

CHARACTERIZATION, FUNCTIONAL PROPERTIES AND APPLICATIONS OF POLYSACCHARIDES

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Abstract

Natural polysaccharides are versatile and sustainable biopolymers with wide-ranging applications in food, pharmaceutical, and biomedical fields. Their structural diversity, biocompatibility, and functional flexibility make them key materials for developing innovative, eco-friendly technologies. This study focuses on two plant-derived polysaccharides, inulin and pectin, which are valued for their renewable origin and multifunctional properties. Inulin, commonly extracted from chicory roots, functions as a prebiotic fiber that supports gut microbiota and metabolic health. Pectin, obtained mainly from citrus peels and apple pomace, exhibits excellent gelling and stabilizing properties, making it indispensable in food processing and drug formulation. The research provides a comparative analysis of their molecular structures, extraction methods, and functional roles, emphasizing both traditional (hot-water and acid) and emerging green extraction technologies such as microwave-assisted, enzymatic, and ultrasonic methods. These sustainable approaches enhance yield and purity while minimizing environmental impact. Furthermore, the study explores the integration of inulin and pectin into functional foods, nutraceuticals, and controlled-release drug systems, underlining their contributions to product quality and human health. Their biodegradability and safety position them as crucial components in advancing a circular bioeconomy. Overall, the study highlights the strategic importance of inulin and pectin in fostering health, sustainability, and innovation.

Keywords: biopolymers, polysaccharide, pectin, food, industry, inulin, properties.

INTRODUCTION

Natural polysaccharides are versatile biopolymers of growing industrial and scientific interest due to their renewable origin, biocompatibility, and structural diversity. This paper focuses on two plant-derived polysaccharides — inulin and pectin — as representatives of functional biopolymers with significant technological and health-promoting properties. Inulin, a fructan-type carbohydrate commonly extracted from chicory roots and Jerusalem artichoke tubers, functions primarily as a prebiotic fiber, improving gut microbiota balance and supporting metabolic health. Pectin, a complex heteropolysaccharide obtained mainly from citrus peels and apple pomace, exhibits gelation, stabilizing, and emulsifying properties, making it indispensable in food and pharmaceutical formulations.

Recent advances in green extraction methods — such as microwave-assisted, ultrasonic, and enzymatic extraction — have improved yield, purity, and sustainability compared to conventional hot-water or acid methods. The paper discusses the physicochemical characteristics, structural features, and multifunctional applications of inulin and pectin, highlighting their role in advancing functional foods, nutraceuticals, and biodegradable formulations.

Polysaccharides are structurally complex macromolecules composed of monosaccharide units linked by glycosidic bonds. They are essential components of plants, microorganisms, and animals, fulfilling structural, storage, and protective functions. Their renewability, biodegradability, and functional versatility make them valuable for

use in food, pharmaceutical, cosmetic, and biomedical industries [1–3].

Among the most prominent plant-derived polysaccharides, inulin and pectin stand out for their multifunctional properties. Inulin, a β -(2→1)-linked fructan, serves as a carbohydrate reserve in many plants, especially members of the Asteraceae family, such as chicory (*Cichorium intybus* L.) and Jerusalem artichoke (*Helianthus tuberosus* L.) [4,5]. Its degree of polymerization (DP) typically ranges from 2 to 60, influencing solubility, sweetness, and fermentability [6]. Pectin, a galacturonic acid-rich heteropolysaccharide, forms part of the primary cell wall and middle lamella of higher plants and is especially abundant in citrus peels and apple pomace [7].

Both inulin and pectin represent renewable bioresources with broad industrial importance. Inulin functions as a prebiotic that selectively stimulates beneficial intestinal microbiota such as *Bifidobacterium* and *Lactobacillus* [8], while pectin exhibits gel-forming, stabilizing, and thickening properties crucial for food texture modification and drug formulation [9, 10]. The rising global demand for eco-friendly and biofunctional ingredients has stimulated research into novel extraction and modification technologies that enhance yield and purity while minimizing environmental impact [11].

EXPOSITION

Structural Characteristics of Inulin and Pectin: Polysaccharides exhibit remarkable structural and compositional variability, which dictates their functional properties and biological effects. Inulin is a linear β -(2→1)-linked fructan chain terminated with a glucose unit, displaying a degree of polymerization (DP) from 2 to 60 depending on the plant source and harvest conditions [4, 6]. It occurs naturally in over 36,000 plant species, particularly within the Asteraceae family, including chicory, Jerusalem artichoke, and globe artichoke. The molecular size distribution determines

solubility and texture — short-chain oligofructoses (DP <10) act as soluble dietary fibers and sweeteners, whereas long-chain inulins (DP >20) function as fat replacers and structural modifiers in food formulations [6].

Pectin differs fundamentally as a complex heteropolysaccharide primarily composed of α -(1→4)-linked D-galacturonic acid residues, with neutral sugar side chains (arabinose, galactose, rhamnose) attached to its rhamnogalacturonan regions [7,9]. The degree of esterification (DE) and acetylation control its gelling mechanism: high-methoxyl pectins (DE >50%) form gels under acidic, high-sugar conditions, while low-methoxyl pectins (DE <50%) rely on calcium-mediated ionic crosslinking [9,19]. These structural distinctions endow pectin with excellent rheological and stabilizing behavior, making it a cornerstone of the food and pharmaceutical industries.

Both inulin and pectin exhibit biocompatibility and selective bioactivity. Inulin resists enzymatic digestion in the upper gastrointestinal tract and reaches the colon intact, where it undergoes microbial fermentation producing short-chain fatty acids (SCFAs) such as acetate, propionate, and butyrate [4, 6]. Pectin degradation generates oligosaccharides that contribute to cholesterol reduction, immune modulation, and improved gut function [9, 22].

Extraction and Processing Technologies: Traditional hot-water extraction and acid hydrolysis are still commonly used to recover inulin and pectin, yet these techniques often involve long processing times and possible degradation of polysaccharide chains [12, 15]. To overcome such limitations, modern research focuses on green extraction technologies — particularly microwave-assisted (MAE), ultrasonic-assisted (UAE), and enzyme-assisted (EAE) methods — which enhance yield, shorten processing time, and preserve molecular integrity [10, 14, 16].

Redondo-Cuenca et al. [4, 6] employed Response Surface Methodology (RSM) to

optimize inulin and fructo-oligosaccharide (FOS) extraction from several sources. The study identified optimum parameters of 62–80 °C, 22–60 min extraction time, and 27–37 mL/g solvent-to-solid ratio, yielding up to 81.1 g/100 g dw in Jerusalem artichoke and 70.5 g/100 g dw in chicory. Fourier-transform infrared (FTIR) and HPLC analyses confirmed β -(2→1) linkages and a molecular mass of ~1.6 kDa, typical for short-chain inulin. Importantly, the research demonstrated the potential of globe artichoke by-products as a low-cost raw material for inulin extraction, promoting circular bioeconomy principles [4].

For pectin, conventional acid extraction remains the industrial standard, typically conducted at pH 1.5–3.0 and 60–90 °C for 1–3 hours. However, modern approaches such as microwave-assisted and enzyme-assisted methods have demonstrated superior efficiency and environmental performance [9, 16]. These techniques minimize chemical degradation and maintain esterification levels, which directly affect gelling capacity and viscosity. Enzyme-assisted extraction using pectinase or cellulase selectively breaks down the cell wall matrix, improving diffusion of soluble pectin without the use of strong acids [15]. Such sustainable approaches are consistent with global efforts to develop eco-friendly processing technologies for high-value biopolymers.

Functional, Nutritional, and Technological Properties: The unique molecular structure of inulin and pectin determines their functional versatility. Inulin exhibits dual solubility and texturizing functions. Short-chain inulin (oligofructose) is highly soluble and mildly sweet, while long-chain inulin (DP > 20) forms thermally stable particle gels upon cooling of concentrated solutions. These crystalline gels entrap water and generate smooth, spreadable textures comparable to lipid matrices, making inulin an ideal fat replacer in low-fat dairy and bakery products [6, 4]. It also demonstrates thermal stability up to 140 °C, acid sensitivity below pH 4, and

Newtonian flow behavior at low concentrations. These physicochemical traits enable its application across a wide spectrum of foods, from yogurts and ice creams to cereal bars and beverages [6, 4].

Beyond technological uses, inulin offers significant nutritional benefits. Its fermentation by *Bifidobacterium* and *Lactobacillus* species produces SCFAs that regulate intestinal health, improve calcium absorption, and modulate lipid and glucose metabolism [1, 6]. Human studies confirm reduced serum cholesterol, improved stool frequency, and a lower glycemic index in inulin-enriched diets [6, 4].

Pectin complements these properties with its excellent water-binding and gelation capacity. It functions as a stabilizer and thickener in foods such as jams, sauces, and beverages, and as a film-forming polymer in edible coatings [9, 19]. The rheological properties of pectin are directly affected by DE and molecular weight; low-methoxyl pectins form “egg-box” calcium-crosslinked gels, while high-methoxyl types form acid-induced gels used in confectionery [9]. Pectin-based hydrogels also exhibit mucoadhesive and controlled-release characteristics, which make them ideal for pharmaceutical and biomedical applications [22].

Recent research highlights the synergistic integration of inulin and pectin in composite systems. Inulin–pectin blends enhance mechanical strength, water retention, and encapsulation efficiency in probiotic and bioactive delivery matrices [23, 24]. These hybrid systems combine inulin’s prebiotic benefits with pectin’s film-forming capacity, paving the way for biodegradable packaging materials and functional hydrogels for tissue engineering.

Industrial and Health Applications: In the food sector, inulin and pectin play pivotal roles in developing health-oriented formulations. Inulin serves as a fat and sugar replacer, improving creaminess and mouthfeel in dairy desserts and yogurts while reducing caloric content [6, 4]. Pectin remains indispensable for its gelling and

stabilizing properties in fruit-based products and beverages [9, 19]. The dual use of inulin and pectin enhances product texture, stability, and nutritional value while reducing dependence on synthetic additives.

In nutraceutical and biomedical applications, both polysaccharides are valued for their safety, biodegradability, and physiological functionality. Inulin acts as a prebiotic dietary fiber, promoting balanced gut microbiota, reducing inflammation, and improving lipid metabolism [1]. Pectin contributes to cholesterol reduction, glycemic regulation, and colon-targeted drug delivery due to its selective degradation by colonic microflora [22, 24]. Moreover, pectin-based hydrogels and inulin–pectin composites are used in drug encapsulation, wound healing, and biodegradable film formation, reflecting their potential as green biomaterials [23, 24]. The valorization of agricultural by-products such as chicory pulp, apple pomace, and artichoke residues provides a sustainable source of these polysaccharides. This practice supports the principles of the circular bioeconomy, reducing waste and adding value to agro-industrial chains [4, 25, 26].

Future Perspectives: The advancement of polysaccharide research is now moving toward nanostructured and multifunctional systems. Inulin and pectin are being explored for use in nanocomposites, edible coatings, and responsive hydrogel matrices capable of delivering nutrients, bioactives, or pharmaceuticals in a controlled manner. The combination of these polysaccharides with nanocellulose, chitosan, or polyphenol-loaded nanoparticles can further enhance mechanical strength, antimicrobial activity, and antioxidant potential, broadening their technological scope.

Emerging green chemistry and biorefinery strategies will allow the complete valorization of biomass residues, producing polysaccharides, phenolic compounds, and organic acids from the same raw material stream. Integrating these processes into sustainable supply chains will reinforce the role of inulin and pectin as key

biopolymers in the circular bioeconomy. Continued research on structure–function relationships, biopolymer modification, and functional hybrid materials is expected to accelerate innovation in food, pharmaceutical, and environmental sectors.

CONCLUSION

Inulin and pectin exemplify the functional and structural diversity of natural polysaccharides. Their renewable origin, molecular adaptability, and multifaceted applications render them indispensable in both food and pharmaceutical industries. Modern green extraction technologies — notably microwave- and enzyme-assisted methods — have enhanced efficiency, yield, and environmental sustainability.

Inulin’s role as a prebiotic and fat replacer complements pectin’s gelling and stabilizing capacity, providing a synergistic platform for innovative functional products and biodegradable materials. Their incorporation into industrial processes promotes sustainability, human health, and circular economy integration. Continued interdisciplinary research on structure – function relationships and process optimization will further expand their industrial relevance and contribution to bio-based innovation.

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