK, Handa AK, Rao MA. Chemistry and uses of pectin—A review. Crit Rev Food Sci Nutr. 1997;37:47–73. doi:10.1080/10408399709527767
15. Sandarani M. A review: Different extraction techniques of pectin. J Pharmacogn Nat Prod. 2017;3:143. doi:10.4172/2472-0992.1000143
16. Mollea C, Chiampo F, Conti R. Extraction and characterization of pectins from cocoa husks: A preliminary study. Food Chem. 2008;107:1353–1356. doi:10.1016/j.foodchem.2007.09.006
17. Shi X, Chang K, Schwarz J, Wiesenborn D, Shih M. Optimizing pectin extraction from sunflower heads by alkaline washing. Bioresour Technol. 1996;58:291–297. doi:10.1016/S0960-8524(96)00120-4
18. Funami T, Nakauma M, Ishihara S, Tanaka R, Inoue T, Phillips GO. Structural modifications of sugar beet pectin and the relationship of structure to functionality. Food Hydrocoll. 2011;25:221–229. doi:10.1016/j.foodhyd.2009.11.017
19. Cui SW, Chang YH. Emulsifying and structural properties of pectin enzymatically extracted from pumpkin. LWT Food Sci Technol. 2014;58:396–403. doi:10.1016/j.lwt.2014.03.015
20. Petkowicz CL, Vriesmann LC, Williams PA. Pectins from food waste: Extraction, characterization and properties of watermelon rind pectin. Food Hydrocoll. 2017;65:57–67. doi:10.1016/j.foodhyd.2016.10.040
21. Franchi ML, Marzialetti MB, Pose GN, Cavalitto SF. Evaluation of enzymatic pectin extraction by a recombinant polygalacturonase (PGI) from apples and pears pomace of Argentinean production and characterization of the extracted pectin. J Food Process Technol. 2014;5:352. doi:10.4172/2157-7110.1000352
22. Yang J-S, Mu T-H, Ma M-M. Extraction, structure, and emulsifying properties of pectin from potato pulp. Food Chem. 2018;244:197–205. doi:10.1016/j.foodchem.2017.10.059
23. Gawkowska D, Cybulska J, Zdunek A. Structure-related gelling of pectins and linking with other natural compounds: A review. Polymers (Basel). 2018;10:762. doi:10.3390/polym10070762
24. Lara-Espinoza C, Carvajal-Millán E, Balandrán-Quintana R, López-Franco Y, Rascón-Chu A. Pectin and pectin-based composite materials: Beyond food texture. Molecules. 2018;23:942. doi:10.3390/molecules23040942
25. Ishii T. Feruloyl oligosaccharides from cell walls of suspension-cultured spinach cells and sugar beet pulp. Plant Cell Physiol. 1994;35:701–704. doi:10.1093/oxfordjournals.pcp.a078658
26. Bunzel M, Ralph J, Lu F, Hatfield RD, Steinhart H. Lignins and ferulate–coniferyl alcohol cross-coupling products in cereal

grains. J Agric Food Chem. 2004;52:6496–6502. doi:10.1021/jf048690z

27. Yoo SH, Lee BH, Lee H, et al. Structural characteristics of pumpkin pectin extracted by microwave heating. J Food Sci. 2012;77:C1169–C1173. doi:10.1111/j.1750-3841.2012.02953.x

28. Li D-Q, Du G-M, Jing W-W, Li J-F, Yan J-Y, Liu Z-Y. Combined effects of independent variables on yield and protein content of pectin extracted from sugar beet pulp by citric acid. Carbohydr Polym. 2015;129:108–114. doi:10.1016/j.carbpol.2015.04.051

29. Rambabu S, Ranawat MS, Bhandari A, Dinesh P. The study of Guar gum and starch on disintegration time and drug release of fast dissolving tablet in rabbit using single dose randomized parallel design method. Jordan Journal of Pharmaceutical Sciences. 2013 Oct 8;6(3):280-91.

30. Drusch S. Sugar beet pectin: A novel emulsifying wall component for microencapsulation of lipophilic food ingredients by spray-drying. Food Hydrocoll. 2007;21:1223–1228. doi:10.1016/j.foodhyd.2006.10.006

31. Iglesias MT, Lozano JE. Extraction and characterization of sunflower pectin. J Food Eng. 2004;62:215–223. doi:10.1016/S0260-8774(03)00234-8

32. Zouambia Y, Ettoumi KY, Krea M, Moulai-Mostefa N. A new approach for pectin extraction: Electromagnetic induction heating. Arab J Chem. 2017;10:S480–S487. doi:10.1016/j.arabjc.2012.07.018

33. Rodsamran P, Sothornvit R. Microwave heating extraction of pectin from lime peel: Characterization and properties compared with the conventional heating method. Food Chem. 2019;278:364–372. doi:10.1016/j.foodchem.2018.11.067

34. Xu Y, Zhang L, Bailina Y, et al. Effects of ultrasound and/or heating on the extraction of pectin from grapefruit peel. J Food Eng. 2014;126:72–81. doi:10.1016/j.jfoodeng.2013.11.004

35. Abou-Elseoud WS, Hassan EA, Hassan ML. Extraction of pectin from sugar beet pulp by enzymatic and ultrasound-assisted treatments. Carbohydr Polym Technol Appl. 2021;2:100042. doi:10.1016/j.carpta.2021.100042

36. Pacheco MT, Villamiel M, Moreno R, Moreno FJ. Structural and rheological properties of pectins extracted from industrial sugar beet by-products. Molecules. 2019;24:392. doi:10.3390/molecules24020392

37. Méndez D, Fabra MJ, Gómez-Mascaraque LG, López-Rubio A, Martinez-Abad A. Modelling the extraction of pectin towards the valorisation of watermelon rind waste. Foods. 2021;10:738. doi:10.3390/foods10040738

38. Hassan ML, Berglund L, Abou Elseoud WS, Hassan EA, Oksman K. Effect of pectin extraction method on properties of cellulose nanofibers isolated from sugar beet pulp. Cellulose. 2021;28:10905–10920. doi:10.1007/s10570-021-04189-6

39. Khamsucharit P, Laohaphatanalert K, Gavinlertvatana P, Sriroth K, Sangseethong K. Characterization of pectin extracted from banana peels of different varieties. Food Sci Biotechnol. 2018;27:623–629. doi:10.1007/s10068-017-0284-2

40. Wongkaew M, Sommano SR, Tangpao T, Rachtanapun P, Jantanasakulwong K. Mango peel pectin by microwave-assisted extraction and its use as fat replacement in dried Chinese sausage. Foods. 2020;9:450. doi:10.3390/foods9040450

41. Díaz-Rojas E, Pacheco-Aguilar R, Lizardi J, Argüelles-Monal W, Valdez M, Rinaudo M, et al. Linseed pectin: Gelling properties and performance as an encapsulation matrix for shark liver oil. Food Hydrocoll. 2004;18:293–304. doi:10.1016/S0268-005X(03)00078-4

42. Yang X, Nisar T, Hou Y, Gou X, Sun L, Guo Y. Pomegranate peel pectin can be used as an effective emulsifier. Food Hydrocoll. 2018;85:30–38. doi:10.1016/j.foodhyd.2018.06.040

43. Sylvie A, Louise W. Quality assessment of *Borassus aethiopum* Mart fruit pulp pectin precipitated with various solvents. Afr J Food Sci. 2020;14:222–232. DOI: Not available

44. Yapo BM, Koffi KL. Extraction and characterization of highly gelling low methoxy pectin from cashew apple pomace. Foods. 2014;3:1–12. doi:10.3390/foods3010001

45. Yuliarti O, Matia-Merino L, Goh KT, Mawson J, Brennan C. Characterisation of gold kiwifruit pectin isolated by enzymatic treatment. Int J Food Sci Technol. 2012;47:633–639. doi:10.1111/j.1365-2621.2011.02878.x

46. Kazemi M, Khodaiyan F, Labbafi M, Hosseini SS. Ultrasonic and heating extraction of pistachio by-product pectin: Physicochemical, structural characterization and functional measurement. J Food Meas Charact. 2019;14:679–693. doi:10.1007/s11694-019-00327-7

47. Wathoni N, Shan CY, Shan WY, Rostinawati T, Indradi RB, Pratiwi R, et al. Characterization and antioxidant activity of pectin from Indonesian mangosteen (*Garcinia mangostana* L.) rind. Heliyon. 2019;5:e02299. doi:10.1016/j.heliyon.2019.e02299

48. Sabater C, Blanco-Doval A, Montilla A, Corzo N. Optimisation of an enzymatic method to obtain modified artichoke pectin and pectic oligosaccharides using artificial neural network tools: In silico and in vitro antioxidant assessment. Food Hydrocoll. 2021;110:106161. doi:10.1016/j.foodhyd.2020.106161

49. Sharma R, Ranawat MS, Sayra B, Bhandar A, Chouhan CS. Statistical screening of starch paste and guar gum on hardness and disintegration time of fast dissolving tablet. Int. J. Pham. Pharm. Sci. 2012;1012(4):85-9.

50. Canteri-Schemin MH, Fertonani HC, Waszczynskyj N, Wosiacki G. Extraction of pectin from apple pomace. Braz Arch Biol Technol. 2005;48:259–266. doi:10.1590/S1516-89132005000200013

51. Chan SY, Choo WS. Effect of extraction conditions on the yield and chemical properties of pectin from cocoa husks. Food Chem. 2013;141:3752–3758. doi:10.1016/j.foodchem.2013.06.097

52. Hanssen NMJ, Kraakman MJ, Flynn MC, Nagareddy PR, Schalkwijk CG, Murphy AJ. Postprandial glucose spikes, an important contributor to cardiovascular disease in diabetes? Front Cardiovasc Med. 2020;7:570553. doi:10.3389/fcvm.2020.570553

53. Alssema M, Ruijgrok C, Blaak EE, Egli L, Dussort P, Vinoy S, et al. Effects of alpha-glucosidase inhibiting drugs on acute postprandial glucose and insulin responses: A systematic review and meta-analysis. Nutr Diabetes. 2021;11:11. doi:10.1038/s41387-021-00142-2

54. Jones M, Gu X, Stebbins N, Crandall P, Ricke S, Lee S. Effects of soybean pectin on blood glucose and insulin responses in healthy men. FASEB J. 2015;29:596.16. DOI: Not available

55. Bianchi F, Larsen N, Tieghi TDM, Adorno MAT, Kot W, Saad SMI, et al. Modulation of gut microbiota from obese individuals by in vitro fermentation of citrus pectin in combination with *Bifidobacterium longum* BB-46. Appl Microbiol Biotechnol. 2018;102:8827–8840. doi:10.1007/s00253-018-9258-2

56. Martínez-Martínez E, López-Ándres N, Jurado-López R, Rousseau E, Bartolomé MV, Fernández-Celis A, et al. Galectin-3 participates in cardiovascular remodeling associated with obesity. Hypertension. 2015;66:961–969. doi:10.1161/HYPERTENSIONAHA.115.06032

57. Seropian IM, Cassaglia P, Miksztowicz V, González GE. Unraveling the role of galectin-3 in cardiac pathology and physiology. Front Physiol. 2023;14:1304735. doi:10.3389/fphys.2023.1304735

58. Yellon DM, Hausenloy DJ. Myocardial reperfusion injury. N Engl J Med. 2007;357:1121–1135. doi:10.1056/NEJMra071667

59. Hu X, Zhang K, Xu C, Chen Z, Jiang H. Anti-inflammatory effect of sodium butyrate preconditioning during myocardial ischemia/reperfusion. Exp Ther Med. 2014;8:229–232. doi:10.3892/etm.2014.1707

60. Hu X, Fu W, Jiang H. HMGB1: A potential therapeutic target for myocardial ischemia and reperfusion injury. Int J Cardiol. 2012;155:489. doi:10.1016/j.ijcard.2011.12.020

61. Xue H, Zhao Z, Lin Z, Geng J, Guan Y, Song C, et al. Selective effects of ginseng pectins on galectin-3-mediated T cell activation and

apoptosis. Carbohydr Polym. 2019;219:121–129. doi:10.1016/j.carbpol.2019.05.020

62. Sharma RB, Kumar A, Dixit A. A Modern Approach on Mouth Dissolving Drug Technology: Film-Based Oral Delivery. Journal of Drug Delivery & Therapeutics. 2025 Aug 1;15(8).

63. Picot-Allain MCN, Neergheen VS. Pectin: A multifaceted biopolymer in the management of cancer: A review. Heliyon. 2023;9:e22236. doi:10.1016/j.heliyon.2023.e22236

64. Niu H, Dou Z, Hou K, Wang W, Chen X, Chen X, et al. A critical review of RG-I pectin: Sources, extraction methods, structure, and applications. Crit Rev Food Sci Nutr. 2024;64:8911–8931. doi:10.1080/10408398.2023.2180324

65. Jin H, Li M, Tian F, Yu F, Zhao W. An overview of antitumour activity of polysaccharides. Molecules. 2022;27:8083. doi:10.3390/molecules27228083

66. Bai Y, Gilbert RG. Mechanistic understanding of the effects of pectin on in vivo starch digestion: A review. Nutrients. 2022;14:5107. doi:10.3390/nu14235107

67. Lou J, Zhang B, Zheng Y, Liu M, Qu Y. Hawthorn pectin plays a protective role in myocardial ischaemia by regulating intestinal flora and short chain fatty acids. Curr Res Food Sci. 2024;9:100863. doi:10.1016/j.crfs.2024.100863

68. Freitas CM, Coimbra JS, Souza VG, Sousa RC. Structure and applications of pectin in food, biomedical, and pharmaceutical industry: A review. Coatings. 2021;11(8):922. doi:10.3390/coatings11080922

69. Voragen AG, Coenen GJ, Verhoef RP, Schols HA. Pectin, a versatile polysaccharide present in plant cell walls. Struct Chem. 2009;20(2):263–275. doi:10.1007/s11224-009-9442-z

70. Srivastava P, Malviya R. Sources of pectin, extraction and its applications in pharmaceutical industry—An overview. Indian J Nat Prod Resour. 2011;2(1):10–18.

71. Sriamornsak P. Chemistry of pectin and its pharmaceutical uses: A review. Silpakorn Univ Int J. 2003;3(1–2):206–228.

72. Kaushik K, Sharma RB, Agarwal S. Natural polymers and their applications. Int J Pharm Sci Rev Res. 2016;37(2):30–36.

73. Fegade VC, Narkhede SB, Kumar R. Formulation and evaluation of paracetamol tablet to assess binding property of *Limonia acidissima* pectin. Trop J Pharm Life Sci. 2023;10(5):01–11.

74. Wang SY, Meng YJ, Li J, Liu JP, Liu ZQ, Li DQ. A novel and simple oral colon-specific drug delivery system based on the pectin/modified nano-carbon sphere nanocomposite gel films. Int J Biol Macromol. 2020;157:170–176. doi:10.1016/j.ijbiomac.2020.04.150

75. Jain V, Shukla N, Mahajan S. Polysaccharides in colon specific drug delivery. J Transl Sci. 2015;1:3–11.

76. Gómez B, Gullón B, Yáñez R, Schols H, Alonso JL. Prebiotic potential of pectins and pectic oligosaccharides derived from lemon peel wastes and sugar beet pulp: A comparative evaluation. J Funct Foods. 2016;20:108–121. doi:10.1016/j.jff.2015.10.029

77. Larsen N, Bussolo de Souza C, Krych L, Barbosa Cahú T, Wiese M, Kot W, et al. Potential of pectins to beneficially modulate the gut microbiota depends on their structural properties. Front Microbiol. 2019;10:223. doi:10.3389/fmicb.2019.00223

78. Slavin J. Fiber and prebiotics: Mechanisms and health benefits. Nutrients. 2013;5(4):1417–1435. doi:10.3390/nu5041417

79. Mudgil D, Barak S. Composition, properties and health benefits of indigestible carbohydrate polymers as dietary fiber: A review. Int J Biol Macromol. 2013;61:1–6. doi:10.1016/j.ijbiomac.2013.06.044

80. Roman-Benn A, Contador CA, Li MW, Lam HM, Ah-Hen K, Ulloa PE, et al. Pectin: An overview of sources, extraction and applications in food products, biomedical, pharmaceutical and environmental issues. Food Chem Adv. 2023;2:100192. doi:10.1016/j.focha.2023.100192