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Structure, Extraction Methods, Application In Food Products And Health Of Pectin

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Abstract: Pectin is a polysaccharide, separated from citric and non-citric fruits. It is composed that the plants cell wall which is present in the organised 3 layers. The structural areas known as homogalacturonan (HG), rhamnogalacturonan-I (RG-I) and rhamnogalacturonan-II (RG-II) domains. The various methods can efficiently extract pectin, with their effectiveness largely influenced by the mass transfer properties of the solvents used. Pectinase is an important enzyme widely used for formulating new products in various industries such as food, nutraceutical, pharmaceutical and cosmetic. Pectin contributes numerous health benefits such as digestive health, supports the regulation of blood sugar and cholesterol levels, and promotes overall well-being. It also acts as a prebiotic by being fermented by beneficial gut microbiota, producing health-promoting metabolites. Its consumption has been associated with reduced inflammation, allergy prevention, and supportive roles in cancer therapy. This study highlights the structure of pectin, extraction methods, application in food products and health benefits.

Keywords: Extraction, Pectin, Structure, Health

I. Introduction

Pectin is a polysaccharide (Khubber et al., 2023), it is composed that the plants cell wall which is present in the organised 3 layers such as middle lamella primary and secondary cell wall. Polysaccharides and polyuronides make up the cell wall's structural components (Singhal & Hulle, 2022). The structure of the cell wall is around 2 to 35% (Niu et al., 2024). Generally, it is huge amount of pectin present in the internal lamella layers between near plant cell walls. Moreover, it is also contained in primary cell walls but less amount or absent of pectin present in the secondary plants cell wall (Chan et al.,2017). The pectin name originates from Greek word 'pektos' which meaning of the word is hard and firm (De Cindio., 2015). Robert Hooke, a famous scientist in the field of microscopy and cellular biology, made the innovative detection of the structural components known as plant cell walls in the year of 1665, which significantly contributed to the initial understanding of plant structure and the cell theory that would later be developed. Following this important revelation, a series of further investigations and studies into cellular structures were undertaken by researchers, notably including Preston and Clarke in the year of 1975, as well as Knox in the following year of 1979, which collectively expanded upon Hooke's initial findings and enhanced the overall comprehension of plant cell structure and function (Singhal & Hulle, 2022). The components of pectin are (1→4)-α-D-galacturonic acid (GalA) residues, interspersed with rhamnose units and side chains of neutral sugar including galactose and arabinose. Its main domains contain homogalacturonan (HG) which is composed of units of galacturonic acid and the galacturonic acid assigned with neutral monosaccharides like arabinose, rhamnose, galactose, glucose, mannose and xylose, forming rhamnogalacturonan-I (RG-I), rhamnogalacturonan-II (RG-II) and xylogalacturonan (XG) (Khubber et al., 2023).

The pectin separated from citrus and non-citrus fruits. It plays a crucial structural role in plant tissues and has gained significant industrial importance due to its multifunctional properties. It is a natural and non-hazardous polysaccharide that has become an essential component in the food manufacturing unit due to its wide range of functional properties. It is extensively utilized as a substance that gel to provide structure in jams and jellies, as a thickening agent to improve texture in sauces and beverages, and as a stabilizer to maintain consistency in dairy and confectionery products. In addition, pectin plays an important role as an emulsifying agent, helping to blend ingredients that would otherwise separate. Beyond these technological applications, pectin is also recognized as a valuable source of soluble dietary fiber. As such, it contributes to digestive health, supports the regulation of blood sugar and cholesterol levels, and promotes overall well-being. This dual functionality serving both technological and nutritional purposes makes pectin a unique and multipurpose component in modern food formulations. (Roman-Benn et al, 2023).

The global market demonstrated substantial economic value in 2012, reaching a total market valuation of approximately 958 million USD. This significant market size reflected the established demand for pectin across various industrial application, particularly in food processing and pharmaceutical sector. Following this baseline year, market analysts projected a healthy growth line for the pectin industry over the subsequent years. Specifically, the marketplace was expected to expand at a CAGR (Compound Annual Growth Rate) of 7.3 percent throughout the time period for the forecast spanning from 2018 to 2023. In 2018, Europe emerged as the dominant regional player in the global pectin market, establishing itself as the largest consumer and market leader for this natural polysaccharide. The European market demonstrated remarkable scale, with total consumption reaching approximately 31,000 metric tons during that year. This substantial volume translated into a market valuation of roughly 420 million USD, underscoring the significant economic importance of pectin within the European food and pharmaceutical industries (Picot-Allain et al, 2022). Growing consumer demand for clean-label ingredients and sustainable utilization of agro-industrial by-products has further increased interest in pectin research. The structure, methods of extraction, use in food products, and health benefits of pectin are discussed in this article.

II. Structure of pectin

Pectin exhibits a complex macromolecular structure characterized by three primary structural domains that collectively define its physiochemical properties and functional behaviour in various applications. The first and abundant structural component is the homogalacturonan (HG) domain, which founds the backbone of pectin molecules and is commonly described as the “smooth” area due to it is relatively linear and unbranched polymeric structure consisting predominantly of α-(1–4) linked with D-galacturonic acid residues. This homogalacturonan domain can undergo structural modifications through substitution reactions, wherein single monosaccharide units or short oligomeric chains of D-xylose and D-apiose attach to specific positions on the galacturonic acid backbone. When D-xylose residues substitute at the C-2 or C-3 locations of D-galacturonic acid (D-GalpA) units, the resulting modified structure is designated as the xylogalacturonan (XG) domain, while substitution with D-apiose at these same positions produces the apiogalacturonan (AG) domain, both representing specialized variants of the smooth region with different functional characteristics (Niu et al., 2024). In difference to the comparatively simple HG structure, pectin also contains two clearly different structural areas known as RG-I (Rhamnogalacturonan-I) and RG-II (rhamnogalacturonan-II) domains, both of which are collectively termed the "hairy" sections of pectin molecules. The RG-I domain features a repeating disaccharide backbone of alternating α-(1→4)-linked α-(1→2)-linked L-rhamnose units and D-galacturonic acid, with various side chains composed of galactose, arabinose, and further neutral sugars attached primarily to the rhamnose residues. The RG-II domain represents the most structurally complex region of pectin, containing a homogalacturonan backbone decorated with highly branched oligosaccharide side chains comprising at least twelve different types of sugars, including with rare components like aceric acid, apiose, and 2-O-methyl xylose, linked through more than twenty different glycosidic linkages. (Niu et al., 2024). Generally, 65 % of HG, from 20 to 35 percent of RG-I and then 10 percent of RG-II present pectin in the plant cell structure (Singhal & Hulle., 2022).

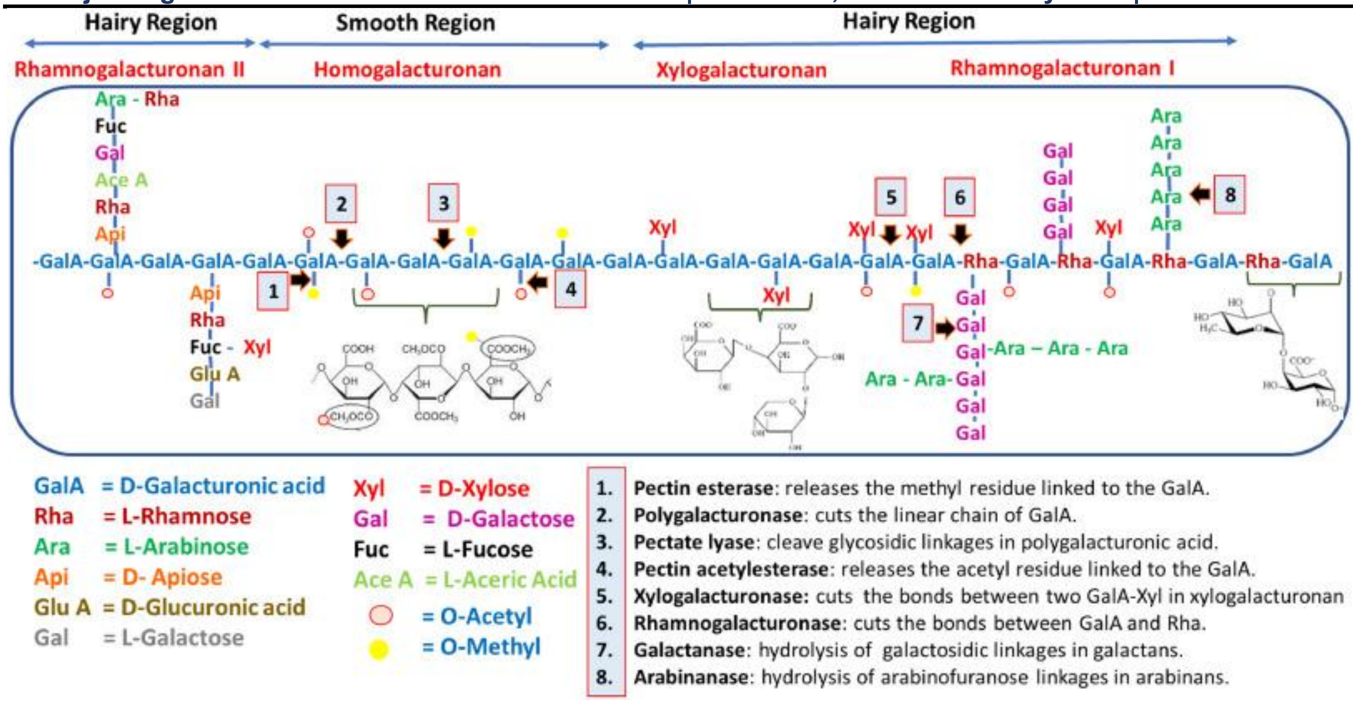

Figure: 1. Structure of pectin (Roman-Benn et al. 2023)

III. The sources of pectin (citrus and non-citrus fruits)

Generally, the commercial (marketable) pectin is extracted from citric fruit peels around 85.5% like lime, orange lemon but minimum amount of pectin from pomace (apple) around 14.0% and 0.5% of pectin from pulp (sugar beet) (Picot-Allain et al, 2022). Various citrus fruit peel and pomace (apple) are obtainable in huge volumes as by-products from essential oil manufacturing industry and fruit juice shop, whereas sugar beet pulp is obtained from sugar industry. Tropical and subtropical fruit by-products, largely generated through agro-industrial processing, constitute a significant and abundant sources of pectin. Tropical and subtropical fruit by-products may be possible source of pectin, according to several lines of documentation from the literature (Table 1).

Table 1

Sources of pectin from citric and non-citric fruit peels

Name of the fruit peel	**Pectin content**	**Reference**
Banana	12.5%	Mao et al, 2024
Goji berry	18.07%	Geng et al, 2024
Baobab fruit	32.42%	Demir et al, 2024
Pine apple	16.24%	Shivamathi et al, 2022
White dragon	9.38%	Nguyen et al, 2019
Jack fruit	21.5%	Ying et al, 2018
Passion fruit	12.67%	de Oliveira et al, 2016
Pomegranate	24.05%	Moorthy et al, 2015
Papaya	25.41%	Maran et al, 2015
Mango	28.86%	Maran et al, 2015
Watermelon	25.71%	Maran et al, 2014
Apple pomace	12.32 %	Hoque et al, 2025
Grape's pomace	32.3%	Minjares-Fuentes et al, 2014
Lemon	43%	Akachat et al, 2025
Orange	19.24%	Maran et al, 2015
Pomelo	26.63	Hossain et al, 2024
Sweet lime	37.21%	Rai et al, 2025

IV. Extraction methods of pectin

The pectin is drastically combined with hemicellulose, cellulose, protein, etc. to sustain the constancy of plant cell walls. However, the pectin is extract from plants cell wall by several extraction procedures. Different methods can efficiently extract pectin, with their effectiveness largely influenced by the mass transfer properties of the solvents used. The technique that delivers a higher qualitative yield is considered more appropriate. According to the basic principles of organic chemistry, some innovation approaches such as aqueous, percolation, maceration, decoction, Soxhlet, and hydro distillation are included under the conventional extraction method. The non-conventional techniques including microwave, enzymes, ultrasound, pulsed electric field and supercritical method with strong acids and alkalis. These extraction techniques require low time, energy, and solvent (Niu et al., 2024 and Singhal & Hulle., 2022).

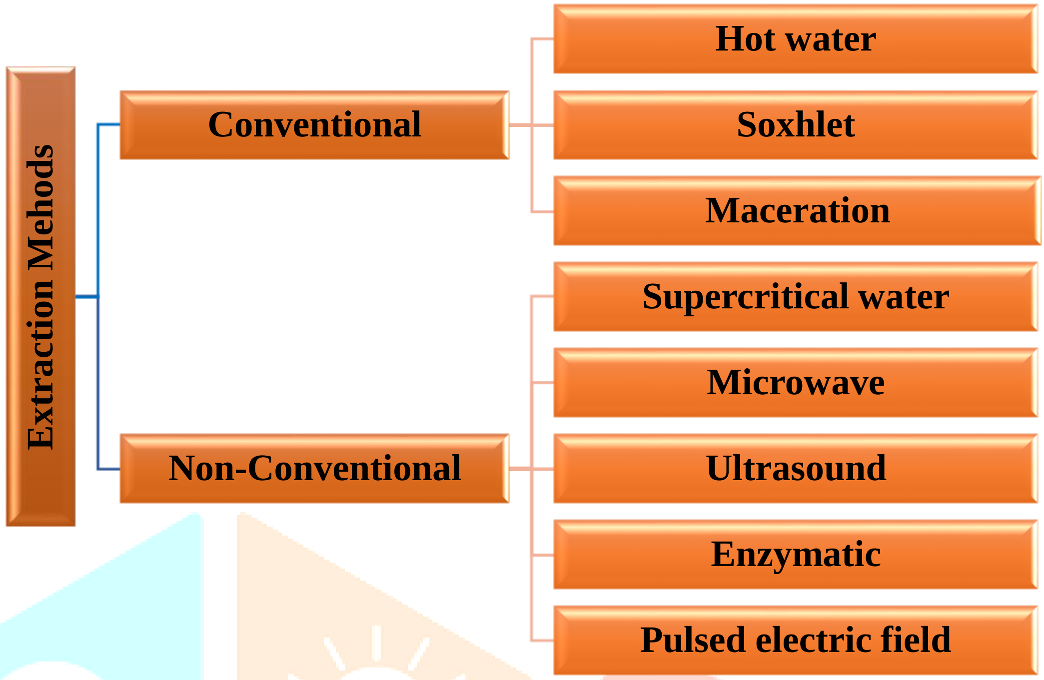

Figure: 2. Types of Extraction Methods

4.1 Conventional methods

Pectin is traditionally extracted via an aqueous with an acidic environment, usually maintained within pH range of 1.5 to 3.0. The method is characteristically carried out at higher temperatures ranging from 75°C to 100°C for 1-3 hours. The total yield and worth of the take-out pectin is influenced by numerous critical factors, such as pH of the medium, solid to solvent ratio, particle size of the sample, as well as extraction time and temperature. In recent years, the principles green chemistry has encouraged the replacement of conventional mineral acids with more environmentally friendly organic acids including citric and acetic acid. These are benefits to decrease the eco-friendly effect of the method while producing compounds that align with increasing demand for “clean label” items in the food manufacturing companies. Nevertheless, organic acid commonly possess lesser hydrolysing capabilities compared to mineral acid, which can lead to variations in yield. Despite this limitation, their use favoured because they enable the production of safter, more natural, and consumer-friendly pectin extracts (Singhal & Hulle., 2022).

4.1.1 Maceration

Maceration is one of the oldest and simplest extraction method used to obtain valuable compounds from plant materials. This technique refers to the gradual penetration of solvent into plant materials to dissolve soluble constituents while gently breaking down the matrix without applying intense heat or pressure. Plant material, such as powdered peels, leaves, or pomace, is immersed in a solvent of selected polarity typically water, ethanol, hydro alcohol combinations, or other organic solvents at room temperature or under controlled conditions during cold maceration. The mixture is permitted to stand for hours or days after this process, which frequently includes sporadic stirring to improve mass transfer. This process is characterized by diffusion-controlled solubilization whereby the solvent diffuses into the plant cellular structure, solubilizes the phytochemicals and then diffuses back out into the bulk solvent phase, driven by concentration gradients between the inside and outside of the tissue matrix. Maceration takes advantage of the principle that “like dissolves like”, where the polarity of the solvent influences which classes of compounds are preferentially extracted, and its efficiency is influenced by variables like solvent choice and polarity, time, temperature, and the physical state (particle size) of the plant material. This aligns with general extraction studies where cold maceration remains a viable method for extracting heat-sensitive constituents due to its minimal thermal degradation, ease of execution, and low equipment requirement, making it suitable for both research and small-scale industrial operations.

4.1.2 Soxhlet Extraction

Soxhlet extraction is a conventional solid-liquid extraction technique commonly used to separate bioactive compounds, including pectin, from the plant materials. Initially, the raw material such as fruit peels or agro-industrial residues is properly cleaned to eliminate the impurities, dried, and pulverized into a fine substance to increase surface area. A known amount of the powdered sample material is located into a porous thimble, which is positioned inside the Soxhlet extractor. An appropriate extraction solvent typically acidified water or organic acid solution is added to a round-bottom flask which is attached to the Soxhlet equipment. The system is heated using a heating mantle, causing the solvent to boil and evaporate. In the condenser, the solvent vapours rise and cool before condensing into liquid. The condensed solvent drips onto the sample contained in the thimble, allowing soluble pectin to diffuse into the solvent. Once the extraction container has been filled to a specific amount, the dissolving pectin solvent siphons back into the boiling flasks. This cycle is repeated continuously for several hours until sufficient extraction is achieved. After completion, the extract is filtered, and pectin is recovered by alcohol precipitation, followed by drying. The Soxhlet technique of extraction functions on the principles of continuous solvent reflux and diffusion-driven mass transfer. During each extraction cycle, freshly condensed hot solvent comes into contact with the plant matrix, enhancing the solubilization of pectin. The higher temperature weakens hydrogen bonds and electrostatic interactions within the cell wall polysaccharide network, promoting the release of pectin into the solvent (Sathanya et al, 2025).

4.2 Non-conventional methods

4.2.1 Supercritical fluid extraction

Subcritical water mentions to water heated above its boiling point (100 °C) under high pressure. In this state, water exhibits reduced permittivity, making it behave as a less-polar solvent. Elevated temperatures also lower its surface tension and enhance diffusivity, thereby improving its ability to extract pectin from agro-industrial residues. However, excessive heat can lead to pectin degradation, with the critical temperature threshold varying according to the composition of the raw material. At higher temperatures, undesirable Maillard reactions may occur, causing browning of the extracted pectin. Additionally, while extraction efficiency increases, other components of cells (impurities) become more soluble as well, potentially affecting the purity of the final product.

4.2.2 Microwave assisted extraction

Microwave-assisted extraction utilizes microwave energy to enhance mass transfer into the extraction solvent. The process functions by exposing a dielectric material to a microwave field, where heating occurs through ionic conduction and dipole rotation within both the sample matrix and the solvent. At the same time, microwave energy induces the electrophoretic movement of ions and electrons, leading to the formation of an electric field. This electric field promotes particle motion, while the reorientation of polar molecules results in dipole rotation. To ether, these phenomena facilitate efficient energy release and rapid heat generation within the system. Compared with conventional extraction methods, MAE demonstrates superior efficiency in terms of reduced extraction time, lower solvent consumption and high pectin yield. Although the degree of esterification is lower than that obtained through conventional extraction (Singhal & Hulle., 2022) and (Picot-Allain et al., 2022).

4.2.3 Ultrasound assisted extraction

Ultrasonic waves are mechanical vibrations that occur beyond the range of human hearing (16 Hz–20 kHz). In practice, frequencies between 20 and 100 kHz are often used for ultrasound-assisted extraction. The frequency of ultrasound is an important factor, as it determines the size of microbubbles and their resistance to mass transfer. At higher frequencies, cavitation the formation and collapse of bubbles in liquid becomes less intense and less frequent. Ultrasound-assisted extraction offers several advantages. It significantly reduces extraction time while increasing yield. This is achieved through acoustic pressure fluctuations that generate microbubbles. When these bubbles collapse, they release microjets that disrupt cellular structures, allowing solvents to penetrate more effectively. Once inside the cells, solvents promote swelling and hydration, enlarging pores and enhancing diffusion, which accelerates mass transfer. Research has consistently demonstrated the benefits of this technique such as less energy consumption, few amounts of solvent use, low processing time and higher yield. These features make ultrasound has been successfully applied to recovery of pectin from fruit waste materials and by-products, highlighting its potential in valorising agricultural residues (Picot-Allain et al., 2022).

4.2.4 Pulsed electric field extraction

Pulsed electric field (PEF) technique is a non-thermal, efficient and green technique increasingly applied to recover huge number of bioactive compounds from the food processing wastes. This technique is particularly attractive because it overcomes many of the limitations of traditional methods such as long processing time, high solvent use, and thermal degradation. This method can enhance yield and efficiency with lower energy input. The electroporation reduces the resistance of cell membranes and thus greatly facilitates mass transfer between the intracellular and extracellular environment. Intracellular bioactive compounds that are normally sequestered within intact cells can now diffuse out into surrounding solvent more readily, significantly improving extraction efficiency. This mechanism also softens the tissue matrix, allowing solvent to penetrate deeper and increasing the surface area available for solute transfer. Critical process parameters including electric field intensity, specific energy input, pulse frequency, pulse number, and temperature must be optimized for each matrix and target compound. Generally, increasing field strength and specific energy enhances membrane permeabilization and extraction yield, yet overly aggressive conditions can lead to excessive damage or degradation of sensitive compounds. Because PEF is predominantly non-thermal, it preserves heat-labile compounds better than conventional thermal extraction methods. The advantage of PEF extraction is its compatibility with green chemistry principles. It often requires low volume of organic solvent, minimum amount of energy and less processing times compared to traditional methods.

4.2.5 Enzyme assisted extraction

The efficiency of pectin extraction through enzyme-Assisted Extraction largely depends on the catalytic potential of enzymes, which provide high selectivity and specificity during the reaction. By interfering with cellular components, enzymes quickly the release of pectin, thereby reducing the time of extraction. Compared to conventional methods, ultrasound-Assisted Extraction (UAE) offers several advantages such as it prevents equipment corrosion caused by strong acids, yields higher quality pectin due to enzyme specificity, and requires less energy since the process occurs at lower temperatures. Generally used enzymes in pectin extraction include cellulases, hemicelluloses, xylanases, protopectinases and proteases. However, their high cost remains a major drawback. In this method, buffers replace strong acids as solvents because enzymes are highly sensitive to pH. Even though UAE operates at lower temperatures, it is consuming more time (Picot-Allain et al., 2022).

4.2.6 Subcritical water extraction

Subcritical water refers to aquatic heated beyond its boiling point of 100 °C while maintained under sufficient pressure to remain in the liquid state. Under these conditions, water exhibits a reduced dielectric constant and behaves more like a low polar solvent. The higher temperature also decreases surface tension and enhances diffusivity, which collectively improve solvent penetration and mass transfer efficiency. These properties enable subcritical water to effectively extract pectin from agro-industrial by-products. However, extraction at excessively high temperatures may result in the degradation of pectin, with the critical temperature limit depending on the structure and chemical composition of pectin present in the raw material. In addition, high-temperature conditions may trigger unwanted Maillard reactions, leading to browning and deterioration of pectin quality. Moreover, along with enhanced pectin extraction, the solubility of various intracellular elements and impurities may increase, potentially compromising the purity of the final pectin product (Roman-Benn et al., 2023).

V. Application of pectin

Pectin has used in numerous applications, including in the food manufacturing industries as a stabilizer, film coating agent, thickener, emulsifier, and so on, as well as in the biological and pharmaceutical fields as a drug carrier, drug supplements, drugs for disease treatment and prevention, etc., and it can also be used as a precipitant, stabilizer, adsorbent, water-holding agent, etc. in the environmental and chemical fields (Niu et al., 2024). Pectinase is an important enzyme widely used in industry today. It helps in processing fruits and vegetables, and is also used in making wine, tea, coffee, and some medicines. Outside of food and health, pectinase is useful in textile work and paper production. It also helps clean wastewater that contains pectin and is used to remove gum from plant fibres. Because of all these uses, pectinase is considered one of the most valuable enzymes in modern industry (Roman-Benn et al., 2023). It is finding growing use in the plastics manufacturing industry. Its natural biodegradability makes it an eco-friendly alternative to petroleum-based materials. Along with this, pectin offers unique properties that enhance the performance of bioplastics. This combination of sustainability and functionality is driving its rising importance in the sector (Dixit et al., 2025).

Pectin's unique biological properties make it highly valuable in the pharmaceutical manufacturing units. It is commonly used in drug formulations for oral delivery, as well as in the creation of beads, aerogels, tablets, gels, hydrogels, and compression-coated dose forms. Beyond its functional role, pectin's antibacterial, prebiotic, antioxidant, and antiglycation activities further enhance its appeal for pharmaceutical applications. Additionally, pectin has proven effective in nanoencapsulation of bioactive compounds, helping to extend their shelf life and improve stability. Pectin has emerged as an important material in food packaging, and it is also ability to interact with polymers like cellulose and alginate to form edible coatings and films. These pectin-based films are biodegradable and not only provide an eco-friendly alternative to conventional packaging but also offer enhanced antimicrobial and antioxidant properties, creating them highly effective for the preserving food quality (Picot-Allain., 2022). The main uses of pectin are as textured element and stabiliser in the food products, whereas it is used in beauty (cosmetic) products and individual care items such as stabilising and thickening of lotions and shampoos). In the pharmaceutical industry, pectin is used in the formulation of controlled-release matrix tablet, for example, as a carrier material in colon-targeted drug delivery. The disposal of petroleum food packaging materials causes pollution and is a global concern. In this regard, the development of pectin edible coating is considered as a promising strategy which is gaining considerable momentum (Dixit et al., 2025).

VI. Health benefits

RG-I (Rhamnogalacturonan) pectin, which is found through less temperature alkaline extraction, has become a major focus of scientific research. Its unique structural properties make it extremely valuable in the field of functional foods and biomedicine. It is remarkable health-promoting effects such as anti-cancer, anti-inflammatory activity, anti-obesity potential. It also demonstrates strong antioxidant capacity, helping to protect cells from damage. Beyond these, RG-I pectin plays a role in immune regulation and supports gut health as a natural prebiotic. Together, these benefits explain why it continues to attract growing global interest. (Niu et al., 2024). Pectin is indigestible in humans but acts as a prebiotic by being fermented by beneficial gut microbiota, producing health-promoting metabolites. Its consumption has been associated with reduced inflammation, allergy prevention, improved blood glucose and cholesterol control, and supportive roles in cancer therapy. Beyond nutrition, pectin is used in drug and nutraceutical distribution organizations due to its biocompatibility. Additionally, its ability to encapsulate and retain bioactive compounds in emulsions or hydrogels enhances treatment effectiveness and prolongs therapeutic action (Roman-Benn et al., 2023). The pectin is a one of the soluble dietary fibre with has various health benefits for physiological and also gastrointestinal effects, including it slows down how quickly the stomach empties and food moves through the gut, which lowers sugar absorption and adds bulk to the stool. Propionate, acetate, and then butyrate are short-chain fatty acids formed during the intestinal fermentation of pectin. These elements play a significant role in protecting against and managing intestinal disorders, metabolic syndrome, like ulcerative colitis and Crohn's disease, certain cancers, obesity, diarrhoea, and hypertension. A pectin-rich diet has been shown to lower total cholesterol and decrease levels of low-density lipoprotein (LDL) in the blood, while leaving high-density lipoprotein (HDL) stages unaffected. (Roman-Benn et al., 2023).

VII. Conclusion

Pectin is a kind of multifunctional natural polysaccharide, having wide application in the food, pharmaceutical as well as health industries. The structure including the homogalacturonan, rhamnogalacturonan-I and rhamnogalacturonan-II domains is mainly responsible for its physicochemical and biological properties. Citrus and non-citrus agro-industrial by-products are among the diverse low-cost raw materials for pectin. Advances in conventional as well as non-conventional extraction techniques rendered the extraction process more efficient, yielding superior products of higher quality both semantically and content-wise and supported by green processing concepts. Pectin is widely used in food, either as a gelling agent or to stabilize/acidify foods. Its biodegradability and biocompatibility have also led to its use in pharmaceuticals, nutraceuticals, and biodegradable packaging products. In health aspects, pectin is known as a soluble fiber and prebiotic that supports gut health and metabolism. Pectin as a biomaterial remains a promising biopolymer and is becoming more significant in sustainable food systems and health promoting applications. The future of pectin extraction lies in integrating these innovative techniques with industrial processes, ensuring sustainability, efficiency, and economic viability. By valorising agricultural waste and adopting eco-friendly technologies, industries can meet the growing demand for pectin while minimizing environmental impact and contributing to sustainable development goals.

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