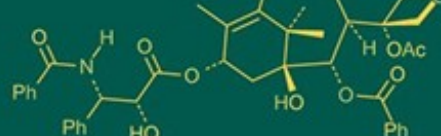


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Pectin-based edible packaging: advances in extraction, film development and fresh produce preservation

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ABSTRACT

Growing environmental concerns over petroleum-based plastic packaging have increased interest in sustainable, biodegradable, and edible alternatives for food packaging applications. Pectin, a naturally occurring plant polysaccharide, has gained considerable attention as a promising biomaterial for edible packaging due to its biodegradability, biocompatibility, non-toxicity, and excellent film-forming ability. Moreover, recovering pectin from fruit and vegetable processing by-products supports agro-waste valorisation and aligns with circular economy principles. This review discusses major pectin sources and recent extraction technologies, including conventional acid extraction and green methods such as microwave-assisted, ultrasound-assisted, enzyme-assisted, subcritical water extraction that critically influence yield and structural attributes governing film functionality. Fabrication strategies for pectin-based edible films, particularly solvent casting and extrusion, are evaluated, with emphasis on the role of plasticizers in modulating film microstructure and functionality. Future research must optimise green extraction, composite/active systems, and cost-effective large-scale production for sustainable food packaging. Overall, pectin-based edible films provide a promising approach for sustainable food packaging and agro-industrial valorisation.

Keywords: Pectin, Extraction, Edible film, Food packaging

1. Introduction

Petroleum derived polymers, particularly conventional plastics, are extensively employed in food packaging because of their versatility, lightweight nature, durability, transparency, and ease of processing. However, their persistence in ecosystem and contribution to plastic pollution have driven intense interest in sustainable, bio-based and edible alternatives aligned with circular economy principles. (Mellinas *et al.*, 2020; Syarifuddin *et al.*, 2025) [31, 44]

Among the naturally occurring biopolymers, pectin a high-value heteropolysaccharide abundant in the primary cell walls and middle lamella of plant tissues, has emerged as a promising material for edible packaging due to its excellent film-forming ability, biodegradability, biocompatibility and non-toxicity. Although citrus peels and apple pomace are widely recognised as conventional sources of pectin, recent studies have increasingly explored the utilisation of diverse agro-industrial residues, including banana peels, watermelon rinds, pumpkin waste and cocoa husks, as alternative sources for pectin recovery and value addition. (Roy *et al.*, 2023) [40]

However, the conversion of agricultural residues into high quality pectin suitable for edible film production presents several extraction and processing challenges. Conventional hot-acid extraction is often associated with prolonged processing durations, high energy requirements, chemical waste generation and uncontrolled degradation of the polymer structure. To overcome these limitations, environmentally friendly extraction approaches, including ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE) and enzymatic extraction, have gained increasing attention. These techniques offer high efficiency, shorten processing time and better preservation of pectin structure.

Pectin-based edible films have considerable potential for maintaining the quality of fresh and minimally processed foods by regulating moisture and gas transfer. Such films can contribute to reducing respiration and moisture loss, delaying physiological deterioration and ultimately extending the shelf life of perishable commodities. (Chandel *et al.*, 2022; Tristante *et al.*, 2024) [8, 47] However, the inherent brittleness and limited flexibility of pectin films can restrict their practical application. The incorporation of appropriate plasticizers and optimisation of film-formulation and processing conditions are therefore necessary to enhance flexibility, mechanical strength and overall film performance. (Tak *et al.*, 2019) [45]

Against this background, the present review provides an overview of recent advances in pectin extraction from conventional and emerging agricultural resources, emphasising how extraction techniques influence the structural and functional properties of the recovered pectin. It further examines recent developments in the formulation of pectin-based edible films, including their barrier, mechanical, functional characteristics, ac

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tive packaging applications across different food systems, major technological limitations and future research opportunities for developing efficient, scalable and environmentally sustainable pectin-based packaging solutions.

2. Pectin

Pectin is an abundant and structurally complex heteropolysaccharide primarily obtained from the cell walls and middle lamellae of terrestrial plants. It is particularly rich in dicotyledonous plants and non-graminaceous monocots, where it constitutes approximately 30-35% of the primary cell wall polysaccharides. (Mohnen, 2008) [34] Pectin plays a crucial structural role in maintaining cell adhesion, wall porosity, and mechanical strength of the cell wall. Owing to its biodegradability, biocompatibility, non-toxicity, and excellent physicochemical properties, pectin has gained considerable importance in the food, pharmaceutical, and biomedical industries. Pectin was first isolated in 1825 by the French chemist Henri Braconnot (Adetunji *et al.*, 2017) [1] Chemically, it is predominantly composed of linear chains of α - (Adetunji *et al.*, 2017; Belkheiri *et al.*, 2021) [1, 4]- linked D-galacturonic acid (GalA) units, which form the backbone of the polymer. The galacturonic acid content typically exceeds 65%, a characteristic that defines commercial pectin (Mohnen, 2008) [34] The carboxyl groups at the C-6 position of GalA residues may be partially esterified with methanol to form methyl esters, whereas some hydroxyl groups may be acetylated. (Willats *et al.*, 2006) [52] The extent of methyl esterification and acetylation significantly influences solubility, gelling behaviour, and interaction with other biopolymers. Structurally, pectin is one of the most complex polysaccharides in nature and is organized into three principal domains: homogalacturonan (HG), rhamnogalacturonan I (RG-I), and substituted galacturonans, which include rhamnogalacturonan II (RG-II) and xylogalacturonan (XGA) (Mohnen, 2008; Roy *et al.*, 2023) [34, 40] Homogalacturonan (HG) is the most abundant pectin types, comprising approximately 65% of the pectin polysaccharide. The HG region, known as “smooth” pectin, contains linear chains of α - (Adetunji *et al.*, 2017; Belkheiri *et al.*, 2021) [1, 4]-linked D-galacturonic acid residues, which may be partially methyl-esterified at the C-6 carboxyl group and occasionally acetylated at the O-2 or O-3 positions (Voragen *et al.*, 2009) [51] This domain plays a major role in gel formation. In low-methoxyl pectin, gelation occurs through calcium-mediated ionic cross-linking between free carboxyl groups via the well-known “egg-box” model, whereas high-methoxyl pectin forms gels under acidic conditions and high sugar concentrations through hydrogen bonding and hydrophobic interactions. (Belkheiri *et al.*, 2021) [4] Rhamnogalacturonan (RG) is a branched region of pectin and is subdivided mainly into rhamnogalacturonan I (RG-I) and rhamnogalacturonan II (RG-II). RG-I region, known as “hairy” pectin, consists of a repeating disaccharide backbone of α - (Adetunji *et al.*, 2017; Anoraga *et al.*, 2024) [1, 2]-L-rhamnose and α - (Adetunji *et al.*, 2017; Belkheiri *et al.*, 2021) [1, 4]-D-galacturonic acid, with side chains of neutral sugars such as arabinose and galactose attached to the rhamnose residues. (Mukhiddinov *et al.*, 2000) [35] These side chains significantly influence the solubility, viscosity, and emulsifying properties of pectin. RG-II, although present in smaller quantities, possesses a highly complex and conserved structure containing rare sugars. It contributes to cell wall stability through borate-diester cross-linking and plays a critical role in maintaining plant cell wall integrity. (Mohnen, 2008; Chandel *et al.*, 2022) [34, 8] Xylogalacturonan (XGA) is a rarely expressed type of pectin, usually found only in the reproductive tissues of plants. It is another substituted HG structure in which the β -linked xylose at the O-3 position is further substituted with another β -linked xylose at O-4. (Roy *et al.*, 2023) [40]

3. Sources of pectin

The mere presence of high pectin content in fruits and vegetables does not determine their suitability as commercial raw materials for pectin extraction. (Thakur *et al.*, 1997) [46] Although widely distributed in terrestrial plants, only selected sources are commercially vi-

able because of considerations such as yield, extraction efficiency, gelling quality, availability of raw materials, and economic feasibility. Pomace, a by-product often discarded during fruit and vegetable processing, holds significant potential for pectin extraction. Currently, commercial pectin is primarily obtained from agro-industrial byproducts such as apple pomace and citrus peels, alternatively, other sources of pectin comprise of cocoa husk, sunflower heads, sugar beet, pumpkin, watermelon, and pears. Citrus peels (from lemon, lime, orange, and grapefruit) contain approximately 20_30% pectin on a dry weight basis, while apple pomace contains about 10_15% pectin. (Srivastava *et al.*, 2011) [41] These sources differ in structural and functional characteristics, with citrus pectin generally characterised by higher galacturonic acid content and superior gelling properties, whereas apple pectin contains higher neutral sugars and exhibit distinct rheological behaviour. Thus, the choice of raw material significantly influences the purity, degree of esterification, neutral sugar composition, and functional performance of the extracted pectin in food and pharmaceutical applications.

4. Pectin extraction

Pectin extraction is the initial step in purifying pectin from plant materials, aiming to maximise yield while preserving quality. The process relies on mass transfer into the extraction solvent, where acid and heat hydrolyse protopectin in the cell wall, releasing soluble pectin that diffuses into the liquid phase. Extracted pectin is then filtered, concentrated, precipitated using alcohol or other non-solvents, washed, and dried. Both conventional hot-acid extraction and advanced methods such as ultrasound, microwave, and enzyme-assisted extraction are widely employed, with efficiency governed by pH, temperature, time, acid type, and liquid-to-solid ratio. Key quality indicators of the extracted pectin include yield, degree of esterification, and galacturonic acid content. (Chandel *et al.*, 2022; Picot-Allain *et al.*, 2022) [8, 38]

4.1 Conventional methods of extraction

The most common method used for industrial pectin production from plant sources is the conventional acid extraction (CAE) also termed acid-assisted extraction. This method generally involves low pH (1.5_3.0) and high temperature (75_100°C) treatment of the pectin source for up to 3 h. The extraction of pectin using conventional methods requires high temperature treatment and, subsequently high energy input. Conventional extraction depends on several factors, such as temperature, pH, solvent properties, solid-to-solvent ratio, particle size, and diffusion rate. (Marić *et al.*, 2018) [29]

Inorganic or mineral acid, including sulfuric acid, hydrochloric acid, and nitric acid, are commonly used in pectin extraction due to their low cost and strong hydrolysing ability, as they readily release hydrogen ions to convert protopectin into soluble pectin. However, despite their effectiveness, mineral acids raise environmental and safety concerns and may overly break down pectin molecules. Traditional mineral acid extraction has limitations, including the degradation of valuable plant compounds, loss of volatile components, higher production costs, and environmental risks. (Kumar *et al.*, 2020) [22] In contrast, organic acids are increasingly preferred as environmentally friendly alternatives, as they tend to cause less depolymerisation and better preserve the molecular weight and functional properties of pectin. The use of organic acids instead of mineral acids in the extraction of pectin leads to reduced hydrolysis and depolymerization. Citric acid was reported to be a less pectin-degrading agent compared to HCl (Picot-Allain *et al.*, 2022) [38] Hydrochloric acid, having a higher acid dissociation constant, produces a higher concentration of hydrogen ions to hydrolyse pectin and form lower molecular weight polymers.

4.2 Microwave assisted extraction

Microwave-assisted extraction (MAE) is an advanced green technology that utilises non-ionizing electromagnetic radiation (typically 0.915–2.45 GHz) to achieve rapid, eco-friendly biopolymer recovery. Unlike conventional conductive heating, MAE delivers targeted, vol

umetric heating directly to the solvent-matrix mixture, significantly reducing extraction times, energy consumption, and organic solvent usage (Venkatesh *et al.*, 2004; Kumar *et al.*, 2020)^[49, 22]

The mechanism relies on dielectric heating caused by dipole rotation and ionic conduction within polar solvents and the plant matrix. Rapid volumetric heating generates intense localised internal pressure, breaking down cell walls and improving capillary porosity. This structural disruption enhances solvent penetration, accelerates mass transfer, and promotes fast diffusion of pectin into the extraction medium. (Belkheiri *et al.*, 2021; López-Salazar *et al.*, 2023)^[4, 26] Microwave power (W) directly dictates the heating rate and internal pressure buildup, making it a critical process parameter alongside pH, irradiation time, and solid-to-liquid ratio. (Kute *et al.*, 2015)^[25] By enabling precise control over thermal degradation, MAE maximises yield while helping preserve key functional characteristics of the extracted pectin.

4.3 Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) is a versatile method widely used in food processing for various purposes such as extraction, drying, emulsification, homogenisation, and the inactivation of microbes and enzymes. It is a non-thermal and efficient method that enhances pectin yield and quality while reducing processing time, energy, and solvent consumption (Chemat *et al.*, 2017; Panwar *et al.*, 2023)^[9, 37] Ultrasonic waves are mechanical vibrations with frequencies above the upper limit of human hearing (approximately 20 kHz). In UAE, frequencies typically ranging from 20 to 100 kHz are commonly employed. It generates high shear force due to the implosion of cavitation bubbles; rupture of the biological membranes, and penetration of the solvent in cellular materials. Extraction temperature is a key determining factor governing the quality of pectin. Ultrasound treatment can modify the structural and functional properties of pectin, including reducing molecular weight, altering the degree of methylation, and degrading neutral sugar side chains. It may also enhance antioxidant activity and influence the rheological properties of pectin. (Zhang *et al.*, 2013)^[54] The efficiency of UAE depends on factors such as ultrasound frequency and intensity, sonication time, solvent type, and temperature. Among these, frequency strongly affects cavitation behaviour and mass transfer; higher frequencies generally produce smaller bubbles with lower cavitation intensity. (Kumar *et al.*, 2021)^[23]

4.4 Enzyme-assisted extraction (EAE)

This method also known as biological extraction, employs enzymes to break down the plant cell wall by hydrolysing cellulose or hemicellulose, aiding in the release of pectin trapped within the complex network. Commonly used enzymes include cellulase, protopectinase, hemicellulase, and xylanase. Enzymatic treatment cleaves the glycosidic bonds in pectin, reducing the solution's viscosity and thereby making filtration and centrifugation easier. (Belkheiri *et al.*, 2021)^[4] Enzyme-assisted extraction of pectin depends on the ability of enzymes to exhibit reactions with accurate specificity and selectivity. The extraction of pectin using enzyme-assisted extraction presents several benefits, namely, (i) no corrosion of equipment by acids; (ii) low processing temperature is required, thereby reducing energy consumption; (iii) specificity of enzymes produce increased quality pectin (Marić *et al.*, 2018)^[29]. The disadvantages include the higher reaction time, the high cost of the enzymes, which prohibits their implementation by industries, and the variable results obtained due to enzyme strain differences. (Dang *et al.*, 2025)^[13] Enzymatic extraction demonstrates diverse conditions suited to different pectin sources, each emphasising the optimisation of enzyme types, concentrations, and specific extraction parameters to enhance yield and properties.

4.5 Subcritical water extraction (SWE)

SWE is one of the most promising green extraction technologies, also known as pressurized hot water extraction or superhot water extrac-

tion (Hawthorne *et al.*, 2000)^[18]. It is an efficient method for isolating pectin from plant sources like fruit peels and agro-waste, using water at high pressure and moderate temperatures (100–160 °C) to hydrolyse protopectin into soluble pectin. The specific properties of water, such as boiling point, polarity, and dielectric constant, alter systematically with temperature, resulting in increased diffusion rates and reduced viscosity and surface tension, allowing water to behave similarly to organic solvents at elevated temperatures. As water's dielectric constant falls from 79 at 25 °C to about 33 at 200 °C, extracting both ionic and non-ionic components is possible. It is widely considered safe and suitable for isolating diverse bioactive compounds for food and pharmaceutical applications. The subcritical extraction method has high extraction efficiency and causes no pollution to the environment, though it may alter the physical and chemical properties of pectin. The advantage of this process is that the extraction rate is faster and acid solvents limited (Hawthorne *et al.*, 2000; Anoraga *et al.*, 2024)^[18, 2].

5. Characterisation of extracted pectin

Characterisation of extracted pectin is essential for assessing its quality, functionality and suitability for food and edible-packaging applications. Pectin properties are strongly influenced by the source material and extraction conditions, with important parameters including degree of esterification (DE), methoxyl content, galacturonic acid (GalA) content, molecular weight, rheological behaviour and thermal stability.

The degree of esterification, which represents the proportion of galacturonic acid residues esterified with methyl groups, is a major determinant of pectin functionality. Pectin is generally classified as high-methoxyl pectin (DE > 50%) or low-methoxyl pectin (DE < 50%). High-methoxyl pectin forms gels primarily through hydrogen bonding and hydrophobic interactions under acidic conditions and high soluble-solids concentrations, whereas low-methoxyl pectin forms calcium-mediated egg-box networks through interactions between free carboxyl groups and divalent cations (Ciriminna *et al.*, 2017)^[11]. Methoxyl content and GalA concentration are also important indicators of pectin structure and purity, with higher GalA content generally reflecting greater pectin purity and potential for effective polymer-network formation.

The rheological properties of pectin are governed by molecular weight, concentration, degree of methylation, pH, temperature and ionic interactions. Higher molecular weight and polymer concentration generally increase viscosity through enhanced chain entanglement, while calcium ions and methylation influence gelation and viscoelastic behaviour (Chan *et al.*, 2017)^[7]. Thermal characteristics, commonly assessed using differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA), provide further information on moisture loss and the thermal degradation of the polysaccharide matrix. These structural, rheological and thermal characteristics collectively determine the processing behaviour and functional performance of pectin in edible film applications (Kazemi *et al.*, 2019; Majid *et al.*, 2023)^[21, 28].

6. Pectin-based edible films

Edible films are thin, food-grade layers formed from biodegradable biopolymers that provide a protective barrier between food and the surrounding environment. They help regulate the transfer of moisture, oxygen, carbon dioxide and other solutes, thereby contributing to the maintenance of quality and extension of shelf life. Various polysaccharides, proteins and lipids have been investigated as film-forming materials; among them, pectin has attracted considerable attention because of its abundance, excellent film-forming capacity, transparency, biodegradability and biocompatibility (Rostamabadi *et al.*, 2024; Tristante *et al.*, 2024)^[39, 47].

Pectin-based films can also serve as carriers for functional compounds such as antimicrobials, antioxidants and flavouring agents, providing opportunities for the development of active packaging systems (Tak *et al.*, 2019)^[45]. Their semi-permeable nature enables con-

trolled moisture and gas transfer, which can reduce water loss and respiration, delay senescence and help maintain firmness, colour and other quality attributes of fresh produce (Chandel *et al.*, 2022)^[8]. Incorporation of plasticizers, particularly glycerol, improves chain mobility and flexibility while reducing brittleness, thereby enhancing the suitability of pectin films for practical packaging applications. These films can also be fabricated into three-dimensional structures such as edible pouches, which provide additional protection and facilitate handling of food products (Behrooznia *et al.*, 2024)^[3]. The functional performance of pectin-based films is closely associated with the structural characteristics of pectin, particularly GalA content and DE. These properties influence the mechanical strength, moisture resistance and gas-barrier characteristics of the resulting films (Çavdaroglu *et al.*, 2023)^[6]. For successful food-packaging applications, pectin films should combine adequate mechanical and barrier properties with safety, biodegradability, desirable sensory characteristics, cost-effectiveness and scalability. Thus, optimisation of pectin composition and film-formulation conditions is essential for developing efficient and commercially viable edible packaging systems.

6.1 Formation of edible film

The formation of edible films involves the dispersion or dissolution of film-forming biopolymers in suitable solvents, followed by the incorporation of functional additives such as plasticizers, antimicrobials, colourants and flavouring agents. Controlled heating and pH adjustment may be applied to improve polymer dispersion and solution homogeneity. The resulting film-forming solution is subsequently cast onto a suitable surface and dried under controlled conditions to obtain a continuous and stable film matrix. Pectin is particularly suitable for edible film formation because its galacturonic acid backbone and abundant hydroxyl and carboxyl groups facilitate intermolecular interactions and film development. Film characteristics are strongly influenced by pectin molecular weight and degree of esterification. Low-methoxyl pectin can form rigid, ionically cross-linked networks in the presence of calcium ions, while high-methoxyl pectin generally produces more flexible films. The incorporation of plasticizers, particularly glycerol, sorbitol and polyethylene glycol, enhances polymer-chain mobility, reduces brittleness and improves film flexibility and handling properties (Vieira *et al.*, 2011; Roy *et al.*, 2023)^[50, 40]. The fabrication method and formulation parameters substantially influence the mechanical, barrier and optical properties of edible films. Therefore, appropriate selection and optimisation of polymer concentration, plasticizer type and concentration, pH, temperature, drying conditions and other functional additives are essential for producing pectin-based films with the desired properties for food packaging applications (Minzanova *et al.*, 2018)^[33].

6.1.1 Spraying method

Film spraying is a wet-process method used to create food-packaging films by atomizing and spraying a film-forming solution onto a surface to produce a thin, uniform film. The film-forming solution is prepared by dissolving biopolymers in water or a water-based solvent and adding any required ingredients such as plasticizers or active compounds. This solution is then atomized and sprayed onto a substrate using dedicated spray equipment; the droplets merge on the substrate to create a continuous liquid layer, which is subsequently dried through solvent evaporation. The properties and uniformity of the resulting film are influenced by the pectin type and concentration, solution viscosity, spray parameters, substrate characteristics, and drying conditions. Optimisation of these factors is therefore essential for obtaining films with desirable flexibility, thickness, and barrier properties (Gaona-Sánchez *et al.*, 2016)^[17].

6.1.2 Casting methods

Solution casting is the most commonly employed wet process technique for developing pectin-based films in food packaging applications, primarily because it is the simplest laboratory-scale film-forming method. The process has three primary steps: dissolution, casting,

and drying. First, a suitable solvent is chosen to dissolve the polymer, and the polymer is mixed thoroughly into the solvent by stirring. Next, the uniform solution is poured into a prepared mold to shape an even film. Finally, as the solvent evaporates during drying, polymer chain mobility decreases, promoting intermolecular hydrogen bonding and chain entanglement that solidify the polymer matrix into a structural film. Its main advantage is that films can be produced easily without specialized equipment. Since most food-processing materials cannot be moulded at higher temperatures without causing permanent structural changes, the lower temperature during processing is another advantage. Drawbacks include its restriction to sheet formation, lengthy drying times, and poor suitability for large-scale production (Flórez *et al.*, 2023; Pan *et al.*, 2025)^[15, 36].

6.1.3 Extrusion method

Extrusion is the widely applied method for producing polymeric films at commercial scale. No solvent is required in the extrusion method, and high viscosity polymers can be used. Extrusion offers several key benefits: it eliminates the need for solvents, allows efficient processing of high viscosity polymers under diverse temperature and pressure conditions which cannot be offered by solvent casting and results in films with superior mechanical strength, elongation, and transparency. The procedure of extrusion consists of three zones: 1) feeding zone, the polymers are treated by rotating screws with increasing pressure, mixed together and carried into next zone; 2) kneading zone, where mechanical shear promotes mixing and increases the strain, temperature and density of the material; and 3) heating zone, when the temperature above glass transition temperature (T_g), heating and plasticization will take place, and this procedure is related to the thermo-plastic performances of film components (Suhag *et al.*, 2020; Roy *et al.*, 2023; Pan *et al.*, 2025)^[42, 40, 36].

6.2 Properties of pectin-based edible film

The functional performance of pectin-based edible films is governed by their mechanical, barrier, optical, thermal, and functional properties, which collectively determine their effectiveness as food-packaging materials. These properties are influenced by pectin type and concentration, degree of esterification, polymer composition, plasticizers, cross-linking agents, blending polymers, active compounds, and processing conditions such as drying temperature, casting technique, and film thickness (Butler *et al.*, 2023; Syarifuddin *et al.*, 2025)^[5, 44]. Mechanical properties, including tensile strength, elongation at break, elastic modulus, and puncture resistance, are essential for maintaining film integrity during handling and storage. Pectin generally forms strong but relatively brittle matrices because of extensive hydrogen bonding and restricted polymer-chain mobility. Plasticizers such as glycerol, sorbitol, and polyethylene glycol improve flexibility and elongation by increasing chain mobility, although excessive incorporation can reduce tensile strength and increase moisture sensitivity (Galus *et al.*, 2013; Pan *et al.*, 2025; Syarifuddin *et al.*, 2025)^[16, 36, 44].

Barrier properties determine the transfer of moisture and gases between the food and surrounding environment and consequently influence product shelf life. Although the hydrophilic nature of pectin limits its water resistance, barrier performance can be improved through blending with other biopolymers, incorporation of hydrophobic components, and cross-linking. Plasticizers generally increase water-vapour permeability, whereas pectin films can provide effective oxygen barriers, making them useful for oxygen-sensitive foods (Butler *et al.*, 2023; Pan *et al.*, 2025)^[5, 36]. Optical characteristics such as transparency, opacity, colour, and UV-blocking capacity are also important for product visibility and protection against light-induced deterioration. These properties can be modified through film composition, thickness, and incorporation of phenolic extracts, essential oils, or other UV-absorbing compounds (Pan *et al.*, 2025)^[36].

In addition to providing passive protection, pectin films can function as active packaging systems by incorporating antioxidants, antimicrobials, essential oils, and plant extracts. Such bioactive components

can inhibit oxidation and microbial growth, thereby contributing to improved food quality and extended shelf life. However, their incorporation may alter the mechanical and barrier characteristics of the films, necessitating careful optimisation of concentration, compatibility, controlled release, and stability within the polymer matrix (Butler *et al.*, 2023; Syarifuddin *et al.*, 2025)^[5, 44].

7. Pectin-based packaging for fresh produce preservation

Fruits and vegetables are highly prone to postharvest losses caused by mechanical injury, moisture loss, increased respiration, and microbial deterioration. Pectin-based edible films and coatings offer a sustainable approach to minimize these losses by forming semi-permeable barriers that regulate gas exchange and moisture transfer, thereby reducing respiration, delaying senescence, and maintaining quality during storage (Huang *et al.*, 2021; Bourtoom, 2008; Kumar *et al.*, 2023; Mariño-Cortegoso *et al.*, 2025)^[19, 24, 30].

Pectin is particularly suitable for horticultural applications because of its gel-forming capacity, biocompatibility, and natural availability. Its performance can be further enhanced through incorporation of essential oils, fatty acids, plant extracts, and nanomaterials, which improve moisture resistance, flexibility, and antimicrobial activity while helping preserve sensory quality (Chandel *et al.*, 2022; Behrooznia *et al.*, 2024)^[8, 3]. However, wider commercial adoption is constrained by production costs, regulatory requirements, processing challenges, and concerns regarding nanoparticle migration and safety (Kumar *et al.*, 2023; Mariño-Cortegoso *et al.*, 2025)^[24, 30]. Nevertheless, pectin-based packaging represents a promising circular and sustainable alternative to conventional plastics for reducing postharvest food losses. Recent studies in this area are summarised in Table 2.

8. Challenges and future prospects

Commercial-scale production of pectin based edible films remains constrained by the low efficiency, high energy demand, and environmental concerns associated with conventional acid extraction. Although emerging green extraction technologies offer more sustainable alternatives, their industrial implementation requires substantial investment in equipment, process optimisation, and scale-up. In addition, variability in raw materials can lead to inconsistencies in pectin yield, composition, and functional properties, making quality standardisation a major concern for large-scale production. Consumer acceptance is further influenced by the film's appearance, colour, odour, taste, texture, safety, and cost. The moisture sensitivity and limited mechanical strength of pectin films may restrict their use under demanding packaging conditions. Therefore, successful commercialisation requires cost-effective processing, consistent quality, regulatory compliance, improved film performance, and greater consumer awareness. Future research should prioritise sustainable pectin extraction, scalable processing, and the development of multifunctional packaging systems. Incorporating natural antioxidants, antimicrobial agents, essential oils, microcapsules, and nanomaterials could improve the protective performance and sensitivity of active and intelligent packaging. Approaches like microencapsulation, nanomaterial use, and QR or barcode-based tracking are being developed to improve packaging indicators' sensitivity and consumer accessibility. Further studies should evaluate processing efficiency, film performance, life-cycle impacts, economic feasibility, safety, regulatory compliance, and consumer acceptance to support commercialisation and promote the conversion of agro-industrial waste into sustainable packaging materials.

Table 1. Pectin sources, extraction conditions and resulting pectin characteristics

Source	Extraction method	Extraction conditions	Yield (%)	Pectin characteristics	Reference
Watermelon rind	Conventional heat extraction	pH 2.0 , 90 °C , 100 min	18.20	High equivalent weight (1000 g/mol), GalA 68.5%,	Mamiru and Gonfa 2023 ^[32]
Mango peel	Conventional heat extraction	pH 2.2, 90 °C, 30 min	11.08 ± 1.23	High degree of esterification (DE > 60%), high viscosity	Valdivia <i>et al.</i> , 2021 ^[48]
Lemon peel	MAE	450 W , pH 1.0, 4 min	41.40	DE = 68.2%, MeO = 8.5%, GalA = 74.2%	Chung <i>et al.</i> , 2024 ^[10]
Watermelon rind	MAE	300 W, 20 min, 90 °C pH 1.5	19.08	GalA = 62.4%, DE = 48.5%	Forouhar <i>et al.</i> , 2023 ^[14]
Lemon peel	UAE	pH 1.0, 55 °C, 60 min	37.90	DE = 64.5% high intrinsic viscosity, superior gelling ability	Chung <i>et al.</i> , 2024 ^[10]
Citrus peels	UAE	24 min, pH 1.9, 40 °C, 37%amplitude	28.82	DE 55.29 ± 0.51%, MeO 7.19 ± 0.15%	Panwar <i>et al.</i> , 2023 ^[37]
Sunflower heads	SWE	8 bar, 120 °C, 20 min	6.57 ± 0.6	GalA = 82%, DE = 38.4%	Ma <i>et al.</i> , 2020 ^[27]
Cocoa pod husk	SWE	120 °C, 10 min	6.58%	DE 37.87 ± 2.83% AUA 66.53 ± 6.56%	Anoraga <i>et al.</i> , 2024 ^[2]
Pomelo peel	EAE	pH 4.5 47 °C for 10 h cellulase enzyme	11.94	DE: 47.71 ± 1.18% GalA: 56.34 ± 1.58% MeO: 6.62 ± 0.37%	Yu <i>et al.</i> , 2024 ^[53]

(MAE- Microwave assisted extraction, UAE-Ultrasound assisted extraction,SWE-Subcritical water extraction, EAE-Enzyme assisted

extraction, GalA- galacturonic acid content,DE- degree of esterification, AUA-Anhydrouronic acid, MeO- Methoxyl content)

Table 2. Recent applications of pectin-based edible packaging in fresh produce preservation

Source	Composition matrix	Food product	Major effect reported	Reference
Orange peel	Pectin matrix cross-linked with CaCl ₂	Fresh-cut apple	Delayed enzymatic browning; CaCl ₂ improved tensile strength	Cotrim <i>et al.</i> , 2025 ^[12]
Grape pomace	Pectin-grape pomace extract active composite	Fresh Strawberries	Demonstrated antibacterial/antioxidant activity, inhibiting yeast and mold growth	Kaynarca <i>et al.</i> , 2024 ^[20]
Commercial /Citrus pectin	Gum acacia–pectin–pullulan composite + glycerol/sorbitol	Ivy gourd	Extended shelf life by ~35%; enhanced resistance against <i>Pseudomonas aeruginosa</i>	Suresh <i>et al.</i> , 2022 ^[43]

9. Conclusion

Pectin is a promising natural biopolymer for sustainable edible packaging, enabling valorisation of agro-industrial by-products and reducing dependence on petroleum-derived plastics. However, the properties of pectin and the performance of the resulting films are strongly influenced by the source, extraction method, and processing conditions which determine galacturonic acid content, degree of esterification and molecular structure. Conventional acid extraction remains widely used, greener alternatives such as microwave-assisted, ultrasound-assisted, enzyme-assisted, and subcritical water extraction offer promising alternatives, although their efficiency and economic feasibility vary depending on the raw material and processing conditions. Therefore, optimisation and appropriate selection of extraction conditions are essential for obtaining pectin with desirable characteristics for film production.

Pectin-based films, fabricated via solvent casting, spraying, or extrusion, can be tailored using plasticizers such as glycerol to improve flexibility and reduce brittleness. Depending on their formulation, these films possess desirable mechanical, barrier, optical, and thermal, a properties, suitable for diverse food applications. Commercial development of pectin-based edible packaging therefore requires an integrated approach that considers raw-material standardisation, sustainable extraction methods, suitable film formulations, large-scale production, regulatory requirements, food safety, consumer acceptance, and production costs. Further research should combine material development with pilot-scale processing, storage and shelf-life studies, sensory evaluation and economic feasibility.

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