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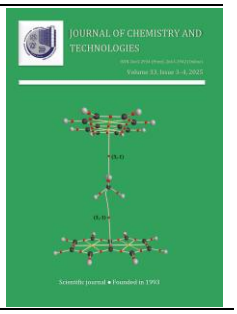

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XANTHAN: RESEARCH INTO INNOVATIVE MODIFICATION STRATEGIES AND INDUSTRIAL APPLICATIONS

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Abstract

The article presents a review of current approaches to the modification of xanthan aimed at expanding its functional properties. The chemical structure of xanthan is analyzed, with particular emphasis on the organization of the main polysaccharide backbone and side chains containing carboxyl, hydroxyl, acetyl and pyruvate groups. Their key role in the formation of intermolecular interactions, gel network development, sorption capacity and the immobilization of biologically active compounds and modifying agents is demonstrated. Available data on the conditions of chemical engineering of xanthan-based systems are summarized using examples of various modification strategies, and structural features of modified gel matrices are discussed. The main application areas of xanthan in the chemical, food, pharmaceutical, cosmetic, medical, water treatment and petroleum industries are outlined, with illustrative examples of technological performance. The prospects of xanthan as a versatile platform for the development of composite materials and controlled delivery systems for active components are highlighted. The need for further research focused on the design of modified xanthan forms with predictable structure–function relationships to advance chemical engineering applications is emphasized.

Keywords: xanthan gum; modification; gelation; rheological properties; immobilization; biopolymer composites.

КСАНТАН: ДОСЛІДЖЕННЯ ІННОВАЦІЙНИХ РІШЕНЬ МОДИФІКАЦІЇ ТА ПРОМИСЛОВОГО ЗАСТОСУВАННЯ

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Анотація

У статті представлений огляд сучасних підходів до модифікації ксантану задля розширення його функціональних властивостей. Проаналізована хімічна будова ксантану, зокрема організація основного полісахаридного ланцюга та бічних фрагментів, що містять карбоксильні, гідроксильні, ацетильні та піруватні групи. Показана їхня ключова роль у формуванні міжмолекулярних зв'язків, гелеутворенні, сорбційній здатності та можливості іммобілізації біологічно активних речовин і модифікуючих агентів. Узагальнені дані про умови хімічного інжинірингу ксантанових систем на прикладах різних видів модифікацій та надані дані про структурну організацію модифікованих гелів. Окреслені напрями застосування ксантану в хімічній, харчовій, фармацевтичній, косметичній, медичній, водоочисній та нафтопереробній галузях. Наведені приклади технологічної ефективності. Підкреслені перспективи використання ксантану як універсальної платформи для створення композитних матеріалів і контрольованих систем доставки активних компонентів. Доведена необхідність подальших досліджень, спрямованих на розробку модифікованих форм ксантану з прогнозованими структурно-функціональними параметрами для розвитку хімічного інжинірирнгу.

Ключові слова: ксантанова камедь; модифікація; гелеутворення; реологічні властивості; іммобілізація; біополімерні композити.

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Introduction

Xanthan gum (XG) was first identified in the 1950s at the National Center for Agricultural Research of the United States Department of Agriculture (USDA). Industrial-scale production of XG began in 1960, and the commercial product became available on the market in 1964. It was the second microbial polysaccharide to be industrially commercialized, following dextran, which entered large-scale production in the 1940s. Xanthan gum is recognized as non-toxic, non-sensitizing, and non-irritating to the skin and mucous membranes; in 1969, it was officially approved by the U.S. Food and Drug Administration (FDA) for use in food and pharmaceutical products [1].

The primary objectives of this study are to systematize current data on the chemical and physical modification of xanthan gum, as well as to identify promising directions for its application in industry and other sectors of economic activity. This comprehensive approach enables the formation of an integrated view of the current state of scientific developments and provides a foundation for further research into the role of xanthan gum in innovative biopolymeric materials.

The range of applications of xanthan gum continues to expand each year [2]. At present, xanthan gum is included in more than 90 % of cosmetic products intended for everyday use. In parallel, its application as an adsorbent in wastewater treatment technologies is increasing: xanthan-based filtration systems have demonstrated high efficiency in the removal of dyes, while hydrogels formed from xanthan gum serve as carriers for the controlled release of pharmaceutical compounds.

Within the framework of this review, the molecular structure of xanthan gum is examined with a detailed analysis of functional groups that determine its capacity for modification and composite formation. In addition, its applications in the food, pharmaceutical, medical, petroleum, and cosmetic industries are discussed, along with its use in wastewater and soil remediation technologies [3].

In summary, xanthan gum combines unique structural and functional characteristics that underpin its high versatility as a biopolymeric platform for the development of functionalized materials. Therefore, the subsequent discussion appropriately begins with a detailed analysis of the molecular structure of xanthan gum, as it defines the potential sites for modification and forms the basis for the development of its properties and practical applications.

Results and Discussion

Structure of Xanthan Gum

Xanthan gum is characterized by a complex supramolecular organization. The xanthan molecule consists of a β-D-(1→4)-glucan backbone. Individual glucose residues are substituted with trisaccharide side chains that determine the functional specificity of the polymer. These side chains are composed of a β-D-(1→4)-glucuronic acid residue positioned between two β-D-(1→2)-mannose units (Fig.).

The mannose residue closest to the main chain may carry an acetyl group at the C6 position, while the terminal mannose can contain a pyruvate group forming a cyclic ketal between the C4 and C6 positions.

The ratio of these functional groups is variable and depends on fermentation conditions, strain type, and the composition of the culture medium. In typical xanthan gum, approximately 30–40 % of terminal mannose residues contain pyruvate groups, which promote the formation of more rigid and highly ordered gel structures. In contrast, 60–70 % of the mannose residues adjacent to the backbone are acetylated, a modification that reduces the extent of interchain interactions and significantly affects polymer solubility.

The combined presence of acetyl and pyruvate groups is a key determinant of the rheological behavior of xanthan gum, including its pronounced shear-thinning (pseudoplastic) behavior, stability over a wide pH range, thermal resistance, and tolerance to high salt concentrations. By adjusting synthesis and fermentation parameters, the degree of these substitutions can be controlled, enabling the production of xanthan gum with tailored properties for specific technological applications [4].

Figure presents the chemical structure of xanthan gum.

Engineering approaches include the optimization of biotechnological synthesis–such as genetic modification of Xanthomonas producer strains to enhance yield or to alter the polysaccharide structure–as well as a variety of chemical modification strategies applied to xanthan gum [5].

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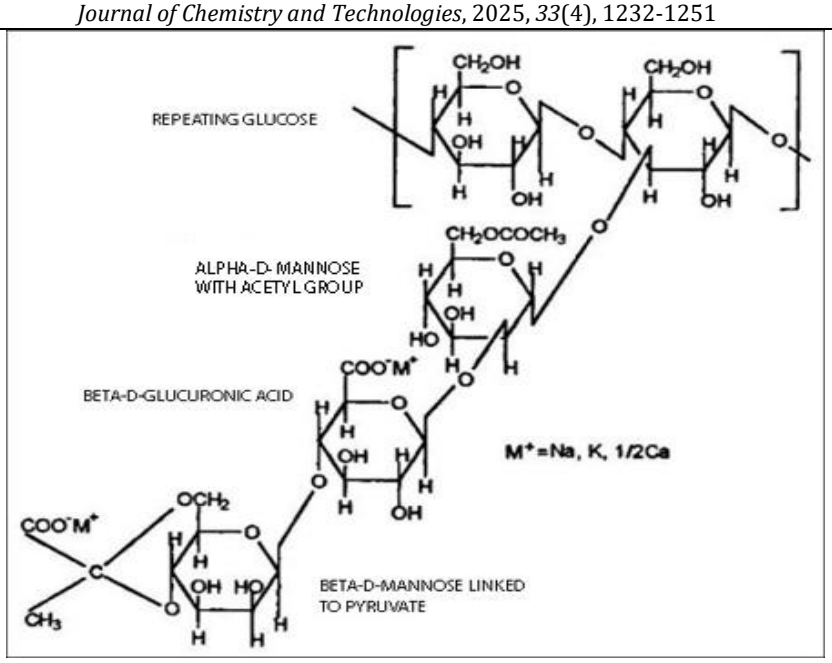

Figure. Schematic representation of the xanthan gum repeating unit and its trisaccharide side chains [4]

Some authors discuss the chemical structure of xanthan gum from a different perspective. Owing to the presence of glucuronic acid and pyruvic acid moieties in its side chains, xanthan gum represents a highly charged polysaccharide with a relatively rigid polymer backbone. The pyruvate content in xanthan gum typically ranges from 2.5 to 4.4 %, indicating that not every terminal D-mannopyranose residue within the side chain carries a pyruvate group. To date, xanthan gum with the highest reported pyruvate content (8.69 %) has been obtained exclusively through genetic engineering of the X. campestris strain CGMCC 15155, which produces a highly viscous xanthan variant.

A low pyruvate content results in reduced viscosity of xanthan polymer solutions, whereas a higher pyruvate content promotes the formation of more viscous and mechanically robust gels. The degree of acetylation within the xanthan molecule is also variable and depends on the specific polymer sample. A higher extent of O-acetylation of mannose residues decreases the gel-forming ability of xanthan gum in aqueous systems, as acetyl groups are hydrophobic and hinder interchain association and the formation of ordered supramolecular structures.

In addition, the hydrogen atoms of acetyl, pyruvate, and carboxyl groups in D-glucuronic acid residues can be substituted by various cations (e. g., Na^+, K^+, Ca^{2+}, Mg^{2+}). As a result, the trisaccharide side chains are not always structurally identical. The presence of acetyl and pyruvate groups confers a polyanionic character on xanthan gum, enabling the formation of ionic interactions with cations as well as hydrogen bonding with macromolecules of other biopolymers and organic compounds of diverse nature. Although the mechanisms underlying the formation of such matrices may differ, our investigations indicate that the general principles governing structural organization remain consistent.

The controlled content of acetyl groups plays a decisive role in regulating intermolecular interactions, particularly hydrogen bonding, which contributes to the thermal stability and cohesiveness of xanthan gels. Although acetyl groups alone are not the sole determinants of gelation, their presence enhances the stability of the three-dimensional network, especially during cooling and in the presence of cations involved in ionic bonding [6].

In xanthan gum, both the content and distribution of acetyl groups are critical for conformational stability. These groups are predominantly localized at the O-6 position of the internal mannose residues within the trisaccharide side chains (up to ~85 %) and, according to recent data, may also occur on terminal mannose residues in approximately 5–20 % of repeating units. Approximately half of the terminal D-mannose residues contain pyruvate substitutions at the 4,6-O positions, imparting an anionic character to the polymer. This structural variability governs the balance between hydrophilicity, charge density, and the degree of interchain association, thereby influencing viscosity, gelation behavior, and synergistic

interactions with other polysaccharides in food and pharmaceutical systems.

Within the xanthan system, D-glucose, D-mannose, and D-glucuronic acid are present in a molar ratio of 2:2:1, which classifies xanthan gum as a uronate exopolysaccharide [6].

The molecular weight of xanthan gum typically ranges from approximately 2×10^6 to 2×10^7 Da and is strongly influenced by the genetic characteristics of the producing strain, nutrient composition, and fermentation conditions. The macromolecular conformation–whether helical or more extended–is dynamic and varies depending on pH, temperature, ionic strength, salt concentration, fermentation duration, and extraction and purification methods. These factors collectively determine the rheological behavior of xanthan solutions and their stability under demanding technological conditions [6].

Xanthan gum readily dissolves in both cold and hot water. In aqueous solutions, its macromolecules are capable of self-association, leading to the formation of a three-dimensional gel network as ionic strength or concentration increases. This network is formed through double-helical conformations stabilized by intermolecular hydrogen bonds. Xanthan gum exhibits pronounced pseudoplastic behavior, whereby solution viscosity decreases with increasing shear rate. The macromolecular structure and its conformational state dictate the rheological properties, stability, and functional performance of the polysaccharide. Consequently, xanthan gum is widely used as a thickener, dispersant, emulsifier, and stabilizer at very low concentrations (0.05–1 %). It maintains stability across a broad pH range (2–12) and over wide temperature intervals, accounting for its high industrial value and extensive application [7].

According to the authors of [6], in the solid state xanthan gum adopts a helical conformation in which the side chains are oriented inward, along the main backbone. However, the precise spatial organization of the macromolecule remains a subject of ongoing debate.

In study [8], the authors investigated the influence of ionic strength on the formation of xanthan gum hydrogels. It was demonstrated that increasing concentrations of divalent and trivalent cations–also regarded as modifying agents–reduce the porosity of the gel network and increase the storage modulus (G′), indicating a denser packing of polymer chains. Furthermore, at high ionic strength, the gels exhibit a lower degree of swelling while better retaining their shape upon heating and pH variation. Most importantly, the findings of [8] confirm that the gelation mechanism of xanthan gum involves not only conformational transitions (helical ordering of polymer chains) but also ion-mediated interchain association through cationic bridges. This dual mechanism provides a more comprehensive explanation for the variability in structural and rheological properties observed in xanthan-based gels.

Gelation Mechanisms and Principles of Modification in Xanthan Systems

As noted above, the structural organization of xanthan gum–specifically its rigid β-D-(1→4)-glucan backbone and mannose–glucuronic acid side chains bearing acetyl and pyruvate groups–determines the ability of XG molecules to form ordered conformations in aqueous systems. This supramolecular architecture governs the transition from individual macromolecules to a three-dimensional gel network through the formation of single- and double-helical structures and their subsequent association.

Investigation of these processes is of fundamental importance, as they determine the rheological properties, stability, biocompatibility, and potential for controlled modification of xanthan gum for food, pharmaceutical, medical, and environmental applications.

In study [9], the effects of cyclic heating and cooling on the rheological properties of xanthan hydrogels were analyzed. The results demonstrate the necessity of controlling temperature regimes and cooling rates in xanthan-containing hydrogel systems. Microscopic analysis revealed that repeated heating alters the spatial network structure of xanthan chains, leading to partial disruption of intermolecular interactions and conformational rearrangements, which in turn cause a decrease in viscosity. Since temperature fluctuations significantly affect the polymer network of xanthan gum, these factors must be taken into account in the development of modified thermally stable hydrogels and emulsions.

Work [8] provides a comprehensive analysis of the fine structural organization of xanthan in aqueous systems containing low concentrations of this uronate polysaccharide using X-ray diffraction of oriented fibers in the solid state. To date, this approach remains the only method capable of characterizing ordered polysaccharide structures with atomic resolution.

The authors of [9] convincingly demonstrate that xanthan gum is not a static molecule but an adaptive polymer system that dynamically

changes its conformation in response to external conditions. This finding is of key significance for the development of advanced materials, as it enables targeted control over xanthan structural transitions, allowing modulation of its mechanical behavior, texture, and stability. Ultimately, this adaptability facilitates the effective tailoring of xanthan gum for applications in the food, pharmaceutical, cosmetic, and biotechnological industries. Thus, the double-helix model represents a well-founded conceptual framework and serves as a key tool for controlling gelation processes and hydrogel stability in technological applications and materials design based on xanthan gum.

Modification with carboxymethyl cellulose is described in study [10], where etherification of xanthan gum with monochloroacetic acid (MCAA) via the Williamson reaction mechanism resulted in the synthesis of carboxymethyl xanthan (CMXG). The formation of CMXG was confirmed by Fourier-transform infrared spectroscopy (FTIR), which revealed an increased number of carboxyl groups within the polymer structure. Chemical modification was further verified by proton nuclear magnetic resonance (^{1}H NMR) spectroscopy. X-ray diffraction (XRD) analysis was employed to investigate the crystalline structure of CMXG, enabling assessment of the degree of ordering and changes in intermolecular interactions.

Consistent with the findings reported in [11], CMXG exhibited improved solubility compared to native xanthan gum; the resulting gels were transparent rather than opalescent, accompanied by a reduction in molecular weight and enhanced thixotropic behavior. It is likely that, as a consequence of chemical modification, interchain interactions do not achieve complete conformational ordering and instead terminate at the stage of single-helix formation or partially ordered structures.

Integration of results obtained using different methodological approaches highlights the coexistence of both physical (conformational) and chemical (modification-driven) mechanisms influencing the properties of xanthan gum. It is precisely the interplay between these mechanisms that enables fine-tuned regulation of xanthan behavior across diverse technological environments through the use of various modifying agents.

In study [12], the formation of modified systems based on xanthan gum (XG) and chitosan was demonstrated. The systems were formed under acidic conditions, which led to the deprotonation of carboxyl groups in the xanthan structure, resulting in negatively charged carboxylate groups ($–COO^–$), while the amino groups of chitosan were protonated to form positively charged groups ($–NH_3^+$). These oppositely charged functional groups interacted with each other, giving rise to electrostatic interactions between chitosan and xanthan gum.

It was shown that XG-based composites are biodegradable in soil, exhibiting different degradation rates, which makes them attractive candidates for environmentally friendly packaging solutions and applications in eco-oriented material development.

Despite numerous advantages, xanthan-based coatings exhibit several functional limitations. In particular, they lack intrinsic antioxidant activity, rendering films produced from modified xanthan susceptible to oxidative degradation. Moreover, such films do not provide protection against ultraviolet radiation, which may accelerate the spoilage of photosensitive products, and they do not exhibit antibacterial activity, thereby increasing the risk of microbial contamination of packaged goods, including food products.

At the same time, as discussed above, xanthan gum possesses substantial potential for chemical and functional modification. Experimental evidence confirms the feasibility of using xanthan gum as a functional hydrogel matrix capable of efficiently immobilizing bioactive compounds, as well as serving as a platform for chemical modification with antioxidants, antimicrobial agents, preservatives, and UV-protective components.

The authors of [13] rightly emphasize the advantages of physical modification of hydrocolloid matrices over chemical approaches, as physical methods avoid the use of toxic reagents and are technologically simpler for food-related applications. However, the primary scientific value of this study lies not so much in the analysis of structural interactions per se, but in the demonstration of effective encapsulation (immobilization) of curcumin.

In study [14], an innovative encapsulation system for kidney tea saponins was proposed, based on porous starch, sodium alginate, and xanthan gum. This system provided a high encapsulation efficiency (≈79 %) and enabled controlled release of bioactive compounds–less than 20 % in the stomach and more than 80 % in the intestine. The use of enzymatically modified starch in combination with XG significantly

enhanced the stability and bioavailability of saponins, representing a promising strategy for the development of functional foods and nutraceuticals with antidiabetic potential.

In study [15], the authors proposed a combined encapsulation system for propolis, consisting of liposomes embedded within a hydrogel matrix based on xanthan gum and salep. This approach enabled simultaneous stabilization of liposomes, enhanced control over the release of phenolic compounds, and improved mucoadhesive properties of the material. Morphological and spectroscopic analyses confirmed the successful integration of liposomes into the gel network, while in vitro digestion modeling demonstrated preserved and increased bioavailability of phenolic compounds compared with free propolis.

Study [16] highlights that, in addition to chemical modifications (e. g., hydrophobic or hydroxypropyl substitution), physical modification of xanthan gum represents a promising direction, particularly high-pressure homogenization. This method does not require toxic reagents and is more environmentally benign, although it involves exposure to elevated temperature and/or pressure. Since many food-processing operations include thermal treatments (e. g., sterilization, cooking, frying, drying), investigation of the effects of high-temperature and high-pressure regimes on the structure and rheological behavior of xanthan hydrogels is highly relevant. Nevertheless, the properties of such biopolymer solutions after intensive processing remain insufficiently studied and require further investigation. As illustrated by the chemical structure of xanthan gum (Fig. 1), hydroxyl and carboxyl groups serve as potential reactive centers for xanthan modification. Their involvement in physical, chemical, chemo-enzymatic, and plasma-based treatments, as well as combinations thereof, enables improvement of XG properties as a biomaterial.

In study [17], high-pressure valve homogenization was shown to be an effective tool for the mechanical (physical) modification of xanthan gum without the use of chemical reagents. SEC–MALS data confirmed a reduction in molar mass and radius of gyration, accompanied by an increase in polydispersity, while circular dichroism (CD) spectroscopy indicated a more disordered conformation and partial loss of association junctions within the weak gel network. Collectively, these effects were interpreted as “chain scission” and network dilution, which enhance flowability and pumpability of the system but reduce elasticity and shape retention. The observed effects were found to be irreversible under the investigated processing conditions. The practical significance of this work lies in the development of an algorithm for controlled tuning of xanthan gum rheology for liquid and drinkable formulations or pourable systems.

The authors in [1] describe four approaches to xanthan gum modification. Interestingly, physical processing methods include mechanical treatment, emulsification/oil treatment, and blending with proteins or other unmodified polymers.

Physical modification methods of xanthan gum (XG) are aimed at altering its rheological properties, which is of particular importance for the development of biomaterials, including injectable hydrogels for biomedical applications and delivery systems for active compounds in low-permeability environments. The rheological properties of xanthan solutions are influenced by polymer concentration, the state of the solution (dynamic or quiescent), as well as the degree of water purification. In particular, ions present in water (e. g., Na^+, Ca^{2+}) reduce viscosity by interacting with the carboxyl groups of glucuronic acid residues.

Xanthan gum is capable of interacting with proteins to form more complex polymeric networks, which are predominantly generated through electrostatic interactions. In such systems, proteins act as crosslinking agents and exhibit their functional potential mainly under acidic conditions (pH 2.8–5.5).

Modification of xanthan gum also occurs in the presence of divalent and trivalent ions. Ion concentration is a key factor governing the rate of crosslinking. Metal ions interact with the carboxyl groups of glucuronic acid residues, converting xanthan hydrogels into mechanically stiffer networks.

Studies [18; 19] demonstrated that the addition of mono- and divalent cations (e. g., Na^+, K^+, Ca^{2+}) to xanthan solutions alters gel structure. An increase in ionic strength reduces electrostatic repulsion between negatively charged pyruvate and glucuronate residues along XG chains, leading to denser chain packing and increased hydrogel stiffness [18]. Conversely, at low ionic strength, electrostatic repulsion remains effective, maintaining a more open gel structure with a less compact network.

In study [20], the authors analyzed the effects of Mg^{2+}, Ca^{2+}, and NaCl concentrations on the structure and swelling behavior of XG hydrogels.

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It was found that increasing Ca^{2+} concentration significantly shortened gelation time, increased the shear modulus, and reduced the degree of swelling, whereas NaCl exhibited a less pronounced effect.

Overall, these findings indicate that divalent cations form stiffer and less compliant gels with more compact morphologies compared to monovalent cations, highlighting the role of cation-mediated bridging in interchain association of xanthan gum.

A comprehensive review [21] focused on the influence of trivalent cations on xanthan behavior in solution. In particular, trivalent ions (e. g., Cr^{3+}, Fe^{3+}) were shown to strongly promote interchain association and the formation of denser gel structures due to their ability to form bridges between carboxyl groups and pyruvate/glucuronate residues along the polymer chains. This results in increased stiffness, reduced volumetric swelling, and enhanced gel stabilization. Notably, the effects of trivalent cations differ substantially from those of mono- and divalent cations owing to their higher charge density and greater crosslinking potential.

In study [22], it was demonstrated that the addition of remedial components (e. g., phosphates, sodium lactate, ethyl lactate) led to a decrease in the dynamic viscosity of xanthan gum solutions, while the pseudoplastic behavior was preserved. An increase in the ionic strength of the medium through the addition of simple salts (e. g., Na^{+}, Ca^{2+}) also reduced dynamic viscosity and the degree of shear-thinning at low polymer concentrations; however, at high xanthan concentrations, salt addition could result in an increase in dynamic viscosity.

In study [23], it was shown that the addition of NaCl, KCl, and especially $CaCl_2$ significantly alters the rheological and tribological properties of mixtures containing xanthan gum (XG) and fucoidan. Cations screen the charged groups of the biopolymers, leading to compaction of the macromolecular structure and a decrease in intrinsic viscosity ([η]). FTIR analysis confirmed the rearrangement of intermolecular interactions in the presence of salts, with the most pronounced effects observed for Ca^{2+}. Tribological tests demonstrated a reduction in the friction coefficient and improved lubricating properties of the system. Overall, the study indicates that divalent cations markedly enhance conformational changes and functional properties of XG-containing hydrocolloid mixtures.

As can be seen, the influence of ions on the viscosity and structure of xanthan gels is dual in nature. At low salt concentrations, cations (particularly Na^{+}) screen the charges of the side chains and weaken interchain electrostatic repulsion, resulting in decreased viscosity and a loosening of the gel network. In contrast, at higher ionic strength or in the presence of multivalent cations (e.g., Ca^{2+}, Al^{3+}), more stable interchain contacts and "binding" of helical fragments occur, promoting network densification and increased gel strength. Thus, ions can either weaken or reinforce XG gels, depending on their valency and concentration.

Study [24] describes the effects of hydrothermal treatment on the rheological properties of xanthan gum at different temperatures (120–180 °C). It was found that at lower temperatures (120 °C), the rheological properties of xanthan gum remained similar to those of the untreated polymer. However, at higher temperatures (above 140 °C), significant changes were observed, including a broader Newtonian plateau in flow curves, alterations in dynamic viscoelasticity, and changes in complex viscosity. Hydrothermal treatment also affected the micromorphology of xanthan gum, rendering the material surface smoother.

The results of study [3] demonstrate the feasibility of forming a biodegradable hydrogel film via physical modification of xanthan gum (XG) and chitosan (CS) for the removal of heavy metals (Cd^{2+}, Ni^{2+}, and Cu^{2+}) from aqueous solutions. The adsorption of heavy metals ions depended on pH, contact time, adsorbent dosage, and the initial concentration of metal ions. The authors reported that the biofilm retained regeneration capacity over five adsorption–desorption cycles, indicating its potential effectiveness for industrial application in water treatment systems.

Modification with chitosan enhanced the adsorption properties of the xanthan-based hydrogel, rendering this approach an innovative solution for water purification and supporting the consideration of this type of modification for other industrial applications.

Chemical modification of xanthan gum is not limited to ionic interactions; covalent bonds may also be formed within the matrix. The dissolution rate of XG in water can be increased by chemically altering its molecular structure to reduce intermolecular interactions, for example, through treatment with formaldehyde [24]. In general, chemical modification also includes the formation of covalent bonds with organic molecules

intended to act as comonomers or crosslinking agents. Gels formed via covalent crosslinking exhibit controlled release behavior, improved elasticity, and increased mechanical strength.

Starches are commonly employed as modifying agents in such systems [25–28]. In these materials, an increase in swelling degree and pore size has been observed; however, diffusion of anions is hindered due to strong electrostatic repulsion between negatively charged groups of xanthan gum. This effect should be taken into account in the design of pharmaceutical formulations, particularly those containing anionic functional groups intended for binding.

Modification of xanthan gum can also be achieved by altering the landscape of functional groups, for example through deacylation [28], including treatments under alkaline conditions [29], hydrophobic modification [30], and substitution of hydroxyl groups with acid-reactive derivatives such as maleic anhydride or acryloyl chloride [31], as well as by carboxymethylation. Carboxymethylated xanthan gums exhibit enhanced interactions with cells, water, and other substances, which broadens their functional applicability [11].

To expand the performance characteristics of xanthan gum, graft copolymerization has also been employed as a chemical modification strategy. In study [11], graft copolymerization of ethyl acrylate (EA) onto xanthan gum was carried out using potassium persulfate (KPS) as an initiator. The resulting copolymers exhibited improved solubility, enhanced thermal stability, and increased sorption capacity toward Zn^{2+} ions, making them suitable for applications in water treatment systems and controlled release of active substances [32, 33].

To improve the bioavailability of drugs intended for transport across the oral mucosa, xanthan gum (XG) was modified using L-cysteine. Thiolation was achieved through the formation of an amide bond, which led to enhanced mucoadhesive properties of the polymer and improved control over swelling behavior. As a result, stronger adhesion to mucosal tissues and increased efficiency of controlled release of active compounds were observed. Evidence presented in [17, 32] confirms that xanthan gum is an effective polymer for the development of mucoadhesive drug delivery systems, such as nasal and injectable gels, owing to its ability to form stable gels and interact with mucosal surfaces.

The possibility of simultaneous modification of carboxyl and hydroxyl groups was also investigated using newly developed interpenetrating network hydrogels based on xanthan maleate and N-isopropylacrylamide (XGM-NIPAm). Crosslinking was performed using N,N′-methylenebisacrylamide (BIS) or cyclodextrin acrylate (A-CD). The structures crosslinked with A-CD were highly porous, less sensitive to electrolytes compared with BIS-crosslinked analogues, and exhibited an improved lower critical solution temperature (LCST) [34].

In one study, xanthan gum was modified with amylose using a chemo-enzymatic approach. This strategy is widely applied in copolymerization reactions of polysaccharides involving phosphorylase. As reported in [1], amino-functionalized maltodextrin was first chemically grafted onto xanthan gum via a condensation reaction with ionized carboxyl groups ($–COO^-$). Subsequently, enzymatic polymerization of glucose-1-phosphate was carried out at the ends of maltodextrin chains using phosphorylase, yielding amylose-modified xanthan gum. This polymer formed a gel in an ionic liquid, which transformed into a hydrogel upon replacement of the ionic liquid with water. The resulting hydrogels exhibited higher elasticity compared with conventional xanthan-based hydrogels. Additionally, the system was ionically crosslinked by immersion in an aqueous $FeCl_3$ solution, which stabilized the hydrogel through coordination with Fe^{3+} ions.

The obtained results indicate the feasibility of simultaneous modification of both carboxyl and hydroxyl groups; however, it remains unclear whether this can be achieved exclusively via a chemo-enzymatic approach. It is important to emphasize that this study provides valuable insights into ionic interactions between carboxyl groups of glucuronic acid residues and trivalent metal ions (Fe^{3+}), suggesting the formation of spatial structures that are likely to disrupt the native helical conformation of the polysaccharide.

An energy-efficient and resource-saving approach to polysaccharide modification that has attracted increasing attention is plasma-chemical irradiation, which is classified as a solid-phase (“dry chemistry”) method. This technique enables cleavage of chemical bonds followed by the formation of new reactive carbon species. The penetration depth of plasma is limited to approximately 100 nm; therefore, this method is considered a surface modification technique. Study [1] describes examples of applying plasma-chemical irradiation for the modification of xanthan gum.

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Study [35] demonstrates that ultrasonic treatment is an effective method for the physical modification of xanthan gum. The authors established a clear relationship whereby increasing ultrasound power and treatment duration leads to a noticeable decrease in the viscosity of XG solutions as a result of partial depolymerization and disruption of supramolecular associates. Importantly, the pseudoplastic behavior of the system remains unchanged, as confirmed by fitting several rheological models. This approach broadens the possibilities for precise tuning of XG rheology in food, pharmaceutical, and cosmetic products, particularly in applications requiring lower viscosity or improved control of flow properties.

Thus, modification of xanthan gum–either via graft copolymerization with vinyl monomers or through the formation of interpenetrating polymer networks with synthetic or natural copolymers–enables targeted alteration of its structural and mechanical characteristics. The introduction of new functional groups or crosslinking of macromolecular chains affects hydrophilicity, interchain interaction density, ionic sensitivity, and thermal stability of the polymer matrix. These parameters are decisive for hydrogel formation, structural organization, and functional performance.

The authors in [4; 6] also describe the physicochemical properties of xanthan gum, emphasizing its ability to dissolve in both cold and hot water, across a wide pH range, including deionized water. The viscosity of xanthan gum solutions remains stable at low pH values and elevated temperatures over prolonged periods, and gel structure is largely unaffected by the addition of high salt concentrations. Moreover, owing to its strong water-binding capacity, xanthan gum solutions exhibit good stability under freeze-thaw conditions.

At very low concentrations, xanthan gum dramatically increases the viscosity of liquids to which it is added. At higher concentrations, it forms a mucilaginous paste that visually resembles a gel but is technically not a true gel, as noted by the authors [4; 6].

Xanthan hydrogels are capable of forming stable emulsions with oils or triglycerides. Under mechanical treatment (e. g., whipping), frictional forces between polysaccharide molecules and lipid phases are reduced, leading to the formation of a plastic mass. In this process, polysaccharide blocks lose their deformability, resulting in the formation of a stable emulsion [1]. This phenomenon has found wide application in the production of ointments, cosmetic formulations, and paste-like products such as mayonnaise-type sauces. Notably, such products can be manufactured with reduced caloric content, as sugars and fats do not determine emulsion stability, which is instead governed by the polysaccharide hydrogel matrix.

Within the framework of innovative strategies aimed at expanding xanthan functionality [1], systems based on XG combined with synthetic modifiers–such as polypyrrole (PPy) and methylcellulose (MC)–are of particular interest.

Polypyrrole (PPy) is a representative conductive polymer that provides electroactivity and magnetic field sensitivity, making it especially relevant for applications in neuroengineering and electrostimulation therapy. Its combination with xanthan gum enables the development of materials with tunable electromechanical properties.

Methylcellulose (MC) is a thermoresponsive polymer capable of forming injectable gels at body temperature. Its combination with XG ensures prolonged gel stability, biocompatibility, and ease of administration, which are critical factors in therapeutic and pharmaceutical applications.

Accordingly, the consideration of XG in combination with synthetic polymeric modifiers is driven by the objective of extending its functional potential for biomedical applications, tissue engineering, and targeted drug delivery.

For example, study [36] investigated the properties of xanthan gum modified with alkenyl fragments. It was reported that hydrophobic modification of xanthan gum reduces moisture absorption, partially improves thermal stability, and alters rheological behavior-decreasing elasticity in dilute solutions while increasing viscosity in concentrated systems due to self-association of hydrophobic chains.

In study [37], hydrophobic modification of xanthan gum was investigated via etherification of its hydroxyl groups with octyl chloride in two different reaction media–ethanol (HMXG1) and dimethyl sulfoxide (DMSO, HMXG2). The results demonstrated that the reaction medium significantly affects the degree of substitution and the resulting properties of the modified polymer. HMXG1 exhibited a higher degree of etherification and greater molecular weight, a lower critical aggregation concentration (~0.2 %), and superior emulsifying performance compared with HMXG2 (~0.35 %). Both modified samples retained the characteristic pseudoplastic rheological behavior

of native xanthan; however, HMXG1 proved to be a more effective amphiphilic thickener and emulsion stabilizer. These findings indicate that the choice of reaction medium is a key factor in controlling hydrophobization efficiency and the functional properties of modified xanthan gum.

Study [38] demonstrated the effective stabilization of oil-in-water emulsions using a combination of shellac (SL) and xanthan gum (XG) under acidic conditions (pH 3.5). The authors showed that at a mass ratio of SL:XG = 4:1, stable emulsions were formed in which XG generated a weak three-dimensional network in the continuous phase and interacted with the SL interfacial layer on oil droplet surfaces. This structural organization provided a sufficient yield stress to prevent coalescence and creaming. The application of ultrasonic treatment reduced droplet size to below 300 nm and significantly enhanced storage stability, even under acidic conditions, thereby opening prospects for the development of natural emulsified products with acceptable acidity.

Nevertheless, it should be noted that there are risks associated with the formation of unsafe, partially toxic, or therapeutically ineffective modified biocomposites. Consequently, investigation of biocompatibility has become a critical next step in studying the production routes and properties of existing xanthan-based biocomposites that have found widespread application across various sectors of the economy.

This line of research [38] also addresses the potential for unpredictable changes during the release of active substances–particularly pharmaceuticals–from matrices of modified xanthan hydrogels. Special attention is paid to conditions under which biodegradation of such composites is complete, without the formation of residual biopolymers that cannot be fermented by the intestinal microbiota. This issue is of paramount importance for both food and pharmaceutical developments. Accordingly, particular emphasis is placed on toxicological evaluation and environmental safety of modified xanthan-based materials.

In study [39], it was shown that xanthan gum (XG) interacts differently with the anionic surfactant SDS and the nonionic surfactant Tween 80. In the case of SDS, association occurs after overcoming electrostatic repulsion and subsequently proceeds via hydrophobic interactions. In contrast, Tween 80 interacts with XG mainly through hydrophobic contacts and hydrogen bonding. Despite the presence of hydrophilic acetyl and pyruvate groups, XG possesses amphiphilic domains capable of forming aggregates with surfactants. These findings are important for optimizing polymer–surfactant systems in food emulsions, pharmaceutical formulations, and cosmetic products where controlled stability and texture are required.

Study [40] examined the effects of NaCl, sucrose, and pH on the intrinsic viscosity [η] of dilute mixtures of xanthan gum (XG) and guar gum (GG). Synergistic behavior was observed only under acidic conditions (pH ≈ 3), highlighting the importance of electrostatic interactions between the anionic groups of xanthan and neutral or weakly charged regions of guar gum.

In study [41], the interaction between xanthan gum (XG) and locust bean gum (LBG), which is well known for exhibiting synergistic gelation through direct interchain contacts, was investigated. The authors employed high-pressure treatment as a physical approach to densify the polymer network and enhance intermolecular interactions without the use of chemical crosslinkers. In this system, xanthan gum acts as a structural scaffold, while LBG modulates the strength and stability of interchain associations.

In study [42], the effect of acidification on the conformation and gelation behavior of commercial xanthan gum (XG) and a pyruvate-free sample (PFX) was investigated, both individually and in mixtures with konjac glucomannan (KGM). The authors demonstrated that decreasing pH increases the from coiled (disordered) conformation to ordered helical structure) transition temperature in pure XG solutions, while simultaneously lowering the gelation temperature in XG–KGM systems. For commercial xanthan, at pH values of approximately 4.5–4.25, a two-step increase in viscoelastic moduli was observed: first due to interactions between KGM and pyruvate groups, and subsequently due to interactions with partially depyruvated XG segments. At pH values below approximately 4.0, the behavior of XG became similar to that of PFX, indicating an almost complete loss of pyruvate as a result of acid hydrolysis. XG–KGM mixtures prepared at pH 3.5–4.0 formed gels with high moduli at 20 °C, but exhibited pronounced softening at temperatures close to 37 °C, producing a “melt-in-the-mouth” effect comparable to gelatin–yet achieved within a fully plant-based polysaccharide system. These results confirm that the degree of XG pyruvation and pH control represent powerful tools for designing thermoresponsive, gastronomically

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valuable textures, opening new opportunities for gel-based products in food, medical, and dietary applications.

In study [43], composite agar/LBG/xanthan (ALX) gels were investigated as a plant-based alternative to high-Bloom gelatin. The authors showed that incorporation of a locust bean gum–xanthan mixture into agar gels nearly halved gel hardness, increased elasticity (by approximately 8 %), markedly reduced syneresis (from 2.33 % to 0.52 %), and lowered both gelation and melting temperatures, resulting in textures much closer to those of gelatin.

In this context, the development of functionalized polymer systems based on modified xanthan gum represents a particularly promising direction. In recent years, research efforts have focused on incorporating polyphenols, metal oxides, organic acids, and natural antioxidants–especially plant extracts rich in anthocyanins, betalains, and other pigmented biomolecules–into xanthan-based films. Such additives not only reduce film permeability to ultraviolet radiation and impart color, but also induce pH-responsive behavior. As a result, functionalized biopolymer materials acquire characteristics of intelligent packaging systems, capable not only of protecting food products but also of acting as indicators of product freshness.

Overall, the structural features of xanthan gum–namely the presence of pentasaccharide repeating units, acetyl and pyruvate substituents, and the ability of macromolecules to form ordered single- and double-helical conformations–govern its rheological properties and behavior in different environments. Modifying the degree or nature of these structural elements enables targeted control over viscosity, gelation capacity, solubility, and intermacromolecular interactions.

Practical Applications of Modified Xanthan Gum

When combined with alginate, pectin, chitosan, carrageenan, proteins, or starches, xanthan gum (XG) significantly enhances gelation ability, encapsulation efficiency, as well as barrier and antibacterial properties. As a result, XG-based composite systems represent a versatile platform for the development of three-dimensional scaffolds, biomedical hydrogels, intelligent films, food and agricultural coatings, sorption materials, and carriers for active compounds. Such multifunctionality defines XG as a fundamental component of modern biopolymer technologies focused on sustainability, safety, and high technological efficiency.

The benefits of hydrocolloids in pharmaceutical formulations have been recognized for a long time [44]. A comprehensive analysis of the origin, application fields, and physicochemical properties of xanthan gum in hydrogel and other structured forms is presented in study [45]. Depending on the therapeutic purpose and route of administration, xanthan gum serves as a key polymer in various pharmaceutical formats, including hydrogels, superporous hydrogels, matrix systems, nanoparticles, microspheres, niosomes, bilayer mucoadhesive systems, nasal and ophthalmic gels, dermal creams and patches, as well as injectable and colon-targeted (enteric) dosage forms.

In particular, xanthan-based hydrogels exhibit distinctive swelling behavior and controlled drug release profiles due to the regulation of porosity through crosslinking. For example, superporous hydrogels formed with the incorporation of 2-hydroxyethyl methacrylate and acrylic acid provide rapid water uptake owing to their high permeability and capillary action.

In matrix systems, xanthan gum functions as both a gelling agent and a controlled-release matrix in sustained-release tablet formulations. Xanthan-based microspheres, especially when combined with polyvinyl alcohol, form three-dimensional interpenetrating polymer networks that ensure stable and reproducible drug delivery.

In the field of nanotechnology, xanthan gum is employed as a stabilizer and carrier in the formation of gold and iron nanoparticles, as well as in the development of nanoemulgels for targeted delivery to brain tissue or for anticancer applications. In niosomal systems, which are structurally similar to liposomes but exhibit enhanced stability, XG acts as a gelling agent, influencing viscosity, particle size, and distribution uniformity.

Furthermore, mucoadhesive systems based on xanthan gum are widely used for buccal delivery, ophthalmic gels, nasal in situ gels, and dermal patches. Xanthan gum has also found applications in cosmetic gels, antibacterial creams, injectable carriers with controlled release, and colon-targeted formulations for the treatment of gastrointestinal diseases.

In contemporary studies on food hydrocolloids, particular attention is given to biopolymer hydrogels formed through synergistic interactions between polysaccharides that individually are unable to form stable gels [46]. One of the most promising combinations is xanthan gum (XG) with konjac glucomannan (KGM).

Study [47] reports the development of a thermoresponsive and mucoadhesive hydrogel based on a graft copolymer of xanthan gum and poly(N-isopropylacrylamide), designed as a platform for prolonged local delivery of an antifungal peptide against Candida albicans. Owing to the biocompatibility of XG and its ability to form stable gel networks, effective peptide encapsulation and temperature-dependent controlled release at the infection site were achieved. The resulting system demonstrates strong potential as a universal hydrogel matrix for local anti-infective therapies with controlled pharmacokinetics.

The interaction between xanthan gum and konjac glucomannan has also been investigated in studies [48; 49]. The association between these biopolymers can occur via different mechanisms, including type-A binding (association between KGM chains and ordered, helical xanthan structures) and type-B binding (association between KGM chains and disordered xanthan segments). A xanthan structure enriched with pyruvate residues provides additional opportunities for specific binding and modulation of the gel characteristics.

The combination of xanthan gum with konjac glucomannan (KGM) serves as a model system for synergistic gels, in which xanthan dictates the configurational assembly mode, while the fine structure of its side chains determines the strength and initiation temperature of binding and, consequently, the final gel strength. It has been shown that a reduction in pyruvate content shifts the system toward type-A (helix-driven) assembly and strengthens the gel, whereas an excess of pyruvate enhances electrostatic repulsion and suppresses ordering. Acetylation, in contrast, stabilizes the helical conformation and reinforces the polymer network.

According to study [50], synergistic interaction between xanthan gum (XG) and konjac glucomannan (KGM) is initiated already during mixing at 20 °C, without the need for prior heating. Even at concentrations of 0.5 % XG / 0.5 % KGM, the mixtures exhibit gel-like behavior, with the storage modulus (G′) exceeding the loss modulus (G″), and the material partially recovering its shape after deformation, indicating an elastic rather than purely viscous gel nature. Heating induces a gel-to-sol transition; however, subsequent cooling results in the formation of a stronger network due to reordering of xanthan chains and enhanced interchain interactions with KGM. In the presence of KCl, the synergistic effect becomes even more pronounced, highlighting the critical role of ionic strength in stabilizing intermolecular interactions.

In study [51], the effect of freeze–thaw treatment on the formation mechanism of synergistic gels based on xanthan gum and konjac glucomannan (KGM/XG) was investigated. Particular attention was paid to structural changes induced by different temperatures and numbers of freeze–thaw cycles. It was demonstrated that such treatment promotes densification of the gel network, reduction in porosity, and an increase in structural ordering, as confirmed by SEM, SAXS, rheological measurements, and texture analysis.

The growing demand for natural texturizing agents in the cosmetic, pharmaceutical, and food industries has intensified interest in polysaccharide gels that combine technological efficiency with favorable sensory properties. Examples of such successful composites include systems based on xanthan gum combined with galactomannans such as guar gum (GG) and locust bean gum (LBG) [52]. The authors demonstrated that synergistic gelation is governed not only by the mannose-to-galactose (M/G) ratio, but also by the spatial distribution of galactose residues along the polymer chain. In the case of guar gum (GG), characterized by an M/G ratio of 1.3–1.5 and a relatively uniform distribution of galactose units, dual interaction with xanthan was observed–via both junction zones and segregation-driven associations. This resulted in significantly higher viscosity and enhanced gel stability. In contrast, locust bean gum (LBG), with a higher M/G ratio (3.0–3.2) and a less regular galactose distribution, exhibited interactions predominantly limited to junction zones, leading to weaker synergistic effects.

In our view, junction zones represent regions of polymer I chains that are partially or completely devoid of side-chain branching, enabling close interaction with polymer II (e.g., xanthan gum). Within these zones, hydrogen bonding, van der Waals forces, and other intermolecular interactions can develop, facilitating the formation of stable supramolecular structures. This mechanism underlies the synergistic interaction between polymers I and II and is essential for the formation of composite hydrogels.

Segregation, by contrast, refers to the spatial separation of polymer I regions from clusters of galactose residues in polymer II (e. g., the side branches of guar gum), which hinders effective interaction between polymers I and II. Although

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galactose itself is hydrophilic, excessive clustering creates steric hindrance that prevents polymer II from being efficiently incorporated into the structural framework of polymer I. This molecular landscape is described as the "segregation effect". At the same time, segregated fragments of polymer II may reorient toward less branched regions of polymer I, where conditions are more favorable for stable intermolecular interactions. Under appropriate pH conditions and in the presence of cations, the formation of ionic interactions is also possible.

Thus, junction zones primarily define the structural framework of the gel, whereas segregated regions contribute to its ordering and stabilization.

Against this background, a comparison with the systems described in study [48] is particularly informative, where strong synergistic interactions with xanthan were observed not for GG, but for konjac glucomannan (KGM). Although KGM is not a typical galactomannan, it possesses a long, relatively unsubstituted backbone that can form well-organized structures with xanthan, especially in the presence of ions that reduce electrostatic repulsion. Consequently, in the XG/KGM system, synergy is primarily driven by thermally induced ordering of the helical structure of xanthan, whereas in XG/GG systems the dominant mechanism involves side-chain-mediated hydrophilic interactions through galactose residues.

Authors in study [53] described the formation of synergistic gels (SIGs) based on xanthan gum and LBG in systems where one polysaccharide predominates. It was found that in LBG-rich systems, cooling leads to the formation of flexible, branched structures in which LBG chains establish hydrogen bonds with individual xanthan chains, resulting in a heterogeneous "sea–island" type morphology. In contrast, in systems dominated by xanthan gum, cooling induces a transition of xanthan chains from a disordered to a helical conformation, followed by aggregation of LBG chains into thick bundles that assemble into a three-dimensional gel network.

One of the key challenges associated with biopolymer hydrogel–based composites is the excessive tackiness of residual films after gel drying, which significantly reduces the consumer appeal of the final product. In response to this issue, study [54] demonstrated that combining xanthan gum with galactomannans–specifically guar gum and, in particular, locust bean gum [53; 54] – results in pronounced synergistic effects that reduce surface tackiness while improving structural homogeneity and overall biogel stability.

These findings are consistent with the conclusions reported in another study [48]. Both works emphasize the critical role of xanthan chain conformation, the influence of ionic strength, and the polymer's ability to undergo ordered aggregation in governing synergistic behavior.

To systematize the available data and visualize the synergy between different biopolymer pairs, a comparative Table has been compiled, illustrating the interaction features of xanthan gum with guar gum, locust bean gum, and konjac glucomannan.

Table

Comparative characteristics of biopolymers as synergistic partners of xanthan gum

Feature / Property	Guar Gum (GG)	Locust Bean Gum (LBG)	Konjac Gum (KGM)
Main monomer units	Mannose + Galactose	Mannose + Galactose	Mannose + Glucose
Monomer ratio	M/G ≈ 1.5	M/G ≈ 3.5	M/Glu ≈ 1.6
Degree of branching (galactose)*	High (high frequency of galactose side branches)	Low (low frequency of galactose side branches)	Minimal or absent (galactose side branches are rare or absent)
Polymer type	Galactomannan	Galactomannan	Glucomannan (in the presence of trace galactose, sometimes classified as a galactomannan)
Water solubility	High	Lower	Moderate
Synergy with xanthan gum (XG)	Strong (driven by high galactose branching density)	Moderate (due to low galactose branching density)	Pronounced (but sensitive to pH, cation type, and concentration)
Mechanism of interaction with XG	Junction zones + segregation	Predominantly junction zones	Type A (helical XG + KGM), Type B (non-helical XG + KGM)
Film formation / Gel formation	Soft	Dense	Dense, elastic, cation-dependent
Hydrophobic properties of XG blends	Stable	Less stable	Increase at high ionic strength (Na^+, Ca^{2+})

*Degree of branching refers primarily to the frequency and distribution of galactose side units along the polysaccharide backbone.

Comparative Table provides deeper insight into why some studies favor the XG + guar gum system, whereas others prioritize XG + konjac glucomannan. Guar gum (GG) is characterized by dense galactose branching, which promotes the formation of a stronger hydrogen-bonded network with xanthan, resulting in high viscosity and a soft, elastic texture. Such properties are considered ideal for food and cosmetic formulations where sensory comfort and flexibility are required. In contrast, locust bean gum (LBG) exhibits sparse galactose branching, leading to weaker synergy with xanthan; however, it forms denser films, making it particularly suitable for film-forming applications with reduced surface tackiness. Konjac glucomannan (KGM) contains virtually no galactose side branches, and therefore its synergistic mechanism with xanthan differs fundamentally, manifesting in two distinct modes (Type A and Type B).

In study [55], xanthan samples with varying contents of acetyl and pyruvate groups were compared, together with the effects of ionic strength (NaCl) and polymer concentration. Based on rheological measurements and differential scanning calorimetry (DSC), a unified model of synergy between xanthan and konjac glucomannan (KGM) was proposed. The coexistence of two interaction pathways–helical and coil-based – was demonstrated, giving rise to two types of gels with different melting temperatures. Compared to earlier studies, this work is distinguished by the use of KGM as a "clean" model system, well-defined xanthan samples with controlled composition, and the integration of previously conflicting models into a single conceptual framework.

In study [56], physical crosslinking of quince seed gum (QSG) with xanthan (XG) and locust bean gum (LBG) was investigated to enhance the viscoelastic properties of polymer solutions. The QSG–LBG system was shown to form true gels with high mechanical strength and reduced tan δ (G″/G′) even at elevated temperatures, whereas the QSG–XG combination resulted only in increased structural organization without the formation of a rigid three-dimensional network. These findings indicate that the synergism between xanthan and QSG is less pronounced than that observed with classical galactomannans such as LBG, where interaction with the double-helical structure of xanthan leads to true gel formation.

In studies [57, 58], composite systems of xanthan with sodium alginate–another important representative of uronate polysaccharides–were examined. The results demonstrated that incorporation of xanthan gum into alginate hydrogels significantly improves their rheological properties, particularly viscosity and structural stability.

The findings reported in study [58] further confirmed that the developed alginate–xanthan suspension is effective in the management of gastroesophageal reflux disease (GERD), a debilitating condition affecting approximately 40 % of the Western population. Moreover, the newly developed alginate–xanthan formulation was shown to be more cost-effective than the commercially available reference product Gaviscon.

Further analysis of the literature revealed an emerging direction in biopolymer modification research, with growing attention focused on starch modification. Study [59] investigated the effect of xanthan gum on high internal phase emulsions (HIPEs) stabilized by octenyl succinic anhydride–modified starch (OSA starch) for food 3D-printing applications. The addition of xanthan increased the viscosity of the continuous phase, reduced droplet coalescence, and enabled the formation of stable HIPEs suitable for extrusion-based 3D printing. In addition, improved thermal stability of β-carotene encapsulated within the HIPEs was demonstrated.

In study [60], the authors provide a comprehensive overview of a wide range of approaches for the development of xanthan-based composites and chemically modified xanthan derivatives. These include crosslinking, amidation, and graft copolymerization with various monomers–such as acrylamide, methacrylic and acrylic acids, methyl methacrylate, and N-vinylpyrrolidone–as well as chemical modification involving epichlorohydrin, glutaraldehyde, polyvalent cations, and polyelectrolytes. The resulting materials exhibit tunable swelling behavior, enhanced mechanical strength, improved thermal stability, sensitivity to pH and ionic strength, increased adhesion, and controlled release of active substances. Such structures are regarded as highly promising for use in pharmaceutical systems for sustained and targeted drug delivery, biomedical coatings, water purification sorbents, as well as in "smart" gels and sensing matrices.

In another study [61], a different type of chemical modification of xanthan gum was described, namely the formation of metal–polymer complexes via crosslinking of the XG matrix with Ca^{2+}, Fe^{3+}, Zn^{2+}, Cu^{2+}, and other

transition metal ions. These ions coordinate with carboxyl, pyruvate, and hydroxyl groups of the polymer. The resulting metal–xanthan composites exhibit altered chain conformations, increased rigidity, enhanced heavy-metal ions sorption capacity, antibacterial activity, ion-regulated swelling behavior, and stability under harsh environmental conditions. These properties indicate their high potential for wastewater treatment, catalyst support materials, biocompatible barrier systems, and ion-sensitive controlled-release platforms.

Study [62] focused on hybrid composites exhibiting osteoconductivity and controlled release of the antibiotic ciprofloxacin hydrochloride (CPFXH). The introduction of carboxymethyl and sulfate groups into xanthan gum, followed by photo-crosslinking with gelatin methacrylate (GM), enabled the formation of hydrogels with high efficiency of biomimetic mineralization, which is crucial for bone tissue engineering. This work demonstrates how functionalization of xanthan with carboxymethyl and sulfate groups can significantly expand its application potential and contribute to the development of novel biomedical products and technologies.

In another investigation [63], the therapeutic efficacy of low-molecular-weight xanthan gum (LM-XG) for the treatment of osteoarthritis was evaluated. A comparative analysis of LM-XG and sodium hyaluronate (SH), a standard clinical treatment for osteoarthritis, revealed that LM-XG protected cartilage from degradation in a manner comparable to high-molecular-weight xanthan (HM-XG) and SH. Furthermore, LM-XG reduced nitric oxide (NO) levels in synovial fluid, stabilized knee joint width, and thereby promoted cartilage regeneration. Notably, LM-XG demonstrated higher efficacy than SH despite a less frequent dosing regimen (every two weeks instead of weekly), making it a promising candidate for replacing SH in clinical practice.

It should be noted that low-molecular-weight xanthan gum is obtained via controlled depolymerization, during which β-(1→4)-glycosidic bonds in the main chain or weaker bonds within the side trisaccharide units (mannose–glucuronic acid–mannose) are cleaved.

In study [64], a hydrogel system based on konjac glucomannan and xanthan gum with encapsulated Bacillus subtilis within metal–phenolic networks was investigated. This system provided effective protection of the probiotic, exhibited antimicrobial, antioxidant, and anti-inflammatory properties, and significantly accelerated the healing of infected wounds. Together with the findings of study [65], which described the synergistic action of xanthan and curdlan combined with MXene and magnesium to form an immobilizing matrix, these results highlight the strong potential of microbial polysaccharide-based hydrogel dressings for the treatment of infected wounds.

Studies [66; 67] demonstrated that the combination of tamarind gum and xanthan gum leads to the formation of two types of synergistic gels. In systems dominated by xanthan, a continuous network structure composed of xanthan aggregates is formed, whereas samples with a high content of tamarind gum exhibit a so-called “sea–island” morphology, where clusters of tamarind gum are embedded within a xanthan-rich matrix. It was shown that increasing the concentration of tamarind gum enhances its interaction with xanthan and, consequently, contributes to higher gel hardness.

In study [68], the authors analyzed the interactions between micellar casein (MC) and xanthan gum (XG) at various mixing ratios and pH values. Study [69] focused on the effect of fucoidan on the rheological properties of xanthan gum–guar gum mixtures. The authors found that at fucoidan concentrations up to 0.5%, a synergistic increase in viscosity and consistency was observed, whereas further increases in fucoidan content led to deterioration of rheological characteristics.

Study [70] elucidates the mechanisms and patterns of interaction between polysaccharides of different ionic types and wheat starch during the formation of xanthan-based composite gels. It was demonstrated that the addition of polysaccharides significantly alters the structural and functional properties of the gel by affecting the gelatinization process. In particular, polysaccharide incorporation slows down starch gelatinization, induces disruption of double helices, and leads to defects in the crystalline lattice, ultimately resulting in weakening and loosening of the gel matrix.

Thus, the selection of an effective synergistic partner for xanthan gum depends not only on the type of polysaccharide but also on its structural characteristics, including chain regularity, degree of substitution, hydrophilic–hydrophobic balance, and functional group reactivity. This opens up prospects for the design of adaptive gels with predictable properties for both food and pharmaceutical applications.

Xanthan gum is also widely used to stabilize livestock feed additives, agricultural herbicides, fungicides, pesticides, fertilizers, and in toothpaste formulations. It is employed to control droplet size and dosage uniformity in agricultural formulations. Xanthan has been approved for use as a packaging-related additive in the paper and cardboard food-packaging industry.

In ceramic manufacturing, stabilizers, pigments, and polishing agents play a key role in glaze formation–a glassy coating that provides decorative appearance and protects ceramic products from environmental exposure. The addition of xanthan gum to glaze formulations improves their rheological properties, promotes uniform application, and enhances the quality of the final product.

In oil recovery operations, xanthan gum is used to form gels through interactions with trivalent metal ions, such as chromium (Cr^{3+}). These gels exhibit high viscosity and are capable of suspending proppants–solid particles that keep rock fractures open during hydraulic fracturing. This ensures efficient transport of proppants to target zones and improves well productivity.

Xanthan gum is also applied in the production of self-degrading explosive formulations. In combination with boron or iron, it forms gels that stabilize explosive mixtures and enable controlled degradation after use, thereby enhancing safety and reducing the environmental impact of residual explosive materials.

In the cosmetic and photographic industries, xanthan gum is used to form synergistic gels in combination with locust bean gum. These gels exhibit improved rheological properties, ensuring the stability of emulsions, creams, and related products. In photography, such gels are utilized to produce stable coatings and emulsions with controlled viscosity.

In the field of tissue engineering, xanthan gum is employed to fabricate three-dimensional matrices that mimic the extracellular matrix. Modified xanthan-based hydrogels support cell adhesion, proliferation, and differentiation, making them suitable for the regeneration of various tissue types [1].

Due to its unique physicochemical and biological properties, xanthan gum is also employed in the development of bioactive coatings for implants, where it promotes integration with surrounding tissues and reduces the risk of implant rejection.

Study [71] compares xanthan gum (XG) and hydrolyzed polyacrylamide (HPAM) as polymers for enhanced oil recovery (EOR) via polymer flooding technology in petroleum engineering. The results demonstrate that XG, as a biopolymer with high resistance to mechanical stress, elevated temperatures, and high salinity, represents a more environmentally friendly and economically viable alternative to HPAM, particularly under harsh reservoir conditions.

In study [72], an innovative approach to xanthan gum modification was proposed through the introduction of a supramolecular structure based on host–guest interactions between β-cyclodextrin and adamantane. This modification (XG–β-CD/AD) significantly improved the rheological properties, thermal stability, and salt tolerance of the polymer, which is especially important for oil recovery applications under extreme conditions of high temperature and mineralization.

In study [73], hydroxypropylated xanthan gum (HXG) was synthesized via etherification of xanthan with propylene oxide under alkaline conditions and compared with native XG in terms of rheological and hydrodynamic behavior during pipe flow. The incorporation of hydroxypropyl substituents was shown to enhance intermolecular associations and the formation of a spatial network, resulting in increased viscoelastic response and more effective friction reduction in turbulent flow compared to unmodified XG. In this context, xanthan gum acts as a fundamental polysaccharide scaffold, while chemical modification governs structure formation and, consequently, the rheological and hydrodynamic functionality of solutions–features that are critically important for shale gas and oil extraction.

The results reported in study [74] demonstrate the effective use of xanthan gum in concrete technology as a viscosity-modifying agent that enhances stability, cohesion, and homogeneity of cementitious mixtures. This is particularly relevant in applications requiring high stability without loss of flowability, such as self-compacting concrete (SCC), shotcrete, underwater concrete, and pumpable cement slurries. Xanthan gum prevents segregation, washout of cement paste, and ensures uniform distribution of components during transportation and placement, making it a promising component of biopolymer-based admixtures for environmentally efficient construction materials.

In study [75], the effectiveness of xanthan gum as a natural, biodegradable corrosion inhibitor for carbon steel in acidic media (1 M HCl) was

confirmed. XG was shown to form a protective adsorption film on the metal surface, thereby reducing the corrosion rate. Owing to its numerous functional groups (hydroxyl, carboxyl, and pyruvate), xanthan gum can interact with the metal surface via electrostatic interactions and hydrogen bonding. A key finding was the identification of a synergistic effect between XG and the anionic surfactant SDS (sodium dodecyl sulfate): the addition of SDS promotes the formation of a denser adsorption layer, thereby enhancing corrosion protection. In contrast, in combination with SDBS (sodium dodecylbenzenesulfonate), XG exhibits competitive adsorption, which hinders stable film formation and reduces inhibition efficiency. Thus, the inhibition mechanism involves co-adsorption of XG and SDS on the metal surface, forming a protective barrier that impedes the diffusion of H^+ ions to the metal. These findings are of practical importance for the development of sustainable and non-toxic anticorrosion systems, in which xanthan gum may serve as an environmentally safe alternative to conventional toxic inhibitors.

Study [76] reports the effectiveness of a ZnO/SiO_2/xanthan nanocomposite in reducing asphaltene deposition in shale and carbonate reservoirs. The system enables efficient adsorption of asphaltenes, reduces their aggregation, and improves rock permeability. Additionally, a wettability alteration from oil-wet to water-wet conditions was demonstrated, which is a favorable factor in enhancing oil recovery.

In study [77], the authors emphasize the potential of targeted modification of xanthan gum hydrogels through the incorporation of winery lees extract (WLE) to enhance their rheological and functional properties. This approach demonstrates promising opportunities for food waste valorization and reduction of production costs.

Conclusions

The present review demonstrates that xanthan gum is a key biopolymer platform for the development of composite materials with broad applicability across multiple sectors of the economy. The modification strategies analyzed in this article clearly show that the physicochemical, rheological, and performance properties of xanthan can be significantly expanded and precisely tailored through targeted structural interventions.

This work systematizes current approaches to xanthan modification aimed at localized alteration of its structural and functional characteristics. It has been shown that grafting functional moieties onto hydroxyl and carboxyl sites of the polysaccharide backbone, as well as interchain crosslinking involving side-chain interactions, leads to profound transformations of biopolymer behavior. Particular attention is given to the ability of modified xanthan systems to form mechanically reinforced hydrogels in the presence of metal ions and organic composite components.

Composite systems incorporating xanthan with other polymeric matrices–including those involving metal cations and positively charged groups of biological polymers–are identified as effective tools for tuning rheological, mechanical, and operational parameters of xanthan-based materials. Collectively, these modifications induce changes in the spatial organization of gel networks, enhance thermal stability, improve flow behavior, and increase resistance to electrolytes and pH fluctuations. These effects directly determine the scope of practical applications of xanthan across diverse industrial domains.

It is emphasized that intermolecular interactions play a decisive role in modified xanthan systems. Hydrogen bonding, coordination-driven ionic interactions, and hydrophobic effects collectively govern the formation and stabilization of supramolecular architectures. Hydrogen bonds between hydroxyl and carboxyl groups stabilize the helical conformation of xanthan chains, particularly under conditions of high ionic strength or low temperature. Coordination with multivalent ions (e.g., Ca^{2+}, Fe^{3+}) results in ionic "bridges" between polysaccharide chains, enabling the formation of robust network hydrogels. Simultaneously, the introduction of hydrophobic fragments imparts amphiphilic character to xanthan, promoting intramolecular hydrophobic associations between grafted groups. These noncovalent interactions collectively enable modified xanthan gels and composites to achieve coherent three-dimensional architectures with optimized mechanical performance.

The industrial relevance of these modification strategies is substantial. Xanthan gum is already widely used as a thickener and stabilizer in food, pharmaceutical, and cosmetic formulations. Its modified derivatives–particularly anionic gels and amphiphilic complexes–have gained importance in water and wastewater treatment due to their high efficiency in binding metal ions and organic contaminants. In the oil and gas industry, modified xanthan-based gel systems are employed to

enhance hydrocarbon recovery and stabilize drilling fluids. Moreover, the inherent biocompatibility of xanthan opens new opportunities for drug delivery systems and biomedical materials, while its incorporation into sensor platforms and environmental monitoring technologies supports the advancement of sustainable and "green" solutions.

The generalizations presented in this review provide a scientific basis for the rational selection of modifiers and optimization of their concentrations, thereby facilitating the efficient design of novel xanthan-based materials.

In summary, innovative strategies for xanthan modification unlock a wide range of opportunities in biopolymer chemical engineering. Future research should focus on integrating experimental and computational approaches to achieve a deeper understanding of the relationships between structural transformations and functional properties. Particularly relevant directions include the development of environmentally benign reagents for controlled modification, scaling of processes to industrial levels, and integration of xanthan systems with nanomaterials and intelligent formulation optimization methods. These efforts will ensure continued progress in the design of high-performance biopolymer materials with predictable and tunable properties for diverse applications.

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