# A Critical Review of the Microbial Exopolysaccharide Xanthan

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doi: https://doi.org/10.15255/CABEQ.2024.2348

Review
Received: June 26, 2024
Accepted: April 24, 2025

Xanthan gum, a microbial exopolysaccharide produced by *Xanthomonas campestris*, exhibits exceptional rheological behavior, structural versatility, and environmental resilience, making it indispensable across food, pharmaceutical, cosmetic, and industrial sectors. This review critically examines its biosynthesis, molecular configuration, and physicochemical properties, with emphasis on how cultivation parameters and polymer architecture influence its functionality. It highlights the role of side chain composition, ion interactions, and macromolecular conformations in determining xanthan's unique pseudoplasticity and stability. The paper further explores advancements in novel feedstocks and sustainable production techniques. Future research directions are identified, including enhanced control of structure-function relationships, enzyme-based modifications, and xanthan's role in emerging fields like 3D bioprinting and biodegradable materials. Overall, xanthan gum is positioned as a model hydrocolloid for both current industrial use and future innovation in biomaterials science.

*Keywords*

xanthan gum, microbial exopolysaccharide, rheological properties, industrial applications, biopolymer, biosynthesis

## Introduction

Many industries are increasingly seeking environmentally friendly ingredients for their products. Microbial biopolymers, such as xanthan gum, are gaining importance due to their renewable nature and diverse industrial applications. Xanthan, a microbial exopolysaccharide (EPS), offers unique chemical, physical, and rheological properties that make it suitable for various uses. Although EPS are abundant in nature, their industrial production remains costly. Xanthan gum, derived from *Xanthomonas campestris*, is cost-effective and can be considered a model material for molecular-level applications.

Xanthan gum is known for its ability to influence rheological properties in aqueous systems, including high viscosity at low concentrations that remains stable with temperature and pH changes. This makes it valuable across several industries. In the food sector, it is used as a stabilizer, emulsifier, thickener, and suspension agent[1] in products like salad dressings, sauces, noodles, juices, and baked goods. It also offers freeze-thaw stability, making it useful in frozen doughs. Beyond food, xanthan is used in pharmaceuticals, personal care products, cleaning agents, ceramic coatings, paints, inks, and crude oil recovery.

### Microbial exopolysaccharides (EPS)

Microbially produced polysaccharides (EPS) are an essential class of extracellular biopolymers secreted by microbial cells. Unlike intracellular polymers such as starch, cellulose, or polyhydroxyalkanoates (PHA), EPS are released into the surrounding environment where they perform protective functions—shielding cells from desiccation, mechanical stress, and facilitating surface adhesion or biofilm formation.[2] EPS are structurally diverse and can be water-soluble or insoluble, depending on their composition and the producing microorganism. These polymers include polyesters, polyamides, inorganic polyanhydrides, polynucleotides, and polysaccharides.[3,4] The properties and conformations of EPS vary significantly between microbial species, contributing to their functional adaptability.[5,6]

A major advantage of microbial EPS over plant- or algae-derived polysaccharides is the tunability of their properties. In contrast to photosynthetic eukaryotes, which are limited by fixed bio-

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synthetic pathways, bacteria offer metabolic flexibility. This allows for controlled biosynthesis under varying conditions, facilitating the production of tailored biopolymers like xanthan. These features underscore the growing industrial and scientific interest in microbial EPS.

## Xanthan: microbial synthesis and technological processing

In contrast to other EPS, the information on genetics of xanthan is well documented and therefore plays a major role in the selection of certain strains of bacteria.[7] The biosynthetic pathway for xanthan (shown in Fig. 2) is quite complex. The pathway is, next to the microbial reproduction process, the determining factor for the composition of the resulting xanthan product.[8] The biosynthesis of xanthan begins with the Entner-Doudoroff (ED) pathway (Fig. 1)[9] (also known as the 2-keto-3-deoxy-6-phosphogluconate (KDPG) pathway), a glycolytic pathway commonly found in aerobic bacteria. This pathway generates key intermediates such as phosphoenolpyruvate (PEP) and acetyl-CoA through the catabolism of substrates. Additionally, the tricarboxylic acid (TCA) cycle provides the energy required for xanthan biosynthesis.[10]

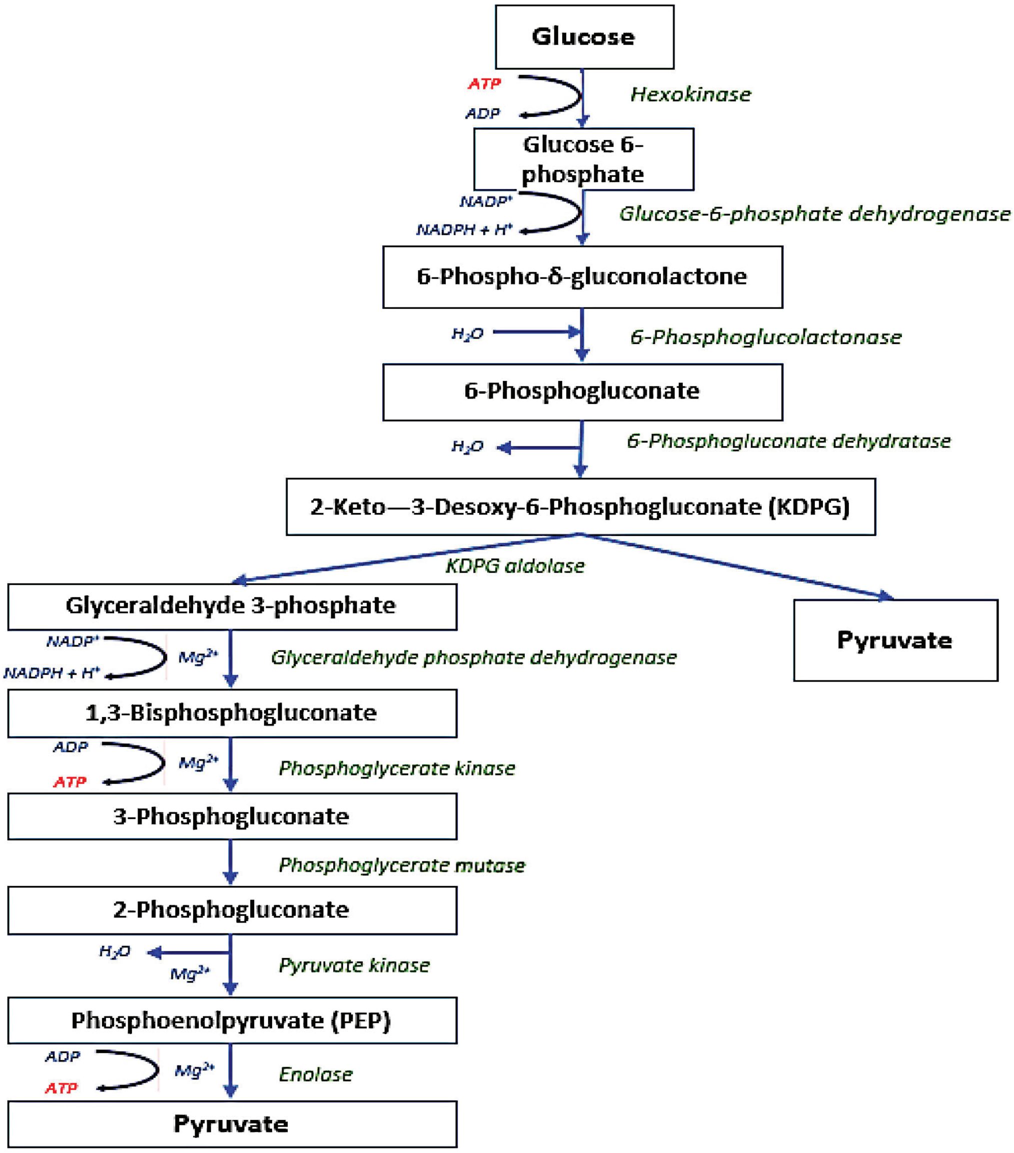


Fig. 1 – *Scheme of the Entner–Doudoroff (ED) pathway. In the ED pathway, glucose is converted to pyruvic acid in fewer steps than it is in the pathway of glycolysis.*[9,11,12]

The tricarboxylic acid pathway includes the linkage of two glucose molecules with the trisaccharide consisting of an acetyl-mannose, glucuronic acid and pyruvyl-mannose that become the side chain. Basically, xanthan is built up from sugar nucleotides present in the cytoplasm, acetyl-CoA, and phosphoenolpyruvate (PEP) with an inner membrane polyisoprenol phosphate (IDP) as an acceptor. The sequential addition of monosaccharides from the nucleotide-sugar-phosphates (UDP-glucuronic acid, GDP-mannose, IDP-glucose) includes CoA acetylation to form the pentasaccharide repeating unit. Hence, IDP-glucose, GDP-mannose, UDP-glucuronic acid, PEP, and acetyl-CoA are connected via IDP-linked intermediates.[13,14]

The sequential addition of monosaccharides to the growing polysaccharide chain is mediated by the glycosyltransferase enzyme, which facilitates the transfer of sugar molecules from the nucleotide-sugars (UDP-glucuronic acid, GDP-mannose, IDP-glucose) to the acceptor molecule. Acetylation, facilitated by the transfer of O-acetyl groups from acetyl-CoA, is crucial for the final modification of the side chains. The CoA acetylation transfers the O-acetyl group to the nonterminal D-mannose residue, a critical step in the biosynthesis. The complete formation of the xanthan polymer requires the abundant availability of CoA and the appropriate substrates for each step of the pathway. Once the pentasaccharide chain is assembled, it is ultimately secreted outside the bacterial cell.[15]

## Microbial cultivation

### *Dependence of genetic setup of active bacteria*

Biosynthesis of polysaccharides in general is enzymatically catalyzed by cells directly in the cytoplasm; these products are used in different parts of the cell. Biosynthesis and polymerization do not only happen in the cytoplasm, but also in the plant´s Golgi apparatus, which can synthesize complex matrix polysaccharides of the cell wall. Cellulose, for example, is synthesized at the plasma membrane, whereas pectin and hemicelluloses are synthesized in the Golgi cisternae and are then transported to the cell surface. The biocatalytic pathway determines the place where the polysaccharide is formed.[18]

In the case of xanthan gum, the bacterium *X. campestris* produces xanthan via an enzymatic process.[19] In nature, these bacteria can be found on the leaves of cabbage, corn, and other vegetables. It was believed for a long time that the bacteria are pathogenic and the main cause for the black rot disease.[20,21] The bacteria form anaerobic Gram-negative rods, which cause a black rod by darkening the vascular tissues on crops. These types of bacteria are classified by the host plant they attack. Nevertheless, after studying the genetic background of *X. campestris* metabolism and the biosynthesis of xanthan, it was concluded that the bacteria are probably not responsible for the pathogenic behavior. In con-

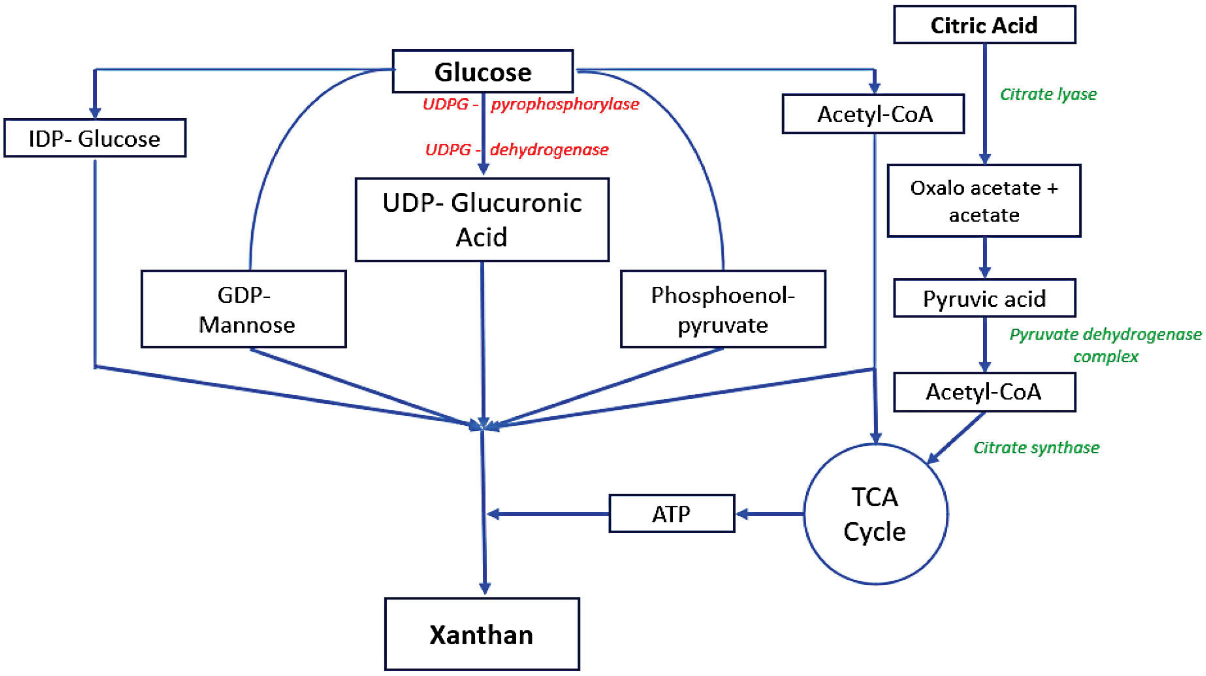


Fig. 2 – *Simplified overview of the biosynthesis of xanthan and the citric acid (TCA) metabolic pathway,*[16] *UDP-Glucuronic acid (Uridine diphosphate glucuronic acid), GDP-Mannose (Guanosine diphosphate mannose), IDP-Glucose (polyisoprenol phosphate)*[17]

trast, there is even evidence that the species contributes to survival pathways of *Xanthomonas* sp. on host plants.[22–24]

### *Dependence on carbon and nitrogen-source*

In industry, xanthan is usually produced in discontinuous cultivation batches of *X. campestris*, but it can also be produced in continuous microbial production systems.[25] The bacteria are kept in an optimized medium containing appropriate types and quantities of carbon- and nitrogen compounds as nutrients. These sources for carbon and nitrogen vary due to availability. In Austria, the company Jungbunzlauer uses, e.g., corn as carbon source, because it is locally available.[26] In other regions, producers may use other locally available carbon sources, like sugar beet molasses, sugarcane, corn, date extract, etc.[27,28] As nitrogen source, e.g., soya beans and yeast extract are widely used. More recently, glycerol was used with a glycerol-tolerant strain of *X. campestris*.[29] Xanthan properties are a result of biosynthesis and hence these sources play an integral part. For example, studies have shown that the source of nitrogen can influence the pyruvate content in the xanthan side chains.[30] Initial broth volume, substrate feed concentrations, inoculum density, and the dissolved oxygen level (DO) are crucial process parameters and, when optimized, result in high product concentration after the microbial production.[31,32]

Table 1 summarizes the optimal conditions for maximizing xanthan gum production based on several key process parameters. These include carbon and nitrogen sources, the C/N ratio, inoculum density, dissolved oxygen levels, initial broth volume, substrate feed concentration, and fermentation time. Each parameter is crucial for ensuring optimal microbial growth and high xanthan yield. For example, sugar beet molasses, glucose, and glycerol are preferred carbon sources, while yeast extract and soybean meal are key nitrogen sources. The C/N ratio (10:1 to 20:1) is critical for maintaining a balance of nutrients that supports both microbial growth and polysaccharide production. Additionally, parameters like dissolved oxygen levels (30–50 % saturation) and fermentation time (48–72 hours) play an important role in maximizing the yield.

The production consists of two basic cultivation phases, starting with the microbial growth and product (xanthan) formation stage, where a strain is cultivated under optimal nutritional conditions. The second stage is the downstream processing phase after the microbial cultivation, in which xanthan, as an extracellular product, is isolated from the cell suspension and then further processed. Fig. 3 shows a simplified flow chart of an industrial xanthan production process. It is important to note that, in case of a genetically stable, robust production strain, stock cultures can be stored for extended periods so that the microbial strain does not change over time.

Table 1 – *Conditions for high xanthan polymer yield*

| Parameter | Optimal conditions | Explanation |
|---|---|---|
| Carbon source | Sugar beet molasses, glucose, glycerol, sucrose | Sugar beet molasses is widely used due to local availability. Glucose and sucrose are common alternatives in industrial production systems. Glycerol is used with glycerol-tolerant strains.[33,34] |
| Nitrogen source | Yeast extract, soybean meal, ammonium salts | Complex nitrogen sources such as yeast extract and soybean meal promote higher yields. Ammonium salts are often used in industrial applications.[35] |
| C/N ratio | 10:1 – 20:1 | The optimal carbon-to-nitrogen (C/N) ratio ensures proper microbial growth and maximal xanthan production. A C/N ratio higher than 20:1 may lead to nitrogen deficiency, affecting polysaccharide production.[36] |
| Inoculum density | 2–10 % (v/v) | Higher inoculum densities generally improve xanthan production, but overly dense cultures can lead to oxygen depletion and reduced yields.[37] |
| Dissolved oxygen level (DO) | 30–50 % saturation | Oxygen availability directly impacts the metabolic pathways of *X. campestris*, with higher DO levels promoting enhanced polysaccharide biosynthesis.[33,34] |
| Initial broth volume | 2–10 L for batch, continuous culture with high flow rates | The initial broth volume influences oxygen transfer and mixing, which are critical for uniform xanthan production.[38] |
| Substrate feed concentration | 10–30 g $L^{-1}$ for carbon sources | High carbon concentrations are important for high xanthan yield but must be optimized to prevent substrate inhibition.[37] |
| Fermentation time | 48–72 hours for batch culture | For batch cultures, the optimal fermentation time to achieve maximum yield generally ranges from 48 to 72 hours, depending on the growth rate of *X. campestris*.[38] |

During strain maintenance, the strain is usually kept in a lyophilized state or in frozen glycerol culture stocks for long-term storage. As a first step of the biotechnological upstream processing before the microbial cultivation, the inoculum is prepared. In this step, a small amount of the production strain is transferred from long-term storage, revitalized, and added to a liquid pre-culture medium (“inoculum culture”). Typically, the inoculum makes up around 5–10 % of the total liquid batch volume. During the microbial production, freshly produced xanthan surrounds the cells and hinders the nutrients and oxygen from reaching them. Consequently, high xanthan concentrations in the inoculum result in a long lag phase in the aerobic microbial production. Therefore, for an optimal microbial production process, an inoculum with a low xanthan content is needed. Yield and quality are influenced by adjustable microbial cultivation parameters, such as temperature (25–35 °C),[39,40] pH-value (7.0–8.0),[41] duration (24–72 h),[41] agitation rate (100–600 rpm),[42,43] dissolved oxygen,[44] and even the type and geometry of the bioreactor and the type and geometry of the stirrer.[45,46] Post microbial production, the bacterial suspension is pasteurized for inactivation, and insoluble particles (cells) are filtered off. If needed, a

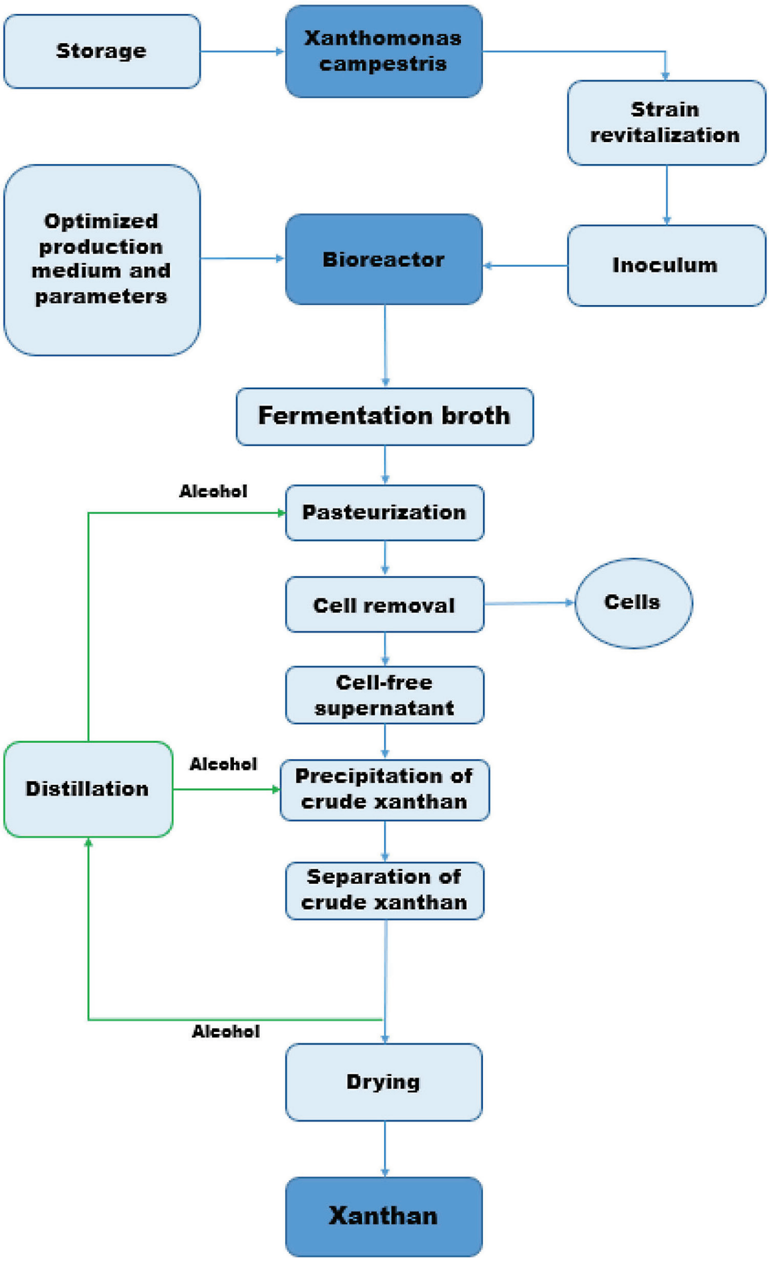


Fig. 3 – *Flow chart of an industrial xanthan production process. At the beginning of industrial xanthan production, the production strain used to form the inoculum must be taken from stocks. Following microbial cultivation, the broth is pasteurized, filtered, and xanthan is separated from the suspension. Subsequently, drying, grinding, and packaging are carried out.*[49]

further purification processes can be applied to the xanthan before the next step. A patented enzymatic purification process can be applied to obtain high-grade xanthan gum.[47] In the next step, the xanthan gum is recovered by precipitation with alcohol. The alcohol (e.g., methanol, ethanol, isopropanol) is recovered from the suspension again via distillation.[48] At this stage, xanthan gum must be dried to remove the humidity. At the end, the dry xanthan is ground and packed waterproof, ready to be used.

## Global production, regulation and leading producers

Xanthan gum, a polysaccharide first discovered in 1959 in the United States, quickly transitioned into commercial production in 1960. It is widely used in both food and non-food applications due to its unique rheological properties. In the European Union, xanthan gum is approved as a food additive under the code E 415, where it functions as an emulsifier, gelling agent, thickener, stabilizer, and foaming agent.[50] It is also registered under CAS 11138-66-2 for both food and industrial applications. In the United States, it is authorized by the FDA under 21 CFR 172.695. Xanthan gum is also recognized in many other countries around the world, including Canada, Australia, and several Asian nations, where it is used in both food and industrial applications, including oil drilling, pharmaceuticals, and cosmetics. The *Codex Alimentarius*, an international food standards organization, also recognizes xanthan gum as a safe food additive in accordance with international trade guidelines.[51] As of 2021, the global market for xanthan was valued at approximately USD 650 million, with annual production estimated at 160,000 tons.[52] The market is forecasted to grow significantly, reaching an estimated USD 1.2 billion by 2030, driven by increasing demand in various industries, particularly in the food and beverage, oil and gas, and pharmaceutical sectors.[53]

Fig. 4 illustrates the global market breakdown by industrial sectors. The largest portion of the xanthan market is occupied by the food and beverage sector, owing to the broad array of applications ranging from food thickening to stabilizing emulsions. While the oil and gas industry also utilize substantial amounts of xanthan, particularly in the form of drilling fluids, it represents a smaller share in comparison due to a lower variety of applications. Other industries, such as cosmetics, pharmaceuticals, and personal care, make up a smaller yet significant share of the market.

The largest global producer of xanthan gum is PR China, which accounts for over 30 % of global production. PR China and other countries in the Asia-Pacific region dominate the xanthan gum manufacturing sector due to lower production costs, domestic demand, and strong government support for the biotechnology and biopolymer industries. Several large-scale manufacturers, including Fufeng Group, Meihua Group, and Deosen Biochemical, operate in this region.

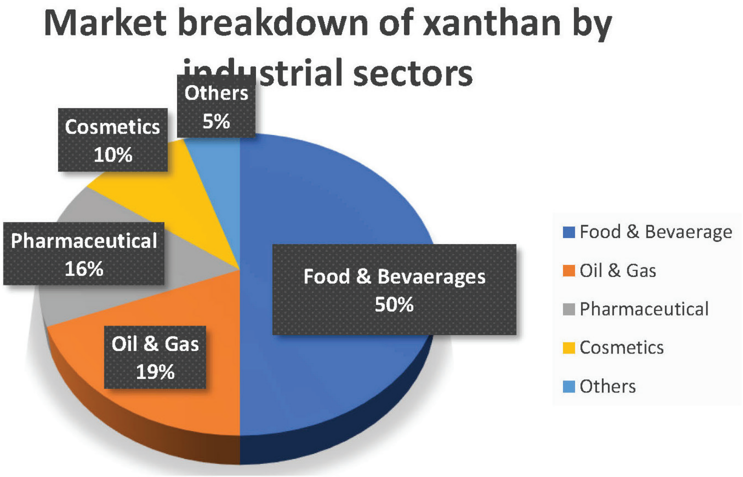


Fig. 4 – *Market breakdown of xanthan by industrial sectors*[52,54]

In Western countries, significant growth is projected in the xanthan gum market, especially as the demand for gluten-free products continues to rise. Xanthan is an essential ingredient in the production of gluten-free foods, providing texture and viscosity. Moreover, its use in enhanced oil recovery and drilling fluids for oil and gas extraction contributes to an increasing demand for xanthan gum in energy-related industries.[52,54]

Table 2 presents the estimated annual production volumes of xanthan gum by leading producers, categorized by their respective companies and regions.[55]

CP Kelco and Fufeng Group are the largest global producers, each with annual production estimated at 30,000–50,000 tons of xanthan gum. Producers in PR China, such as Fufeng Group, Deosen Biochemical, and Meihua Group, dominate the global production, with high-volume output driven by low production costs and strong domestic demand.

## Unimer composition with molecular variability

Xanthan´s molecular structure has been intensively studied.[59] The monomer repeating unit´s structure is shown in Fig. 5. This repeating unit consists of a cellulose-like backbone of β-(1,4) linked D-glucose molecules that alternately are linked to a trisaccharide side chain consisting of two mannose units and a glucuronic acid molecule

Table 2 – *Estimated annual xanthan gum production by major global producers*[56–58]

| Producer | Estimated annual production (tons) | Notes |
|---|---|---|
| CP Kelco (USA) | 30,000 – 40,000 | CP Kelco is one of the largest producers globally and has multiple production sites worldwide. |
| ADM (USA) | 20,000 – 30,000 | ADM is a significant player in the xanthan gum market, particularly in the food and beverage sector. |
| Jungbunzlauer (Austria) | 8,000 – 12,000 | Jungbunzlauer produces a wide range of food ingredients, including xanthan gum. |
| Cargill (USA) | 10,000 – 15,000 | Cargill is a major global food and agricultural products company that also produces xanthan gum. |
| DuPont Danisco (USA) | 10,000 – 15,000 | DuPont Danisco is well-known for its production of various food ingredients, including xanthan gum. |
| Vanderbilt Minerals (USA) | 2,000 – 5,000 | Vanderbilt Minerals focuses on specialty chemicals, including xanthan gum production. |
| Fufeng Group (China) | 30,000 – 50,000 | Fufeng Group is one of the largest producers of xanthan gum, particularly for the food and beverage market. |
| Deosen Biochemical (China) | 20,000 – 25,000 | Deosen Biochemical is a major supplier of xanthan gum with production capacity in China. |
| Meihua Group (China) | 25,000 – 30,000 | Meihua Group is one of China's leading manufacturers of xanthan gum and other biopolymers. |
| Hebei Xinhe Biochemical (China) | 15,000 – 20,000 | Hebei Xinhe is a well-established producer of xanthan gum with a strong presence in Asia. |

in between. A variability of around 30–40 % of the terminal mannose residues of the side chain are linked to a pyruvate group, while the central mannose moiety is approximately 60–70 % acetylated.[60] Acetyl and pyruvic acid content vary, depending on the production, the nutrients, and the bacterial species used. The main chain is consistent, but the side chains vary; some go even without any pyruvate or acetate.[48] Due to the high number of carboxyl groups, the side groups of xanthan are highly anionic when xanthan is in an aqueous medium. Average molecular weights and the polydispersity can be quite different. This depends on how xanthan is used and also on the batch, and under which conditions it was produced. In literature, some variations are found. This is mainly due to the fact that not all published results originate from one xanthan batch, a material with variations typical for biopolymers. Xanthan can be quite different in its properties for all the reasons mentioned before.

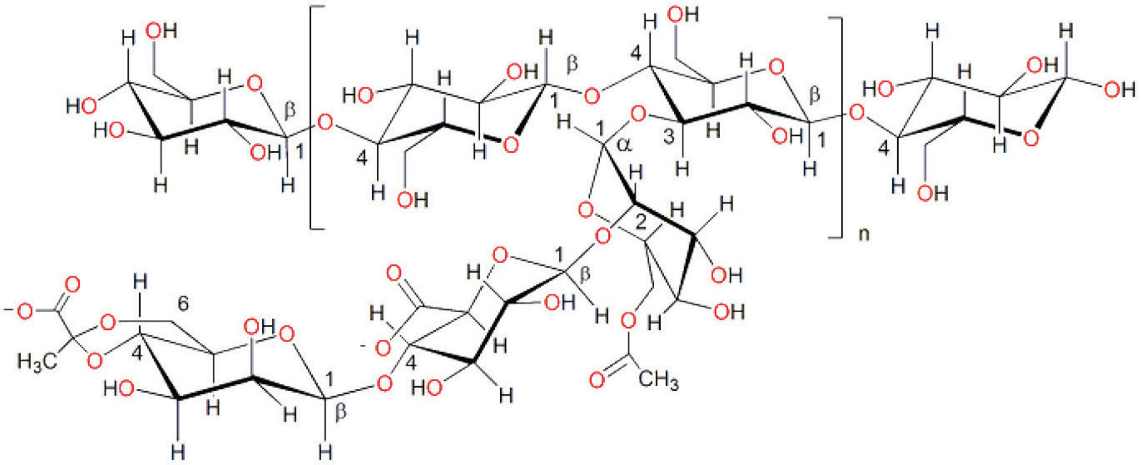


Fig. 5 – *Xanthan repeating unit: β-(1,4)-D-glucoses with α-(1,3)-linked triose-branches consisting of a partially (60–70 %) C6-acetylated mannose β-(1,2)-connected glucuronic acid and another optionally (30–40 %) C4-pyruvate derivatized β-(1,4)-linked mannose (created with Biova Draw 2021)*

## Xanthan: Oligomer and polymer characteristics

### Molecular weight distribution

Molecular weight distributions in xanthan exhibit a wide range, due to several factors. Firstly, the molecular weight distribution (polydispersity) is determined by the specific strain of *X. campestris* used; the exact genetics of a given bacterial strain is a determining factor for polydispersity. The biotechnological production process is also an important factor, alongside the type of substrates provided and the duration of microbial cultivation. The measuring method for the determination, sample preparation, and concentration also plays into the resulting distribution values. In the published literature, one finds mean values for a certain xanthan that was used in the experiments. Previous studies on xanthan have reported weight average molar masses ($M_w$) ranging from $0.5 \cdot 10^6$ to $6 \cdot 10^6$ g mol$^{-1}$ in an aqueous environment.[61–65,120]

The polydispersity of xanthan in aqueous media depends on the mechanical treatment of xanthan. For instance, high-pressure homogenization (HPH) leads to a decrease in viscosity due to degradation of the biopolymer.[66–68] Some studies have shown that the molecular weight of xanthan is not significantly reduced by mechanical force; instead, changes in the polydispersity and molecular structure are observed.[66,67,69] The polydispersity index ($M_w/M_n$; $M_n$: number average molecular mass) is found between 1.10, 1.55, and 2.54, depending on the intensity of the xanthan treatment. The higher the intensity of the treatment, the greater the polydispersity, as disruption of aggregates and microgels, disruption of double stranded structures, and a decrease in molecular weight and increased polydispersity lead to a loss of viscosity in hydrocolloidal xanthan systems.[67]

### Conformation

When examining the secondary structure and its conformation, one might expect the glucose molecules to arrange themselves in a beta sheet structure. However, they do not, due to the highly charged side chains and their repulsive and attractive forces. The xanthan chain adopts a right-handed helical structure, as shown in Fig. 6.[70] This model was constructed under vacuum conditions. In reality, under aqueous conditions, the xanthan chain carries thousands of charges. Several studies on the structure of xanthan have confirmed its helical structure.[71] X-ray diffractometry has made it possible to verify that the side chains stabilize the main chain through the formation of hydrogen bonds.[70]

Atomic force microscopy (AFM) has made it possible to show that xanthan´s helical conformation constitutes a double helical structure. These double helices are distorted in aqueous solution. AFM images showed clear resolution of the periodicity with a value of 4.7 nm.

Under aqueous conditions, the temperature and the ionic strength of the solvent highly influence the structure.[73] In regard to this conformation, it should be noted that xanthan undergoes a transitional change. The first transition from the native to the denatured state is irreversible. These changes with heating and cooling alternate between a denatured flexible coil and a stiffer renatured helix, as shown in Fig. 7.

The conformation indicates whether the polymer is renatured or native; the conformation, in turn, depends on the medium it is dissolved in and the temperature.[74,75] In aqueous conditions with an ionic environment, the main transitions occur between 46–52 °C,[76–78] but vary with a given type of xanthan, and strongly depend on the ionic strength of the solvent. The most important part for the polymer structure is the pyruvic acid and acetic acid res-

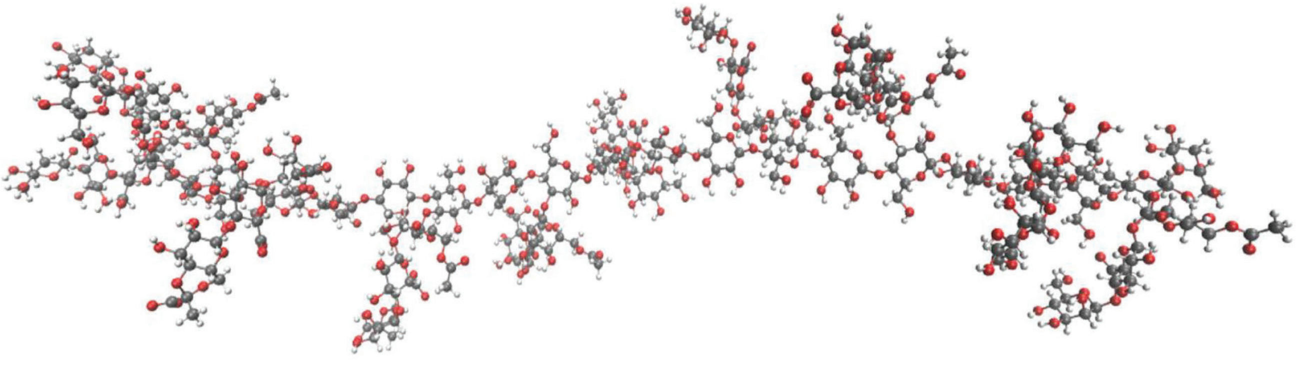


Fig. 6 – *Three-dimensional model of a xanthan oligomer with ten repeating units shows the helical twist*[72]

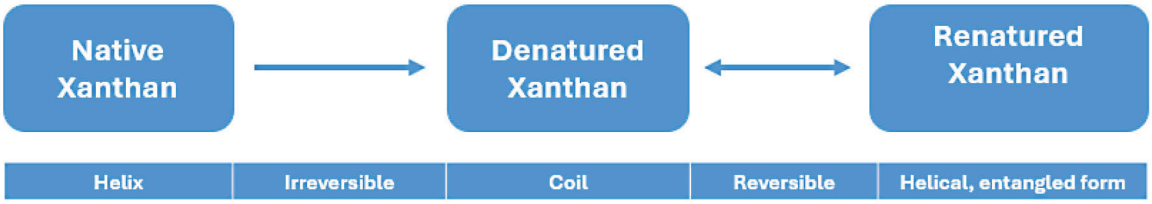
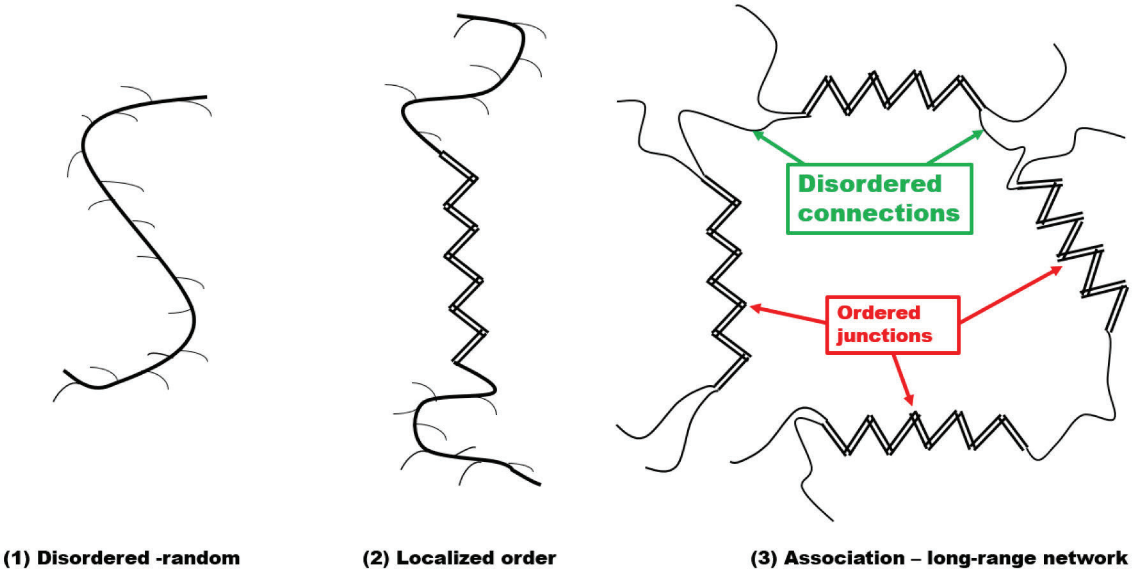


Fig. 7 – *Transitional states of xanthan, between helix, coil, and helical, entangled aggregate, while heating and cooling*

idues; the quantity of and ratio between these residues are influenced by the salt concentration prevailing during the biosynthesis. Overall, xanthan must stay below the melting point.[51] Optical rotation and sedimentation equilibrium measurements showed that the conformational transitions coincide with rheological properties, mainly the viscosity.[79]

Properties of xanthan water-modifier (XWM) systems can also be influenced by the preparation method used. The method determines a considerable part of the functionality in an application, and can cause a lot of unnecessary problems.

We particularly wish to highlight that the widely cited theory[109–112] stating that xanthan forms a double helix under certain conditions, appears far-fetched and lacks definitive proof. It is also difficult to imagine the formation of a double helical structure as in an aqueous medium, the enormous number of like-polarized charges on the side chains would prevent this. It would be like two like-polarized magnets repelling each other rather than forming a larger magnet. It is rather realistic that some entanglements of the stiffer renatured rods are interpreted as double helical forms, rather than a real double helical formation. These effects are further enhanced up to a certain threshold, by multivalent ions. The renaturation is not only influenced by the ionic strength of the solvent and temperature,[80] but also by the xanthan itself. In an aqueous environment, the addition of salt increases the degree of mismatched pairings during renaturation.[81] This influences single strains and increases the formation of aggregates. In general, xanthan shows a higher affinity to aggregate formation after being thermally treated. This is the result of the conditions during the transition.[82,83] This phenomenon has long been discussed and was not clearly understood before.[84,85] More recently, the topic resurfaced and it was concluded that the transition is a two-step process, as shown in Fig. 7 and Fig. 8.[109] If the temperature during treatment is lower than the temperature range in which xanthan undergoes the transition, it maintains a rod-like form and tends to form larger objects and networks by hydrogen bonding. During the transition, xanthan forms coils, which can be considered the more flexible denatured form of xanthan. While cooling down, it goes back into a helical rod form.[86] The reason behind these changes is the enthalpic interactions that compensate the entropy loss during the transitions. Hydrogen bonding, dipolar or electrostatic interactions are stabilizing factors. Repulsion forces between negatively charged groups in the side chains have a destabilizing effect.



**(1) Disordered -random** **(2) Localized order** **(3) Association – long-range network**

Fig. 8 – *Schematic illustration of: (1) the disordered conformation of xanthan, (2) the mechanism of local conformational ordering; and (3) lateral association of the ordered chain sequences giving a weak gel-like network*[114]

At the polymer chain ends, the entropy loss is not compensated; that is why these chains are disordered. The whole polymer chain needs to have a certain length to obtain stability. The transition from a disordered entropically favorable to an entropically unfavorable structure can also be seen as a mechanism for chain growth.[87] Fig. 8 shows the formation of junctions, entanglements, and growth in a schematic way. This particular formation of a network is similar to the start of the formation of weak gels.

The formation of a xanthan water-modifier (XWM) system exhibiting properties similar to those of a weak gel, is attributed to the linkage of multiple xanthan chains. This linkage occurs within so-called linking zones, which are very weak and can be disrupted by even slight stress. Minimal deformation is sufficient to induce flow in the XWM system once more. These various states and conformational changes of xanthan explain many of the rheological properties and corresponding stabilities towards system stresses of XWM systems, as summarized in Table 3 within the context of hydrocolloid systems. From the aspect of tuning and optimizing current technical applications and finding new applications for xanthan, it is of great importance to understand the molecular and macromolecular interactions that are responsible for the stabilization of XWM systems and their resulting properties. Recent research has shown a correlation between xanthan´s thickening properties and its ability to form secondary structures, influenced by the valence and number of cations coordinated at the tri-mannose side chain. Divalent cations are able to reversibly bridge neighboring single xanthan strains via chelate-like complexation and form new macromolecular structures. These larger objects therefore affect viscosity of XWM systems.[88]

## Dimensions, particle structure, and size dynamics of xanthan gum

The hydrodynamic radii and particle size for xanthan exhibit a broad range. These parameters depend on the type of supermolecular structure present in a given sample of xanthan (helical, rod-like, or coil-shaped). The nature and properties of the xanthan itself determine the particle dimensions. The dispersion medium, depending on the application and preparation method, as well as the nature and presence or absence of counter-ions in the dispersion medium, play key roles in influencing particle size. For instance, nanogels of xanthan gum can have hydrodynamic radii from 5 nm to 35 nm,[89] which is quite small. Xanthan tends to aggregate and particles grow in size over time. The critical overlap concentration ($c^*$)[90,91] and critical aggregation concentration ($c^{**}$)[92–95] are also important influential factors. Common methods to determine dimensions, particle sizes, and "gel"-networks are DLS (Dynamic Light Scattering) in combination with rheological experiments.[95] Particle sizes can range from a few nanometers up into the micrometer range.[96–99]

## Sample preparation/use of xanthan-water modifier systems

- The preparation method of xanthan gum can significantly influence its properties, particularly its rheological behavior, which may either enhance or hinder its suitability for a desired application. Xanthan can be prepared using various techniques, including: Mechanical stirring (mechanical mixer, magnetic stirrer, …)
- Devices such as Ultra-Turrax, colloid mill, dispersion funnel or a similar homogenizer
- Ultrasonic treatment
- Heat treatment.

The intended application dictates the appropriate preparation method. Firstly, it is essential to determine the key expected functionality. In all cases, hydration is of utmost importance. Xanthan gum can be dispersed in both hot and cold liquids. Like most hydrocolloids, xanthan requires vigorous agitation when introduced into an aqueous environment. The particle size of xanthan needs to be taken into account. Xanthan has a strong tendency to form lumps when added to water. For this reason, the dispersion, the stirring speed, the composition of the solvent (aqueous, salt/ counter-ion concentration) and the particle size need to be considered.

These are the most important parameters for optimal use. Long-chain xanthan tends to disperse more easily but hydrates more slowly. Optimal results can be obtained through high energy input such as with techniques of high-shear capabilities.[48] Sodium chloride solutions are a favorable dispersion medium, they are inexpensive, easy to handle, and facilitate hydration by countering the highly anionically charged xanthan particles. Xanthan can also be dissolved in other media, such as in acids or alkaline solutions, but hydration is much better if it is first mixed with water before the acid or base is added.[100] This leads to a better separation of particles and therefore a better dispersion of particles. Particle size is a very important factor in the hydration process as well. Fig. 9 shows the dependence of particle size on hydration.[16] Rule of thumb: the smaller a particle, the faster the hydration process. On the negative side, however, small particles clump together much faster, which explains one of the difficulties of xanthan sample preparation in a research environment.

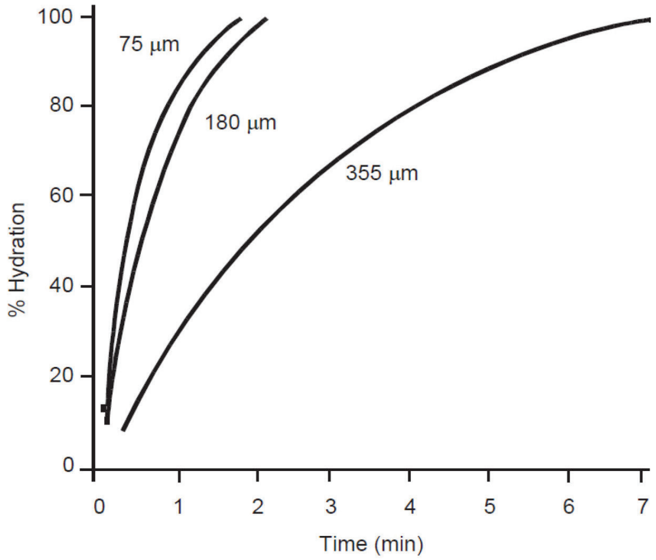


Fig. 9 – *Effect of particle size (μm) on the hydration of xanthan gum*[48]

As an example, a change in counter-ions can lead to different results. Variations in rheological performance have been observed when hydrogels were prepared with, e.g., $Na^+$, $Ca^{2+}$ and $Fe^{3+}$. The hydrogel containing $Ca^{2+}$ showed higher tolerance to mechanical stress than the one with $Na^+$. This is most likely due to a higher degree of aggregation and the formation of larger structures and networks. The Debye length of ions has an important influence, along with the cross-linking potential of multivalent ions. The hydrogel with $Fe^{3+}$ showed hard and brittle properties and was less tolerant to induced stress.[101] Depending on the concentration, a few problems can occur. The higher the concentration, the harder it is to eliminate air bubbles from the XWM system. In some applications with lower concentrations, these air bubbles will not affect the product or production, as they will dissolve over time. In research and quality control, however, air bubbles must be removed before any measurements can be conducted.

## Xanthan: nano-structured interfaces by hydrocolloidal objects

The key feature of XWM systems is their ability to absorb water, hence the ability to influence the viscosity of an aqueous system. An XWM system may absorb 30–60 times its own volume in water. This ability is determined by the ionic concentration of the aqueous environment. In deionized or distilled water, the absorption rate is up to 500 times its own mass. The absolute absorption and swelling capacity depend on the type and degree of the XWM system network.[102,103]

## Stability of xanthan-water modifier systems

As mentioned previously, the molecular composition and the macromolecular structure and conformation explain many of the unique properties of XWM systems. Table 3 provides an overview of these correlations. XWM systems are usually highly pseudoplastic, hence, viscosity decreases with increasing shear force. Before going into more detail on the rheological properties of XWM systems, a short discourse on colloidal aggregation is necessary. The overall performance of an XWM system relies heavily on the concentration, kind of cationic environment (modifier), and type of stress applied on the system during preparation. These parameters subsequently define the overall performance by defining the homogeneous and heterogeneous partition of the system.[104]

### *Colloidal aggregation*

The aggregation process of an XWM system relies on the similarities of a mixture, although it is not a homogenous mixture *sensu stricto*, rather an intermediate between a solution and a heterogeneous mixture. An XWM system is a suspension of particles in a liquid. The XWM system can be stable or unstable. A stable system shows individual particles, while an unstable system forms aggregates. Aggregates form over time: Firstly, dimers are visible, followed by the formation of higher structures and networks. In an aqueous XWM system, particles will collide and, due to attractive forces, adhere to one another irreversibly. This process is often accompanied by an increase in molecular weight, which is an indicator of aggregation.[105] The aggregation influences the rheology of an XWM system. XWM systems react to shear stress proportionally. With increasing shear rates, the viscosity is reduced. Analogous to the conformational change when heated and cooled down again, xanthan shows the ability to recover the initial viscosity. As previously discussed, xanthan is stabilized as a rod-like structure by counter-ions in the system. The counter-ions minimize the electrostatic repulsion between the highly anionic trisaccharide side-chains. The ordered chains then tend to build quaternary structures, so-called aggregates, a network that is held together by hydrogen bonding and entangled polymer chains. In the case of an XWM system with stiff rods, the rheology will show high viscosity at low shear rates.[106] This makes xanthan ideal in many industrial applications, e.g., for suspensions, as stabilizer in emulsions and foams.[107]

Fig. 10 shows the flow curve of a 1.0 % XWM system (xanthan gum) in a 0.1 M sodium chloride solution. The system exhibits high viscosity at low shear rates, forming a plateau that reflects its pro-

Table 3 – *Properties and corresponding stabilities/compatibilities of xanthan*[48]

| Macromolecular structure | Rheological properties | Stability/compatibility | Application examples |
|---|---|---|---|
| Rod-like structures (helical) stiff, quaternary structures/ networks (aggregates), anionic side chains | High viscosity at low concentration | Ionic strength variations, heat resistance | EOR (Enhanced Oil Recovery) reservoir flooding |
| Complex aggregates<br>Weak intermolecular forces | High viscosity at low shear rates<br>High viscosity at low conc.<br>High elastic modulus<br>Pseudoplastic rheology | pH-value<br>Shear forces<br>Ionic strength variations | Suspensions<br>(e.g., food industry) |
| Backbone protected by large overlapping side chains | High degree of pseudoplasticity,<br>Low degree of thixotropy | Enzymes<br>Chemicals<br>Acids, bases | Pharma and medical applications (e.g., drug delivery) |

nounced resistance to flow. This region corresponds to the yield stress, the minimum stress required to initiate flow highlighting the structural stability of the system.

As the shear rate increases, shear stress also rises, and the apparent viscosity decreases markedly, eventually approaching values near that of water. This shear-thinning behavior is characteristic of non-Newtonian fluids such as xanthan-based systems. Notably, the system shows no significant heat dissipation under shear, and its viscosity recovers almost instantly once the stress is removed, indicating excellent thixotropic recovery.[104] The yield stress and flow characteristics of XWM systems are influenced by factors such as polymer chain transitions and variations in intermolecular interaction potential, which can alter the structure and flow behavior of the gel network.

### *Influence of ionic environment and xanthan concentration on viscosity*

Rheological experiments like oscillatory and continuous shear stress show the effect of certain parameters on the viscosity of an XWM system. These parameters are temperature, concentration, and ionic strength of the environment. These rheological experiments apply the principle of stress on the system and the response of the XWM system. One response is the terminal relaxation time of the XWM system. The relaxation time increases exponentially with the concentration of xanthan.[108] The effect of counter-ions depends on the concentration of xanthan. At low xanthan concentrations, counter-ions decrease the viscosity when added in small amounts. The reason behind this effect is that intermolecular interactions are reduced and therefore the rate of aggregation is slowed down. At high xanthan

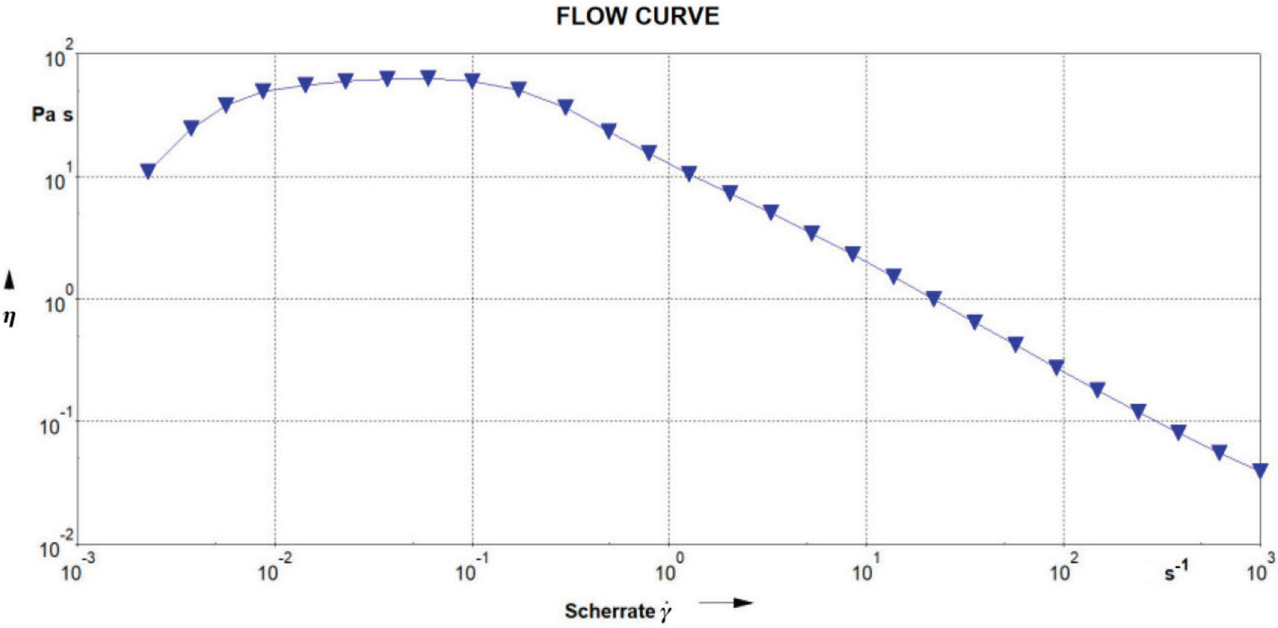


Fig. 10 – *Flow curve of a 1.0 % XWM system in 0.1 M sodium chloride solution*

concentrations, counter-ions increase the viscosity due to their high interaction potential.[109,110] Larger counter-ions increase the viscosity stronger than smaller cations. This is true for mono- and bivalent counter-ions.[111] Divalent cations have a greater effect on viscosity than monovalent ones, regardless of their ionic radii, because of ion bridging between xanthan chains.[112] When the concentration of counter-ions is higher than 0.1 % w/v, the XWM system becomes independent of counter-ions.[113]

### *Influence of pH-value on viscosity*

XWM systems are not easily affected by pH changes in the range between 1 and 13. Below pH 3, the pyruvic acid acetyl groups are lost,[114] while above pH 9, the side chains undergo stepwise deacetylation.[115] Both have no drastic effect on an XWM system´s viscosity. The viscosity of an XWM system emulsion in food applications can be influenced by the pH-value.[116] Xanthan, being a highly anionically charged polymer, reacts to pH change with a change in its charge density in the side chains. This further leads to a change in the interaction potential and reduces aggregation effects. After neutralization, the side chains become ionized again and reorient themselves to the previous conformation and viscosity.

### *Influence of temperature on viscosity*

XWM systems can tolerate temperature change until the transition temperature is reached while still keeping the viscosity at a constant level. Due to the conformational transition, the viscosity drops. This is a reversible process as already discussed in the "Unimer composition" section. The transition temperature range and the conformational change of the polymer chains depend on the counter-ion concentration in the solvent, and can lie somewhere from 40 °C up to above 90 °C. The helix-coil transition of the (1,4)-β-ᴅ-glucose backbone leads to a decrease in rigidity with rising temperature.[117]

## Compatibility of xanthan gum

### *Alcohol*

Xanthan itself is not dissolvable in alcohol, but alcohol can be mixed into XWM systems. The large number of applications with xanthan in the food and nonfood industry leads to the circumstance that applications with alcohols are also being investigated. A recent study focused on the behavior of XWM systems in the presence of different amounts of ethanol. The study concluded that xanthan concentration and the volume ratio of added ethanol favor a phase separation during the conformation transition. Turbidity formation during the phase separation could also be observed. Aggregate and network formation was also increased by an increased interaction potential at high ethanol content. A proof of heterogeneity was observed by monitoring the zeta potential while adding ethanol. An XWM system mixed with ethanol still undergoes conformational transition. Transition happens when water is preferentially adsorbed by xanthan polymer chains. It was suggested that the phase separation can be used for purification processes.[118] A study of a mixture between an XWM system and poly(vinyl alcohol) revealed that hydrogen bonding formed higher network-like structures.[119] Xanthan – ethanol mixtures found application in cocktails and chocolate liqueurs.[48,120] Xanthan gum can also be precipitated with alcohol from pure xanthan solutions, mixtures, and microbial cultivation broths.[121]

### *Enzymes*

Hydrolytic enzymes, like proteases, cellulases, pectinases, and amylases that are used in food consumption do not degrade xanthan gum. These enzymes are not able to attack the glucose backbone, because it is protected by the trisaccharide side chains.[48] A certain enzyme, xanthan lyase (E.C. 4.2.2.12), is able to remove pyruvate residues on the side chains, which leads to reduced viscosity. Precisely, xanthan lyase catalyzes the eliminative cleavage of the terminal β-ᴅ-mannosyl-(1,4)-β-ᴅ-glucuronosyl linkage of the xanthan side-chain; a 4-deoxy-α-l-threo-hex-4-enuronosyl group remains at the side-chain´s terminus. Another enzyme, hydrolase xanthan depolymerase (endo-β-1,4-glucanase, E.C. 3.2.1.4), is able to separate the glycosidic binding of the backbone of xanthan and other polysaccharides like carboxymethyl cellulose. This way, the xanthan polymer chain length is reduced along with the viscosity as well.[122] The development of synthases and transferases is steadily improving. The goal of current research is to find appropriate enzymes suitable to alter polysaccharide structures efficiently.[123,124]

### *Interaction potential (with galactomannans/glucomannans)*

It is quite common to use galactomannans and glucomannans together with xanthan. Interactions of xanthan with galactomannans depend on the pH-value, the counter-ion concentration of the solution, and the ratio of xanthan to galactomannan. Galactomannans like guar, locust bean, cassia, and tara gum help to stabilize and/or increase the viscosity of a solution. The same is true of glucomannans such as konjac mannan.[125,126] The interaction of xanthan with galactomannans results in a high interaction potential. This not only causes higher viscosities but also enhanced gelation. The degree of polymerization and the number of side chains is the most important factor on the interactions between xanthan and galactomannans.[144] If xanthan is present in its denatured form as random coils, it has a higher interaction potential as after transition when its conformation is a stiff rod-like structure.[127] Acetate and pyruvate content in xanthan is influential on its interaction behavior.[128] The interaction potential of galactomannans increases with polymer chain length, corresponding to higher molecular weight. Xanthan gum with a high pyruvate content exhibits stronger synergistic interactions with galactomannans.[129] Xanthan with minimized acetate content has a higher interaction potential with guar gum than standard xanthan.[130]

## Applications

Xanthan gum's unique rheological and physicochemical properties have led to its widespread use across multiple industries. As a hydrocolloid, it imparts viscosity, thermal stability, compatibility with various salts and pH ranges, and pseudoplastic behavior in liquid systems, making it highly functional in both aqueous and complex formulations as, e.g., combination with other hydrocolloids like locust bean gum and carrageenan. These features have made xanthan gum a multifunctional ingredient in industries ranging from food and pharmaceuticals to oil recovery and biomedical applications.

Xanthan gum's adaptability across sectors is due to its ability to form highly viscous solutions and stable gels, even under harsh processing conditions. Depending on the application, it can function as a thickener, stabilizer, suspending agent, or matrix former. Table 4 summarizes the key application areas and functionalities of xanthan gum across industries:

### Food industry

In food systems, xanthan is primarily used for texture modification, suspension, stabilization, and emulsion control. Its high viscosity at low concentrations, coupled with thermal and pH stability, makes it ideal for diverse applications, including salad dressings, sauces, dairy products, baked goods, and beverages. For example, in frozen products, xanthan provides freeze–thaw stability, preventing syneresis and improving mouthfeel. When combined with galactomannans (e.g., guar or locust bean gum), synergistic effects enhance texture and stability.

#### *Dairy products*

In applications, xanthan is not usually used in a pure form. Mixtures of xanthan with other stabilizers deliver superb performance. A number of dairy products make use of the rheological properties of stabilizers. Stabilizers are used not only for stabilization but also for the mouthfeel and flavor.[131,132] An extension of shelf life is also an important factor for dairy products.[133] Xanthan is typically blended with galactomannans, guar, locust bean gum, and carrageenan. All these are stabilizers and, depending on the application, they are mixed together for frozen and cooled dairy products. These stabilizers are used in products like ice cream, milk shakes, sour cream, water ices, sherbet, cottage cheese, and whipping cream.[134] Ready-to-use blends of locust bean gum, guar, and xanthan mixtures improve also the heat transfer during processing, heat shock protection, and control of ice crystal formation.[48]

#### *Baking industry*

Xanthan enhances a variety of properties in many baked goods. It influences doughs by enhancing the smoothness, elasticity, helps with aeration and improves gas retention.[48] In baked goods, the use of xanthan gum increases the cohesion of starch granules, contributes to the structure and increases shelf-life due to moisture retention.[135] For frozen wheat products and bread, xanthan gum improves the freeze-thaw stability. Using xanthan in refrigerated doughs increases the volume, texture, and moisture retention.[136]

Table 4 – *Representative applications of xanthan gum across industries*

| Industry | Application areas | Functionality | Key properties |
|---|---|---|---|
| Food | Dressings, sauces, dairy, bakery | Thickening, stabilization, suspension | High viscosity, freeze–thaw stable |
| Pharma/Medical | Gels, tablets, wound dressings, dysphagia | Controlled release, adhesion, gelling | Biocompatible, shear-thinning |
| Cosmetics | Creams, lotions, toothpaste | Emulsion stabilization, texture | Smooth gel formation |
| Oil recovery | Enhanced Oil Recovery (EOR) | Viscosity enhancement under stress | Salt- and heat-tolerant |
| Environment | Soil conditioning, 3D printing | Water retention, matrix formation | Biodegradable, eco-friendly |

### *Bread*

Bread containing xanthan gum is softer than bread without, even after days of storage.[137] The use of xanthan in combination with enzymes (amylases and lipases) improves the quality of partially baked breads. Overall, guar gum delivers better results when combined with enzymes.[138] An addition of xanthan to the bread mixture results in an increase in bread height [139] and a reduction in moisture loss and crumb firming during bread storage.[140] Gluten-free breads often use rice, maize, and quinoa flours. In combination with xanthan, stickier doughs (higher water content) produce loaves of higher volume and softer crumb.[141] Hydration is a key factor that influences the final characteristics of gluten-free breads. For good and rapid hydration of doughs and batters, a fine mesh xanthan is used. Such fine mesh ensures better mixing with the ingredients.[142] Test of combinations of different additives with xanthan also demonstrated an increase in baking volume due to xanthan´s capability to bind water and help with the hydration of doughs. Additional benefits are that xanthan allows the use of lower quantities of other additives.[143]

### *Cakes*

Similar as in bread doughs, the addition of fine mesh xanthan gum to cake batters improves the internal structure of crumb, reduces shrinkage, and increases the cake height. Xanthan helps with the uniform distribution of moisture in batters.[144] For instance, the combination of corn flour and xanthan significantly improves the baking quality of sponge cakes.[145]

### *Rice cakes*

Rice cakes are often baked in infrared-microwave combination ovens. Rice flour batters with xanthan deliver high-quality products.[146] Gluten-free rice cakes with xanthan baked this way showed a higher shelf-life capability. Xanthan rice cakes stay softer, have a reduced weight loss and retrogradation enthalpy depending on the oven type used. Infrared-microwave combination ovens deliver products of higher quality.[147]

### *Culinary products*

Xanthan's properties make it ideal for use in this subcategory. That is why it is here that most application options as stabilizer and thickener are found. For example, dressings with xanthan are very stable due to the formation of particle networks.[148] Hydrocolloid use in emulsions in general provides a thickening, structuring or gelling agent in the aqueous environment. A hydrocolloid usually modifies the rheology of the continuous phase and therefore is able to inhibit and even prevent "creaming".[149] Xanthan´s properties make it very potent for this kind of stabilization. This effective way of rheology control works best with lower oil content. The oil droplets are captured, immobilized, and controlled by electrostatic interactions in the XWM system network.[150,151] Higher concentrated emulsions with xanthan exceed 0.1 wt% xanthan. Here, again a rule of thumb: the more oil content, the less xanthan is needed for stabilization. Manageable use levels of xanthan lie around 0.2 % and 0.4 %, depending on the amount of oil used. At high concentrations of xanthan, emulsion droplets become flocculated and build a gel-like network with microscopic areas of separated phases and different viscosities.[152] Further typical culinary products with xanthan gum are sauces, gravies, soups, and convenience foods in general. All have the following in common: excellent long-term stability, and a more or less constant viscosity over a large temperature range. The viscosity drops when used at elevated temperature, such as in soups, sauces or pie fillings. If these products cool down again, the viscosity spontaneously recovers. That provides high quality for pie fillings.

### *Frozen foods*

The addition of xanthan adds stability and consistent viscosity over freeze-thaw cycles and reheating for consumption. Pre-cooked frozen foods and frozen doughs are prone to dehydration. For this reason, starch pastes with xanthan are added for protection.[153] Syneresis control is guaranteed with the addition of xanthan against gel shrinkage. Low pH reduces the syneresis control.[154] In a recent study of wheat gluten xanthan mixtures, the rheological analysis showed that an addition of xanthan gum improved the freeze-thaw stability of the wheat gluten network.[155]

## Pharmaceutical and medical applications

In the pharmaceutical sector, xanthan gum is particularly valued for its bio-adhesiveness, biocompatibility, and ability to form stable gels or suspensions that are non-toxic and biodegradable. It serves a critical role in developing both conventional and novel drug delivery systems.

Xanthan serves as a multifunctional excipient in pharmaceutical formulations used as a thickener, stabilizer, and controlled-release agent in suspensions, gels, ophthalmic solutions, and tablets. Its high biocompatibility has led to its use in drug delivery, tissue scaffolds, and wound dressings. Xanthan-based hydrogels, often in combination with other polymers (e.g., gellan gum), show mechanical

Table 5 – *Applications of xanthan gum in pharmaceutical, biomedical, and cosmetics industries*[160]

| Industry | Applications | Utilization |
|---|---|---|
| Pharmaceutical industry | Solid oral medications | Xanthan gum is used as a binder and disintegrant in solid oral dosage forms, including tablets and capsules, due to its excellent viscosity and gelling properties. It aids in controlled release. |
| | Liquid oral medications | Used as a suspending agent in liquid formulations to ensure uniform dispersion of active ingredients. It improves the stability and texture of suspensions and syrups. |
| | Wound dressings/healing | Xanthan is utilized in hydrocolloid wound dressings, promoting a moist healing environment and preventing microbial contamination. It has biocompatibility and moisture-retention properties. |
| | Drug delivery systems | Used in controlled drug delivery systems, particularly in gels or hydrogels for slow-release formulations. Xanthan’s structure allows for modulated drug release over time. |
| | Ophthalmic medications | Xanthan is used in eye drops and gels, offering viscosity stability and bioadhesive properties to improve drug retention in the eye. |
| | Nasal medications | Acts as a thickening agent and stabilizer in nasal sprays and gels, enhancing the bioavailability and retention time of drugs. |
| | Dosage release | Xanthan’s ability to form viscous gels makes it suitable for controlled release dosage forms, providing a slow and sustained release of active ingredients. |
| | Tissue engineering | Used in scaffolds for tissue engineering, providing structural support for cell adhesion and growth, and aiding in cellular migration. |

properties resembling soft tissue. Furthermore, xanthan is a key component in thickened liquids for dysphagia management. Pharmaceutical industry applications use xanthan for the preparation of various solid, semisolid, and liquid dosage forms. In solid form it is used in tablet or capsule formulations, in liquid medicines as rheology control agent for oral administration. Xanthan is used in ophthalmic liquid doses, where it interacts with mucin.[156] In some forms it is used to control the release of dosages, micro- and nano-particles, and in the form of a biodegradable polysaccharide gel, e.g., for use on skin scaffolds.[157] Xanthan is utilized in nasal medications, where strong adhesive properties are needed.[158] In tissue engineering, it was found that a combination of xanthan and gellan gum with additives can be modified in a way so that the system showed properties very similar to real tissue.[159] Xanthan is also used for surgical wound dressings. For this application, xanthan is mixed with the antibiotic lysozyme and bovine serum albumin.

### *Dysphagia*

A more recent and impactful application of xanthan is in the dietary management of dysphagia, a condition primarily affecting elderly or neurologically impaired patients who have difficulty swallowing. Traditional starch-based thickeners often break down under enzymatic activity (e.g., salivary amylase), leading to unpredictable viscosity changes. In contrast, xanthan-thickened liquids retain their structure, improving safety and comfort for patients with swallowing difficulties.[161–163]

## Cosmetics

The cosmetics industry uses xanthan for rheology control and as a gelling agent. The most common product in the cosmetic industry in which xanthan gum plays a role is toothpaste. Its rheological properties help the toothpaste with extrusion and pumping. Xanthan keeps the toothpaste in form so that it can be applied on the brush and shear thinning improves the dispersion in the mouth.[153] Finally, it also makes rinsing off teeth easier. Further, it is used in cosmetic emulsions. Here, the amount of xanthan in solution greatly influences the attributes before, during, and after application on the skin.[164] Xanthan gum gels give a very soft feeling on the skin due to shear thinning ability, and therefore it is used in creams, lotions, and cosmetic gels. In the cosmetic industry, the filament stretching properties of a cosmetic product is of importance. Emulsions containing xanthan show remarkable stretch-ability compared to other polysaccharides.[165]

## Industrial and environmental applications

At present, xanthan is a widely used water-soluble polymer for polymer flooding in Enhanced Oil Recovery (EOR). Xanthan´s relatively low cost and its biodegradability make it highly desirable in the oil industry. Differences between xanthans make them ideal for varying environmental conditions.[166] The influence of concentration, temperature, and salinity on rheological properties of xanthan gum are really favorable. Other polymers, such as hydrophobically associating polymers, may show better results in their rheological behavior under stress, but in regard to high salinity and temperature, xanthan shows expedient performance.[167] However, a study showed that welan gum exhibited better results compared to xanthan in regard to its rheological properties under stress. Here, welan gum performed better in high salinity and temperature reservoirs, due to its specific macromolecular structure.[168]

### *Soil strengthening*

Traditional additives are used to strengthen collapsible soils. Climate change and environmental consciousness have led to increased application of biodegradable polymers such as xanthan and guar gum. Both decrease dry density and permeability, due to their ability to bind water. The amount of xanthan and curation time is important for high performance against mechanical stress. Interaction between a biopolymer-system and fine soil particles support stabilization. Overall, both biopolymers show high potential as substitutes for non-eco-friendly additives.[169]

### *3D printing of gels*

The 3D printing technology (“additive manufacturing”) is relatively new and novel possibilities are discovered constantly. Fields of application range from printing entire rockets to cutting-edge research in bioprinting organs and tissues, even extending to the printing of customized food products. Different biopolymers such as microbial polyesters (PHA) have been successfully used as inks for 3D printing.[170] A recently published study experimented with the printability of gels based on syrup, xanthan, and konjac gum, and the printing conditions that are necessary to print 3D figures.[171]

## Future trends in novel xanthan derivatives

Xanthan gum has been studied extensively. Its structures (primary, secondary, tertiary, and quaternary) are well reported. The application potential seems endless, as new possibilities of combining with other materials, the use of cheap second-generation carbon feedstocks, and the genetic manipulation of the production strain, open the exploitation of new raw material sources. For instance, the use of spent petro-plastic as a carbon raw material would be an interesting environmentally relevant aspect. In addition, *X. campestris* can be genetically manipulated in such a way that the properties of xanthan are precisely predefined. Understanding and controlling the full interaction potential that comes with the altering natural change in pyruvate and acetylate content and resulting molecular conformations will lead to new discoveries.

## Conclusion

This review has provided a comprehensive and structured insight into xanthan gum, covering its microbial origin, biosynthetic pathways, molecular composition, physicochemical behavior, and its wide range of industrial applications. Key findings highlight that xanthan’s unique rheological properties, such as high viscosity at low concentrations, thermal and pH stability, and pseudoplastic flow stem from its complex molecular architecture, are strongly influenced by cultivation conditions, feedstock composition, and environmental factors.

This review underscores the critical role of genetic and metabolic flexibility in *Xanthomonas campestris*, which allows for tailored production and optimization of xanthan’s structural and functional attributes. Its compatibility with other polymers, response to multivalent ions, and tunable conformation makes xanthan highly versatile in food, pharmaceutical, biomedical, cosmetic, and oil recovery applications.

Despite its well-established industrial use, xanthan gum continues to offer rich potential for innovation. Future research should focus on exploring novel carbon feedstocks (including waste valorization), advancing enzymatic and genetic tools for molecular customization, and leveraging xanthan’s interaction potential in emerging fields such as 3D bioprinting, biodegradable composites, and drug delivery systems.

In summary, xanthan gum is more than just a commercial biopolymer—it is a model system at the intersection of biotechnology, materials science, and applied engineering. Its continued study is poised to contribute significantly to sustainable innovation and cross-disciplinary scientific advancement.

### List of abbreviations

| | |
|---|---|
| EPS | – Exopolysaccharides |
| PEP | – Phosphoenolpyruvate |
| IDP | – Isoprenyl diphosphate |
| GDP | – Guanosine diphosphate |
| UDP | – Uridine diphosphate |
| DO | – Dissolved oxygen |
| $M_w$ | – Weight-average molecular weight |
| $M_n$ | – Number-average molecular weight |
| HPH | – High Pressure Homogenization |
| AFM | – Atomic Force Microscopy |
| DLS | – Dynamic Light Scattering |

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