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REVIEW ARTICLE

Current trends in Pectin as biopolymers: Extraction, Characterization, and its bioactivities

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ABSTRACT
Pectins are polysaccharides composed up of small chains made of neutral hexoses and pentoses that are stretched by a long linear segment of α-(1,4) linked d-galactopyranosyluronic acids interrupted by β-(1,2) linked l-rhamnoses. In all dicotyledonous plants, pectin is a heterogeneous hydrocolloid that is found in the primary cell wall and middle lamella; it is more frequently found in the outer fruit cover or peel than in the inner matrix. Currently, pectins are widely employed as texturizing, emulsifying, stabilizing, and gelling agents in the food, pharmaceutical, and cosmetic sectors. In the pharmaceutical field, pectin is frequently used for the manufacture of medications that treat cancer, lower blood cholesterol, and treat gastrointestinal issues. Pectin is known to quickly break down by colonic microbes; it may be used as a vehicle for the administration of drugs specifically intended for the colon. Formulations based on pectin have demonstrated great potential as innovative biomaterials for the creation of prosthetic and implantable devices. Pectin is also used in many other industries, including the production of edible coatings and films, foams, and alternatives to paper. According to the wide range of applications for which pectin is used, it is essential to investigate novel sources of pectin or alter those that are already available in order to acquire pectin that possesses the desired quality qualities.
***Keyword**: Pectin, biopolymer, isolation, bioactivities.*

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INTRODUCTION

Biopolymers are highly attractive once they are renewable and have relatively low manufacturing expenses. These are the organic substances present in natural sources. The term "biopolymer" originates from the Greek words "bio" and "polymer," which represent nature and living organisms [01]. Due to their abundance and natural availability, biopolymers are currently receiving a lot of interest in the food and pharmaceutical industries [02, 03]. Biopolymers such as pectin, chitosan, cellulose, agarose, agar, and alginate are currently hot study areas [04]. Biopolymers are highly relevant due to their wide range of therapeutic applications, low manufacturing costs, and renewable nature [01]. According to their extensive occurrence, biopolymers are classified into three types and abundances: (i) polynucleotides, (ii) polypeptides/poly amino acids, and (iii) polysaccharides [05]. Pectin is a heteropolysaccharide present in plant cell walls that promotes cell growth and extension [06]. Pectin comes from plants and can be used as a bioplastic material in a variety of applications [07]. Pectin is a group of galacturonic acid-rich polysaccharides that includes homogalacturonan, rhamnogalacturonan I, and the substituted galacturonans rhamnogalacturonan II (RG-II) and xylogalacturonan (XGA) [08]. It is also a naturally occurring biopolymer, and it has been used successfully for many years in the food and beverage industry as a thickening agent, a gelling agent, and a colloidal stabilizer. Because of its gelling characteristics, bioadhesivity, biocompatibility, and non-toxicity properties, pectin is also a promising polymer for use in the delivery of pharmaceuticals [09]. Additionally, pectin possesses a variety of distinctive characteristics that make it an excellent choice for use as a matrix in the retaining and/or conveyance of different drugs, proteins, and cells.

Structure of pectin

As a multifunctional component of plant cell walls, pectin is a linear polysaccharide consisting of a monomer of a-galacturonic acid. Its molecular weight is approx. 60,000-130,000 g/mol. The presence of the free carboxyl groups in pectin gives it its acidic nature. Pectin is both polydisperse and polymolecular (Fig.1). Pectin is exceedingly difficult to isolate because it depends on the storage, process, and source where it comes from [10].

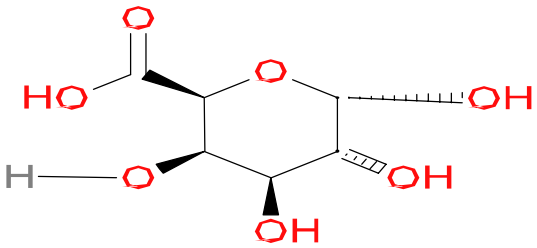

Figure 1: Structure of pectin

In pectin, salt, ammonia, and potassium ions entirely or partially neutralise the carboxylic groups in galacturonic acid, whereas methyl groups partially esterify the acidic groups. Pectin is made up of a subdomain called rhamnogalac (Table 1). Pectin's complex structure (Figure 1) is made up of three sub-domains: rhamnogalacturonan I (RGI), rhamnogalacturonan II (RGII), and xylogalacturonan (XG), which are connected to the homogalacturonan (HG) skeleton [11].

Table 1: Structural composition of pectin

Sub-domains	Amount of component (%)	Structural composition	Reference
Homogalacturonan (HG)	65	Linear homopolymer of GalA partially esterified with methyl esters (α1-4 bonded) at the C-6 position and acetyl esters at the O-2 and/or O-3 positions.	[12, 13]
Rhamnogalacturonan I (RGI)	20 – 35	Repeated disaccharides composed of GalA residues and rhamnose (Rha); Rha residues (20% to 80%) can be placed by neutral sugar side chains (galactose, arabinose, xylose and apiosis).	[14, 15]
Rhamnogalacturonan (RG II)	<10	HG backbone composed of GalA (7 – 9 units) where complex ranches made up of 12 types of monosaccharides (including monomers such as apiose, fucose, acetic acid, DHA or KDO) can exist.	[08, 16]
Xylogalacturonan (XG)	<10	Highly complex branched structure linked through a β-glycosidic bond with GalA's o-3 in HG.	[15]

STRUCTURAL CLASSIFICATION

Degree of Methylation

Pectins can be classified according to their degree of methylation (DM), which is expressed as a percentage based on the number of methylated carboxylic functions per 100 units of galacturonic acid in the main chain [17].

According to their degree of methylation:

1. High-methoxyl (HM) pectin (Figure 2A) with a DM>50%, mostly present in nature as native pectin.
2. Low-methoxyl (LM) pectin (Figure 2B) with a DM of 50%.

The methoxyl content reflects the dispersibility of pectin in water and its ability to form a hydrogel. Pectins containing low and high methoxyl content differ based on their physico-chemical characteristics, resulting in a diversity of uses. The degree of methylation of the extracted pectin depends on the type of plant, its age, and degree of maturation (notably for fruits) [18, 19].

Degrees of Acetylation and Amidation

The degree of amidation (DA) represents the proportion of carboxylic groups in the amide form. The degree of acetylation (DAC) is defined as the proportion of galacturonosyl residues esterified (on the hydroxyl group) with acetyl (Figure 1). Acetylation inhibits gel formation while increasing the stabilising and emulsifying properties of pectins [21-22]. The presence of numerous acetyl groups on sugar beetroot pectin gives it surfactant properties that can be exploited to stabilise emulsions [23, 24]. Amidated pectins are formed by the interaction of pectin carboxymethyl groups (-COOCH3) with ammonia [25, 26].

The degree of amidation (DA) represents the proportion of carboxylic groups in the amide form. It mostly addresses weakly low-methoxy amidated pectin (LMAP). It also boosts pectin's water solubility. [26].

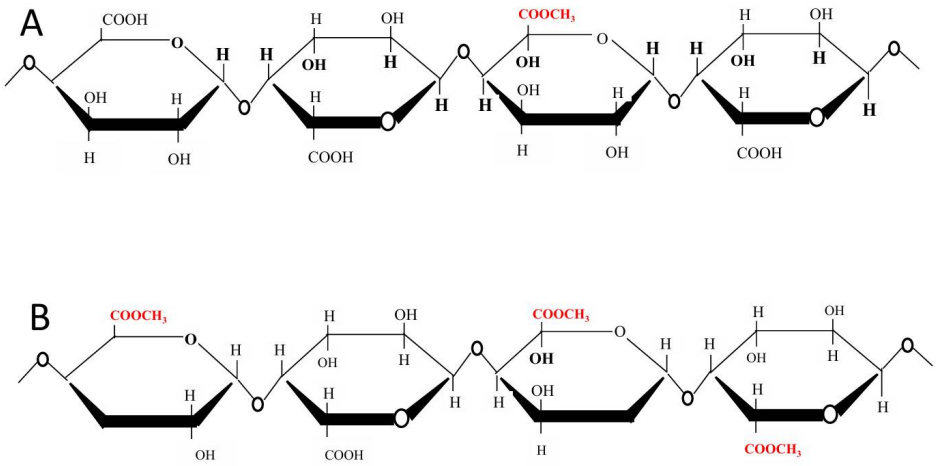

Figure 2: Partially methylated galacturonans. (A) Low-methoxyl and (B) high-methoxyl pectin structure [20].

Sources of pectin

Pectin is a polysaccharide combination that makes up roughly one-third of higher plants' dry cell wall material. The cell walls of grasses contain far fewer of these compounds. The middle lamella of the cell wall contains the largest quantities of pectin, which gradually decreases as one proceeds through the main wall towards the plasma membrane [27]. Although pectin is found in many plant tissues, there are only a few sources that can be used to produce pectin for commercialisation. Since the degree of esterification (DE) and molecular size influence pectins' ability to form gel, pectins obtained from different sources have different gelling properties. due to variations in these parameters. Therefore, detection of a large quantity of pectin in a fruit alone is not in itself enough to qualify that fruit as a source of commercial pectin [28] (Table 2). Currently, citrus peel and apple pomace are the primary sources of commercial pectins.

Table 2: Different sources of pectin

Source	% yield	Reference
Lime peel	23 – 26	[29]
Orange peel	24 – 28	[30]
Pomelo peel	23.19	[31]
Mandarin	21.95	[32]
Grapefruit	27.3 – 33.6	[33]
Apple pomace	4..2 – 19.8	[34]
Sugar beet pulp	7.1 – 24	[35]
Banana peel	2 – 9	[36]
Chicory	12.2	[37]
Cubiu fruit	14.2	[37]
Eggplant peel waste	26.1	[37]
Citron peel	13.4 – 37.52	[38]
Beet pulp	20 – 24.87	[37]
Watermelon rinds	19.3	[37]
Papaya peel	16	[37]
Ponkan peel	25.6	[37]
Potato pulp	14.34	[37]
Tomato	7.55 – 32.6	[39]
Watermelon peel	2.1 – 28	[40]
Passion fruit	10 – 14.8	[36]
Mango peel residues	1.36 – 20.9	[41]

Properties of pectin

Pectins are soluble in water, but they become insoluble in aqueous solutions where they would gel at that same temperature [42]. Monovalent cation (alkali metal) salts of pectinic and pectic acids are usually

soluble in water; di- and trivalent cation salts are weakly soluble or insoluble. Although pectin solutions are not used as thickening agents, they exhibit the pseudoplastic, non-Newtonian behaviour found in most polysaccharides. The viscosity of a pectin solution, like its solubility, is affected by the preparation's molecular weight, DE, and concentration, as well as the pH and presence of counterions in the solution. These physical features are determined by the structure of pectins, which are linear polyanions (polycarboxylate). As a result, the monovalent cation salts of pectins become strongly ionised in solution. Coulombic repulsion causes the distribution of ionic charges along the molecule to remain stretched. When exposed to water, powdered dry pectin clumps together. The clumps are made up of partially dried pectin packets encased in a moist outer envelope. It has been established that clump formation can be avoided by increasing the dispersibility of pectin during manufacture by using a specific treatment or by integrating dry pectin with water-soluble carrier material [43].

Extraction techniques of pectin

The extraction of pectin from natural sources is time-consuming and difficult. Extraction of pectin is dictated by mass transfer into the extraction solvents, therefore the suitability of the extraction process can be determined by both the yield of extracted pectin and the quality of the extracted material [44]. Pectin can be extracted from natural sources using a variety of techniques, including standard heat extraction and novel approaches that include ultrasound, microwaves, and enzymes. Extraction parameters such as particle size, pH, temperature, extraction duration, and solvent type all have a significant impact on pectin yield [45] and drying processes [46]. The particle size of the raw material affects the pectin yield, as in small particles of substrate, more protopectin is available as compared to large particles [47].

Conventional extraction

The two primary steps of the conventional approach are the application of acids to hydrolyze proto-pectin into pectin, later precipitated by ethanol. Pectin extraction takes several hours to obtain a good yield using boiling water [48, 49]. During the extended heating process, low-quality pectins are produced as a result of the beta-elimination and debranching thermal degradation of pectins. Therefore, pectin is extracted in acidic (pH 1.5–3) aqueous medium between 75°C and 100°C for 1–3hours with constant stirring. Acid−base extraction comes under liquid−liquid extraction, which separates biomolecules depending on their acid−base proper ties [50]. In pectin extraction, the use of mineral acids has been linked to higher expenses and environmental problems. The developing concepts of "green chemistry" and "green technology" are currently centred on organic acids, notably acetic and citric acids. Organic acids have poorer hydrolysis powers than mineral acids. Sulphuric acid, hydrochloric acid, and nitric acid are among the most commonly utilised inorganic acids for pectin extraction. The quantity and quality of extracted pectin are affected by a number of parameters, including extraction temperature, solid-liquid ratio, pH, particle size, and extraction time. Pectin is extracted in an acidic aqueous medium and separated from other components using alcohol precipitation after pretreatments including washing with water, blanching with hot water to deactivate enzymes, drying, and grinding to maximise the exchange surface (Table 3). After filtering the resultant coagulate to make the extract more transparent, it is cleaned, vacuum-dried, and then crushed into a fine powder.

Table 3: Pectin extraction by using conventional extraction technique

Pectin sources	Extraction conditions			Yield (%)	Reference
	Solvents	Temperature	pH		
Grapefruit peel	HCl	80^0C	1.5	23.50	[52]
Passionfruit	HCl	98.7^0C	2	14.8	[53]
Beet pulp	HCl	80^0C	1	20.0	[54]
Citron peels	$C_6H_8O_7$	95^0C	1.5	28.31	[55]
Pomelo peels	HNO_3	90^0C	2	23.19	[56]
Papaya peel	HCl	80^0C	2.0	16	[57]
Potato pulp	$C_6H_8O_7$	90^0C	2.04	14.34	[12]
Carrot pomace	-	90^0C	1.3	15.2	[58]
Lime peel	HCl	95^0C	-	15.91	[59]
Ponkan peel	HNO_3	-	1.6	25.6	[60]
Chicory	-	80^0C	1.5	12.2	[61]
Sugar beet pulp	-	80^0C	1.5	7.1	[61]

Non-conventional extraction

Common acidic extraction techniques result in poor yield and a significant environmental effect due to their corrosive nature, longer processing times, and temperature. There are several green methods of pectin extraction, including deep eutectic solvent-based, enzyme-based, microwave, ultrasonic, ohmic, and subcritical water-based techniques.

Microwave-assisted extraction (MAE)

Microwave (MW) is an electromagnetic wave made up of two oscillating perpendicular fields: electric and magnetic fields [62]. MAE is a fast extraction process that produces heat energy in the solvent by electromagnetically radiating the sample at microwave frequencies. Particle movement is caused by an electric field generated by the electrophoretic transfer of ions and electrons, which is activated by microwave radiation; dipole rotation is caused by the alternating displacement of polar molecules [63]. Microwave radiation improves extraction efficiency as compared to conventional heating processes [64]. MWs have frequencies ranging from 300 MHz to 300 GHz on the electromagnetic spectrum. This frequency produces a disorganised rotation of the polar molecules in a MW-irradiated matrix and/or solvent, resulting in heat. However, heat is generated only in the event that the material undergoes dielectric losses or significant absorption of energy. Hence, the absorbed energy is obtained from the expression for dissipation factor (δ):

$$tan\delta = \varepsilon^x/\varepsilon^y$$

Where, ε^x and ε^y is the real (dielectric constant) and complex (dielectric loss factor) part of dielectric permittivity, ($\varepsilon^* = \varepsilon^x - j\varepsilon^y$), respectively. Whereas ε^x is the ability of an irradiated molecule to become polarized by the electric field, ε^y is an indication of the efficiency of transformation of electromagnetic energy into heat. In microwave heating, energy is transferred through two mechanisms: dipole rotation, which involves the reversal of dipoles in polar molecules, and ionic conduction, which involves the displacement of charged ions in the solvent. During acid extraction, pectin depolymerisation can be restricted by MAE [65]. The effects of microwave radiation on the cell wall matrix cause the parenchymal cells to be severed, which greatly exposes the skin tissues (Table 4). Therefore, the permeation of the extracting solvent is increased [66], and extraction efficiency could be increased by increasing microwave power [17, 44].

Table 4: Pectin extraction by using microwave-assisted extraction technique

Pectin sources	Extraction conditions			Yield (%)	Reference
	Solvents	Temperature	pH		
Apple pomace	HCl	-	1.01	15.75	[67]
Dragon fruit	$C_6H_8O_7$	75^0C	2.9	17.01	[68]
Jackfruit rinds	Dist. H_2O	-	-	17.63	[69]
Lime peel	HCl			23.32	[59]
Banana peel	HCl	-	3.0	2.18	[70]
Pumpkin	HCl	80^0C	1.0	11.3	[71]
Watermelon peel	H_2SO_4	-	1.5	19.6	[72]
Pomelo peel	NaOH	-	-	24.2	[21]
Grapefruit	HCl	-	-	27.81	[66]
Sour orange peel	$C_6H_8O_7$	-	1.50	28.8	[73]

Enzyme-assisted extraction (EAE)

Enzyme-assisted extraction is the process of releasing pectin by breaking down the cell wall matrix. Enzymes used in enzyme-assisted extraction include cellulase, hemicellulase, xylanase, pectinase, α-amylase, β-glucanase, and endo-polygalacturonase, among others [74] (Table 5). Plant cell walls are made up of a complicated web of various polysaccharides, including pectin. Enzymatic pectin extraction employs cell wall degrading enzymes with low pectinolytic activity to hydrolyse non-pectin plant cell wall components [75, 76]. In terms of pectin yield, enzymatic extraction is more efficient and environmentally friendly. It depends on the enzyme concentration, reaction temperature, time, particle size of the plant material, and the kind of enzyme [77].

Table 5: Pectin extraction by using enzyme-assisted extraction technique

Pectin sources	Extraction conditions			Yield (%)	Reference
	Solvents	ET	Temperature		
Beetroot	Citrate buffer	Cellulase	30^0C	-	[78]
Butternut squash	Citrate buffer	Cellulase	-	-	[78]
Green tea leaf	HCl	Viscozyme	30^0C	8.5	[79]
Chicory root	HCl	Cellulase-protease	30^0C	-	[80]
Lime peel	Sodium acetate buffer	ValidaseTRL	30^0C	26.3	[80]

Ultrasound-assisted extraction (UAE)

Ultrasounds (Us) are widely employed in the food industry because of their chemical and/or physical properties. Without getting into too much detail, Us has many potential applications in the food business, including extraction emulsification, filtering, cutting, and food preservation [81]. Ultrasound, which typically ranges between 20 and 40 kHz, is used to extract pectin. [82, 83]. Despite electromagnetic waves, they must travel through a medium (solid, liquid, or gas) via a series of expansions that separate molecules. and compression cycles (which forces them together) [84]. When compared to traditional procedures (hydrolysis in an acidic solution), ultrasonic-assisted extraction reduces extraction time while increasing yield. Sound waves travel through a liquid medium, compressing and expanding [85]. Significant advantages of U-assisted extraction include shorter extraction times, smaller equipment, lower energy usage, and higher extraction yields, as well as being more ecologically benign than the standard approach [51] (see Table 6). Investigations into the efficacy of UAE for pectin extraction appear to be increasing, most likely due to a greater understanding of ultrasound technology. In comparing three distinct extraction procedures (CHE, MAE, and UAE) extracting pectin from grapefruit peels, they discovered that intermittent sonication in a water bath rather than continuous sonication offered greater yields [66].

Table 6: Pectin extraction by using ultrasound-assisted extraction technique

Pectin sources	Extraction conditions			Yield (%)	Reference
	Solvents	Temperature	pH		
Apple peel	HCl	63^0C	2.36	8.93	[86]
Passionfruit peel	HNO_3	85^0C	2.0	12.67	[87]
Eggplant peel	$C_6H_8O_7$	-	1.5	33.64	[88]
Grapefruit peel	HCl	66.7^0C	1.5	27.46	[52]
Pomegranate peel	Citrate buffer	-	5	24.8	[89]
Prickly pear	HCl	70^0C	1.5	18.14	[90]

Subcritical water extraction (SWE)

Subcritical water extraction (SWE) is the most popular green and eco-friendly process employed to extract natural resources. Subcritical water is water maintained in the liquid state at temperatures between 100 °C and 374 °C under pressure. In this state, the dielectric constant and polarity of water can be changed [91]. As water is nontoxic, inexpensive, readily available, and can be easily disposed of, using subcritical water for extraction can be both cost-effective and environmentally friendly. Most of the SWE studies on pectin have used extraction pressures and extraction liquid−solid ratios (LSRs) in the range of 20−180 bar and 10−70 mL/g, respectively [92]. The subcritical water can facilitate the extraction of pectin from the plant residues. But also degradation of pectin occurs when the extraction temperature is over a certain temperature threshold and this threshold depends on the composition of the pectin found in the raw materials. Undesirable Maillard reactions may also take place at high temperatures, leading to the browning of the pectin [93]. In the subcritical water extraction process, factors other than temperature that are significant are the extraction time and the liquid/solid (L/S) ratio. Pectin extracted from sugar beet pulp in a subcritical extraction system with ultrasonic treatment yielded 29.1%, which was comparable or even higher than results produced by the conventional method [94].

CHARACTERIZATION OF PECTIN

The characterization of pectin is important for its diverse applications as a gelling agent, thickener, and stabilizer in various products. By analyzing its physicochemical properties, we can optimize texture and consistency, ensuring high-quality outputs. Additionally, pectin offers health benefits, including digestion and lowering cholesterol, making its characterization crucial for developing functional foods. Quality control is enhanced through detailed analysis, enabling consistency in pectin extraction and application. Methods such as calculating pectin yield, measuring moisture and ash content at 550^0C at 6 hours [95], and assessing alkalinity of ash by titration, methoxyl content, and galacturonic acid content using sulfamate/m-hydroxydiphenyl method developed by Cozzi et al., 1991 [96] and Melton et al., 2001 [97]. These all contribute to a better understanding of pectin's characteristics. Color analysis, molecular weight assessment, solubility tests, FT-IR analysis [41], thermal analysis using differential scanning calorimetry, and rheological assessments also enhance the characterization process. Apparent viscosity is determined through a controlled pectin solution, revealing its flow behavior under various conditions. Thorough characterization of pectin maximizes its utility across industries while ensuring safety and efficacy.

BIOACTIVITIES

The pharmaceutical and medical industries can also use pectin as an inventive alternative as the beneficial characteristics and bioactivities of pectin indicate potential for biomedical applications such as drug delivery, tissue engineering, and wound healing.

Anticancer activity

Recently, pectin from various resources and its derivatives have been proven to have antiproliferative effects on various cancer cell lines, such as colon cancer, prostate cancer, breast cancer, and pancreatic cancer [98]. Modified pectins effectively reduce the occurrence and spread of malignant tumors (such as colon and breast cancers) and are promising anti-metastatic agents. Gal-3 (Galectin-3) is a lectin that interacts with cells, and its high expression promotes the proliferation, adhesion, and invasion of tumor cells as well as tumor angiogenesis [99]. Pectin was pretreated by alkali and found that increasing content of RG-I could significantly increase pectin bioactivity, and yet the DE seemed to present a slight influence on anti-cancer activity [100]. The modified pectins exhibit a significant decrease in MW and DE as well as an enormous rise in solubility as compared to natural pectin.

Anti-inflammatory activity

Inflammation is thought to be a normal bodily response to injury or infection that aids in the healing of neurological disorders, cancer, metabolic diseases, and cardiovascular disease, and reducing chronic inflammation is a primary strategy for preventing these diseases [101]. It is a defence mechanism in which the immune system releases chemicals to combat infection and damaged tissue. Inflammation can be either acute, subacute, or chronic. Polysaccharides found in plant cell walls improve the efficacy of treating inflammatory conditions. Inflammation pathology is a complex process caused by microbial pathogens such as viruses, bacteria, prion proteins, and fungi [102, 103]. Lipopolysaccharides (LPS) can excite macrophages, however they are primarily employed as an inflammatory model.The LPS-induced RAW 264.7 (cell lines mouse macrophages) is usually utilized as the anti-inflammation model detecting in vitro [104]. Starfruit (*Averrhoa carambola* L.) contains a water-extractable polysaccharide that has been shown to possess antinociceptive and anti-inflammatory properties in a formalin model, also it has potential health advantages, and may be useful in therapeutic intervention for the management of inflammatory pain. The polysaccharides from S. fruticosa (SFP) can be a new source of an analgesic and anti-inflammatory agent or antioxidant with promising merits for healthy nutrition and therapy [105]. According to study, the anti-inflammatory activity of citrus pectin shows in vivo after oral administration in mice [106].

Immunoregulatory activity

Immunomodulators are natural or manufactured compounds that regulate the immune system [107]. They can elicit immunomodulatory activities by modifying or affecting immune cell systems, resulting in the desired immunological response. They are classified as immunostimulants or immunosuppressives based on their mode of action [108]. Immunomodulators are extracted from animal and plant tissues by biosynthetic, chemical synthesis, and genetic engineering approaches (Fig. 3). Pectin is a critical factor in determining the immunosuppressive activity. More than 80% of pectin contains galacturonic acid residues, which inhibit macrophage activity and delayed-type hypersensitivity. Significantly, the branching area of pectin activates phagocytosis while simultaneously increasing antibody synthesis [109]. The degree of methyl esterification and extent of polymerization influence the immunomodulatory activities of pectin, and these factors can be considered while utilizing it to enhance the immune status [110].

Anticoagulant activity

Pectin possesses anticoagulant activity, which is determined by the number of sulphate groups in the pectin macromolecules (Fig. 3). Pectin sulphate and its derivatives have been investigated as an alternative to heparin in biological applications. Multiple investigations have shown that the structure, degree of sulphate substitution, and molecular weight of sulfated pectin all influence its anticoagulant activity [111]. Sulfated pectins with identical structures but bigger MW demonstrate a higher anti-coagulant efficacy in an in vivo assay [112].

Hypoglycemic activity

Pectin has the potential to improve diabetes problems by lowering oxidative stress, encouraging healthy gut flora, and slowing carbohydrate decomposition. These processes reduce postprandial blood glucose levels and increase glucose tolerance, lowering the development of AGEs [113]. Pectin can alter starch digestibility in vitro by increasing the viscosity of digesta and decreasing amylase activity through intermolecular interactions [114].

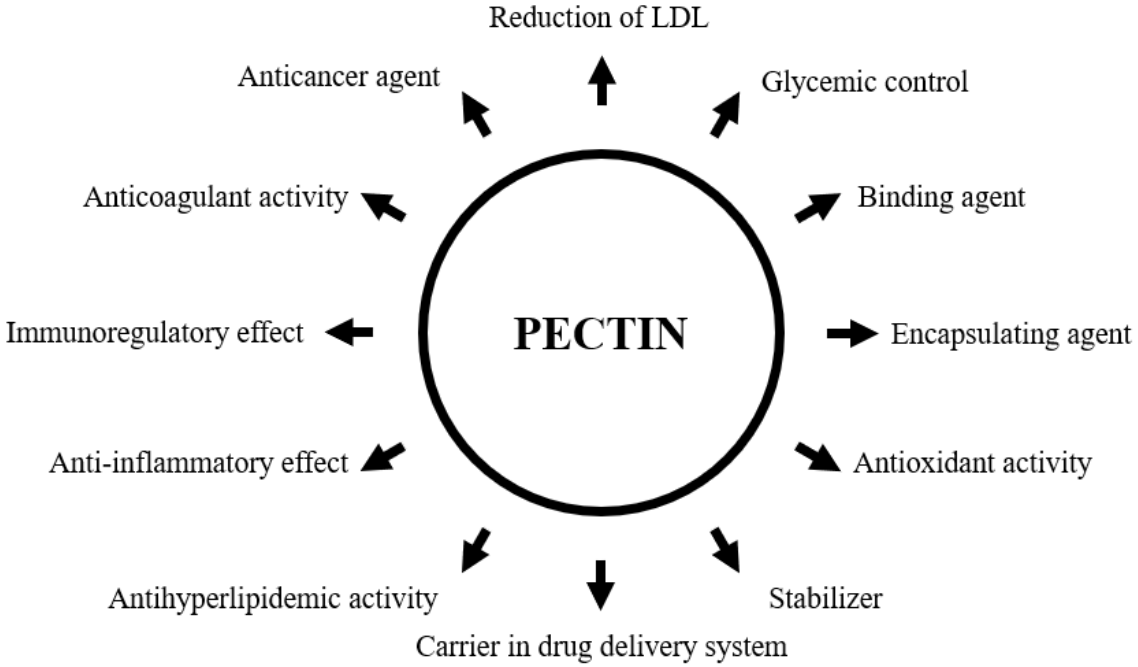

Figure 3: Pharmacological activity of pectin

CONCLUSION

Pectin is widely used as a food additive, nutritive, thickener, emulsifier, and stabilizer in a variety of food, pharmaceutical and cosmetic industries. Its use as a fat and sugar substitute with a rising need for low-calorie foods is expected in the future. Although its presence in an abundance of plant species, pectin offers limited commercial sources. Therefore, in order to obtain pectin of the desired quality at tributes, it is essential to explore alternative sources of pectin or modify those that are currently available. Current trends highlight significant advancements in the extraction, characterization, and bioactivities of pectin. Pectin is currently more accessible for industrial uses through modern methods like enzymatic and microwave-assisted extraction which enhanced its yield and efficiency. Extensive characterization techniques like spectroscopy and chromatography have improved comprehension of the molecular makeup and functional characteristics of pectin. Bioactivities of pectin, specifically its anti-inflammatory, anti-cancer, anti-microbial, and antioxidant qualities have provided novel possibilities for its utilization in the health and wellness domain. Additionally, pectin is potentially an eco-friendly and sustainable substitute for synthetic polymers that fits in with the rising demand. Despite these developments, there continue to be difficulties with scaling up manufacturing methods, improving the consistency of bioactivity assessments, and optimizing extraction techniques. Future research should focus on addressing these issues as well as investigating new and innovative applications of pectin in the domains of drug delivery and environmental sustainability.

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AUTHOR CONTRIBUTION
Both the authors have equally contributed in writing this review.

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