

Pectin-Based Biopolymer Films: From Structural Properties to Smart Food Packaging

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Abstract—Pectin is a naturally occurring polysaccharide, which is widely extracted from plant cell walls and identified as a promising biopolymer for food packaging. Due to its extensive film-forming capacity, intrinsic gelling properties and biodegradable properties, pectin makes it a perfect replacement for the petroleum-based plastics, especially in the food packaging sector. In food packaging sector, bioplastics are preferred rather than petroleum-based plastics since these petroleum-based plastics tend to degrade into microplastics and enter our bodies during the intake of plastic-covered food. This review critically examines the structural and physicochemical properties of pectin that influence the film formation, including the degree of esterification, molecular weight, and interactions with other biopolymers and nanoparticles. This review mainly focuses on adapting strategies to enhance the mechanical strength, barrier performances, and thermal stability through chemical modifications, cross-linking of polymers and incorporation of various bioactive agents.

This review further explores advances in smart pectin-based films, i.e., films with anti-microbial, anti-oxidant, and pH-responsive functionalities, enabling real-time monitoring of food quality and shelf-life extension. Currently, there are various challenges such as scalability, cost-effectiveness, and regulatory considerations which are also discussed in this review. Overall, this review highlights the potential of pectin-based biopolymer films as a next-generation solution for sustainable and intelligent food packaging.

Index Terms—Bioplastic, Pectin, Sustainability, Smart packaging, Biopolymer, Eco-friendly

I. INTRODUCTION

In the current food packaging sector, petroleum-based plastics are widely used owing to their low-production cost, durability and flexibility. However,

this has become a global concern due to their persistence in the environment, contribution to microplastic pollution, and greenhouse gas emissions from petrochemical production. These environmental issues have hastened the quest for biodegradable and renewable replacements for petroleum-based packaging. Pectin is a natural carbohydrate polymer belonging to anionic heteropolysaccharide family. It is primarily extracted from various residues from citrus peel, apple pomace, and other agro-industrial by-products. It has been found to be an innovative candidate for the formation of eco-friendly packaging materials because it is biodegradable, safe, and has natural film-forming capability (Guzzi et al., 2023; Said et al., 2025).

Pectin has a complex structure based on homogalacturonan and rhamnogalacturonan domains, which owes its main physical properties to its degree of esterification (DE) and molecular size. Pectins with high DE (>50%) form firm gels, whereas low-DE types tend to need ionic crosslinking via divalent cations to form gels with equivalent mechanical rigidity (Guzzi et al., 2023). These structural characteristics render pectin highly flexible, with room for modification and compounding with other biopolymers to increase mechanical and barrier performance (Said et al., 2025). Nonetheless, regardless of its possibility, pure pectin films are constrained by brittleness, hydrophilicity, and poor water vapor resistance, making them ineligible for immediate use in food packaging (Priyadarshi et al., 2023).

In a bid to overcome these limitations, recent approaches involved hybrid and nanocomposite films. The addition of polylactic acid (PLA) to bilayer systems has greatly enhanced tensile strength,

elongation, and barrier properties, lowering water and oxygen permeability by several orders of magnitude (Wang et al., 2024). Also, the incorporation of poly(ϵ -caprolactone) nanoparticles has increased tensile strength by almost 3.5-fold with good barrier and thermal stability (Chen et al., 2024). Zinc oxide (ZnO) particle nanocomposites have also been shown to provide robust antimicrobial properties in addition to enhancing structural stability (Khan et al., 2024).

In addition to structural reinforcement, pectin films are being increasingly developed as active and intelligent packaging. Through the inclusion of essential oils, plant extracts, nanoparticles, or natural colorants, scientists have created films with antioxidant, antimicrobial, and hydrophobic properties (Guzzi et al., 2023; Said et al., 2025). Intelligent packaging systems containing natural colourimetric indicators such as anthocyanins and curcumin are especially interesting, as they have the potential to provide visible indicators of food freshness through colour change, providing consumers with immediate feedback regarding food quality (Said et al., 2025). Such technologies are of particular interest in shelf-life extension for delicate foods such as meat and seafood.

Equally significant is the dimension of sustainability: pectin comes from cheap agricultural waste, consistent with circular economy principles. Waste sources not only minimize raw material costs but they also valorize by-products from food processing operations, thereby supporting environmental sustainability (Zhang et al., 2022). Fatty acid or phenolic acid-coated modified pectins also exhibit enhanced hydrophobicity and additional bioactive characteristics, thus enhancing their promise as environmentally friendly packaging solutions (Priyadarshi et al., 2023).

Together, these results show the potential of pectin as a biopolymer for packaging purposes. Although technical issues such as moisture sensitivity and production scalability are still present, innovations in composite design, functionalization, and integration of smart functionalities suggest that pectin-based films may have a key role to play in moving toward greener and more intelligent food packaging systems. This review critically reviews the structural bases of

pectin, chemistries for improving mechanical and barrier properties, and the addition of active and intelligent functionalities, and considers the current challenges and future prospects for commercial translation.

II. STRUCTURAL FEATURES OF PECTIN RELATED TO FILM FORMATION

Pectin is a structural heteropolysaccharide whose backbone is mostly made of α -(1,4)-linked D-galacturonic acid (GalA) with variable methyl-esterification, which determines its film-forming and gelation behavior. The degree of esterification (DE) or methoxylation strongly affects the balance between hydrogen-bonding (common in high-esterified pectins) and ionic crosslinking (in low-esterified pectins), thus influencing the resulting film's network structure (Said et al., 2025).

Recent work further emphasizes that pectin's source and molecular structure (GalA content, degree of esterification, chain length) are key to its film performance: films based on hybrid citrus pectins, for example, show distinct mechanical and barrier properties depending on those structural variables (Said et al., 2025; Xue et al., 2025). A 2024 study achieved "multi-crosslinked" pectin-based plastic films (modified pectin chains + Fe³⁺ ions) that displayed very high mechanical strength and ultra-low gas permeability, illustrating the potential of structural modification to overcome traditional limitations of pectin films (Qiang et al., 2024).

All this modern research confirms that structural tuning (source, DE, chemical modification, crosslinking) remains central to optimizing pectin for film formation and functional packaging.

III. SOURCES OF PECTIN

Pectin is largely present in fruits and vegetables. To be more specific, pectin is present in high quantities in citrus-based fruits (apples, lemons, oranges, etc.). They are also present in vegetables such as carrots, potatoes, beets, etc. Apple pomace and citrus peels have been considered as industrial pectin since they are largely used as a source of pectin in various

industries, especially the food and pharmaceutical industries. Some of the berry fruits such as raspberry, blueberry, strawberry and red currant were also found to have pectin, but not in large quantities.

IV. EXTRACTION METHODS

4.1 ACID EXTRACTION

Acid extraction is the primary commercial method for producing pectin. Traditionally, pectin is extracted by acid extraction using dilute organic or mineral acids (e.g., hydrochloric, nitric, citric) under high heat (50–100°C for 30 minutes to 6 hours) to hydrolyze plant cell walls and mobilize pectin. The key advantages of acid extraction are it is simple, cheap, and easy to adopt but tends to degrade key structural components of pectin (e.g., side chains), degrade molecular integrity, and creates environmentally unfriendly acidic waste streams (Lu et al., 2023; Zoghi et al., 2023).

4.2 MICROWAVE-ASSISTED

Conversely, microwave-assisted extraction (MAE) involves the use of microwave irradiation to rapidly heat the extraction medium internally through the oscillation of polar molecules. This results in effective cell disruption and quick pectin release. MAE provides increased extraction yields within a reduced timeframe, with lower solvent consumption and minimal thermal degradation as compared to traditional heating (Zoghi et al., 2023; Greener Pectin Extraction Techniques, 2025).

4.3 ULTRA-SOUND ASSISTED

Ultrasound-assisted extraction (UAE) utilizes acoustic cavitation—microbubble formation and collapse—to rupture plant tissue and facilitate solvent penetration. UAE shortened the extraction time energy input, and solvent usage while enhancing pectin yield and quality (Zoghi et al., 2023; Sustainability Challenges, 2021).

4.4 HYBRID TECHNIQUE

Combining with other techniques, ultrasound–microwave-assisted extraction (UMAE) or ultrasound–enzyme-assisted extraction (UEAE) increases both extraction yield and pectin functionality further. Hybrid methods allow enhanced

cell disruption, mass transfer, and retain techno-functional (e.g., emulsifying, rheological) and biofunctional (e.g., antioxidant, anti-inflammatory) properties (Cui et al., 2019; Recent Advances in extracting pectin, 2019).

4.5 ENZYMATIC METHODS

Enzymatic extraction involves the use of special enzymes (e.g., polygalacturonases or pectinases) to sequentially degrade cell wall structures and dissolve pectin. The process is mild, producing high-quality pectin with intact molecular properties. Yet, it's expensive, time-consuming, and difficult to implement industrially (Zoghi et al., 2023; Source, Extraction... PMC, 2010).

4.6 HIGH PRESSURE

High-pressure-assisted extraction (e.g., high-pressure pulses) enhances extraction by driving cell permeability and solvent diffusion without high temperatures. It is high in penetration and energy efficiency but demands special equipment and is currently constrained in scope of application (Source, Extraction... PMC, 2010).

4.7 SUB-CRITICAL WATER

Lastly, subcritical water extraction (SWE) or hot compressed water extraction employs water at elevated temperature (100–200°C) and pressure to remain in liquid state, lowering dielectric constant and raising solvent polarity and reactivity. The acid-free green approach avoids the use of acids and selectively removes pectin while retaining structural areas such as rhamnogalacturonan-I (RG-I). SWE provides pure pectin with distinguishing biofunctional characteristics, albeit where too much heat can destroy structures and diminish elasticity (Basak et al., 2022; Lu et al., 2023).

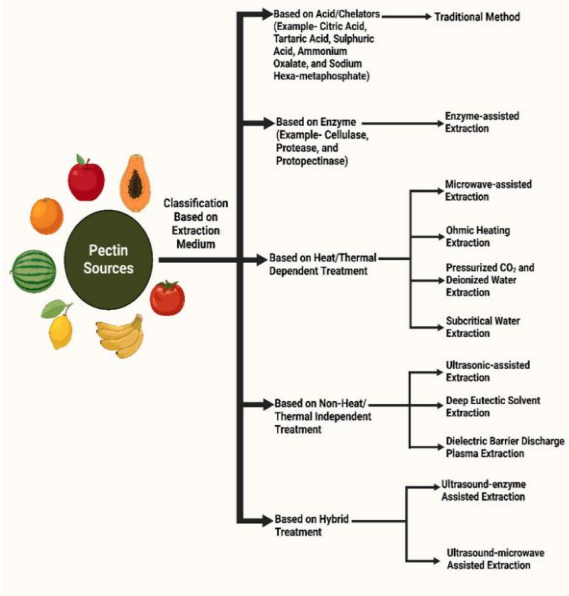


Fig. 1. Various extraction methods (Kalita et al., 2025).

V. FILM-FORMING SOLUTIONS: VISCOSITY, PLASTICIZERS, AND COMPOSITE FORMULATIONS

5.1 VISCOSITY AND CASTING BEHAVIOUR:

Recent studies show that pectin film-forming solutions can be tuned for optimal casting. For example, incorporation of pectin into composite matrices increases solution viscosity appropriately, enabling smooth film formation and controlled thickness in final films — an important parameter for industrial-scale film casting (Xue et al., 2025; Said et al., 2025).

5.2 ROLE OF PLASTICISERS AND ADDITIVES:

Plasticizers remain essential to impart flexibility. A 2025 study on pectin films derived from citrus waste reported that increasing glycerol concentration affects film thickness, water solubility, moisture content, water vapor permeability (WVP), and mechanical properties — underscoring that plasticizer concentration must be carefully optimized based on intended application (Akachat et al., 2025).

Similarly, pectin films blended with essential oils (e.g., lemon oil) or other bioactive components show altered mechanical and barrier behaviors, indicating that additives not only provide functionality

(antimicrobial, antioxidant) but also influence the polymer network and film integrity (Akachat et al., 2025; Castillo-Rodríguez et al., 2025).

5.3 COMPOSITE AND MULTILAYER FILMS

Because pure pectin films often struggle with moisture sensitivity or mechanical brittleness, many recent works adopt composite or bilayer strategies. For instance:

- A bilayer film combining pectin with a biodegradable polymer (PLA) optimized water and oxygen barrier properties, dramatically improved stretchability (elongation at break), and lowered solubility compared with single-layer films (Said et al., 2024).
- Incorporation of nanomaterials or crosslinking agents (e.g., in multi-crosslinked pectin films) has yielded films with enhanced gas barrier, mechanical strength, moisture resistance and even UV and biodegradability performance — pointing toward pectin-based alternatives to conventional plastics (Qiang et al., 2024).

These composite approaches, therefore, appear increasingly promising for real-world food packaging and coating applications.

VI. MECHANICAL PROPERTIES OF RECENT PECTIN-BASED FILMS

Pure pectin films — especially without plasticizers or composite reinforcement — still may exhibit limited flexibility. A 2025 study on citrus-waste pectin showed that glycerol addition improved elongation but tended to compromise tensile strength (Akachat et al., 2025).

By contrast, pectin-based composite films show a much broader and improved property range. For example:

- Pectin–PLA bilayer films achieved elongation at break (EAB) of ~460%, a dramatic improvement over single pectin films; tensile strength remained moderate but adequate for flexible packaging applications (Said et al., 2024).
- Multi-crosslinked pectin films (modified pectin + metal-ion crosslinking) demonstrated very high mechanical strength, indicating that chemical modification is a viable route to overcome

mechanical limitations of native pectin (Qiang et al., 2024).

Thus, recent research suggests that pectin films' mechanical limitations can be effectively addressed via blending, chemical modification, or multilayer design — strategies that significantly expand their applicability beyond low-stress uses.

VII. BARRIER PROPERTIES

7.1 WATER VAPOUR /MOISTURE BARRIER:

A recurring drawback of pectin films is moisture sensitivity. However, modern studies have made notable progress:

- A 2025 study on citrus-derived pectin films with optimized glycerol content demonstrated significantly improved water vapor resistance and controlled moisture content — indicating that formulation optimization can mitigate moisture sensitivity (Akachat et al., 2025).
- Composite films (e.g., pectin-PLA bilayer) achieved very low water vapor permeability — orders of magnitude lower than single-layer pectin films — due to extended diffusion path length and tight intermolecular interactions in the bilayer structure (Said et al., 2024).
- Multi-crosslinked pectin films reported in 2024 exhibited favorable moisture resistance compared to many conventional hydrophilic biopolymers, along with other enhanced properties (Qiang et al., 2024).

7.2 GAS/OXYGEN BARRIER:

Pectin's dense polymer network and high hydrophilicity make it a strong candidate for oxygen barrier applications. A 2025 review on pectin-based active and smart films highlights their excellent oxygen barrier properties, which help reduce respiration rate and prolong shelf life of perishable produce (Said et al., 2025).

Added modifications such as nanomaterials, crosslinking, or bilayer design further refine these barrier properties while keeping the films biodegradable and eco-friendly (Qiang et al., 2024; Xue et al., 2025; Said et al., 2025).

VIII. FUNCTIONAL APPLICATIONS AND COMPOSITE BEHAVIOUR

A 2025 study developed antifungal pectin coatings enriched with polyphenols from natural extracts (HNE-PLE), significantly reducing water vapour permeability and improving tensile strength while preventing fungal deterioration in papaya over 15 days — demonstrating the feasibility of combining mechanical performance with active preservation (Ribeiro et al., 2025).

Pectin-essential oil films (e.g., with lemon oil) have been optimised to balance barrier, mechanical, and functional properties, offering biodegradable alternatives for food packaging while delivering antioxidant/antimicrobial effects (Akachat et al., 2025; Castillo-Rodríguez et al., 2025).

More complex pectin-based films — such as multi-crosslinked plastics — have shown in lab settings excellent gas/moisture barrier, high mechanical strength, UV-blocking, and biodegradability, indicating potential as sustainable substitutes for conventional plastics in certain applications (Qiang et al., 2024).

Additionally, recent comprehensive reviews stress that combining pectin with other polymers (polysaccharides, proteins), nanomaterials, or functional additives can rectify the drawbacks of single-component pectin films, broadening their use-case to functional packaging, coatings, and biodegradable films (Xue et al., 2025; Said et al., 2025; Li et al., 2024).

IX. EMERGING TRENDS

A central objective of current research on pectin-based films is to establish a detailed understanding of how pectin's structural attributes—such as degree of esterification, molecular architecture, and extraction-induced modifications—govern its film-forming behavior, mechanical strength, and barrier functionalities. Numerous studies have demonstrated that extraction techniques, whether eco-friendly subcritical water, ultrasound-microwave combinations, or enzyme-assisted methods, significantly alter pectin chain length, esterification patterns, and branching structures, ultimately influencing gelling capacity, moisture resistance, and

tensile performance (Basak & Annapure, 2022; Cui et al., 2019; Gharibzahedi et al., 2019; Lu et al., 2023; Yang et al., 2019; Yu et al., 2021). These structural shifts govern functional outcomes such as thermal stability, biocompatibility, and water vapor permeability, reinforcing the strong connection between extraction-driven modifications and final material properties (Chandel et al., 2022; Dranca et al., 2018; Sila et al., 2020; Zhang et al., 2022).

In parallel, recent research has highlighted the development of novel composite and hybrid pectin films designed to overcome the mechanical fragility and moisture sensitivity commonly associated with pure pectin matrices. Blends incorporating polylactic acid, starch, chitosan, cellulose nanocrystals, or nanoparticles such as ZnO and poly(ϵ -caprolactone) have been reported to enhance tensile strength, hydrophobicity, antimicrobial activity, and overall barrier properties well beyond those of unmodified pectin films (Chen et al., 2024; Khan et al., 2024; Lara-Espinoza et al., 2018; Priyadarshi et al., 2023; Wang et al., 2024). These functional composites also serve as platforms for embedding bioactive compounds—including antioxidants, antimicrobials, essential oils, and phenolic extracts—which enable pectin films to operate as active packaging materials capable of extending food shelf life by reducing microbial spoilage and delaying oxidation (Guzzi et al., 2023; Priyadarshi et al., 2023; Nisar et al., 2020).

Another rapidly expanding research direction involves smart pectin-based packaging films incorporating naturally derived pH-sensitive pigments such as anthocyanins, curcumin, and betacyanins. These pigments undergo quantifiable color changes in response to biochemical alterations during food spoilage, allowing real-time monitoring of freshness in products such as meat, dairy, and seafood. Studies using *Brassica oleracea* anthocyanins and other plant-based indicators have successfully demonstrated clear colorimetric responses that correlate with changes in pH, temperature, and microbial activity, confirming their promising role as consumer-friendly spoilage indicators (Abdullah et al., 2023; Lopez et al., 2023; Wang et al., 2025; Priyadarshi et al., 2023).

Finally, emerging literature consistently highlights the relevance of a circular economy approach in pectin research. A significant proportion of modern pectin extraction work focuses on valorizing agricultural residues—including fruit pomace, citrus peels, durian rind, broccoli stalks, tomato waste, and other by-products—thereby reducing processing waste and supporting environmentally conscious packaging solutions (Marić et al., 2018; Dranca et al., 2018; Sila et al., 2020; Peighambardoust et al., 2024; Zoghi et al., 2023). By integrating sustainable extraction with advanced materials engineering, pectin-based films have emerged as promising candidates for eco-friendly, functional, and intelligent packaging systems aligned with global sustainability objectives.

X. FUTURE DIRECTIVES

Although much has been accomplished, there are a number of gaps and opportunities that will guide the future of biopolymer films made from pectin:

Improving Moisture and Barrier Properties: Pectin's hydrophilicity is still a major limitation. The future should aim to investigate novel crosslinking mechanisms, hydrophobic surface modifications, and the addition of nanofillers (e.g., graphene oxide, clay, cellulose nanocrystals) to enhance water resistance and oxygen barrier capability at the expense of biodegradability.

Scalability and Industrial Translation: All such studies are mostly done at laboratory scale. To proceed toward commercialization, consideration must be given to the cost-effective, up-scalable extraction and film-forming technologies (extrusion, roll-to-roll casting, electrospinning) that are compatible with industry food packaging needs. Integration with current plastic processing lines will be important.

Smart Packaging Integration: Science should further progress the creation of multi-functional smart films that integrate freshness indicators, antimicrobial properties, and nutrient preservation. Natural colorimetric indicators' stability during storage and under fluctuating environmental conditions should be

enhanced, perhaps through encapsulation or nanocarrier systems.

Safety, Toxicology, and Regulatory Approval: While pectin is GRAS and food-grade, the addition of nanoparticles, essential oils, and other adjuncts requires stringent toxicological tests, migration studies, and regulatory clearances prior to industrial implementation. Future research needs to provide data backing regulatory guidelines for commercial use.

Life Cycle and Environmental Assessment: Extensive life cycle assessment (LCA) research must be conducted to assess the environmental merits of pectin films in comparison to petroleum-based plastics and other biopolymers. These studies will give measurable indicators of sustainability in the form of carbon footprint, biodegradability, and end-of-life disposal.

Blending with Other Emerging Biopolymers: Synergistic mixing of pectin with proteins (gelatin, soy protein, whey), polysaccharides (starch, alginate, carrageenan), and synthetic biodegradable polymers (PLA, PCL) must be tuned to provide customized mechanical and barrier properties for various food types.

Valorization of Various Agro-Residues: Future studies should focus on enlarging the pectin extraction scope from underutilised agro-residues such as broccoli stems, sugar beet pulp, and durian rind. The creation of environmentally friendly extraction processes (e.g., subcritical water, ultrasound, enzyme-assisted) will not only enhance yield but also minimize environmental footprints.

XI. CONCLUSION

In conclusion, the outcome of this review is to determine pectin as a renewable and sustainable biopolymer material of great potential in food packaging, and most importantly, in active and intelligent packaging systems. In the future, research using biopolymers for food packaging needs to balance technical optimization, safety validation, sustainability evaluation, and commercialization strategies. If these hurdles are addressed

methodically, pectin-based biopolymer films can be one of the dominant alternatives to traditional plastics, paving the way for a future of intelligent, safe, and sustainable food packaging.

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