Recent Advances in Pectin Extraction Techniques, Characterization, and Applications

Yan Zhao[1,2], Jianping Zhang[1], Huafa Huang[1], Qinghui Wu[1], Yanjun Huang[1], Xiucai Liu[1], Teng Long[1], Zechun Liu[1,*] , Wei Xie[1,**]

[1]Technology Center, China Tobacco Fujian Industrial Co., Ltd, Xiamen 361021, PR China.
[2]College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, PR China.

Abstract. This review comprehensively focuses on pectin, a versatile plant-derived polysaccharide with diverse applications in food, pharmaceutical, environmental, and industrial domains. The article presents the latest technological advancements in pectin extraction from diverse botanical sources. The discussion highlights innovative methodologies and optimized extraction parameters that enhance both yield and purity. Exploring pectin's structural characteristics and their critical relationship to functional performance, underpinning its multifunctional applications. Particular emphasis is placed on emerging sustainable extraction approaches that align with the growing demand for natural biomaterials. The review concludes by identifying main research directions that will drive future developments in this field, reflecting pectin's significantly as an eco-friendly functional ingredient.

1 Recent Advances in Pectin Extraction Techniques

1.1 Pectin Extraction from Various Plant Sources

Pectin can be extracted from various plant sources using different techniques, each yielding distinct physicochemical properties. Comparative studies of conventional citric acid extraction (CE), microwave-assisted extraction (MAE), and pulsed ultrasound-assisted extraction (PUAE) revealed that CE achieved the highest yield (20.80%), while PUAE-produced pectin contained the greatest galacturonic acid content (88.53 g/100 g) [1]. Structural characterization of pectin from apple, carrot, onion, and tomato demonstrated source-dependent variations, with apple pectin showing the highest degree of methylesterification (78.41±0.83%) and carrot pectin exhibiting minimal co-eluted cell wall polymers [2].

Premna microphylla Turcz leaves have been explored as an alternative pectin source, with microwave-assisted extraction under RSM-optimized conditions yielding 18.25% pectin [3]. Additional agricultural byproducts, including muskmelon peels, melon peels, and husk tomato waste, have also demonstrated pectin-extraction potential. While melon peel waste yielded highly esterified pectin with superior prebiotic activity upon hydrolysis [4]. Husk tomato waste provided pectin with >60% anhydrogalacturonic acid content [5].

1.2 Innovative Methods for Pectin Extraction

Innovative pectin extraction techniques seek to address the drawbacks of traditional methods, which are often time-consuming, energy-intensive, and environmentally harmful. Pectin has been extracted from grapefruit peel using microwave-assisted high-pressure CO_2/H_2O (MW-$HPCO_2$). Under optimal conditions (147 °C, 3 min, and 10 mL g^{-1}), a 27.53% pectin yield was achieved, surpassing the traditional method in both yield and physicochemical properties [6].

A study comparing pulsed ultrasound-assisted extraction (PUAE) and hot-acid extraction (HAE) from onion waste revealed that while HAE achieved higher pectin yields (16.22% for HAE versus 9.83% for PUAE), PUAE was more efficient in terms of time and energy, requiring only 15 minutes compared to 90 minutes for HAE[7]. The extraction of pectin from Artocarpus integer peel using malonic acid-based deep eutectic solvents (DES) was optimized through response surface methodology (RSM). The optimal conditions for different DES systems were determined, and the extracted pectin had desirable properties for food industry applications [8].

2 Characterization of Pectin Structures

2.1 Structural Analysis of Pectin from Different Sources

Pectin has complex structure (Figure 1 [9]) composed of homogalacturonan (HG), rhamnogalacturonan-I (RG-I),

Corresponding authors: * lzc10497@fjtic.cn; **xw10481@fjtic.cn

and rhamnogalacturonan-II (RG-II). The main sources for pectin extraction include citrus fruits, apples, and their processing by-products such as citrus peels and apple pomace [10]. Additional sources comprise sugar beet [11], pumpkin, watermelon, pear, and potato pulp.

Pectin structures exhibit considerable variability across botanical sources. Studies indicate that sugar beet pectin is characterized by elevated acetyl group and neutral sugar content, along with reduced molecular weight, leading to diminished gelling capacity. Conversely, sunflower head residue, which is an oil extraction byproduct, displaying higher galacturonic acid concentration and increased molecular weight, resulting in enhanced gelling performance [12].

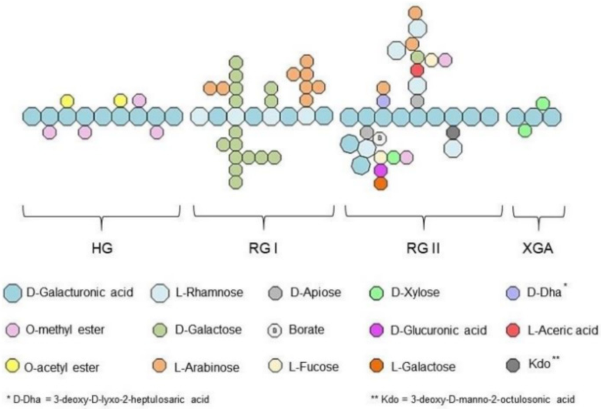

Figure 1. Chemical structure of the pectin molecule[9]

2.2 Techniques for Determining Pectin Molecular Weight and Composition

Significant researches have been made in pectin characterization methodologies in recent years. For molecular weight determination, three advanced techniques have been developed: High-Performance Size-Exclusion Chromatography (HPSEC) coupled with triple detection enables comprehensive molecular parameter analysis [13]. The novel copper ion photometric method improves quantification accuracy through copper-pectinate complex formation, eliminating weighing steps while enhancing reproducibility (CV $< 2\%$) [14]. Moreover, diffusion-ordered NMR Spectroscopy (DOSY) with Partial Least Squares Regression (PLS) modeling provides precise average molecular weight measurements with lower errors (RMSE $< 5\%$) [15].

Structural characterization of pectin involves three key methods: monosaccharide composition analysis utilizing High-Performance Anion Exchange Chromatography (HPAEC), High-Performance Liquid Chromatography (HPLC), and Gas Chromatography (GC-MS). On the one hand, functional group identification including methyl esters and acetyl groups; and glycosidic linkage analysis through methylation or enzymatic methods. On the other hand, for degree of esterification (DE) measurement, while titrimetry offers operational simplicity, it tends to overestimate values, whereas FT-IR spectroscopy yields more accurate results by calculating the peak area ratio between esterified (1740 cm^{-1}) and non-esterified (1600 cm^{-1}) carboxyl groups ($R^2 > 0.98$) [16].

2.3 Impact of Extraction Methods on Pectin Structure

The yield and properties of pectin are influenced by both the raw material sources and the extraction methods. The researches have shown that the content and structural characteristics of pectin significantly among different plant materials, while the extraction method further affects the final pectin yield and quality parameters. Table 1[17] shows that the extraction yield, galacturonic acid content, and esterification degree of pectin from different sources and methods. It can be seen that novel techniques such as ultrasound-microwave-assisted extraction can significantly improve pectin yield compared to traditional acid extraction. For example, the extraction rate from apple pomace can reach 40.66%, representing an increase of approximately 15–20% over conventional methods.

Pectins are classified as high degree of esterification (HM) (DE > 50%) or low degree of esterification (LM) (DE < 50%). Raw materials such as papaya peel and apple pomace yield pectin with a high degree of esterification (>50%), it suitable for gelling applications in food products [18]. In contrast, materials like dragon fruit peel and melon peel produce low-methoxyl pectin (degree of esterification <50%), with galacturonic acid content ranging between 45.17% and 82.00%. Notably, temperature and pH can modify the molecular structure of pectin, which affecting the galacturonic acid content and functional properties.

Table 1 The extraction yield, galacturonic acid content, and esterification degree of pectin from different sources and methods

Source	Extraction Method	Yield (%)	Galacturonic Acid Content (%)	Degree of Esterification (%)
Dragon fruit peel	Acid extraction	2.60	-	28.34
	Ultrasound-assisted extraction	15.67	-	-
Watermelon peel	Acid extraction	1.24	45.17	-
	Microwave-assisted extraction	25.79	-	-
Melon peel	Acid extraction	29.48	48.00	29.33
Potato pomace	Acid extraction	11.70	-	-
	Alkali extraction	23.10	-	-
	Enzymatic extraction	6.00	-	-
	Microwave-assisted extraction	13.79	-	-
Pomelo peel	Acid extraction	16.20	-	-
	Alkali extraction	17.90	-	-

	Subcritical water extraction	19.60	-	-
	Ultrasound-assisted extraction	24.02	-	-
	Enzyme-ultrasound-assisted acid extraction	27.01	-	-
Papaya peel	Enzymatic extraction	28.67	-	62.40
Apple pomace	Acid extraction	26.84	64.48	56.08
	Enzymatic extraction	40.66	57.39	89.41

3 Pectin's Versatile Roles in the Food Industry

3.1 Pectin's Role as a Gelling Agent in Food Products

The gelling properties of pectin originate from its unique ability to form a three-dimensional network structure. It composed of a solid phase, effectively entraps and immobilizes liquid components, thereby establishing a stable gel system with rigid characteristics. Table 2 [19] presents an overview of studies on pectin as a gelling agent and its applications in semi-solid and fluid foods. It is precisely this distinctive structural feature that renders pectin an excellent natural gelling agent, endowing it with significant application value in the food industry.

Table 2. Studies on pectin as a thickening and gelling agent and its application in food

Pectin Type	Food Application	Pectin Concentration (%, w/v or w/w)	Rheological Findings
Apple peels (HM*)	Flavored probiotic yogurt drinks	0.1–0.5	Shear-thinning behavior; gel-like network at low frequencies. 0.5% pectin yielded highest G′, G′′, and storage stability.
Apple pomace (AP)	Set-type yogurt	0.1–1.0	1.0% AP at 4°C increased G′ vs. control, producing firmer, more consistent gel without disrupting gelation.
Citrus peels (HM)	High-protein cultured milk drinks	0.15–1.00	All concentrations formed gels. Aged samples with higher pectin (≥0.85%) exhibited elastic bond formation.
Citrus peels (LMA*)	Acidified camel milk	0.5–2.0	Dose-dependent G′ increase (stronger gels). Pectin-casein micelle complexes confirmed via mechanical spectra.
Citrus peels (LM*)	Low-fat set yogurt	0.05–1.00	Pseudoplastic shear-thinning. LM pectin enhanced G′ and G′′, suggesting strengthened protein network bonds.
Citrus peels (HM)	Black plum peel marmalade	0.3–0.6	Pectin concentration ↑ correlated with ↑ apparent viscosity, firmness, and consistency.
Citrus peels (TLMA*)	Vegan gummy candies	4.0	All samples showed gel behavior (G′>G′′). Emulsion-filled gels (EFG) had higher G′ vs. nonfilled gels, indicating a stronger 3D polymer network.

3.2 Application of Pectin in Food Preservation and Shelf-life Enhancement

Materials made from pectin can significantly prolong the shelf life of food items. A polyhydroxybutyrate-carboxymethyl cellulose-pectin-thymol conjugate coating was applied to prolong tomato shelf life. The film with 0.9% thymol showed excellent mechanical, antioxidant, and antimicrobial properties, and it extended the shelf-life of tomatoes up to 15 days by preventing weight loss, preserving firmness, and delaying changes in biochemical constituents [20].

Pectin modified with resorcinol and 4-hexylresorcinol was utilized for meat preservation. The grafting modification improved pectin's antioxidative and antibacterial properties. The modified pectins successfully inhibited pork spoilage, with 4-hexylresorcinol-modified pectin demonstrating the greatest improvement in extending pork shelf life [21]. Peach gum polysaccharide-based edible coatings effectively preserved cherry tomatoes during cold storage by maintaining firmness, reducing weight loss, inhibiting respiration, and delaying changes in total acidity, ascorbic acid, and sugar content [22].

3.3 The Contribution of Pectin to Food Nutritional Enhancement

Pectin contributes to the nutritional enhancement of foods. As a dietary fiber, it can influence digestion and health. Plant-derived polysaccharides, such as pectin, are key components of the human diet. Pectin can modulate gut microbiota, which is beneficial for gut health. Pectic substances may alleviate gut inflammation and symptoms of inflammatory bowel disease [23].

In the development of functional foods, pectin can be used in combination with other ingredients. Enzymatic hydrolysis of pectin can produce oligomers with potential applications in human nutrition. Pectin can also interact with proteins in food systems, affecting protein digestibility and the bioavailability of nutrients.

Polysaccharides can decrease protein digestibility by modifying protein structure, enhancing the viscosity of the digestive environment, or inhibiting digestive enzymes [24].

4 Pectin in Pharmaceutical and Biomedical Applications

4.1 Pectin-based Drug Delivery Systems

Pectin-based drug delivery systems demonstrate significant potential. Pectin-based hydrogels have been developed as robust and versatile vehicles for oral administration. These systems can be tailored to include substances like surfactants to modify drug release patterns. Using tolbutamide as a model drug, varying surfactants influenced the drug release kinetics. Freshly prepared matrices conformed to the Higuchi model, whereas freeze-dried matrices aligned with the Korsmeyer-Peppas model [25].

Acylhydrazone-derived whole pectin-based hydrogels have been developed as injectable drug delivery systems. Hydrogels synthesized from oxidized pectin (OP) and diacylhydrazine adipate-functionalized pectin (Pec-ADH) through acylhydrazone linkage demonstrated excellent cytocompatibility with L929 cell lines and significant inhibitory effects on MCF-7 cell lines. They also had a high equilibrium swelling ratio and could persistently release 5-FU for more than 12 h [26]. Pectin-based nanostructures have emerged as promising carriers for drug and gene delivery, owing to their inherent biocompatibility, biodegradability, and low immunogenicity, which facilitate effective encapsulation of therapeutic payloads.

4.2 Applications of Pectin in Wound Healing and Tissue Engineering

Pectin-based materials hold significant promise for applications in wound healing and tissue engineering. Mussel-inspired tissue adhesive composite hydrogels prepared from pectin have been developed for burn wound healing. The hydrogels, composed of dopamine-grafted oxidized pectin (OPD) and naphthoate hydrazide-terminated PEO with incorporated Fe^{3+} ions, demonstrated effective hemostasis, biocompatibility, and photothermal properties. The in vivo wound-healing experiment demonstrated that the hydrogel decreased inflammation and accelerated the healing process [27].

Research has explored the use of multifunctional hydrogels composed of oxidized pectin and gelatin for wound healing applications. Oxidized pectin cross-linked with gelatin demonstrated effective wound healing in albino rats. The study examined the cross-linking parameters, swelling behavior, and gelatin release of the hydrogels, confirming they were non-hemolytic and did not induce adverse symptoms [28]. The more experimental results presented in Table 3 [29] collectively validate pectin as a versatile biomaterial, with demonstrated success in wound healing, drug delivery, and tissue engineering applications.

Table 3. Applications of pectin in biomedical fields

Application	Goals	Results
Nanocomposite Hydrogel	To fabricate SP@ZIF-8-PEG-TK nanoparticles encapsulated in sodium alginate-pectin hydrogel for wound healing.	Nanoparticles enhanced fibroblast proliferation (↑35%) and macrophage inflammatory response modulation (TNF-α↑, IL-10↓). 2.Full-thickness wound models showed 90% closure within 14 days (vs. 60% control).
Drug-Delivery Hydrogel	To design pectin-theophylline hydrogels for controlled release in wound dressings.	1.Pectin concentration (5–10% w/v) linearly correlated with sustained release kinetics (R^2=0.98). 2. Achieved 80% drug release over 72 hours.
Wound Dressing Composite	To develop pectin-gelatin matrices loaded with Aloe vera and curcumin for accelerated wound healing.	1. Achieved 80% wound closure in 6 days (vs. 30% control). 2. Exhibited synergistic anti-inflammatory effects (IL-6↓60%).

5 Environmental and Industrial Applications of Pectin

5.1 Pectin in Wastewater Treatment and Environmental Remediation

Pectin and its derivatives have potential applications in wastewater treatment. Pectin-nano zero-valent iron nanocomposites have been studied for their effectiveness in removing heavy metals and their antibacterial properties against waterborne pathogens. The nanocomposite, derived from banana peel pectin and nanoscale zero-valent iron, demonstrated high efficiency in removing chromium-lead mixtures from water. Optimal adsorption conditions were identified, and the nanocomposite showed no phytotoxic or ecotoxic effects [30].

A nanocomposite composed of pectin, chitosan, and zinc oxide has been employed for the adsorption and photocatalytic remediation of carbamazepine in water samples. Pectin derived from waste biomass and its modified forms serve as flocculants, adsorbents, nanobiopolymers, biochar, hybrid materials, metal-organic frameworks, and scaffolds for removing heavy metals, ions, toxic dyes, and other contaminants from wastewater [31].

5.2 Use of Pectin in Biodegradable Packaging Materials

Pectin is increasingly being used in biodegradable packaging materials. Composites made from pectin and cellulose nanofibers have demonstrated great promise for use in modified atmosphere packaging (MAP). These composites, when coated on parchment and used to package refrigerated or sliced fruits, can regulate humidity.

Biodegradable food packaging films have been created using lemon peel pectin and chitosan, enhanced with neem leaf extract. The properties of the films, including physical, optical, mechanical, and antimicrobial characteristics, varied with the concentration of neem leaf extract. The application of films extended the shelf life of apricot fruits by 50% at room temperature [32]. Pectin/starch films enhanced with zinc oxide nanoparticles have been created as an eco-friendly option for biodegradable packaging. These films exhibited excellent processability, transparency, low water vapor permeability, favorable mechanical properties, and high biodegradation rates under natural disposal conditions.

5.3 Industrial Applications of Pectin in Textile and Paper Industries

Pectin-modifying enzymes and pectin-derived materials are utilized in the textile and paper industries. Pectin methylesterases (PME) can be used in these industries. The combination of PME from Datura stramonium with polygalactourenase (PGA) enhanced the clarity of juices from orange, apple, pomegranate, and pineapple. The enzyme exhibited peak activity at 60 °C and pH 9 with 0.3 M NaCl, maintaining stability at 70 °C [33].

Alkaline pectate lyase shows potential for development in the textile, pulp, and paper industries. A modified pectin lyase (PGLA-rep4) from Bacillus clausii showed improved catalytic activity. The enzyme exhibited optimal activity at a pH of 11.0 and a temperature of 70 °C, demonstrating a high efficiency in cleaving methylated pectin. The enzyme exhibited an activity of 554.0 U/mL, with a post-purification specific activity of 822.9 U/mg [34]. Pectin can also be used in the production of biopolymeric films in the packaging-related aspects of these industries, contributing to the development of sustainable packaging solutions [35].

6 Future Perspectives and Challenges in Pectin Research

6.1 Emerging Trends in Pectin Research and Development

Emerging trends in pectin research focus on sustainable and multifunctional applications. Interest in utilizing pectin for active and intelligent packaging is increasing. Pectin-based active packaging incorporates antimicrobial and antioxidant agents, including ascorbic acid and essential oils, to inhibit bacterial growth and absorb oxygen and moisture. Intelligent packaging made from pectin can track food quality in real-time using integrated color-changing indicators [36].

In the realm of biomedicine, electrospun pectin nanofibers are gaining attention as a promising material. Their unique features, including compatibility with biological systems, ability to degrade naturally, and potential for functionalization, make them ideal for use in wound healing. Through the integration of bioactive agents and the combination of pectin with other polymers, enhancements in mechanical, biological, and therapeutic properties are being achieved [23]. Research is also exploring the use of pectin in the development of novel therapeutic agents for diseases like type 2 diabetes mellitus, as pectin has shown potential in regulating glucose metabolism and improving insulin sensitivity [37].

6.2 Challenges in Scaling Up Pectin Production

Scaling up pectin production faces several challenges. A primary concern involves pectin's inherent properties, including low elasticity and high hygroscopicity, which may impact the quality of final products. For instance, the production of edible films using pectin may face limitations in packaging applications due to these properties [38].

Another challenge lies in the commercial-scale manufacturing technologies. The existing extraction methods, such as conventional acid extraction, are often time- and energy-consuming, and they may also produce acidic effluents and cause equipment corrosion. Transitioning to more sustainable and efficient extraction methods, like those using deep eutectic solvents or enzyme-assisted extraction, on a large scale requires significant investment in new equipment and process optimization. Maintaining consistent pectin quality in large-scale production is challenging due to raw material variability, which can affect both extraction yield and the properties of the final product [39].

6.3 Potential for Novel Pectin Applications in Various Industries

Pectin has significant potential for novel applications in various industries. In the food industry, pectin hydrogels can be further developed for 3D printing applications. Low-methoxyl pectin gels, with their viscoelastic properties, adaptable microstructure, and texture properties, can be used as food inks. This could enable the creation of customized food products with enhanced nutritional and functional properties [40].

In the environmental field, pectin-based materials can be explored for more complex pollutant removal. For example, pectin-based hydrogels can be designed to target emerging pollutants, such as endocrine-disrupting compounds or pharmaceuticals in wastewater. Pectin-based nanocomposites can be developed for targeted drug delivery systems. Altering the surface of pectin-based nanoparticles enables targeted delivery to specific cells or tissues, enhancing drug efficacy and minimizing side effects [41].

7 Conclusions

In conclusion, pectin research has made significant progress in recent years, with advancements in extraction techniques, characterization methods, and diverse applications across food, biomedical, and environmental sectors. The ability to extract pectin from various sources using innovative methods, understand its structural and functional properties through advanced analytical techniques, and apply it in multiple industries showcases its potential. Future research should address the development of solvent-free or neoteric solvent-based pectin extraction methods to comply with green chemistry principles, particularly regarding safer solvents and auxiliaries, scaling up production and standardizing pectin - based products for commercial use. However, current literature demonstrates limited application of such green extraction techniques, indicating a significant knowledge gap that requires further investigation. By overcoming these challenges, pectin can play an even more significant role in sustainable development, contributing to a greener and healthier future.

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